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Irrigation Scheduling of Soybeans, Corn, Wheat, and Potatoes (CAMaC Progress Report 87-8)

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A Final Report to

Standard Oil Company of Ohio

by

Blaine L. Blad, Vicki B. Samson and Cynthia J. Hays

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IRRIGATION SCHEDULING
OF
CORN, SOYBEAN, WHEAT AND POTATO
USING THE
CROP WATER STRESS INDEX

Growing demand for water resources increases the need for efficient use of irrigation water. Timely application of irrigation water is an important method of improving the efficiency of irrigated agriculture. The Crop Water Stress Index, CWSI, provides a potentially valuable means of signaling when a crop needs water. This study was initiated to determine if irrigation scheduling of soybeans (*Glycine max* (L.) Merr.), corn (*Zea mays* L.), wheat (*Triticum aestivum*), and potato (*Solanum tuberosum*) using the CWSI is feasible.

The soybean study was conducted during the 1985 and 1986 growing seasons, while the corn, wheat and potato crops were studied only during the 1986 growing season at the Sandhills Agricultural Laboratory. Canopy, air and wet-bulb measurements were gathered daily at about 1400 CDT if cloud conditions allowed.

Treatments of full-irrigation, dryland, and CWSI threshold levels were used to evaluate the results of irrigation scheduling with the CWSI. The full-irrigation plots were irrigated once a week based on soil moisture measurements. Dryland plots received only natural rainfall. Irrigation was initiated in a CWSI plot when the calculated CWSI reached or exceeded the selected CWSI.

The well-watered baseline for corn reported in the literature fit our data well. The baseline used for scheduling irrigation of soybeans taken from the literature was significantly different from the baseline derived from our observed (Tc-Ta) vs. VPD relationship. The data for wheat and potato suggest the baseline obtained from the literature was adequate for irrigation scheduling.

We observed significant yield differences between water treatments for any of the crops we studied. The CWSI irrigation scheduling treatments enhanced water use efficiency for corn, soybean and wheat.

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SOME IMPORTANT DEFINITIONS

(Tc-Ta)	Canopy temperature (TC) minus air temperature (Ta)
VPD	Vapor pressure deficit: saturated vapor pressure (SVP) minus actual vapor pressure (AVP).
VPG	Vapor pressure gradient: the difference between foliage SVP and the SVP of the air.
Upper limit	Represents the approximate maximum that (Tc-Ta) would be expected to rise in the absence of transpiration.
Well-watered baseline	Represents the relationship between (Tc-Ta) and VPD under non-limiting soil moisture conditions with the crop transpiring at the potential rate.
CWSI	Crop Water Stress Index: a value representing the degree of water stress a crop is experiencing. The CWSI is determined by: [(Tc-Ta)-well-watered baseline] + [upper limit - well-watered baseline].

Chapter 1

INTRODUCTION

Agriculture is highly dependent on an abundance of water, be it rainfall or groundwater. In the United States, 27% of the agricultural products sold were produced on irrigated land (Stewart and Musick, 1982). Growing demands for water and high energy costs of pumping water increase the need for irrigated agriculture to become more efficient. Efficiency is improved by optimizing production per unit of water applied. It may not maximize yield.

The timely application of irrigation water is an important method of improving the water use efficiency of a crop. Irrigation scheduling requires knowledge of when to apply water and how much water to apply. The Crop Water Stress Index, CWSI, provides a potentially valuable means of signaling when a crop needs water. Using the crop as an indicator for irrigation scheduling should lead to improved water management.

The objectives of this study were: (1) to determine if irrigation scheduling of soybeans is feasible using the Crop Water Stress Index; and, (2) if the technique is successful, to evaluate the effects of the CWSI irrigation scheduling on plant responses and the soil water balance.

Chapter 2

LITERATURE REVIEW

2.1 Plant Responses to Water Stress

Much has been written on the effect of water stress on plants. Begg and Turner (1976), and Hsaio (1973) provided an overview of crop responses to water stress associated with stomatal resistance (rs), leaf temperature (Tl), plant water potential ($\Psi\rho$), photosynthesis (Ps), and transpiration (Tr), all of which are controlled by environmental factors.

Light and carbon dioxide are the main controlling factors of stomatal resistance. But high air temperatures, high radiation levels, or deficits in leaf water may override their effects (Kramer, 1983). In general, stomatal aperature is controlled by plant water potential ($\Psi\rho$). Values of $\Psi\rho$ which cause reduced stomatal aperature, vary among species. Bradford and Hsaio (1982) found that for herbaceous plants the threshold of $\Psi\rho$ varied from -0.5 to -2.5 MPa. Research has shown that the soybean (*Glycine max* (L.) Merr.) threshold of the adaxial leaf surface ranges from -1.0 to -1.2 MPa, and from -0.7 to -0.9 MPa for tomato, *Lycopersicon esculentum* (Waggoner and Shaw, 1952). Plant water potential ranged from -2 to - 4.3 MPa and -0.5 to -1.6 MPa for dryland and fully irrigated wheat, respectively (Ehrler *et al.*, 1978b). Once a threshold $\Psi\rho$ is reached stomatal resistance increases dramatically (Sullivan and Eastin, 1974). Rawson *et al.* (1978) found that the stomatal resistance of soybean cv. Bragg and Ruse increased when $\Psi\rho$ fell below -1.5 MPa.

Although CO_2 influx to carboxylation sites within leaves travels in the opposite direction of water vapor, CO_2 assimilation and transpiration are closely related. In cereal crops, Boyer and McPerson (1975) reported that photosynthesis of cereal plants at -1.8 to -2.0 MPa leaf water potential was 15 percent lower than the rate of the control plants. Specific photosynthetic processes, such as electron transport, photophosphorylation, and possibly carbon dioxide fixation, appear to be reduced at low water potentials.

Heat stress often accompanies water stress. Separating the different effects is not easy (Lawlor, 1979). Plants have broad temperature limits; however, most plants not acclimated or adapted to desert conditions are damaged or killed if kept at temperatures greater than 35 to 40 C for any extended length of time (Bidwell, 1979).

2.1.1 Yield Response to Water Stress

Yield reductions are a significant aspect of water stress effects since maximum yield is generally the goal of crop production. The opening and closing of stomata affect the rate of CO_2 assimilation which ultimately influences yield. Sorghum (*Sorghum bicolor* L.) grown under dryland conditions had a reduced grain-fill period and average yield was reduced by 24.5 percent compared to irrigated sorghum (Sullivan and Eastin, 1974). Constable and Hearn (1978) found that nonirrigated, rainfed soybean cultivars Bragg and Ruse had significantly lower yields than irrigated soybeans. Wien, *et al.* (1979) reported leaf enlargement nearly ceased when soybeans were subjected to plant water potentials of less than -0.4 MPa. This could decrease translocation of dry matter as suggested by Hsaio (1973).

Timing of water stress has been shown to be an important factor in determining crop yield (Doss, 1974). According to Sionit and Kramer (1977) the effect of water stress on yield depends on the degree of stress and stage of growth when it occurs. The greatest yield reductions in corn (*Zea mays* L.) resulted from water stress during both pollination and grainfill stages, while stress during only the vegetative stage caused the least reduction in yield

(Gardner *et al.*, 1981). The period during mid-pod fill to just before seed enlargement is critical for soybean yield (Kadhem, 1985). Water stress during pod-formation or pod-filling resulted in greater yield reductions than stress during flowering stages of soybean (Sionit and Kramer, 1977 and Doss, 1974). Cultivar differences affect the severity of the water stress effect. Momen *et al.* (1979) found "Hark" to be less sensitive than "Rampage" soybean over all critical water stress periods.

2.2. Factors Affecting Leaf Temperature

Leaf temperatures vary with transpiration rates. They are controlled by environmental factors such as air temperature and radiation load as well as by soil moisture conditions (Wiegand and Namken, 1966). If a plant is adequately supplied with water, stomatal resistance is low, the transpiration rate is relatively high and effective cooling occurs. If the plant undergoes water stress, stomatal resistance increases, thereby causing reduced transpiration and increased leaf temperature (Kirkham, 1983).

The relationships between stomatal closure, transpiration, and leaf temperature are best explained by the energy balance concept. The energy balance accounts for heat gained by a leaf from solar radiation and lost or gained by convection, radiation, and evaporation (Tanner, 1963). According to this concept leaf temperature is largely dependent upon solar radiation, windspeed, and transpiration (Gates, 1968).

2.2.1 Effects of Windspeed and Radiation

Wind affects leaf temperature because it can transfer heat or water vapor away from the leaf (Carlson, *et al.*, 1980). In a situation with high net radiation and low relative humidity, transpiration will increase and leaf temperature will decrease with increasing windspeed. At the same time transfer of sensible heat from the warmer air to the cooler leaves may take place which could increase leaf temperature and/or possibly increase transpiration rate. If the ET demand becomes quite high, increased wind could actually cause stomatal closure, decrease the transpiration, and increase plant temperature. On the other hand, if radiation and ET demand are low, increasing windspeed facilitates mixing of the air surrounding the leaf. This increased mixing could also aid the movement of water vapor away from the leaf thereby increasing transpiration (Gates, 1968).

Clawson *et al.* (1980) observed that wind gusts caused as much as a 0.5 C decrease in corn canopy temperature. Fuchs and Tanner (1966) noted a ± 0.3 C variation in canopy temperature due to wind. Canopy temperature reduction in spring wheat (*Triticum aestivum* L.) was associated with canopy cooling by wind (Berliner *et al.*, 1984).

Leaf and canopy temperature are highly dependent on solar radiation (Rs). Wiegand and Namken (1966) found leaf temperature and incoming solar radiation (Rs) to be highly correlated ($r=0.95$). They noted that an increase in Rs from 348 to 1045 W/m^2 of Rs corresponded to a 9 to 10 C increase in leaf temperature. Canopy temperatures of snap beans (*Phaseolus vulgaris* L.) dropped as much as 4 to 5 C within 60 seconds of a decrease in solar radiation (Bonano and Mack, 1983). Clawson *et al.* (1980) found passage of a cloud resulted in a rapid decrease in corn canopy temperature of 2.0 to 2.5 C. After passage of the cloud and return of full sunlight, canopy temperature returned to the original temperature after approximately 1 minute. Sorghum leaf temperature declined below air temperature with Rs of 348 W/m^2 and rapidly increased to air temperature when the solar radiation flux density increased to 697 W/m^2 (Stone *et al.*, 1975). Waggoner and Shaw (1952) noted that tomato leaves on clear days were 3.3 to 3.8 C warmer than air temperatures, while under 80% cumulus cloud cover the leaves were 0.8 C below air temperature.

2.2.2 Transpiration Effects on Leaf Temperature

Transpiration depends on stomatal resistance, windspeed, and the vapor pressure inside and outside of the leaf. The evaporation of 1 kg of water at 20 C consumes about 2.45 MJ (Rosenberg *et al.*, 1983), cooling the leaf through the dissipation of heat via transpiration (Kramer, 1983).

The difference in water vapor pressure between the leaf and the air surrounding the leaf is the 'driving force' which causes movement of water vapor out of plants (Kramer, 1983). This gradient depends on the amount of water vapor present in the air and air temperature. Evaporation occurs into the air and increases in response to the difference between vapor pressures at the leaf surface and that of surrounding air. An increase in air temperature without an increase in vapor content generally increases transpiration since more heat is available for evaporation. The gradient of vapor pressure is also affected by the fact that the amount of water vapor air can hold increases exponentially with increasing temperature (Rosenberg *et al.*, 1983).

2.2.3 Leaf-Air Temperature Difference and Water Stress

Wiegand and Namken (1966) found that reducing transpiration by withholding water resulted in leaf temperature increases of 2 to 5 C. According to Hsaio (1973), stomatal closure is the main cause for transpiration declines as water stress develops. Thus it follows that stomatal closure of sunlit leaves results in increased leaf temperature if Rs, windspeed, and vapor pressure remain constant (Ehrler *et al.*, 1978a).

Aston and van Bavel (1972) found that pea (*Vigna sinensis* L.) leaves increased 2 C in temperature. Bartholic *et al.* (1972) used a thermal scanner to compare canopy temperatures of cotton (*Gossypium hirsutum* L.) under three irrigation levels. They found dryland cotton was 6 to 7 C warmer than the fully irrigated cotton. On clear, warm days well-watered barley (*Hordeum vulgare* L.) leaves were 6.5 C cooler than barley leaves of a dry field (Millar *et al.*, 1971). Ehrler *et al.* (1978b) noted that at solar noon canopy minus air temperature (Tc-Ta) was negative in fully irrigated wheat and positive in dryland plots.

At high vapor pressure deficits (VPD) cotton leaf temperature was generally 3.2 to 5 C below air temperature (Ehrler, 1973). Even with partially closed stomates, transpiration adequately cooled leaves below air temperature. Carlson *et al.* (1972) found (Tc-Ta) of soybeans to increase (become less negative) when VPD or relative water content, RWC, (the ratio of field fresh weight to turgid fresh weight) decreased. This indicates that the increase in Tc relative to Ta is because of a decrease in evaporative cooling. Carlson *et al.* (1972) noted a negative linear relationship between (Tc-Ta) and RWC since increased stomatal closure caused a reduction in evaporative cooling. Sojka and Parsons (1983) found that (Tc-Ta) was highly correlated with $\Psi\rho$ in soybeans. When drought lowered soil water potential below -0.16 MPa, (Tc-Ta) became positive throughout the day and $\Psi\rho$ ranged from -2 to -4.3 MPa in wheat plots (Ehrler *et al.*, 1978b). Jackson *et al.* (1977) believes (Tc-Ta) is a good indicator of water stress because stress causes stomatal closing, which reduces transpirational cooling and allows sunlit leaves to increase in temperature.

2.3. Temperature Based Stress Indices

2.3.1. Stress-Degree-Day

Based on the stress-induced canopy temperature relative to air temperature, Idso *et al.* (1977) developed the stress degree day (SDD) theory. The SDD concept is based on the idea that a well-watered crop will transpire at the potential rate, causing the crop to be cool relative to the air temperature. When enough water is extracted from the soil, transpiration will be reduced and the crop will increase in temperature.

The SDD is a daily value of (Tc-Ta), where Tc is measured with an infrared thermometer (IRT), generally between about 1200 and 1400 solar time. Daily SDD values are summed, beginning at day i and ending on day N, expressed as:

$$SDD = \sum_{n=i}^{N} (Tc - Ta)_n$$

According to the concept if the SDD becomes positive yield is reduced. Jackson *et al.* (1977) showed that wheat plots receiving adequate water consistently had canopy temperatures well below Ta, a SDD of about -100 for the season, and high yields. Wheat plots with positive SDD values showed yield reductions.

Idso *et al.* (1977) found a linear relationship between SDD values and wheat yield. Idso *et al.* (1980) used a linear regression of SDD on accumulated solar radiation for the season to predict yields of barley, alfalfa, soybean, sorghum, kidney bean, and wheat. Findings similar to those of Idso *et al.* (1977), showed a negative relationship between SDD accumulation and yield of red kidney beans (Walker and Hatfield, 1979). VPD effects on Tc and the SDD value were noted in snapbeans by Bonanno *et al.* (1983). As VPD increased, Tc decreased relative to Ta, and SDD values became more negative in the fully irrigated treatment. At high VPD levels even stressed plants had a Tc lower than Ta. The fully irrigated treatment yield was significantly higher than all SDD treatments, but it received twice as much irrigation water as the 10 and 15 SDD treatments.

2.3.2. Canopy Temperature Variability

Other uses of canopy temperature as a stress indicator are in the calculation of the canopy temperature variance (CTV) and a comparison of Tc of a stressed plot to that of a well-watered reference plot. Clawson and Blad (1982) used the CTV and stressed Tc versus well-watered Tc to schedule irrigations for corn. Irrigation water was applied if the CTV of a plot became greater than 0.8, and in the stressed vs. well-watered plots water was applied when differences between the well-watered and stressed plots of 1 or 3 C occurred. Under mild stress the stressed vs. well-watered difference might be near 0, but CTV fluctuated from 0 to -0.7 degrees. Stressed vs. well-watered differences increased linearly with increased CTV, and as stress increased the CTV leveled off. It was concluded that the CTV method could be used to indicate the onset of stress. The stressed vs. well-watered method indicated the severity of water stress, but yields were reduced when this approach was used.

Hatfield *et al.* (1984) noted that the variability of sorghum Tc measured at solar noon was greatest in nonirrigated fields. As soil moisture was depleted, Tc variance increased. Following an irrigation event, which brought the soil to field capacity, Tc variances were small. The variances increased as the soil water was extracted from the profile. There was no consistent relationship between Tc variance and soil moisture extracted from the 1.50 m profile. They concluded that the variance method wasn't sensitive enough to detect soil moisture depletion for irrigation scheduling. However Tc variance may be useful to evaluate water distribution efficiency in a field.

2.3.3. Crop Water Stress Index

Before Idso *et al.* and Jackson *et al.* (1977) developed the SDD, Ehrler (1973) was examining a similar approach to detect water stress. He believed (Tc-Ta) alone was not an adequate measure of water stress. He (Ehrler, 1973) determined that a linear relationship existed between (Tc-Ta) and VPD, and used a linear regression of (Tc-Ta) on VPD to account for evaporative cooling changes due to VPD.

In 1981 Idso *et al.* (1981b) 'normalized' (Tc-Ta) for VPD, and termed the regression of (Tc-Ta) and VPD for a well-watered crop as the well-watered baseline. The well-watered baseline represents the (Tc-Ta) which would occur at a given VPD when plants are transpiring at the potential rate. At the other extreme is the situation where stress has caused the stomates to close and transpiration is approximately 0. The upper limit, or (Tc-Ta) maximum, is the approximate limit of (Tc-Ta) in the absence of transpiration.

The upper limit is determined by extending the well-watered baseline into the negative VPD region a distance equal to the vapor pressure gradient. The vapor pressure gradient (VPG) is calculated by:

$$\mathrm{VPG} = e_c^* - e_a^*$$

where e_c^* is the saturated vapor pressure at canopy temperature, and e_a^* is saturated vapor pressure at air temperature (Idso *et al.*, 1981b).

The crop water stress index (CWSI) is, at any given VPD, the ratio of the vertical distance of an observed point above the lower line (baseline) to the total distance between the upper limit and the baseline. The resulting value is representative of the degree of water stress experienced by the crop (Idso *et al.*, 1981b). The calculation of the CWSI is graphically explained in Fig. 2.1. Given a VPD of 2.1 kPa, point C represents the maximum (Tc-Ta) if transpiration is 0, point B is the (Tc-Ta) of a crop transpiring at the potential

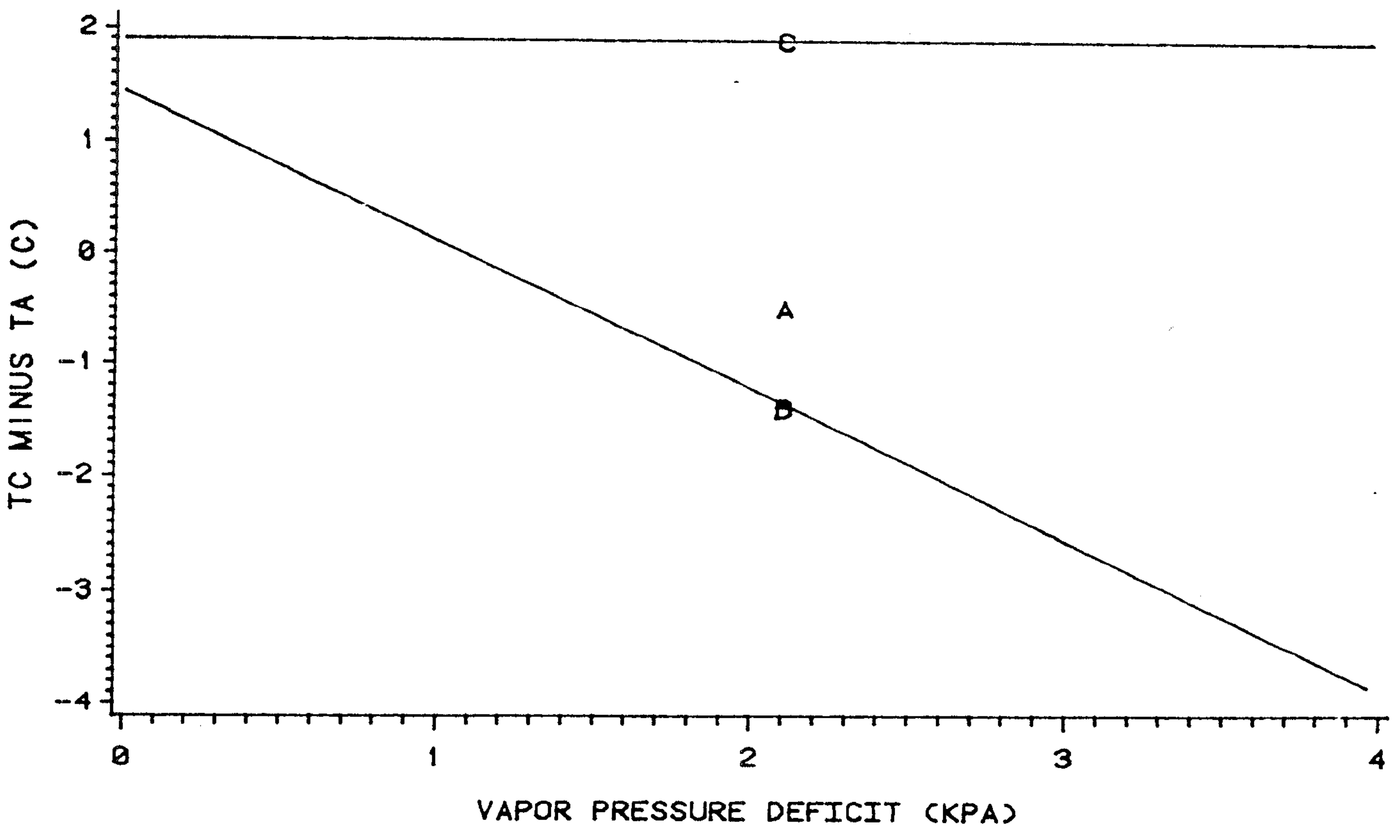


Figure 2.1 Example of a CWSI calculation.

rate, and point A is the current situation. By taking the distance from C to B, and dividing by the distance from A to B, a CWSI value results (Jackson *et al*. 1982a).

2.3.4. Energy Balance Calculation of the CWSI

Net radiation (Rn), soil heat flux (S), sensible heat flux (H), and latent heat flux (LE) affect plant temperatures according to the energy balance concept. The flux of H depends on the air temperature gradient and the aerial resistance to the flow of sensible heat. Aerial resistance (ra), canopy resistance (rc), VPD, Rn, and S affect the flux of LE. Theoretically, the energy balance considerations enable one to relate the CWSI to the amount of plant water stress better than the Idso *et al*. (1981b) method. Jackson (1982b) developed a well-watered baseline based on the energy balance fluxes as follows:

$$(Tc - Ta) = \frac{raRn}{\rho a\ C_p} * \frac{\gamma}{\Delta + \gamma} * \frac{VPD}{\Delta + \gamma}$$

where ρa is the density of air (1.2 kg/m^3), Cp is the heat capacity of air (10^3 J/kg/C), γ is the psychrometric constant (kPa/C), and Δ is the slope of the saturation vapor pressure versus temperature line (canopy saturation vapor pressure, SVP, minus air vapor pressure/(Tc-Ta)). This baseline approximates the situation of a well-watered crop where the canopy resistance, r_c, =0, and transpiration is at the potential rate.

The upper limit equation developed by Jackson (1982b) is:

$$(Tc - Ta) = \frac{raRn}{\rho a\ C_p}.$$

In this equation it is assumed that rc has reached infinity and transpiration is 0. In an experiment with wheat, the CWSI calculated with the energy-balance approach ranged from 0 to 1. It increased until an irrigation event, and then gradually decreased (Jackson *et al.*, 1981). Sensitivity analysis showed (Tc-Ta) to be most affected by ra at low VPD values (Jackson, 1982a).

2.3.5. Factors Affecting the CWSI

Plant and environmental factors which affect Tc, in turn influence the CWSI. The effects of Rn, VPD, and wind on Tc were discussed in section 2.2. The method of Jackson *et al.* (1982b), discussed in section 2.3.4, accounts for Rn, VPD, and wind (implicit in ra), but wind can still cause variation in the CWSI. High windspeeds can cause underestimation, while low windspeeds yield an artificially high CWSI (O'Toole and Hatfield, 1983).

Soil background is another important factor which influences the Tc measurement and thereby the CWSI. Howell *et al.* (1984) observed soil temperatures higher than 60 C in an experiment on cotton. The elevated background temperatures may have caused the CWSI to be greater than 0.2 early in the season, even with adequate soil moisture. Theoretically, the CWSI should range from 0 to 1, although scatter in the (Tc-Ta) and VPD data make exceptions possible. Pinter and Reginato (1981) and O'Toole and Hatfield (1983) reported CWSI values outside the normal range of 0 to 1. Variation in the regression line of (Tc-Ta) on VPD was noted as the cause of extreme CWSI values.

Research results on the variability of the baselines for different crops are conflicting. Differences in the slopes of two alfalfa baselines from 1980 and 1981 were noted by Kirkham *et al.* (1983). Because the range of VPD values differed from 1 to 3 kPa in 1980 and 1 to 7 kPa in 1981, they speculated that the VPD differences could have caused the differences in slopes of the baselines. Howell *et al.* (1984) derived 3 different well-watered baselines for cotton from 3 separate experiments. The first involved row spacing, the second irrigation during different growth stages, and third, irrigation water at 3 salinity levels.

The nonstressed baseline was not affected by row spacing, and the two baselines from the irrigation experiments were identical and consistent with the findings of Idso *et al.* (1984).

Different methods of calculating the CWSI were compared by Abdul-Jabbar *et al.* (1985). They compared the Jackson *et al.* (1982b) equations using 3 different methods of determining ra, as well as the Idso *et al.* (1981b) method. Results of the comparisons show the Idso *et al.* (1981b) and Jackson *et al.* (1982b)-heat transfer methods related well to evapotranspiration-potential evapotranspiration ratio (ET/ETp) and the yield of alfalfa.

A possible explanation for the reported inconsistencies of well-watered baselines is varietal differences in leaf size and architecture. Idso (1984) conducted experiments to: 1) determine if plant architecture, or 2) leaf size affected the baseline equation. Six wheat varieties were compared, all had similar leaf sizes, but different architectures (planophile or erectophile). The baseline applied to each variety equally well. Baselines for 3 leaf sizes (60, 120, and 180 mm diameter) of water hyacinths were determined and compared. The slopes were identical but the intercepts were different. The 60 mm leaved plant had an intercept of 9 C, while the 120 and 180 mm leaved-plants had intercepts near 4 C. Idso concluded that architectural differences in wheat did not affect the slope of the baseline, however, leaf size was a major determinant of leaf temperature, and in turn, the intercept of the well-watered baseline.

2.4 Irrigation Management

2.4.1 Traditional Approaches to Scheduling Irrigation

Irrigation scheduling involves estimating when to irrigate and how much water to apply in order to avoid adverse affects on the yield of the crop.

Soybean yields benefit greatly from timely applications of irrigation water (Meyer and Fischbach, 1980). Yield is one consideration in irrigation scheduling decisions, but efficient use of water may be even more important than yield in many regions of the world. Economic benefits can be realized with proper irrigation scheduling through increased yields and decreased production costs.

The variables that are monitored in irrigation scheduling methods can be categorized into 3 groups: 1) plant, 2) soil, and 3) meteorological. Plant parameters include: plant water potential, stomatal resistance, and leaf temperature. These measurements can indicate the presence and degree of water stress. Plant parameters may be quite variable within a field and thus require many samples to obtain a representative field average. Plant characteristics are thought to be the most responsive to water stress (Sojka and Parsons, 1983) of the three groups. Water should be applied when the plant indicates it is necessary.

Soil moisture measurements have been used to schedule irrigation for many years, in part because of the ease with which these measurements can be made. Some farm managers are experienced enough to determine if irrigation is necessary by feeling how dry soil is. A more precise method employs use of resistance blocks. With resistance blocks the electrical resistance is proportional to the amount of moisture in the soil. Using information gained in this manner one can estimate the amount of water to be applied and when to irrigate. A problem with the use of soil moisture measurements to schedule irrigation is that these are point measurements and may not be representative of the true moisture situation throughout the field.

The use of meteorological methods for estimating ET rates for irrigation scheduling is becoming more common. For example, ET rates obtained with meteorological methods appear in daily newspapers in certain areas and for selected crops. With information about the amount of precipitation received since the last irrigation coupled with the ET information it is possible to estimate the amount of water that should be applied and to predict when irrigation is necessary.

ET estimates for irrigation scheduling can be determined using several methods, each of which may require different types of meteorological data. Blaney-Criddle uses only mean monthly temperature and monthly percent daylight hours, while Penman's approach requires maximum-minimum temperatures, wind run, solar radiation, and dew point temperature data on a daily basis. Rosenberg *et al.* (1983) gives descriptions and equations for these and many other methods of estimating ET.

The American Society of Civil Engineers (1973) compared 15 methods of estimating ET in humid and arid regions. Penman's combination approach gave the best overall results in most locations, although it tended to exceed actual ET in humid locations. With nearly all methods ET estimates must be calibrated against local lysimeter measurements to be confident of obtaining reasonable estimates of crop water use.

2.4.2. Irrigation Scheduling Using the CWSI

It has been postulated that the CWSI can be used as a method of irrigation scheduling, however, most research has focused on the CWSI only as an indicator of crop water stress. Relationships between the CWSI and relative water content, leaf water potential, soil moisture, and yield have been investigated (Abdul-Jabbar *et al.*, 1985; Howell *et al.*, 1984; Jackson, 1982a; and Kirkham *et al.*, 1983 and others).

Plant water potential (Ψp) differences of -0.16 MPa in alfalfa (*Medicago sativia* L.) grown under moisture stressed conditions were detected with the CWSI

(Idso *et al.*, 1981b). In cotton $\Psi\rho$ was highly correlated with the CWSI (Pinter and Reginato, 1981). In cotton Howell *et al.* (1984) found a $\Psi\rho$ of -2.4 MPa for a CWSI of 0.7 and for a CWSI of 1.0 the $\Psi\rho = -2.8$ MPa.

Jackson (1982a) found no unique relationship between soil moisture and the CWSI of wheat. The CWSI increased with time as did the amount of extractable water used; however, after irrigation the CWSI required 5 or 6 days to reach a minimum. This recovery period suggests that no unique relationship exists between the CWSI and soil moisture, at least for wheat.

As alfalfa yield decreased, CWSI increased in a linear manner for the Idso, the Jackson-convective heat transfer, and the Jackson-leaf boundary layer methods (Abdul-Jabbar *et al.*, 1985). Well-watered cotton plots had a mean lint yield of 1,413 kg/ha and maximum CWSI of 0.30. The CWSI of the stressed plots reached 0.63, but the yield was only 256 kg/ha less than the mean well-watered yield (Reginato and Howe, 1985).

Only a few scientists have actually tested the hypothesis that the CWSI can be applied to irrigation scheduling. Using an energy balance approach Slack *et al.* (1981) used the CWSI to schedule irrigation in cotton. Soil moisture status was also used to schedule irrigations in the well-watered treatment. There were no significant yield differences among irrigation treatments but less water was used in the CWSI scheduled treatment. Similar results were also reported by Geiser *et al.* (1980) for a corn crop. Using the CWSI (Idso *et al.* 1981a) to schedule irrigations of soybeans and corn Nielsen (1986) reported that results looked promising. The CWSI threshold was correlated with irrigation water applied and final grain yield for both crops.

Chapter 3

MATERIALS AND METHODS FOR SOYBEAN MEASUREMENTS

A discussion of the measurements gathered is included in this chapter. The experimental site, soil water measurements, infrared thermometry theory, and techniques are explained. Plant characteristics of growth, plant water stress and the measurement of these variables are discussed.

3.1 Experimental Site

This study was conducted in 1985 and 1986 at the Sandhills Agricultural Laboratory (41 37′ N, 100 50′ W) which is in northeast McPherson County, about 65 km (40 mi.) north of North Platte, Nebraska. The site was selected, in part, because the sandy soil there has a low water holding capacity and growing season precipitation seldom meets ET demands.

The Sandhills Agricultural Laboratory (SAL) consists of approximately 22 ha (55 acres) irrigated with a solid set sprinkler system. Most of the cropped area was planted to corn and soybeans, as shown in Figs. 3.1 and 3.2. The individual plots were 18.3 m east-west by 36.6 m north-south (60 x 120 ft.). Each plot was irrigated with sprinklers on 2 m risers, spaced 9 m (30 ft.) apart. The sprinkler laterals bordered each plot on the E-W at 18.8 m (62 ft.) intervals. The irrigation line locations and other details are shown in Fig. 3.3.

3.1.1 Soil Classification

The Sandhills Agricultural Laboratory is located in the Valentine-Anselmo Soil Association, and the soils were mapped as Valentine fine sand, Typic Ustipsamment according to the McPherson County Soil Survey (Sherfey, 1969).

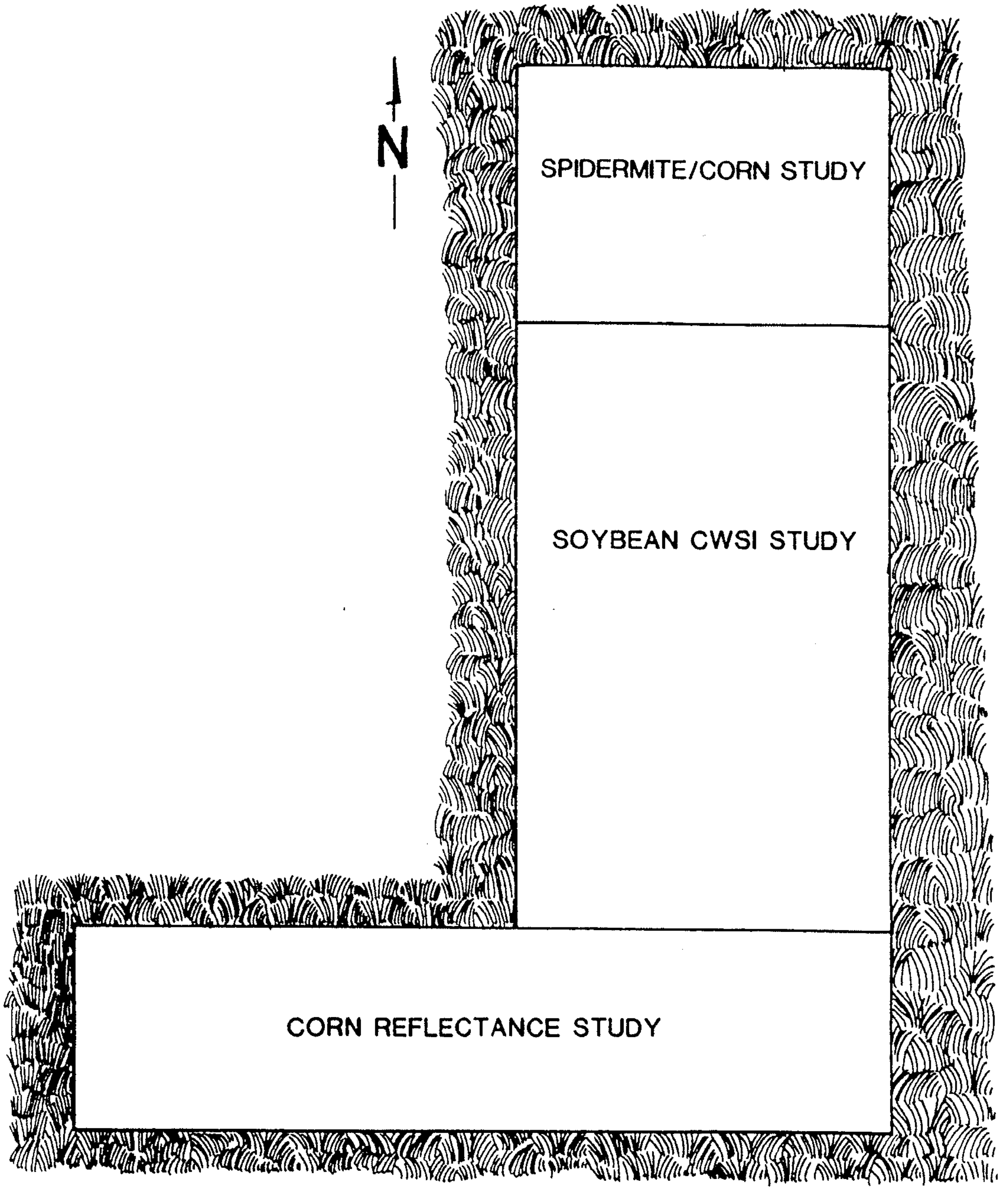


Figure 3.1 Plot areas of the Sandhills Agricultural Laboratory for 1985.

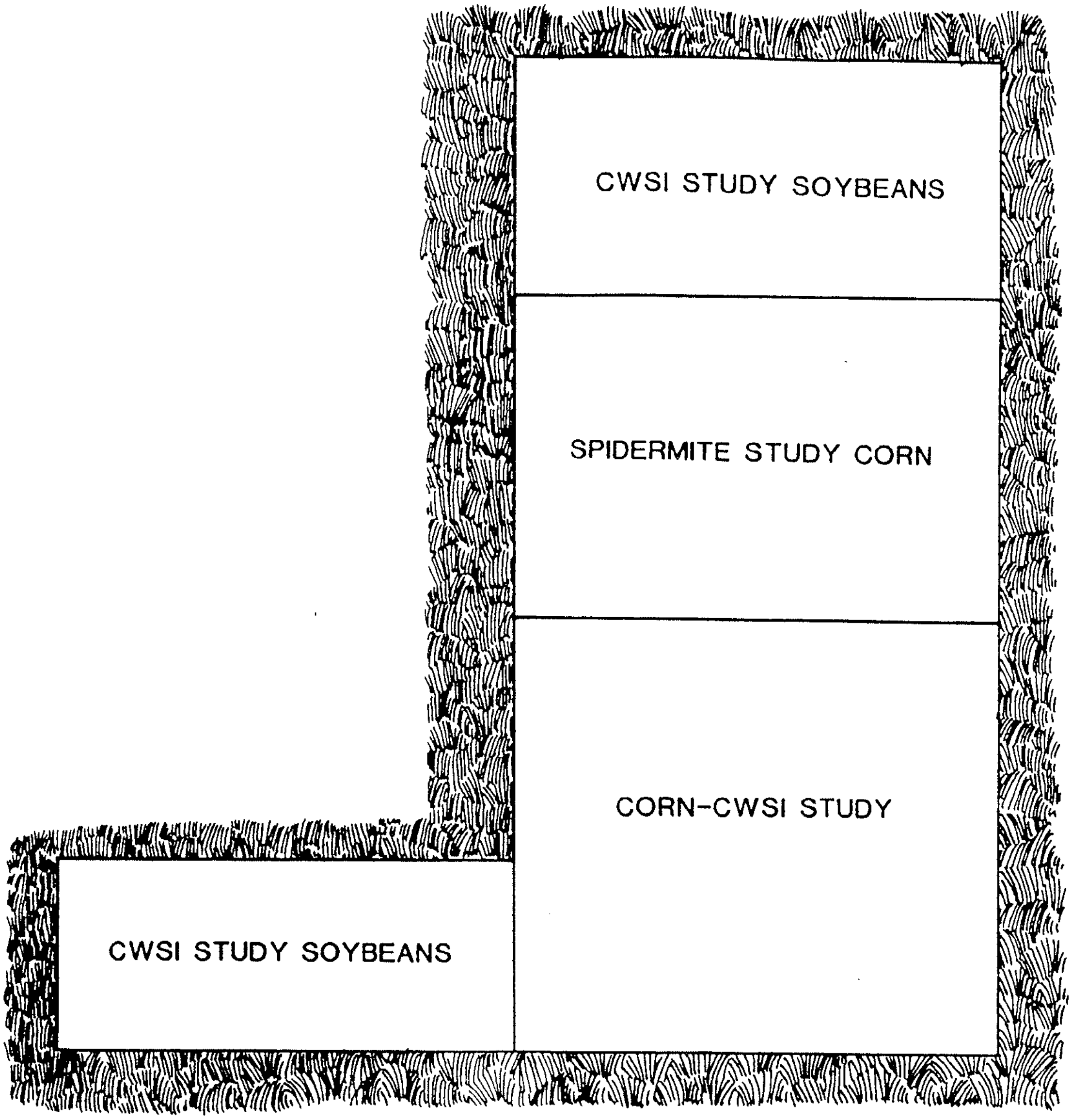


Figure 3.2 Plot areas of the Sandhills Agricultural Laboratory for 1986.

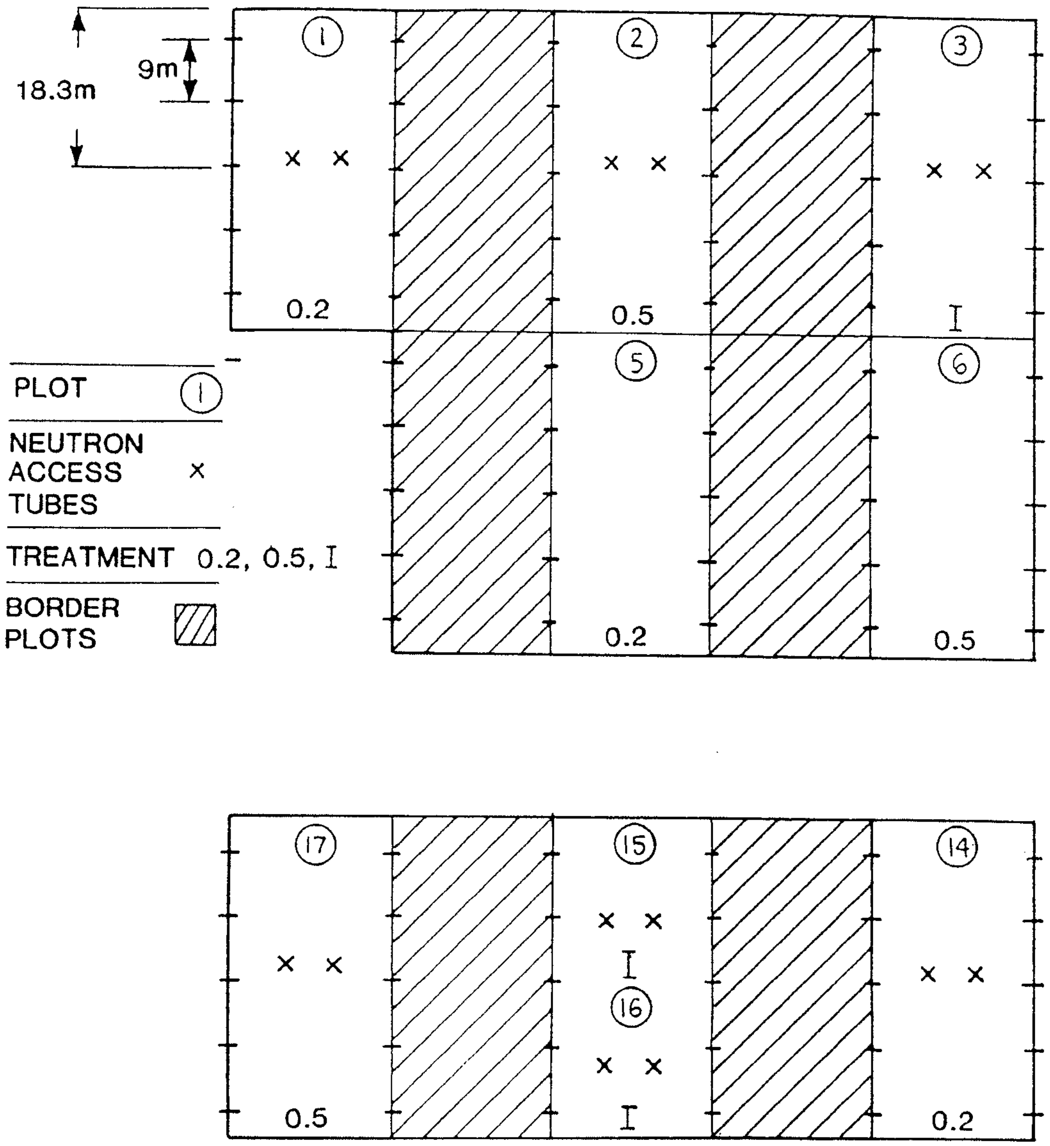


Figure 3.3 Details of the experimental plots at the Sandhills Agricultural Laboratory in 1986.

Lewis (1976) later surveyed 5 sites in the area and found inaccuracies in the original classification. The soils were of predominately fine and very fine sands; however, at some sites buried horizons containing clay (illite and kaolinite) and silt were discovered by Lewis.

Subsequently, the soil of the SAL solid set area has been reclassified as Valentine fine sand, loamy substratum phase. The substratum horizons are important to note because they affect the water holding capacity of the soil. This information is summarized in Table 3.1 for two sites included in the study area.

3.1.2 Cultural Practices

Soybeans (cv. Harosoy) were planted May 18, 1985 and on May 21, 1986, with 0.76 m (30 in) row widths in a N-S orientation. The rate of planting was 58.4 kg/ha (52 lb/acre) which resulted in a final plant population of 127,659 in 1985 and 191,199 plants/ha in 1986. Treflan herbicide was applied as a preplant method of weed control in both years. The plots were mechanically cultivated early in the season, and hand weeding was necessary later in the season.

Twelve rows 4.6 meters (15 ft.) in length, were hand harvested from each plot on 17 October, 1985 and 20 October, 1986. After mechanically threshing and cleaning the seed, 100-seed and total seed weights were recorded and corrected to 13% moisture.

3.2 Soil Moisture Measurements

Soil moisture was measured in 1986 using a neutron hydroprobe (model 503, Campbell Pacific Nuclear Corp., Pacheco, Calif.), while during 1985 a Troxler Electronics, Inc. probe (model 2651, Raleigh, N.C.) was used. Two neutron access tubes were placed in each plot 2-3 weeks after seedling emergence. The locations

Table 3.1 Particle-size distribution (%) and water holding capacity (cm H20/cm soil) by horizon for two sites at the Sandhills Agricultural Laboratory solid set irrigation area. The textural class is defined by: f=fine, s=sand, l=loamy. (after Lewis, 1976).

Depth cm	Horizon	Fine sand	Very fine sand	Total sand	Silt	Clay	Textural class	Avail water
				Site 1				
0-30	A1	42.6	32.0	88.1	5.2	5.6	fs	.05
30-45	AC	42.9	30.9	86.9	6.0	6.6	lfs	.08
45-85	C1	43.1	33.4	88.1	5.8	6.1	lfs	.08
85-120	C2	47.1	40.7	92.7	0.3	7.0	fs	.05
120-140	IIAb	36.2	32.5	77.2	8.4	14.5	fsl	.13
140-155	IIBb	30.6	26.1	64.0	19.7	16.3	fsl	.13
155-177	IIIAb	40.4	33.3	82.7	4.7	12.5	lfs	.08
177-225	IIIC	52.9	30.7	94.6	2.0	3.5	fs	.05
				Site 2				
0-20	Alp	47.1	25.8	89.4	3.5	7.2	lfs	.08
20-43	Al2	47.7	23.8	87.8	2.9	8.7	lfs	.08
43-73	AC	46.1	25.2	88.7	1.7	8.6	lfs	.08
73-135	C1	52.2	23.8	92.5	0.7	6.9	fs	.08
135-180	C2	53.6	23.4	91.9	0.2	7.9	fs	.08

of the access tubes are shown in Fig. 3.3. Soil moisture was sampled at 6 depths: 0.1-.15, .15-.30, .30-.60, .60-.90, .90-1.2, and 1.2-1.5 m. Each depth was sampled for 30 seconds, and ten standard 30 second counts were taken each day that samples were collected. The Campbell probe was cross-calibrated with a Troxler probe which was previously calibrated for the soils in the area.

A water balance approach was used to determine evapotranspiration on a weekly basis and for the growing season. The following equation was used:

$$ET = I + P + Ex$$

where I is the amount of irrigation, P is precipitation, and Ex is the weekly water consumed by the crop as determined with the neutron measurements (Rosenberg *et al.*, 1983). Drainage was assumed to be negligible.

3.3 Infrared Thermometry

3.3.1 Theory

All objects emit radiation in proportion to their temperature. The amount of radiated energy is quantified by the Stefan-Boltzman Law which is:

$$E = \epsilon \sigma T^4$$

where E is the radiation emitted by an object, σ is the Stefan-Boltzman constant ($5.67 * 10^8$ W/m^2/K^4), ϵ is emissivity of the object, and T is the temperature in K (Tanner, 1963). Emissivities for green plant canopies range from 0.96 to 0.98 (Fuchs and Tanner, 1966). By measuring the longwave radiation emitted by a crop and applying Stefan's Law the temperature of a crop canopy can be determined.

3.3.2 Measurement Procedures

An Everest 'Agri-therm' infrared thermometer (Everest Interscientific, Inc., Tustin, Calif.) was used in this study. The specifications of the instrument are: field of view of 3 degrees; resolution of 0.1 C; accuracy of ± 0.5 C; and waveband of 8 to 14 μm. The IRT performance was checked using a portable black body (model C8-1000, Everest Intersci.), each day before and after data were collected.

Data to be used in the irrigation scheduling process were gathered between 1400 and 1500 CDT. Temperature measurements (Tc, Ta, wet bulb temperature, Wb) were not made while the sun was obscured by clouds. A total of 10 instantaneous measurements were taken, 5 facing south and 5 facing north in each of the 9 plots. The IRT was hand-held at approximately 1 to 1.5 m above the canopy at an oblique angle of about 30 degrees.

In 1985 the average canopy temperature for each plot was corrected for reflected incoming longwave radiation as described by Blad and Rosenberg (1976) and Fuchs and Tanner (1966). The corrected canopy temperatures were found to be approximately 0.5 C warmer than the uncorrected canopy temperatures. Because the baseline used in 1986 was derived from uncorrected canopy temperature data, the canopy data gathered during the 1986 experiment were not corrected for reflected incoming longwave radiation.

Because soil temperatures are generally warmer than canopy temperatures during the day, collection of data did not begin until July 24, 1985 (day 205) and on July 10, 1986 (day 191). The crop was at growth stage V8, R1, beginning bloom and V8, R2, full bloom, (Fehr and Caviness, 1977) in 1985 and 1986, respectively. Data collection ended when soybean plants reached senescense, which occurred September 11, (day 254) 1985 and September 17, (day 260) 1986.

Heilman *et al*. (1981) found the difference between actual canopy temperature (Tc) and the composite of Tc and soil to be highly correlated with percent canopy cover. When data collection began July 10, canopy cover was approximately 75%, but by August 5 was at least 95% complete. In 1985 canopy cover did not reach 95% complete until near the end of the study.

On selected days measurements were made hourly from 1100 to 1500, and directional Tc data were gathered. Data were collected during overcast days on a few occasions.

3.4 Irrigation Scheduling Procedures

The calculation of the crop water stress index (CWSI), as discussed in section 2.3.3, requires canopy (Tc), air (Ta), and wetbulb (Wb) temperature measurements. The collection of Tc data was previously explained. The Ta and Wb data were gathered in each plot concurrent with the Tc measurements. A portable, battery-powered aspirated Psychrometer was used in 1985 to gather Ta and Wb measurements in each plot approximately 1 meter above the canopy. A wind aspirated minipsychrometer was used to measure Ta and Wb in 1986. One psychrometer was placed in each plot approximately 1 meter above the canopy. Copper-constantan wire (10 mil) was used to form the wet and dry bulb junctions. The construction of these psychrometers is detailed by Clawson (1980). A digital thermocouple thermometer was used to measure Ta and Wb in degrees C. Tc data were recorded by a portable data logger (Polycorder, Omnidata International, Logan, Utah).

All data were transferred to a personal computer (IBM, PC) where a FORTRAN program was used to determine the CWSI value. The average Tc for a plot was calculated from the north and south facing Tc values. Saturated and actual vapor pressures, SVP and AVP, respectively, were determined using standard meteorological equations (List, 1984). The vapor pressure deficit (VPD) was then determined from the difference between SVP and AVP. The vapor pressure gradient (VPG) was explained in Section 2.3.3., and is evaluated by:

$$\mathrm{VPG} = \mathrm{SVP} - 0.61078 * e^{[(17.26989*(\mathrm{Ta}+\mathrm{B}))/(\mathrm{B}+\mathrm{Ta}+237.3)]}$$

where SVP is in kPa, e is the natural log, B is the intercept of the well-watered baseline, and Ta is air temperature in C (Idso *et al.* 1981).

The upper limit (UL) was determined by:

$$UL = B + (M*VPG)$$

where B and M are the intercept and slope, respectively, of the upper limit and baseline equations (see Idso *et al.*, 1981b). The baseline used in the experiment was a linear regression of VPD on (Tc-Ta) for a well-watered soybean crop. The well-watered baseline developed by Idso (1982) is:

$$(Tc-Ta)\ (baseline) = 1.44 - 1.34 * VPD$$

(Tc-Ta) is at a specific vapor pressure deficit.

Based on the definition of the CWSI (Section 2.3.3), the CWSI was calculated using the following equation:

$$CWSI = \frac{(Tc-Ta) - baseline}{UL - baseline}$$

where (Tc-Ta) minus the baseline is the distance from the observed (Tc-Ta) to the baseline (Tc-Ta). This value is divided by the total distance between the upper limit (UL) and the baseline (Tc-Ta). An example of the CWSI calculation is shown in Fig. 3.4.

The CWSI was calculated in basically the same manner in 1985, except for the upper limit and the baseline equations. The upper limit was set at 3 C, and the baseline equation was:

$$(Tc-Ta) = 2.67 - 2.059 * VPD.$$

Irrigation was applied when the calculated CWSI reached, or exceeded, the assigned CWSI threshold value for a plot. The threshold assigned was based on the degree of water stress desired. The 0.2 theoretically would allow a lesser degree of stress to occur than the 0.5 CWSI threshold. An irrigation event was 2 hours and 15 minutes long with an application of 25 mm of water.

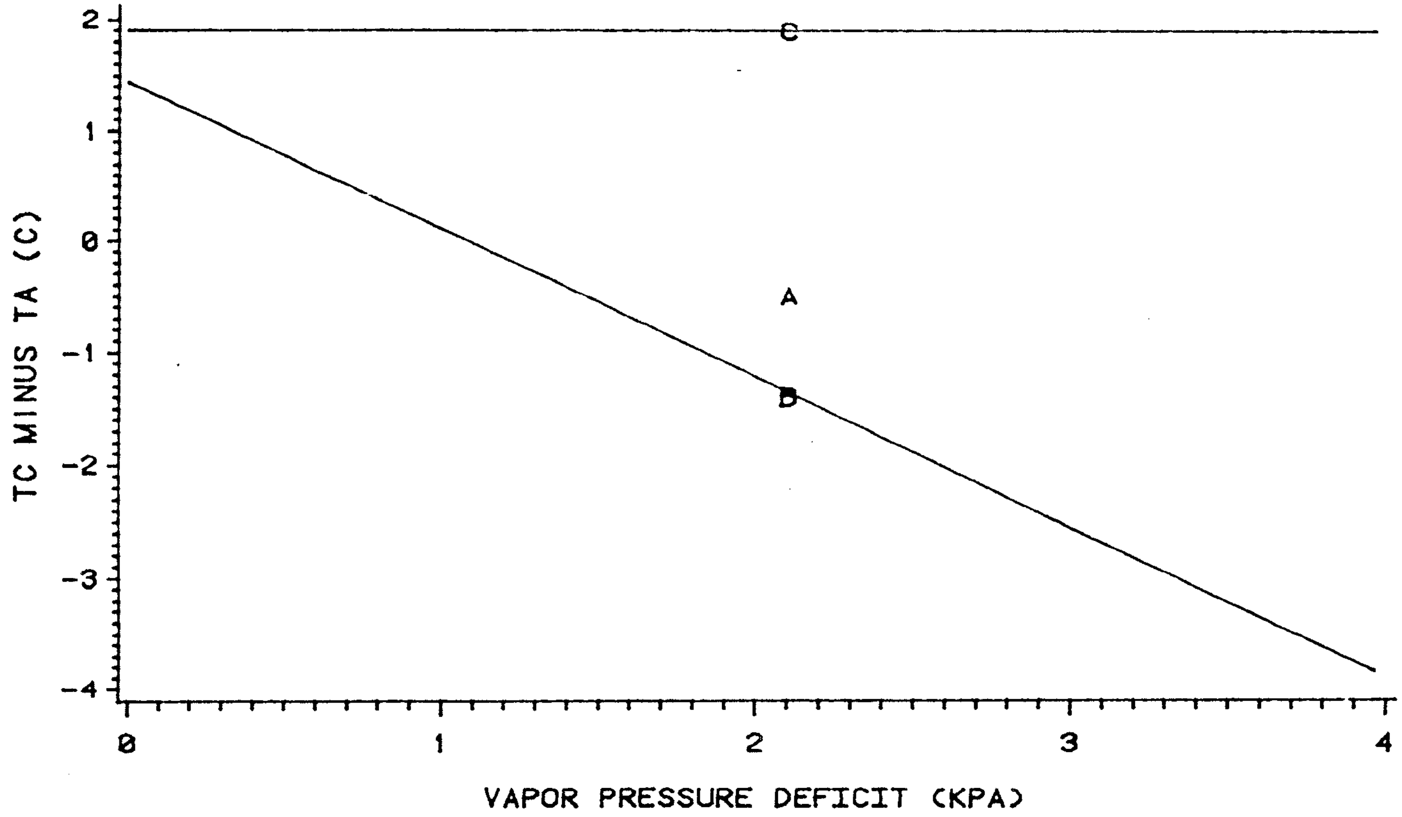


Figure 3.4 Example of a CWSI calculation. At a VPD of 2.1 kPa the baseline (B) is -1.4 C, the upper limit (C) is 1.9 C, and the observed (Tc-Ta) (A) is -0.5 C. The CWSI then is claculated by (-1.4 - -0.5) ÷ (1.9 - -1.4) = 0.27.

3.5 Plant Measurements

Phenological development of the crop was evaluated according to the Fehr and Caviness (1977) descriptions of soybean growth. A summary of the vegetative and reproductive stages is presented in Table 3.2. The same 10 plants in 6 of the plots (2 from each treatment) were examined each week. In addition to assigning reproductive and vegetative growth stages, row gap and plant height were measured. The average stage of 10 plants was used to determine the growth stage of a plot.

Leaf area and dry matter were assessed twice during the growing season. A stationery leaf area meter (LI-3000, LI-COR) was used to determine leaf area for 1 square meter. The area to weight ratio of the per m^2 area was then used to determine total LAI. Phytomass was divided into stems and leaves, and weighed before and after ovendrying.

When conditions permitted, stomatal resistance to water diffusion and leaf water potential were measured. Stomatal resistance (rs) of the abaxial (bottom) and adaxial (top) leaf surfaces was measured using a steady state porometer (LI-1600, LI-COR). Total rs for the canopy was calculated based on the equation for an amphistomatous leaf:

$$rc = \frac{r(ab) * r(ad)}{r(ab) + r(ad)}$$

where r(ab) and r(ad) are resistances of abaxial and adaxial surfaces, respectively (Verma *et al.*, 1979). Total leaf water potential was measured with the Scholander pressure chamber technique (Scholander *et al.*, 1965). Procedures and equipment used for determining plant water potential are described by Ritchie and Hinkley (1975).

Analysis of these data described in this chapter was accomplished with SAS (Statistical Analysis System) analysis of variance and regression procedures.

Table 3.2 Stages of soybean developement (Fehr and Caviness, 1977).

Stage	Stage title	Description
<u>Vegetative</u> <u>Stages</u>		
VE	Emergence	Cotyledons above surface.
VC	Cotyledon	Unifoliate leaves unrolled sufficiently so that leaf edges do not touch.
V1	First-node	Fully developed leaves at unifoliate nodes.
V2	Second-node	Fully developed trifoliate leaf at node above unifoliate node.
V3	Third-node	Three nodes on the main steam with fully developed leaves.
Vn	nth-node	n number of nodes on the main stem fully developed leaves. n can be any number beginning with 1 for V1.
<u>Reproductive</u> <u>Stages</u>		
R1	Beginning bloom	One open flower at any node.
R2	Full bloom	Open flower at one of the two uppermost nodes on the main stem with a fully developed leaf.
R3	Beginning pod	Pod 5 mm long at one of the four uppermost nodes.
R4	Full pod	Pod 2 cm long at one of the four uppermost nodes.
R5	Beginning seed	Seed 3 mm long in a pod at one of the four uppermost nodes.
R6	Full seed	Pod containing a green seed that fills the pod cavity on one of the four uppermost nodes.
R7	Beginning maturity	One normal pod on the main stem maturity that has reached mature pod color.
R8	Full maturity	Ninety-five percent of the pods have reached mature pod color.

Chapter 4

RESULTS AND DISCUSSION FOR SCHEDULING OF SOYBEANS

4.1 Weather Influences

Monthly normals are generally defined as 30-year averages of temperature, precipitation, and other daily weather occurrences. This long-term information is not available for the Sandhills Agricultural Laboratory (SAL) location. Weather data for 1985 and 1986 were collected at an automated weather station at SAL (Hubbard *et al.*, 1983). Stapleton, which is about 25 miles south and east of the lab, has a 30-year record of air temperature and precipitation. Normals for this location are used for comparison of the 1985 and 1986 data collected at SAL (Table 4.1). Daily temperature extremes exemplify the variability of weather at SAL. Minimum temperatures of 8.9 C for July 30, 1985 and -1.7 C for May 18, 1986 were recorded, the maximum temperature was 40 C on July 11, 1985 and was 38.5 C on July 10, 1986. Daily weather data are included in Appendix 1.

Precipitation during the 1985 season totaled 403 mm, of which 157 mm occurred during the irrigation scheduling period, days 205-253 (Fig. 4.1). Rainfall amounts were 79, and 74 mm for pod (R3-R4) and seed (R5-R6) development stages, respectively. In contrast, 476 mm of precipitation were received from May to September, 1986 (Fig. 4.2). Rainfall for 1986 was 73 mm more than in the 1985 rainfall and 120 mm more than the normal rainfall amounts (NOAA, 1982). Usually, 50% of the precipitation for a growing season occurs during May and June. However, in 1986, 66% or 235 mm of rain occurred during pod and seed (R3-R6) growth stages. Thus, 1985 could be characterized as a typical growing season, while the 1986 season was more wet than normal.

Table 4.1 Precipitation (mm) and temperature information (C) for 1985, and 1986. Monthly normals are for 1951-1980 at the Stapleton, Nebraska weather station (NOAA,1982).

	MAY	JUNE	JULY	AUGUST	SEPT	TOTAL (May-Sept)
1985						
MAX	23.7	25.9	30.4	26.9	20.2	
MIN	7.9	9.5	14.9	12.3	7.8	
MEAN	15.7	17.7	23.8	19.6	14.0	
1986						
MAX	18.7	28.3	31.3	28.6	22.8	
MIN	6.4	13.0	14.7	12.7	10.9	
MEAN	14.0	20.1	23.0	20.4	14.0	
NORMALS						
MAX	22.6	28.0	31.9	31.2	25.8	
MIN	6.8	12.4	15.5	14.5	8.6	
MEAN	14.8	20.2	23.7	22.8	17.2	
PRECIPITATION						
Normals	88	92	72	56	48	356
1985	104	90	83	57	69	403
1986	94	64	90	120	108	476

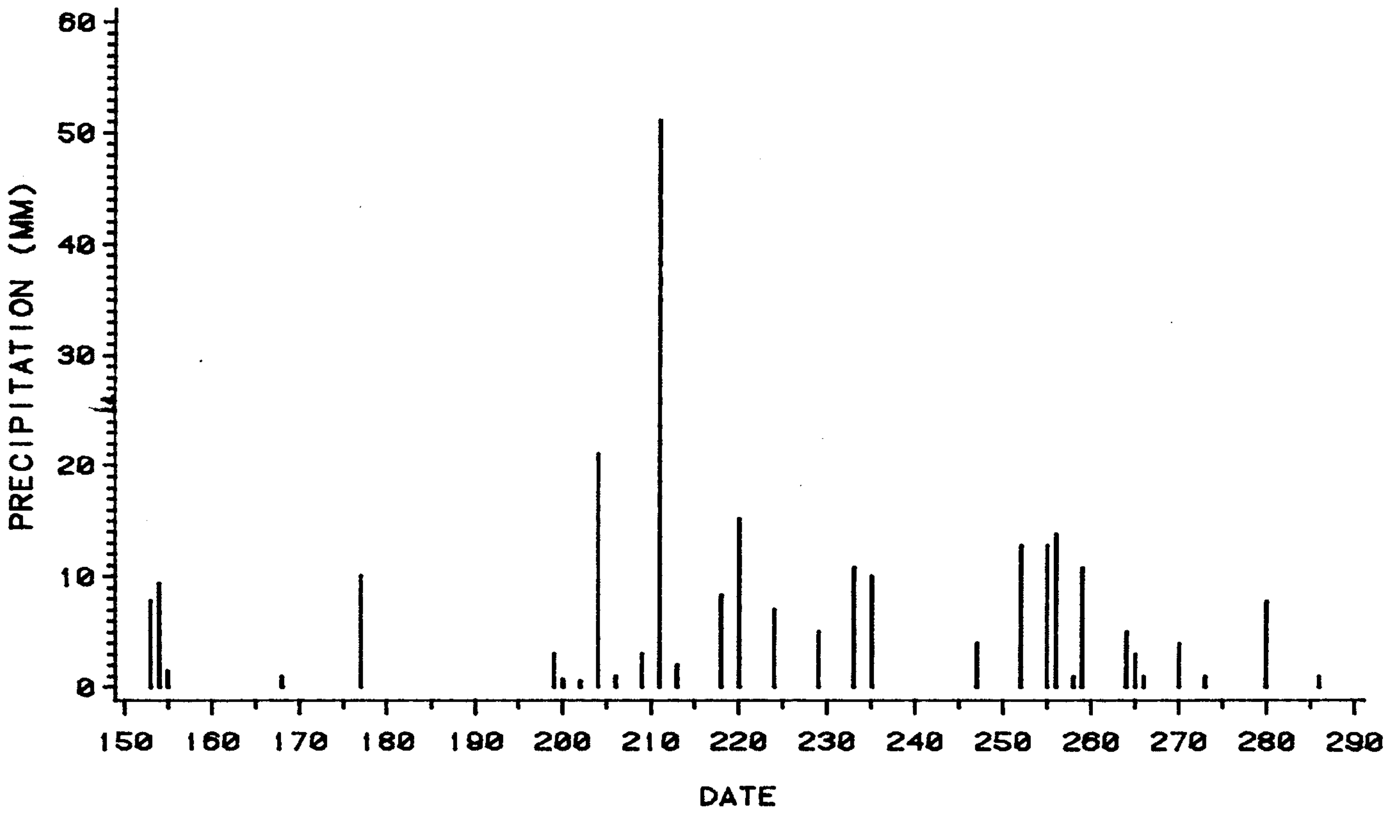


Figure 4.1 Precipitation distribution in mm for June 1 to October 17, 1985.

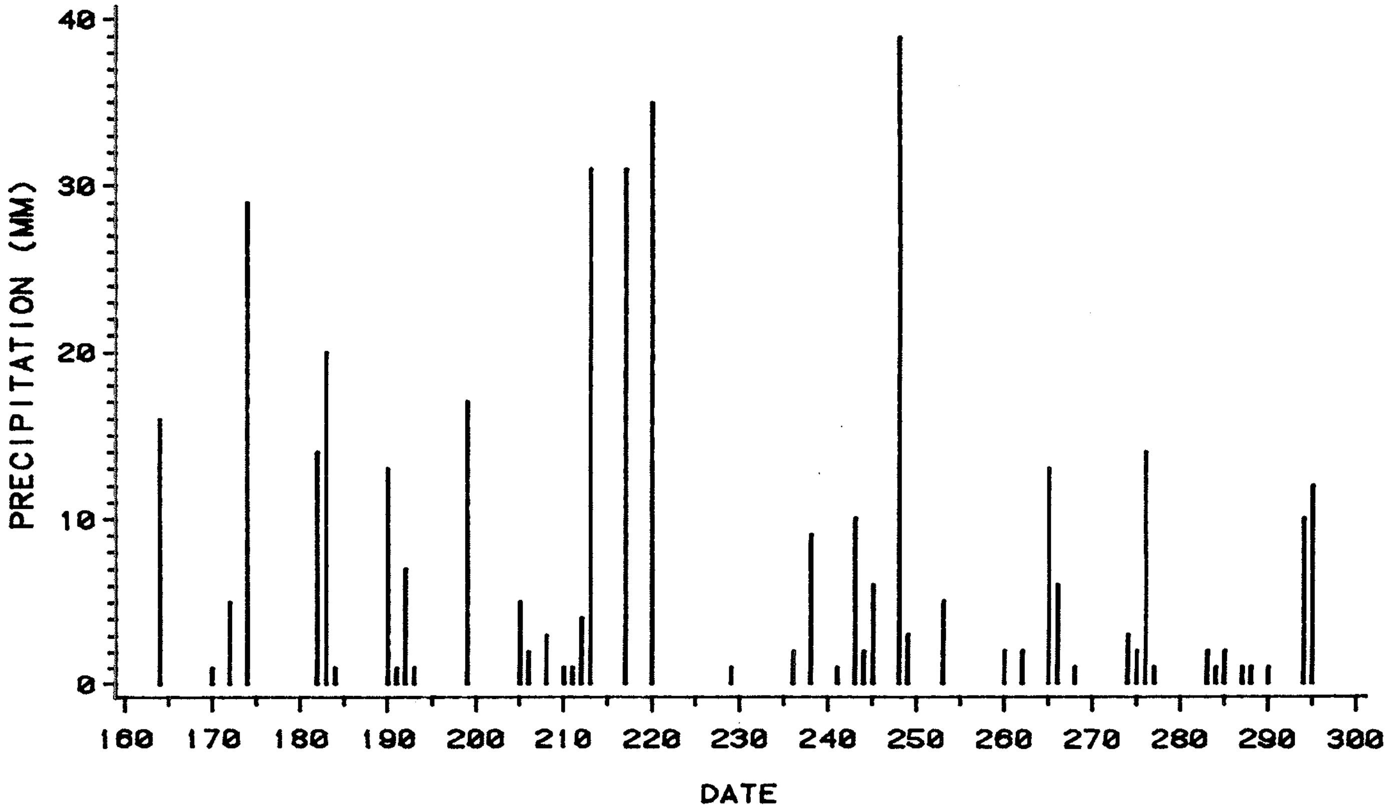


Figure 4.2 Precipitation distribution in mm for June 13 through October 22, 1986.

During the IRT measurement period in 1985 (days 205-253) and 1986 (days 191-260) cloud cover determined whether or not data were collected. The significance of cloud cover is discussed in section 4.2.3. In 1985, 29% of the days were cloudy and in 1986, 45% of the days were overcast or mostly cloudy. Irrigation scheduling data were not collected on these cloudy days.

4.2 Factors Affecting the Measurement of Canopy Temperatures

4.2.1 Incomplete Canopy Cover

The finding that canopy temperature variability is correlated with percent canopy cover (Heilman *et al.*, 1981) is supported by the data from 1986. Because of low plant population in 1985, the canopy did not reach 85% cover until about day 236. The pattern of Tc variability in 1985 is not as distinct as in 1986. The Tc variability for 1985 is shown in Fig. 4.3. The Tc standard deviation (s) of a well-watered plot (Fig. 4.3b) was 1.5 C on day 224, 1985, but decreased to 0.5 C on day 236. Similar patterns appear in the 0.2 and 0.5 CWSI treatment data (Figs. 4.3a and c).

The variability in Tc collected in 1986 is shown in Fig. 4.4. Before day 210, canopy cover was less than about 80%, and the soil temperature influenced the composite Tc. A 0.2 CWSI plot with an s value of about 1.2 C on day 209 is shown in Fig. 4.4a. The canopy was 92% complete by day 218 and s was reduced to less than 1 C for all 3 treatments.

One method of increasing precision is to increase the number of replications. Thus, 20 Tc measurements would have an s value less than that of 10 Tc measurements. Because the variability is reduced when canopy cover reaches about 85% due to less influence of radiation from the soil, the number of Tc measurements could be reduced. However, water stress (Section 2.3.2), wind, and directional effects may still cause considerable temperature variability.

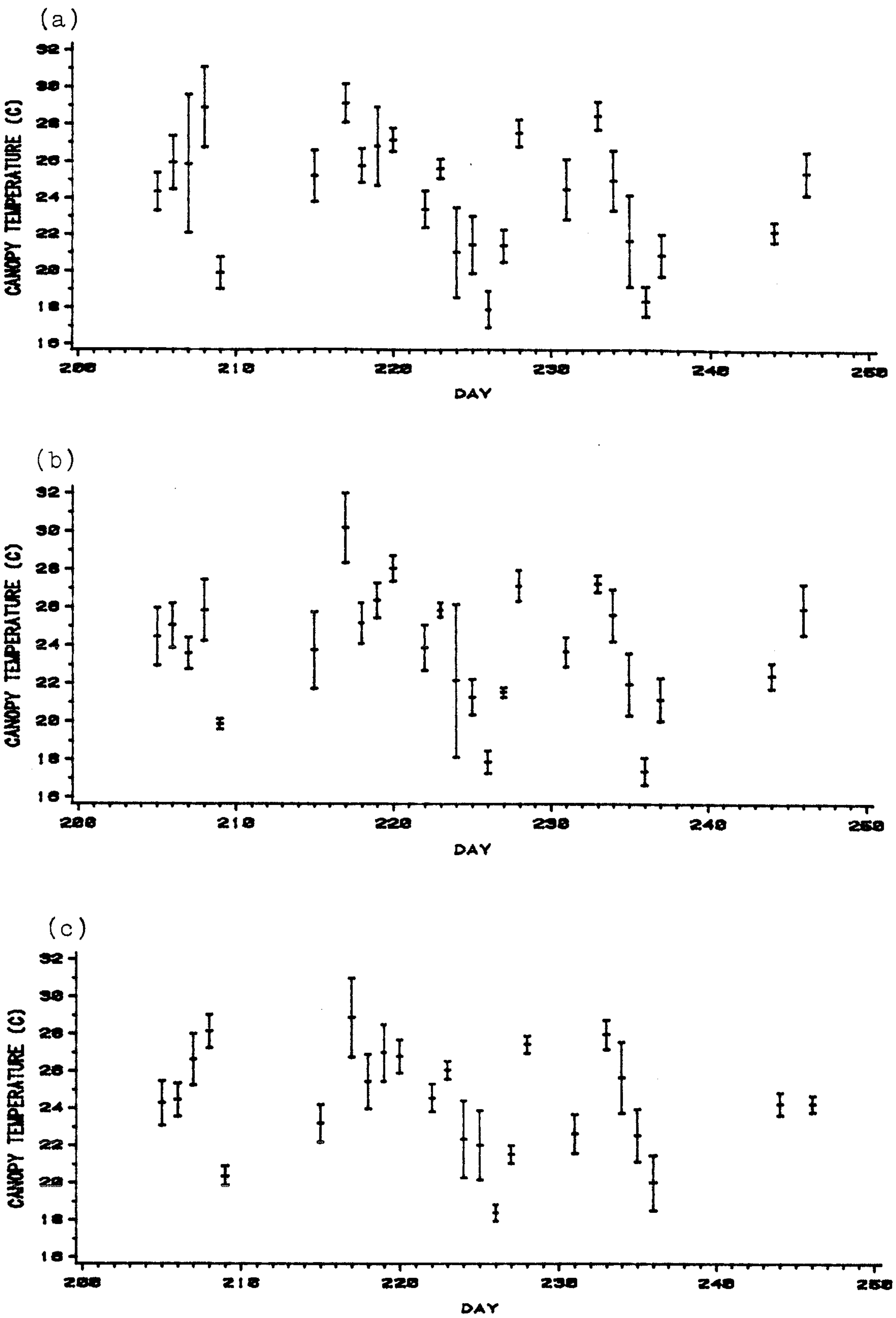


Figure 4.3 Canopy temperature ± 2 standard deviations for (a) 0.2 CWSI, (b) well-watered, and (c) 0.5 CWSI treatments in 1985.

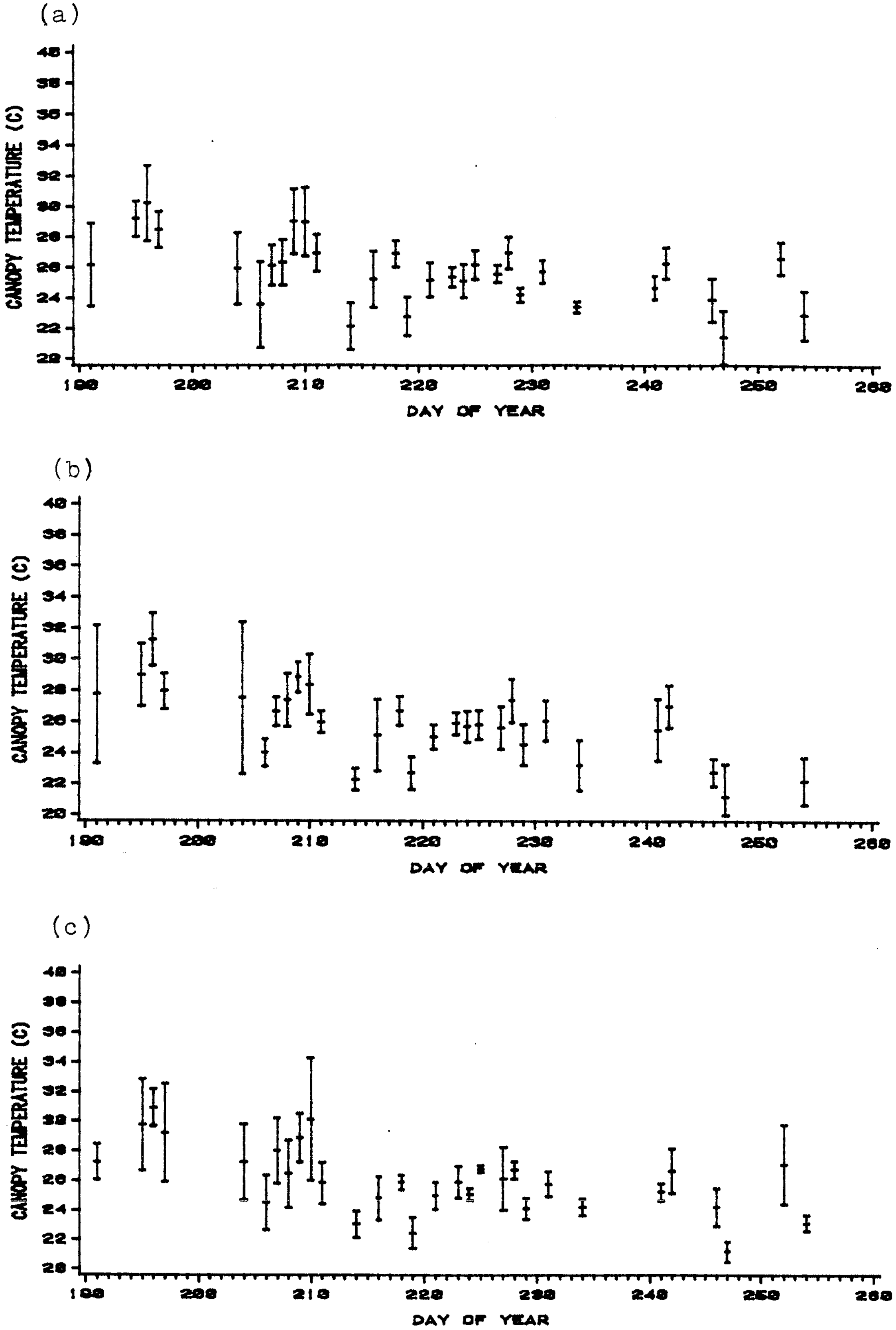


Figure 4.4 Canopy temperature ± 2 standard deviations for (a) 0.2 CWSI, (b) well-watered, and (c) 0.5 CWSI treatments in 1986.

4.2.2 Canopy Temperature Response to Direction

Canopy temperatures taken from 4 directions throughout a day are shown in Figs. 4.5 and 4.6. The directions north, south, east, and west represent the direction the IRT was aimed. Thus at mid-day, the sun would be at the observers back and the IRT would be viewing the sunlit side of the canopy if the IRT was aimed north. Fuchs *et al.* (1967) and Nielsen *et al.* (1984) found that the azimuth of the IRT sensor beam produced systematic differences in Tc for soybeans. Table 4.2 contains F probability statistics, denoted by Pr > F, for both years and the 4 directions. North facing Tc values were significantly higher than east, west or south facing temperatures, while east, west and south facing canopy temperatures were similar (a = 0.05). Orthogonal contrasts showed that any combination of directions which included north had a significantly higher Tc than combinations of south, east and west.

The systematic differences in Tc among directions is due to the amount of sunlit leaves exposed to the IRT sensor beam. Near solar noon, predominantly sunlit leaves are exposed to the IRT aimed to the north, thus a relatively higher canopy temperature is measured. In contrast, a south-aimed IRT views more shaded leaves and results in the measurement of a relatively cooler Tc. This effect is also seen in the east and west Tc values as the solar elevation and solar azimuth changes. Prior to 1200 CDT (Fig. 4.5) the IRT sensor beam aimed east viewed mostly shaded leaves, consequently east-facing Tc values were relatively cool. By 1500, the east Tc was warmer than the west, because more sunlit leaves are exposed to the east-facing IRT after solar noon.

If soybean temperatures are to be used as a basis for irrigation scheduling, then a Tc representative of the field is necessary. Since direction produces differences in Tc, Tc should be measured in more than one direction. Collection of temperatures in all 4 directions would provide a representative average Tc

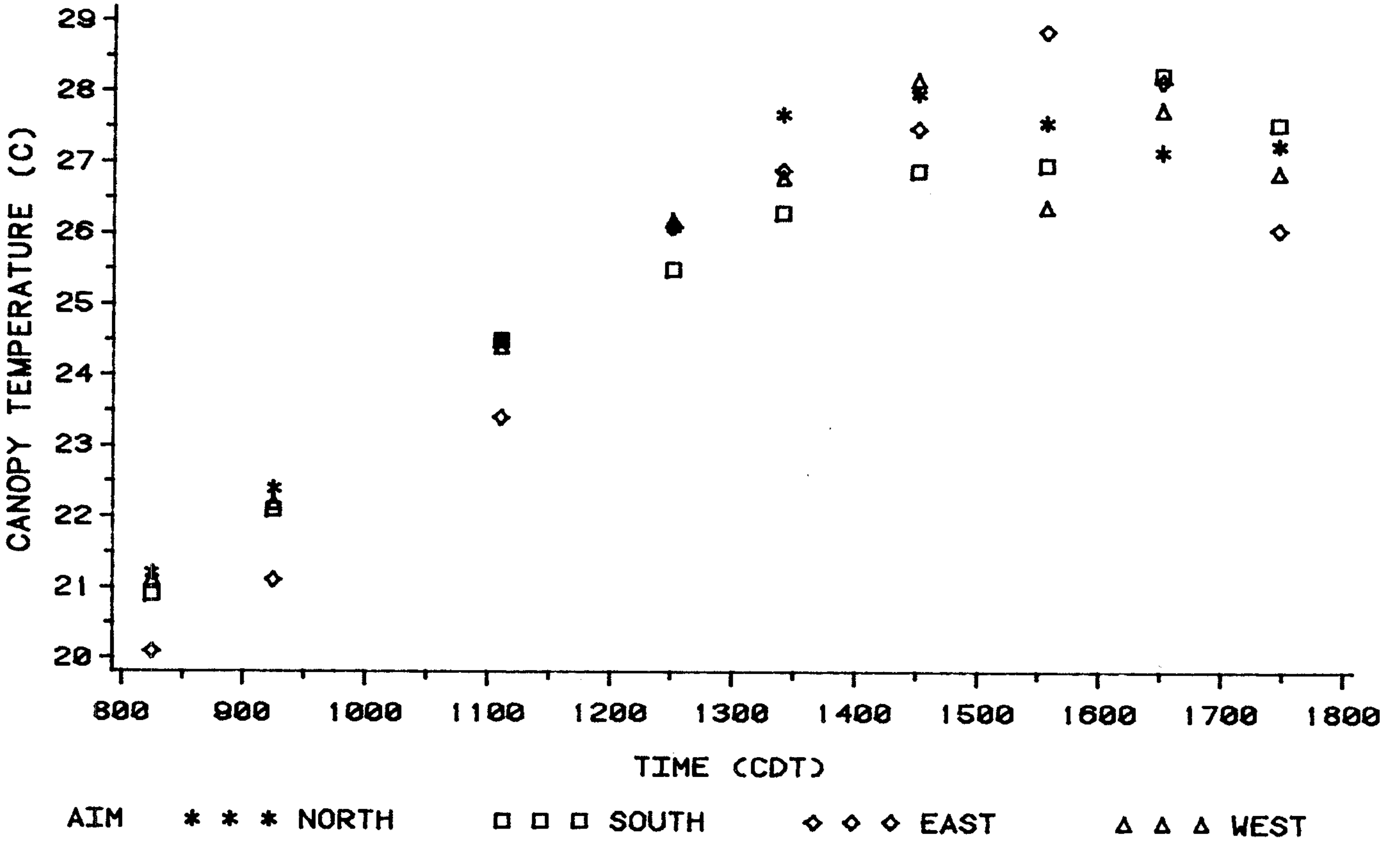


Figure 4.5 Directional Tc observations throughout day 220, 1985 for a well-watered soybean plot.

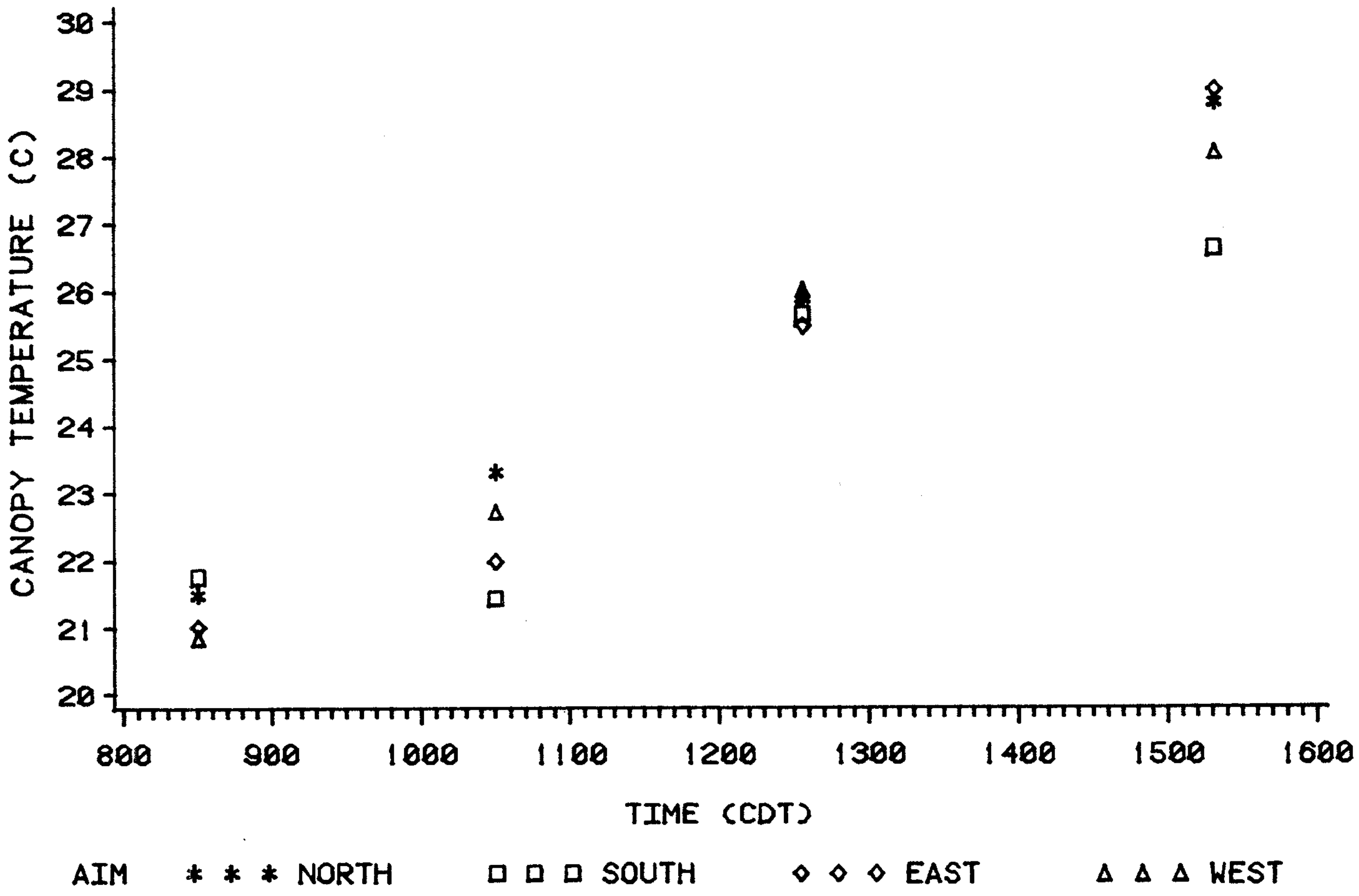


Figure 4.6 Directional Tc observations throughout day 241, 1985 for a 0.5 CWSI treatment.

Table 4.2 Mean and F probabilities for each IRT viewing direction in 1985 and 1986.

Direction		Mean Tc (C)	Pr > F East	 North	 South	 West
1985	E	22.60	---	.0001	.4447	.4944
	N	23.04	.0001	---	.0001	.0002
	S	22.53	.4447	.0001	---	.1475
	W	22.67	.4944	.0002	.1475	---
1986	E	25.11	---	.0015	.2628	.3157
	N	25.94	.0015	---	.0347	.0001
	S	25.4	.2628	.0347	---	.0351
	W	24.85	.3157	.0001	.0351	---

contrasts

	Pr > F 1985	 1986
N+S v. E+W	.0357	.0002
N v. E+S+W	.0001	.0001
N+E v. S+W	.0015	.0281

for irrigation scheduling purposes; however, the average of temperatures taken from the north and south-facing directions should also be acceptable.

4.2.3 Responses to Cloud Cover

The use of the CWSI as an irrigation scheduling tool is somewhat limited by cloud cover conditions. The passage of a cloud causes shading of the canopy leading to reduced air and canopy temperatures.

Photosynthetically active radiation (PAR) was simultaneously measured with Tc, Wb and Ta with about 50% cumulus cloud cover. The effects of a cloud on these variables are shown in Table 4.3. At 1334 CDT, PAR was 2040 uE/m^2/s, Ta and Tc were 25.8 and 24.7 C, respectively. By 1357 CDT, a cumulus cloud obstructed the sun. PAR decreased by 25%, Ta by 1.8 C and Tc by 4 C. The VPD changed by only 0.2 to 0.3 kPa. The problem posed by clouds is that Tc decreases may be about 4 to 5 C while Ta cools by only about 1 to 2 C. Thus (Tc-Ta) during cloud cover is very different from that with an unobstructed sun.

For the CWSI to be meaningful, the input measurements for the CWSI must be collected with an unobstructed sun. If measurements are taken when PAR is low the CWSI will be underestimated relative to measurements taken with an unobstructed sun. Until a method of predicting the Tc or (Tc-Ta) based on net radiation (Rn) is determined, the application of the CWSI will be limited by cloud cover conditions.

4.3 Factors Affecting the Determination of the CWSI

4.3.1 Well-Watered Baseline Variability

The development of the well-watered baselines used in this experiment was discussed in Sections 2.3.3 and 3.4. The baseline and data for the well-watered plots in 1985 are shown in Fig. 4.7. It is easily seen that the arbitrarily

Table 4.3 Average Ta, Tc, Tc-Ta, VPD, Wet bulb, and PAR measurements before, during and after passage of a cloud.

Time (CDT)	Ta (C)	Tc (C)	(Tc-Ta) (C)	PAR ($uE/m^2/s$)	Wb (C)	VPD (kPa)
1334	25.8	24.7	-1.1	2040	19.4	1.5
1357	24.0	20.7	-3.3	500	18.8	1.2
1403	25.5	25.0	-0.5	2020	20.2	1.3
1440	24.6	19.3	-4.3	560	19.5	1.2
1445	26.0	25.5	-0.5	2230	20.2	1.4

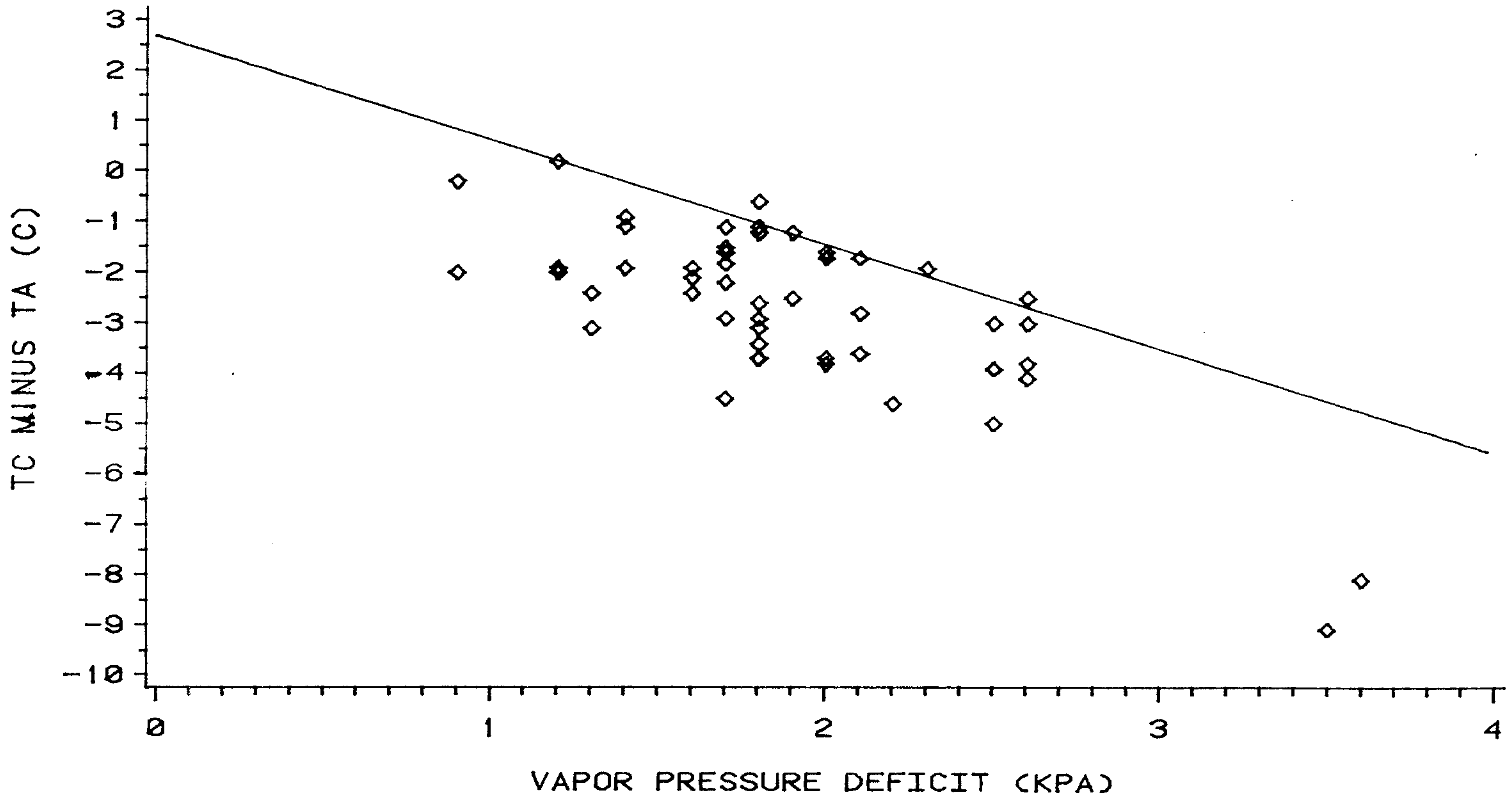


Figure 4.7 Well-watered baseline used in 1985 and the (Tc-Ta) vs. VPD observations, where the baseline equation is:(Tc-Ta) = 2.67 - 2.059 * VPD.

chosen baseline, (Tc-Ta) = 2.67 - 2.059 * VPD, (B. R. Gardner, 1985, personal communication) did not fit the data collected in this study. In 1986, there was a choice of using either the baseline derived from the 1985 data or Idso's (1982) baseline. Because of low plant population and poor canopy cover conditions, the reliability of a well-watered baseline derived from the 1985 data was in question. Therefore, the well-watered baseline developed by Idso (1982) was chosen for the 1986 CWSI irrigation scheduling experiment.

Ideally, (Tc-Ta) data of a well-watered crop should fall near the well-watered baseline. However, as shown in Fig. 4.8a, the (Tc-Ta) values for this study fall below the lower limit. This results in predominantly negative CWSI values. CWSI values should range from 0 to 1 although values outside this range are possible. Predominantly negative CWSI values indicates that the CWSI is not representative of the degree of stress experienced by the crop.

Data for the 0.2 and 0.5 CWSI treatments are shown in Fig. 4.8 b and c, respectively. Most (Tc-Ta) vs. VPD observations for both 0.2 and 0.5 CWSI plots fell on or below the well-watered baseline. Thus, the CWSI values were generally negative and the CWSI threshold was rarely reached in the experimental plots.

A possible explanation for these findings is that differences among soybean varieties could cause variation in the intercept or slope of the well-watered baseline. As discussed earlier, Idso (1984) determined that varietal differences in wheat leaf sizes affected the well-watered baseline, especially the intercept term. Because smaller leaves have Tc values that are closer to Ta, (Tc-Ta) is greater (less negative) and the intercept would be greater than that of a larger leaved crop variety.

Baldocchi *et al.* (1983) found differences in the energy balance of dense and normal pubescent soybeans. The canopy composed of dense pubescent plants had a higher sensible heat flux and a lower latent heat flux than the normal

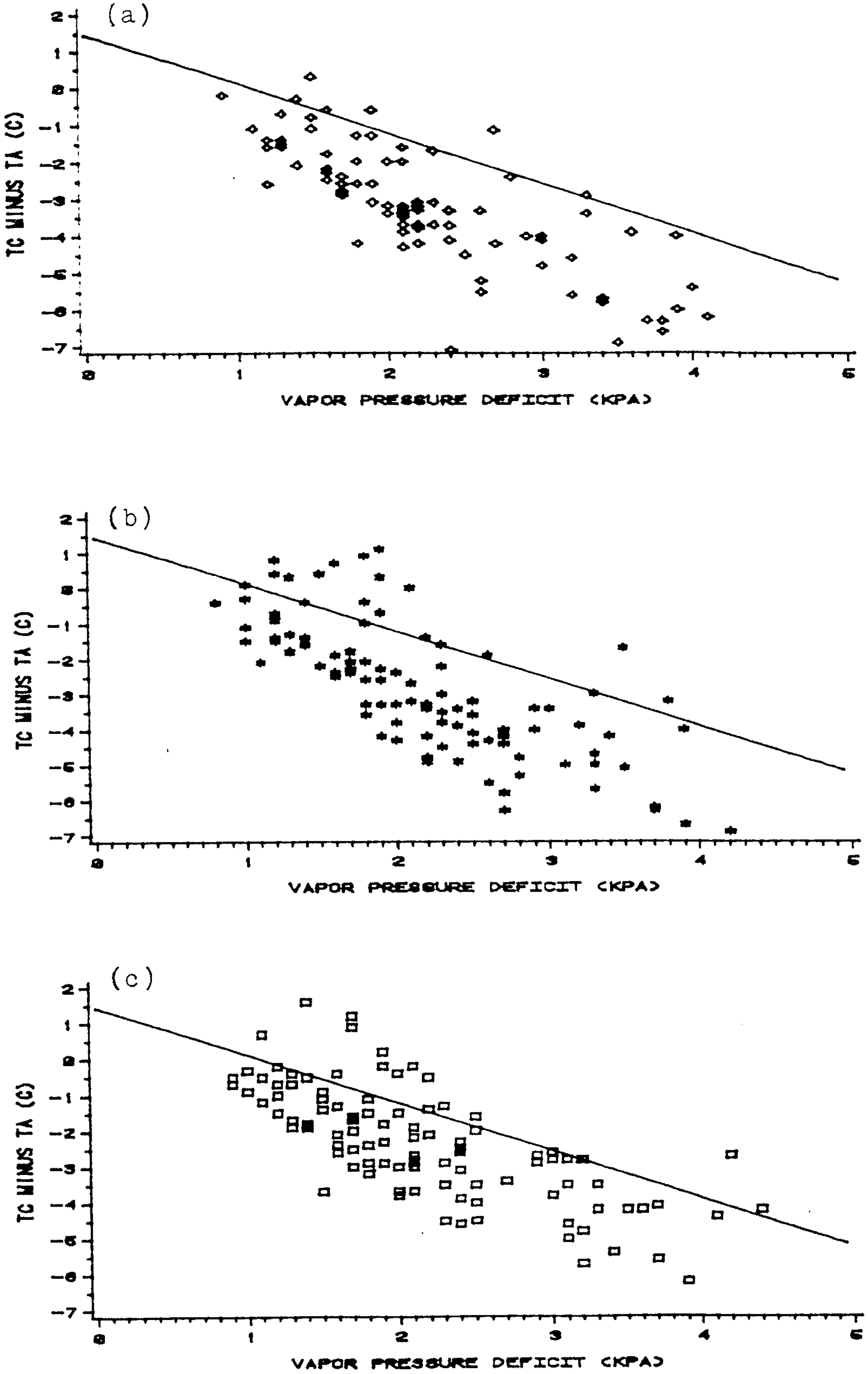


Figure 4.8 The Idso baseline: (Tc-Ta)= 1.44-1.34*VPD used in 1986 and data from (a) well-watered, (b) 0.2 CWSI, and (c) 0.5 CWSI treatments.

pubescent canopy. According to Baldocchi, dense pubescence increases the scattering coefficient or reflectivity of the soybean leaves, which in turn increases penetration of solar radiation into the canopy. This supports Clawson's (1983) findings that under well-watered conditions soybeans with dense pubescence had reduced mid-day canopy and leaf temperatures relative to those with normal pubescence. Thus, differences in leaf pubescence or the leaf size within soybean varieties could affect the intercept of the well-watered baseline.

A critical factor in Idso's equation is VPD. Since VPD regimes differ among locations, it is possible that the VPD data collected for Idso's baseline are not representative of the VPD regime at the SAL experimental site. Lastly, Idso's model could be inaccurate and the (Tc-Ta) vs. VPD relationship does not adequately explain the soybean water-stress situation.

4.3.2 Baseline Equations

The data shown in Figs. 4.9 and 4.10 were collected from well-watered plots without clouds obstructing the sun. Some data were collected under completely overcast conditions, and are included in Figs. 4.11 and 4.12. VPDs of less than 1.0 kPa were characteristic of this overcast data. The results of linear regressions of (Tc-Ta) on VPD are summarized in Table 4.4. The low R^2 values, indicate that the regression equation accounts for only 50 to 60% of the variation. A probable source of the unaccounted variation was day to day variation in weather conditions. In both years, s^2 increased and R^2 decreased from the addition of overcast data. In the 1986, it is interesting that the slopes of the regression equations are almost identical for both sets of conditions. This supports Idso's idea that the intercept may be different among varieties, but generally the slopes are very similar.

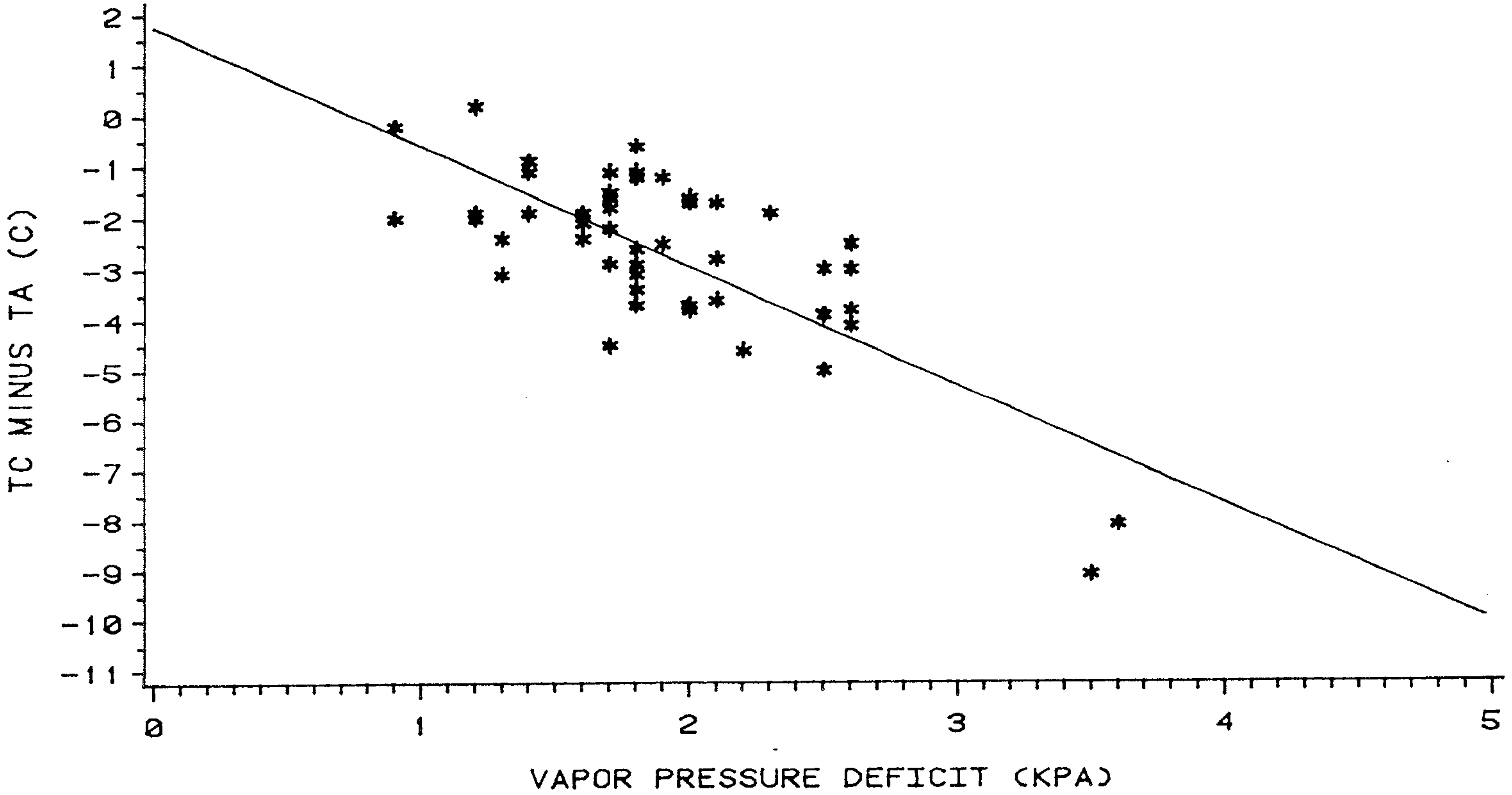


Figure 4.9 Well-watered (Tc-Ta) vs. VPD observations collected during periods when the sun was unobscured by clouds in 1985. The regression equation is: (Tc-Ta) = 1.76 - 2.36 * VPD.

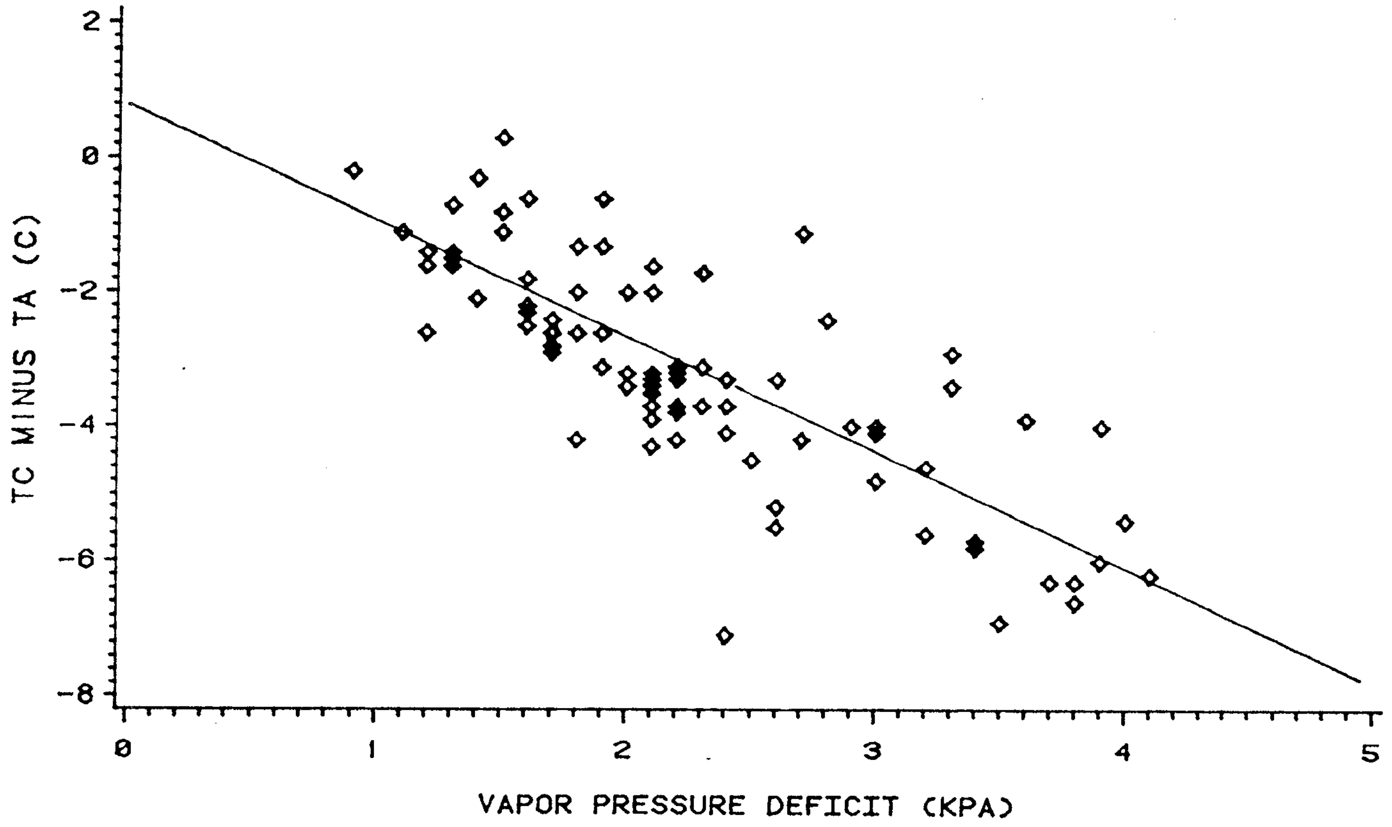


Figure 4.10 Well-watered (Tc-Ta) vs. VPD observations collected during periods when the sun was unobscured by clouds in 1986. The regression equation is: (Tc-Ta)= 0.78 - 1.72 * VPD.

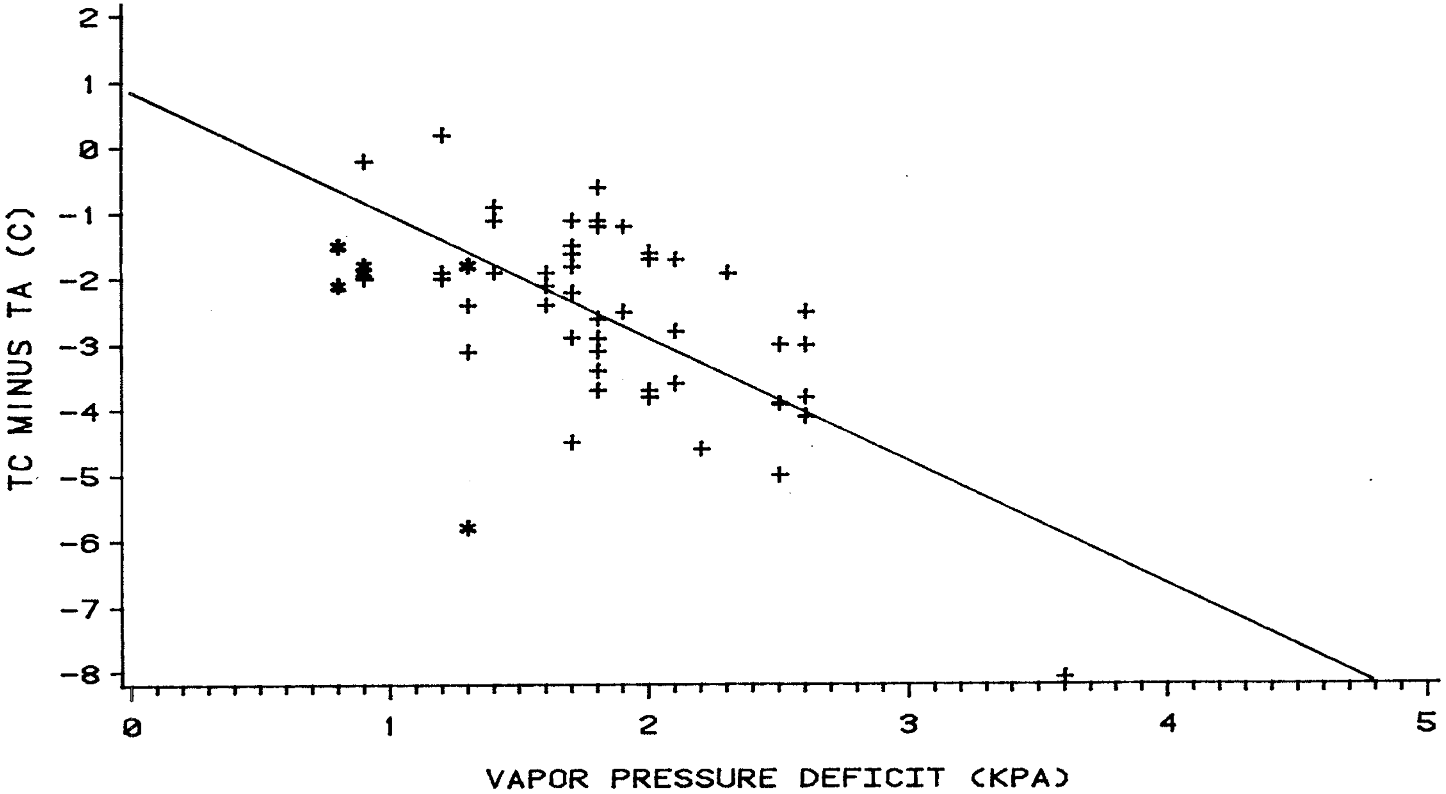


Figure 4.11 Some completely overcast conditions (*) during collection of (Tc-Ta) and VPD data are included with that from clear (+) days in 1985. The regression equation is: (Tc-Ta) = 0.85 - 1.88 * VPD.

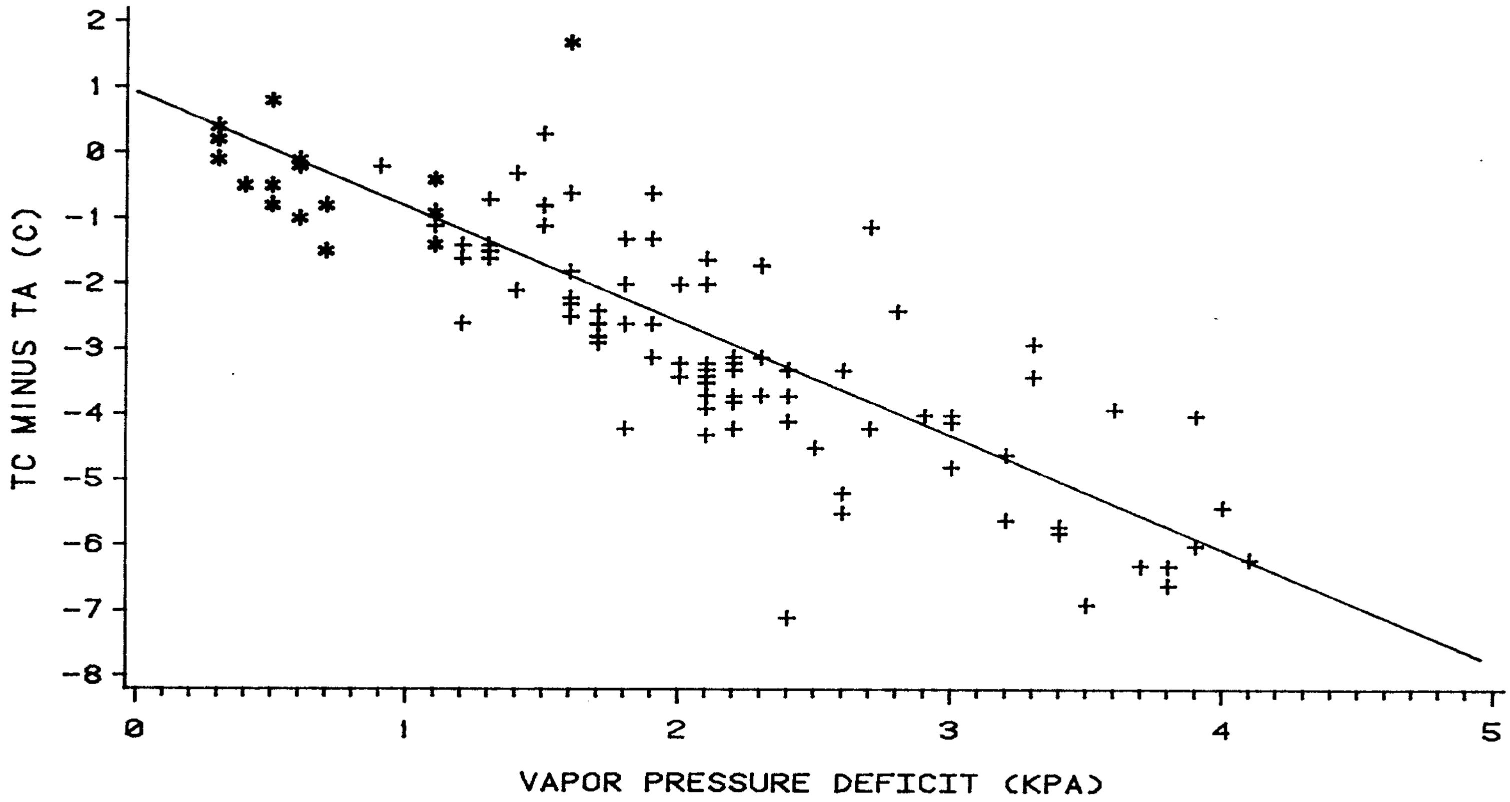


Figure 4.12 Some completely overcast conditions (*) during collection of (Tc-Ta) and VPD data are included with that from clear (+) days in 1986. The regression equation is: (Tc-Ta) = 0.91 - 1.74 * VPD.

Table 4.4 Summary statistics for derived well-watered baselines from 1985 and 1986 data (alpha= 0.05).

1985

----

conditions: clear data N=52
response variable: Tc-Ta independent variable: VPD
variance= 1.30 R^2 = 0.56
intercept= 1.76 T= 3.01 Pr > T= 0.004
slope= -2.36 T= -8.09 Pr > T= .0001

conditions: clear and overcast data N=62
response variable: Tc-Ta independent variable: VPD
variance= 1.64 R^2 = 0.51
intercept= 0.84 T= 2.01 Pr > T = .0408
slope = -1.88 T= -9.03 Pr > T = .0001

conditions: clear data N=52 covariate: Date
response variable: Tc-Ta independent: VPD
variance= 1.26 R^2 = 0.59
intercept= -3.2 Pr > T= 0.304
slope = -2.2 Pr > T= .0001
date Pr > T= 0.110

1986

----

conditions: clear data N=89
reponse variable: Tc-Ta independent variable: VPD
variance= 1.13 R^2 = 0.61
intercept = 0.78 T = 2.24 Pr > T= 0.027
slope = -1.72 T=-11.70 Pr > T= 0.001

conditions: clear and overcast N=106
response variable: Tc-Ta independent variable: VPD
variance= 1.68 R^2 = 0.60
intercept= 0.91 T = 3.0 Pr > T = 0.0034
slope = -1.74 T= -12.5 Pr > T = 0.0001

conditions: clear N= 89 covariate: Date
response variable: Tc-Ta independent: VPD
variance= 1.128 R^2 = 0.61
intercept= -1.89 T = -0.86 Pr > T = 0.3904
slope= -1.63 T= -10.1 Pr > T = 0.0001
date Pr > T = 0.2258

Using date as a covariate in the regression analysis (Steel and Torrie, 1981), variation due to daily weather fluctuations was partitioned. In 1985 and 1986, date was not a significant factor ($Pr > T = 0.110$ and $Pr > T = 0.3904$, respectively). The affect of soil background temperature on Tc in 1985 could be a major source of variation but was not accounted for by a statistical model.

The 1986 regression equation $(Tc\text{-}Ta) = 0.78 - 1.72 * VPD$ has an R^2 of 0.61, and a relatively small s^2. However, 39% of the variation in the regression line was not explained by the data. This may be due to day to day weather variability and factors not accounted for in the Idso method, such as Rn which has been found to be an important factor in the calculation of the CWSI (Idso *et al.*, 1986 and Jackson *et al.*, 1981).

4.3.3 Comparison of the Idso and Jackson Methods of Calculating the CWSI

The Jackson *et al.* (1981) and Idso *et al.* (1981b) methods of determining the CWSI are fundamentally different. The latter is based on the linear relationship between (Tc-Ta) and VPD, while the Jackson method was developed from the energy balance concept. The Jackson method does not require use of a well-watered baseline, instead, Rn, VPD, saturated vapor pressure (SVP), canopy (rc) and aerodynamic (ra) resistances are used to formulate an index of water stress.

Jackson suggests that rc can be determined from the average rs measurements of a well-watered crop. The upper limit equation: (Tc-~~Ra~~ Ta) = ra Rn/p Cp (see Section 2.3), where ra is calculated as rc approaches infinity is simulated from measurements of (Tc-Ta) of a fully senesced crop. The (Tc-Ta) of a senesced crop and rs of a well-watered crop must be measured before implementing Jackson's CWSI.

Jackson's method was used to calculate a second index using 1986 data. Using the steps described above, ra and rc were found to be 5 and 10 s/m, respectively. The value for ra was calculated with a (Tc-Ta) measurement for a partially senesced soybean crop.

Idso's and Jackson's indices are shown in Fig. 4.13. The Jackson CWSI was less variable than Idso's and ranged from 0 to 0.5 except for plot 17 (Fig. 4.13c). Based on these findings, the Jackson index appears to be more appropriate than the Idso CWSI. Idso *et al.* (1986) concluded that the well-watered baseline is curvilinear and also recommended an energy-balance approach.

4.3.4 Sources of Error

Systematic errors can be introduced into CWSI calculations through measurements of Tc, Ta and Wb. These measurements can be influenced by canopy cover, time of day, cloud cover, and the operator of the IRT. The variability of Tc is shown in Fig. 4.14 and Table 4.5. The values of s^2 were as high as 10.12 C, and 5.46 C in 1985 and 1986, respectively. The 1986 data have a lower standard error of the mean, SE.

Errors due to the IRT sensor were minimal, since it has an accuracy of 0.5 C and a resolution of 0.1 C. Before and after each data collection period, IRT temperature readings were compared to those of a blackbody. The IRT reading was always within 0.1 to 0.3 C of the reference temperature. Errors due to clouds and direction of aim were previously discussed in Sections 4.2.2 and 4.2.3.

Air temperature had the highest variance of all the variables; $s^2 = 14.5$ C in 1985 and 11.7 C in 1986. Values of s^2 for Wb were 8.56 C and 5.53 C for 1985 and 1986, respectively. The method of measurement could affect the Ta and Wb values. The thermocouple psychrometer values for Wb and Ta were compared to those from an aspirated (artificially ventilated) psychrometer. Wb measurements were identical for both instruments, but Ta measured with the aspirated psychrometer was 0.6 C greater than that of the thermocouple type (Table 4.6).

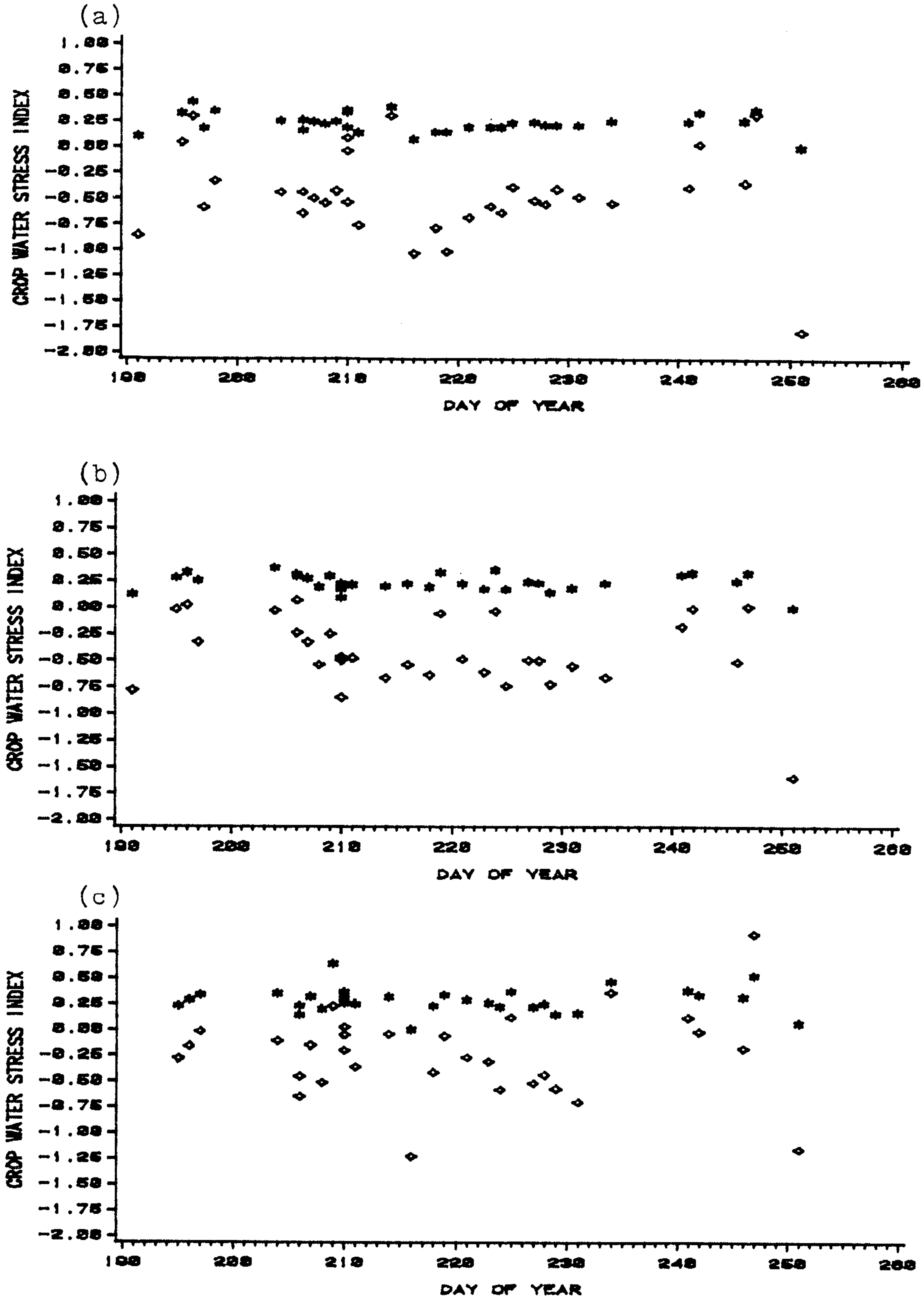


Figure 4.13 The results of two CWSI methods. Idso's (◇) and Jackson's (*) CWSIs for the 1986 (a) 0.2 CWSI (b) well-watered, and (c) 0.5 CWSI treatments.

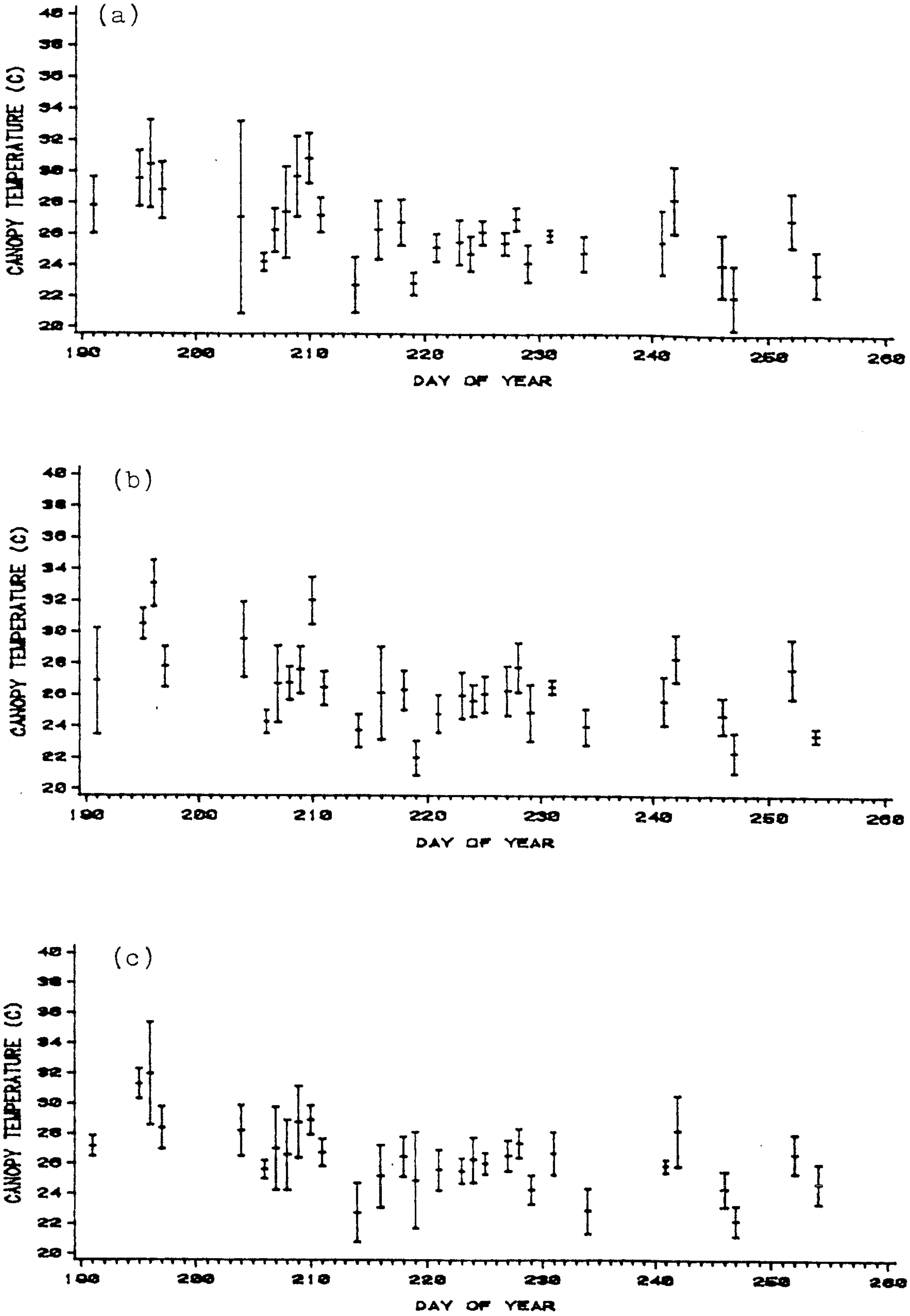


Figure 4.14 Error bars for (a) 0.5 CWSI, (b) 0.2 CWSI, and (c) well-watered treatments in 1986. The bars represent ± 2 standard deviations.

Table 4.5 Statistics of mean, standard error of the mean (SE), minimum and maximum values, and variance (s^2) for variables collected during daily irrigation scheduling procedures.

year	variable	mean	min.	max.	SE	s^2
1985	Tc (C)	23.91	16.50	30.80	0.359	10.18
	Ta (C)	26.51	17.50	33.00	0.261	14.50
	Wb (C)	18.83	12.50	24.50	0.200	8.56
	VPD (kPa)	1.81	0.5	3.6	0.044	0.42
1986	Tc (C)	26.39	21.20	33.90	0.130	5.46
	Ta (C)	29.07	21.30	36.50	0.190	11.70
	Tc-Ta (C)	-2.68	-7.1	1.6	0.10	3.08
	Wb (C)	20.77	13.50	26.50	0.130	5.53
	VPD (kPa)	2.18	0.80	4.4	0.040	0.59

Table 4.6 Comparison of mean Wb and Ta measurements from aspirated and thermocouple (wind-aspirated) psychrometers.

	Wb (C)	Ta (C)
aspirated	20.1	27.3
thermocouple	20.1	26.7
Pr > F	0.9025	0.0024

The thermocouple psychrometer (wind-aspirated), if properly calibrated and maintained, should give a more representative Ta and Wb measurement than an artificially aspirated psychrometer. Since the thermocouple is a very fine wire, it has a small mass and a faster response time than the aspirated psychrometer. During very calm conditions, the wet bulb must be adequately aspirated (approximately 3 to 4 m/s) for the equation to hold true. Thus, the 0.6 C difference in Ta may be due to the difference in response times between the two types of psychrometers.

4.4 CWSI Response to Soil Moisture

Soil moisture has long been used as a reliable method of monitoring water stress. One objective of this study is to determine relationships between soil moisture and the CWSI. Soybeans extract water only from soil depths containing roots or perhaps slightly deeper. Volumetric water content was measured from 6 depths, denoted by D1 (0-.15 m), D2 (.15-.30 m), D3 (.30-.60 m), D4 (.60-.90 m), D5 (.90-1.2 m) and D6 (1.2-1.5 m). The dates when the soybeans began extracting water from each layer are shown in Tables 4.7 and 4.8. Roots did not extract water at D6 until the end of the 1985 growing season. This was true for all plots across the 3 treatments. No significant differences in beginning dates of water extraction from various depths were found.

All treatments in 1986 received two irrigations of 10 mm prior to the CWSI-irrigation scheduling period. Differences in water extraction dates among treatments were noted in 1986. For the 0.5 CWSI treatments, roots began extracting water from D6 by day 190. In contrast, the well-watered plots did not use water from D6 until 20 to 30 days later. Thus, the well-watered and 0.5 CWSI treatments were significantly different ($Pr > F = 0.0354$) at 1.2-1.5 m.

Table 4.7 Dates of beginning root extraction for soybeans in 1985, from the following layers: D1 = 0-.15, D2 = .15-.3, D3= .3-.6, D4 = .6-.9, D5 = .90-1.2, D6 = 1.2-1.5 m.

treatment	plot	rep	D1	D2	D3	D4	D5	D6
WW	4	1	190	190	195	205	205	260
WW	4	2	190	190	195	215	205	300
WW	5	1	190	190	195	215	215	300
WW	5	2	190	190	215	215	215	300
WW	10	1	190	190	220	205	230	300
WW	10	2	190	190	215	205	230	300
WW	11	1	190	190	230	230	260	260
WW	11	2	190	190	215	215	300	300
0.2	2	1	190	190	197	197	200	300
0.2	2	2	190	190	215	215	190	300
0.2	3	1	190	190	205	190	197	300
0.2	3	2	190	190	215	190	190	220
0.2	8	1	190	190	190	205	300	255
0.2	8	2	190	190	215	190	190	300
0.2	9	1	190	190	215	220	245	300
0.2	9	2	190	190	215	205	205	300
0.5	1	1	190	190	197	205	245	255
0.5	1	2	190	190	197	197	250	300
0.5	6	1	190	190	217	234	255	300
0.5	6	2	190	190	197	190	255	255
0.5	7	1	190	190	193	215	255	300
0.5	7	2	190	190	197	215	255	255

Table 4.8 Dates of beginning root extraction for soybeans in 1986, from the following layers: D1=0-.15 m, D2 = 0.15-.3 m, D3 =.3-.6 m, D4 = .6-.9 m, D5 = 0.9 -1.2 m, D6 = 1.2 - 1.5 m.

Treatment	plot	rep	D1	D2	D3	D4	D5	D6
WW	3	1	160	160	170	170	190	255
WW	3	2	160	160	170	165	210	245
WW	15	1	160	165	170	205	190	205
WW	15	2	160	165	170	170	190	220
WW	16	1	160	176	170	200	196	210
WW	16	2	160	170	165	190	196	365
0.2	1	1	160	165	160	190	220	255
0.2	1	2	160	165	165	190	220	190
0.2	5	1	160	165	190	190	196	200
0.2	5	2	160	165	165	190	190	200
0.2	14	1	160	160	185	185	190	190
0.2	14	2	160	165	185	190	190	190
0.5	2	1	160	165	165	190	190	190
0.5	2	2	160	165	165	170	190	190
0.5	6	1	160	165	165	180	190	190
0.5	6	2	160	160	165	190	190	190
0.5	17	1	165	165	185	190	190	190
0.5	17	2	160	165	185	190	190	190

However, since CWSI treatments were not started until day 190, the differences in water extraction dates were not due to the CWSI treatment.

In an effort to determine if volumetric water content corresponds with a range in CWSI values, concurrent soil moisture, Tc, Ta and VPD measurements were made. These measurements are shown in Tables 4.9 and 4.10. One should note the beginning extraction dates when interpreting these tables. The CWSI ranged from -1.5 to 0.0 and volumetric water content ranged from 0.1 to 0.30 (Figs. 4.15 and 4.16). It appears that there was no direct response of the CWSI to soil moisture. For example, soybeans in plot 15 were extracting water from 0-.9 m by day 170. The volumetric water content in this plot decreased from day 195 to 209 at all 4 depths; however, the Idso CWSI was more negative on day 209 than on earlier days. Given the same situation, the Idso CWSI for plot 3 was higher (became less negative) for a lower soil moisture content.

Using a Pearson's correlation technique we found no association between soil moisture and Idso's and Jackson's CWSI values. These results agree with those of Erhler (1973) and Jackson (1982) who found no unique relationship between soil moisture and (Tc-Ta) or the Jackson CWSI.

4.5 Crop Responses to Irrigation Scheduling

4.5.1 Crop Physiological Parameters

Stomatal resistance to the diffusion of water vapor (rs) was measured concurrent with Ta, Tc and Wb. No differences in rs were found for either year among the 3 treatments. Plant water potential, $\Psi\rho$ was collected in 1985, but equipment failure limited the amount of data gathered in 1986. No significant differences in $\Psi\rho$ among treatments was found. Average $\Psi\rho$ on day 220 was 0.84, 0.84 and 0.85 kPa for the well-watered, 0.2 and 0.5 CWSI treatments, respectively.

Table 4.9 (a) Volumetric soil water content measurements for 2 well-watered plots. (b) Concurrent with Tc, Ta and Wb measurements and the resulting CWSI values for 1985.

(a)

Date	Plot	D1 0-.15 m	D2 .15-.3 m	D3 .3-.6 m	D4 .6-.9 m	D5 .9-1.2 m	D6 1.2-1.5 m
217	4	.1725	.1995	.1915	.2040	.2320	.2200
217	11	.1930	.2285	.2110	.2470	.2440	.2475
226	4	.1915	.2235	.2020	.2475	.2585	.2540
226	11	.1485	.1870	.1775	.1835	.2265	.2100
234	4	.1700	.1805	.1530	.1730	.2095	.2005
234	11	.1775	.1915	.1765	.2075	.2245	.2395

(b)

Date	Plot	Tc (C)	Ta (C)	Tc-Ta (C)	Wb (C)	VPD (kPa)	CWSI
217	4	27.6	31.5	-3.9	22.5	2.5	-0.51
217	11	29.0	32.0	-3.0	23.0	2.6	-0.25
226	4	19.1	20.0	-0.9	12.5	1.4	-0.23
226	11	17.6	19.5	-1.9	13.0	1.2	-0.92
234	4	26.1	28.5	-2.4	22.5	2.6	-0.68
234	11	26.1	29.0	-2.9	22.5	1.7	-0.73

Table 4.10 (a) Volumetric water content for two 1986 well-watered plots. (b) Concurrent Tc, Ta, Tc-Ta, Wb, VPD and the resulting CWSI values.

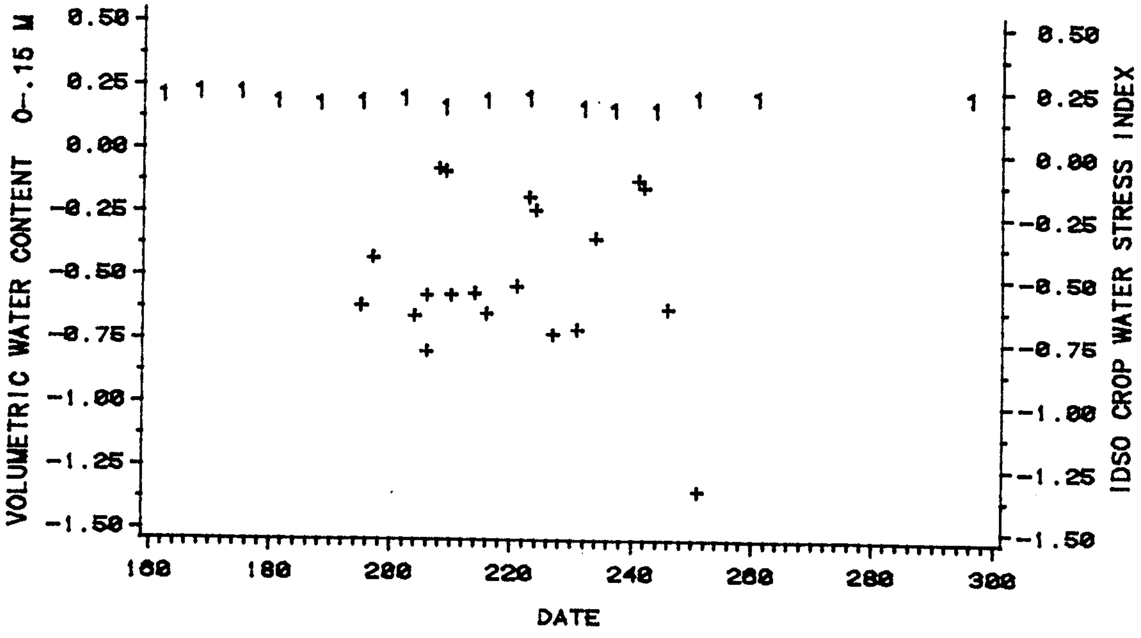
(a)

Day	Plot	D1 0-.15 m	D2 .15-.3 m	D3 .3-.6 m	D4 .6-.9 m	D5 .9-1.2 m	D6 1.2-1.5 m
195	3	.1750	.1620	.2055	.2500	.2700	.2560
195	15	.1400	.1530	.2400	.2375	.1920	.1710
209	3	.1580	.1420	.1850	.2345	.2615	.2500
209	15	.1205	.1365	.1995	.2185	.1815	.1630
216	3	.1855	.1730	.1835	.2235	.2020	.2460
216	15	.1610	.1680	.2150	.2020	.1755	.1565
223	3	.1985	.1825	.2045	.2220	.2495	.2425
223	15	.1745	.1830	.2565	.2305	.1745	.1555
251	3	.2005	.1775	.1690	.1705	.2330	.2330
251	15	.1820	.1810	.2195	.1695	.1660	.1575

(b)

Day	Plot	Tc (C)	Ta (C)	Tc-Ta (C)	Wb (C)	VPD (kPa)	CWSI	
							Idso	Jackson
195	3	29.0	32.7	-3.7	25.3	2.2	-0.62	0.13
195	15	32.1	33.8	-1.7	26.4	2.3	-0.02	0.20
209	3	28.8	32.7	-3.9	18.3	3.6	-0.09	0.33
209	15	28.7	34.1	-5.4	20.0	4.0	-0.25	0.29
216	3	25.1	28.9	-3.8	20.1	2.2	-0.65	0.19
216	15	25.7	29.0	-3.3	20.5	2.2	-0.54	0.22
223	3	25.9	26.6	-0.7	21.3	1.3	-0.19	0.25
223	15	25.5	28.1	-2.6	21.3	1.7	-0.61	0.17
251	3	13.3	13.1	0.2	11.1	0.3	-1.35	0.07
251	15	13.4	13.5	-0.1	11.4	0.3	-1.60	0.00

(a)



(b)

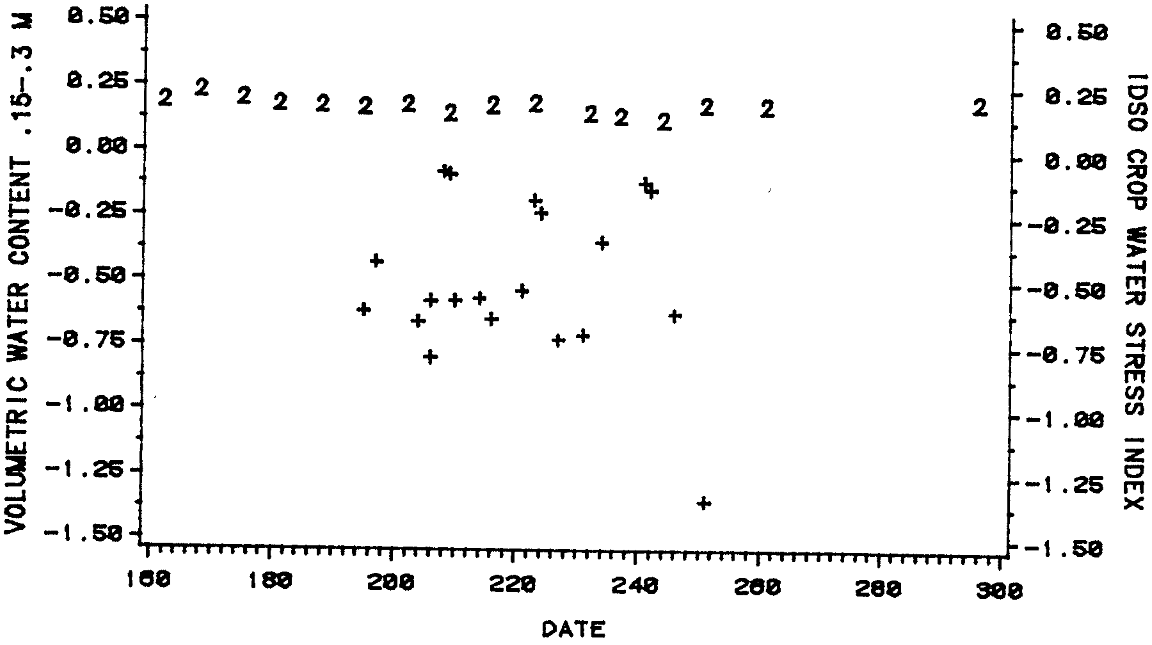


Figure 4.15 Idso CWSI values and volumetric water content where depths 1 and 2 are represented by (a) 0-0.15m and (b) 0.15-0.3 m for a well-watered 1986 soybean plot.

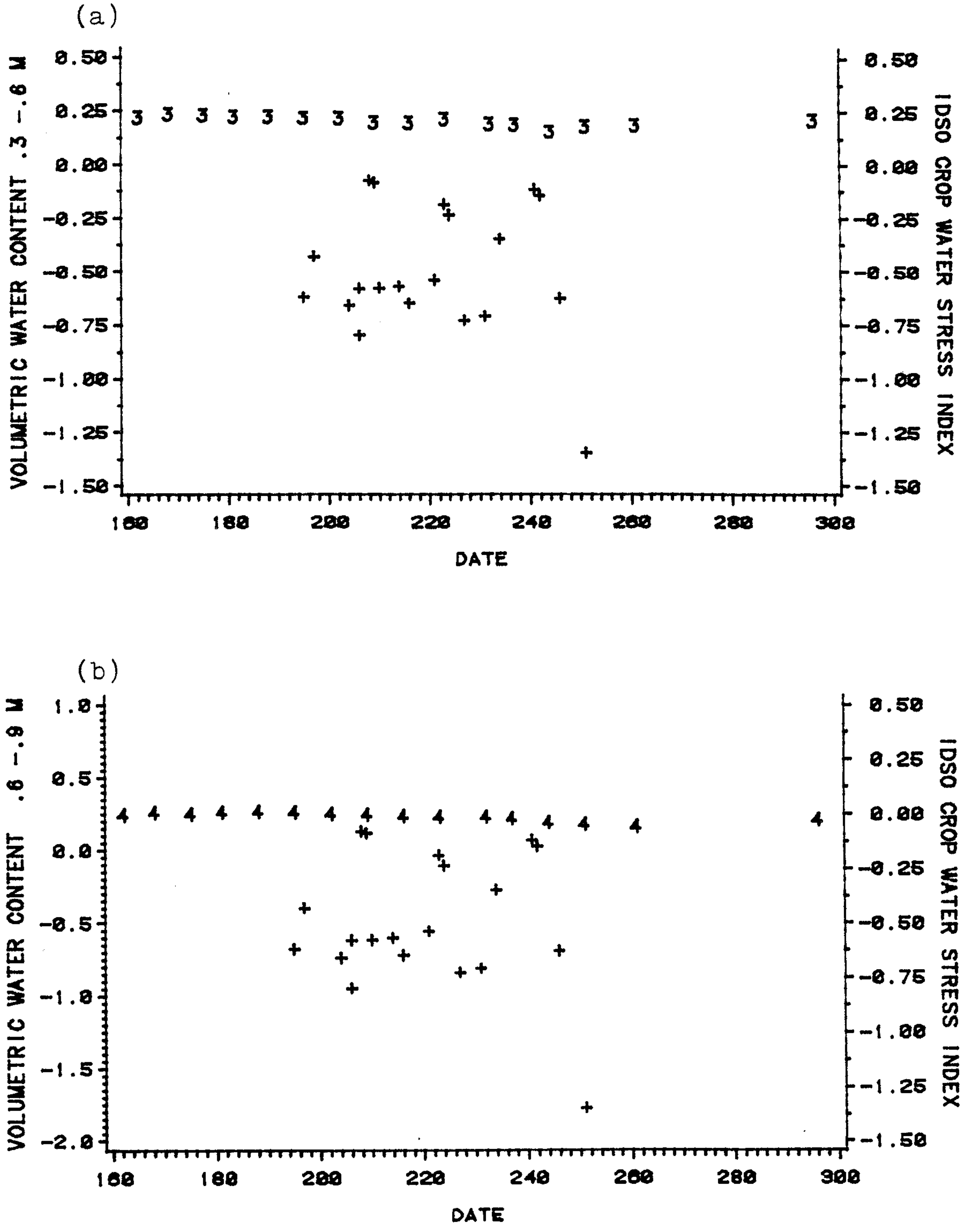


Figure 4.16 Idso CWSI values and volumetric water content with depths 3 and 4 are represented by (a) 0.3-0.6 m and (b) 0.6 - 0.9 m for a well-watered soybean plot.

Physiological measurements vary from plant to plant and are subject to large errors. Leaf age, time of day, location on the stem, and exposure to sunlight affect Ψ_ρ and rs measurements (Lugg and Sinclair, 1979 and Stevenson and Shaw, 1971). Thus, the small amount of data we collected were probably inadequate to statistically show differences among the 3 treatments.

4.5.2 Soybean Development

Stages of soybean development were recorded weekly using the methods of Fehr and Caviness (1977). In 1985, the 3 treatments had significantly different rates of vegetative (v) development ($Pr > F = 0.0251$) and height ($Pr > F = 0.0001$). The well-watered and 0.2 treatments were generally 1 v-stage ahead of the 0.5 treatment. Average soybean heights were 523, 470 and 438 mm for the well-watered, 0.2 and 0.5 CWSI treatments, respectively. The row gap of the well-watered treatment was significantly less than either the 0.2 or 0.5 treatments. In 1986, height was the only parameter which was found to be different, while row gap, vegetative and reproductive stages were similar for the 3 treatments.

Measurements of leaf area index (LAI), number of plants/m, stem and leaf dry matter showed no differences among the 1985 treatments (Fig. 4.17). Differences were detected in 1986 for LAI ($Pr > F = 0.0201$) with maximum LAI of 3.7, 3.2 and 2.8 for 0.2, well-watered and 0.5 treatments, respectively. No differences in number of plants or dry matter were found in 1986.

4.5.3 Yield and Water Use

Ultimately the future utility of the CWSI as an irrigation scheduling tool will depend on how the technique affects the yield and water use efficiency (WUE). Yields in 1985 and 1986 are presented in Table 4.11. The 3 treatments had similar yields and seed weights in 1985; in contrast, 1986 yield and seed

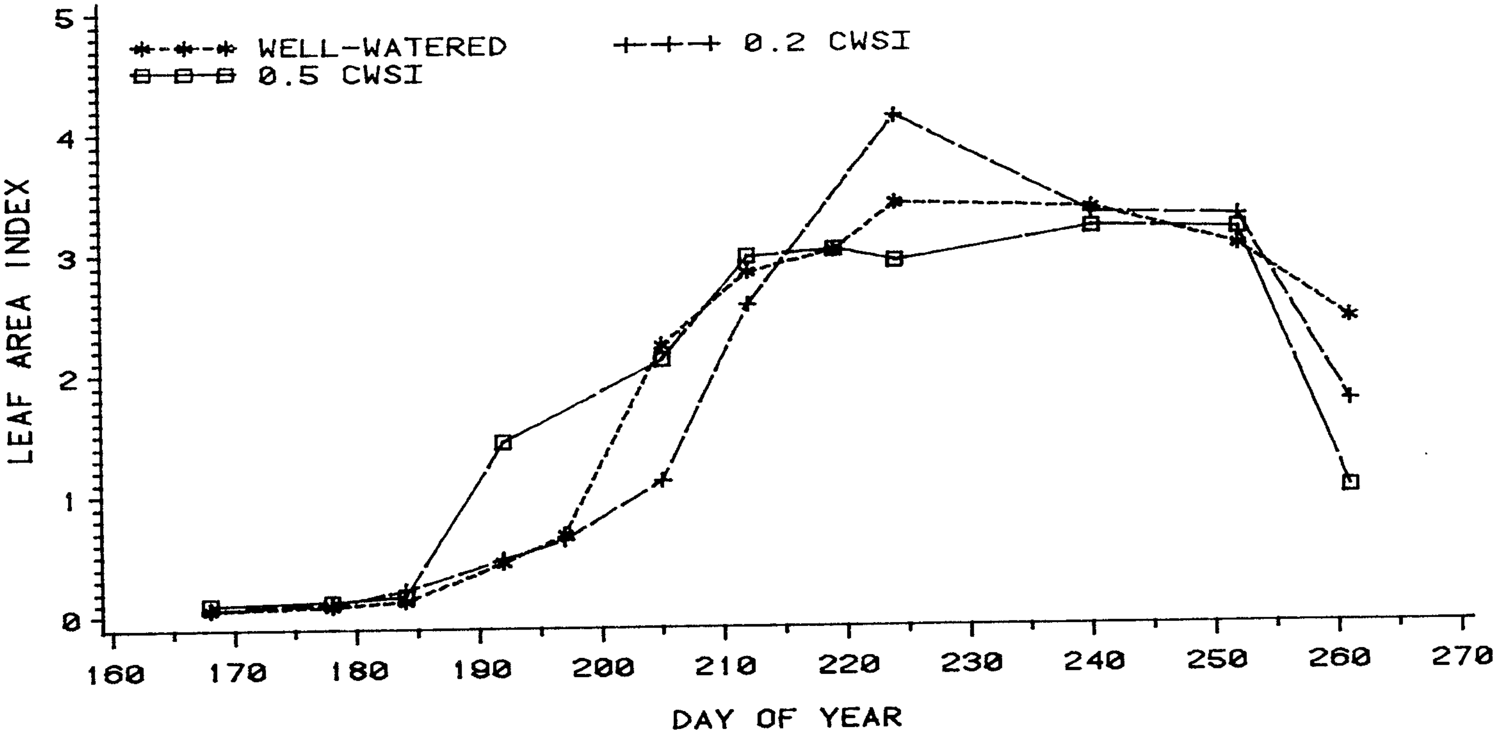


Figure 4.17 Leaf area index throughout the 1985 growing season.

Table 4.11 Yield and 100-seed weight for soybeans, 1985 and 1986. Yields are corrected to 13% moisture.

	Treatment	Yield (kg/ha)	100-Seed Weight (grams)
1985	well-watered	2188	16.1
	0.2 CWSI	2148	16.2
	0.5 CWSI	2251	16.0
(Pr > F) (0.05)		(0.4871)	(0.4072)
1986	well-watered	2824	17.6
	0.2 CWSI	2739	16.9
	0.5 CWSI	2586	16.5
(Pr > F) (0.05)		(0.0444)	(0.0001)

weight were significantly different. The well-watered plots had the highest yield and seed weight of the 3 treatments.

Water use efficiency (grain yield per unit of water) is becoming a major concern in crop production. Irrigation, ET (seasonal water use), and WUE values for the two years are in Table 4.12. Cumulative ET is shown in Figs. 4.18 and 4.19. Differences in the total amount of irrigation water applied and seasonal water use in both years were significant.

Total WUE was determined as the yield divided by the seasonal water use plus the irrigation amount. Irrigation WUE was the yield divided by the amount of irrigation. Total WUE and irrigation WUE values were significantly different for the different water treatments in both years. There was a significantly higher yield per mm of total water use and twice the yield per mm of irrigation water for the 0.5 CWSI treatment relative to that of the well-watered treatment.

Data in Tables 4.11 and 4.12 suggest that more irrigation does not necessarily mean higher yields. In 1985 the moderately stressed treatment had the highest yield and water use efficiencies. The frequently watered treatment in 1986 had the highest yield, but a very low irrigation WUE. Data for both years show that soybeans can yield well without being fully irrigated. By using a moderately high CWSI threshold, irrigation can be reduced without being detrimental to yield. As such, the CWSI approach seems to be superior to the soil moisture approach for scheduling irrigation.

4.6 Summary

The use of the CWSI as an irrigation scheduling method for soybeans was studied at the Sandhills Agricultural Laboratory during the 1985 and 1986 growing seasons. Canopy, air and wetbulb temperatures were gathered daily if cloud conditions were acceptable. Three treatments, well-watered, 0.2 and 0.5 CWSI

Table 4.12 Irrigation, cummulative ET, water use and efficiency for soybeans, 1985 and 1986.

Treatment	Total Irrigation Amount (mm)	Seasonal Water Use Amount (mm)	Total Water Use Amount (kg/ha/mm)	Irrigation Water Use Efficiency (kg/ha/mm)
1985				
well-watered	195	448	4.9	11.4
0.2 CWSI	132	364	5.9	16.3
0.5 CWSI	92	356	6.3	24.9
(Pr > F) (0.05)	(0.0002)	(0.0006)	(0.0492)	(0.0003)
1986				
well-watered	135	572	4.0	20.8
0.2 CWSI	85	534	5.1	41.6
0.5 CWSI	46	526	4.9	66.1
(Pr > F) (0.05)	(0.0090)	(0.0001)	(0.0030)	(0.0001)

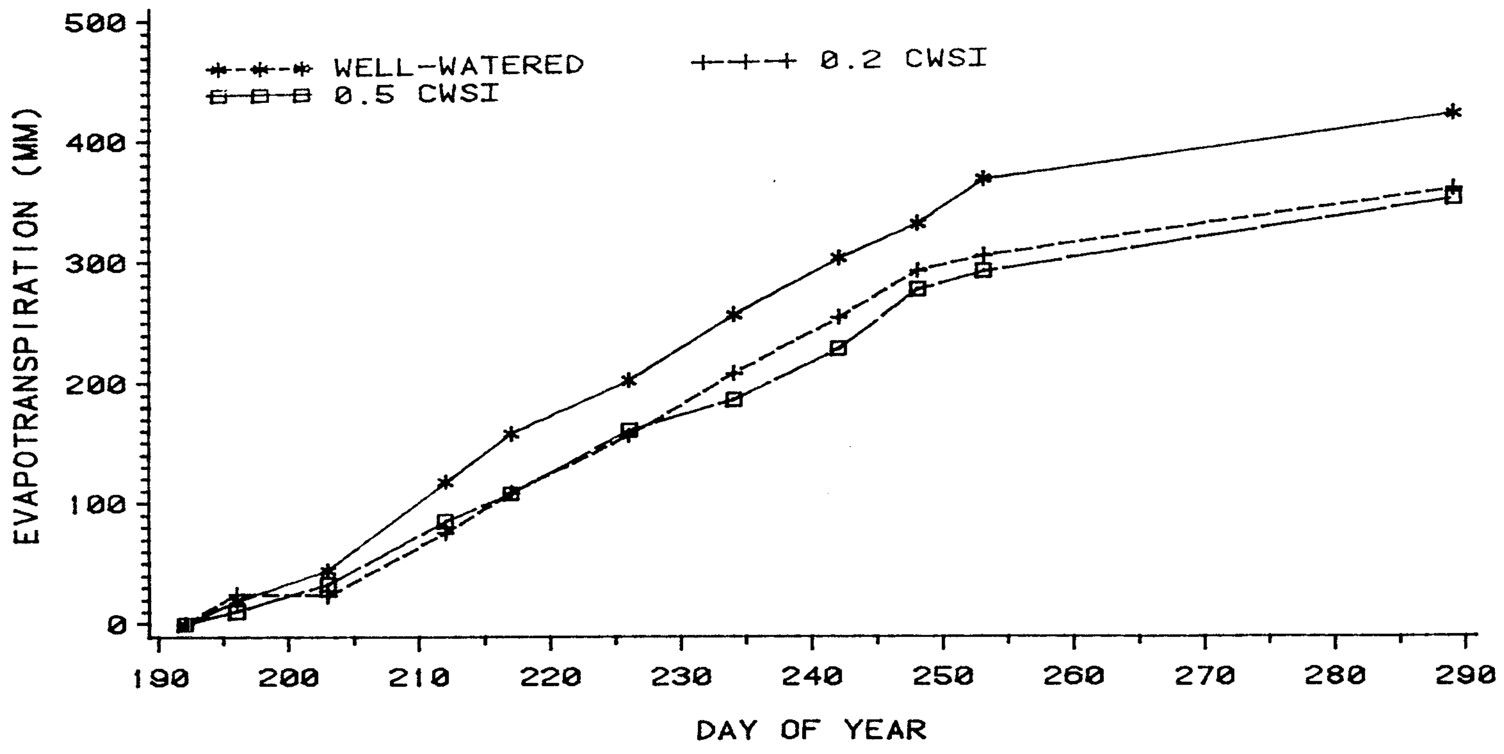


Figure 4.18 Cummulative evapotranspiration for all three treatments, 1985.

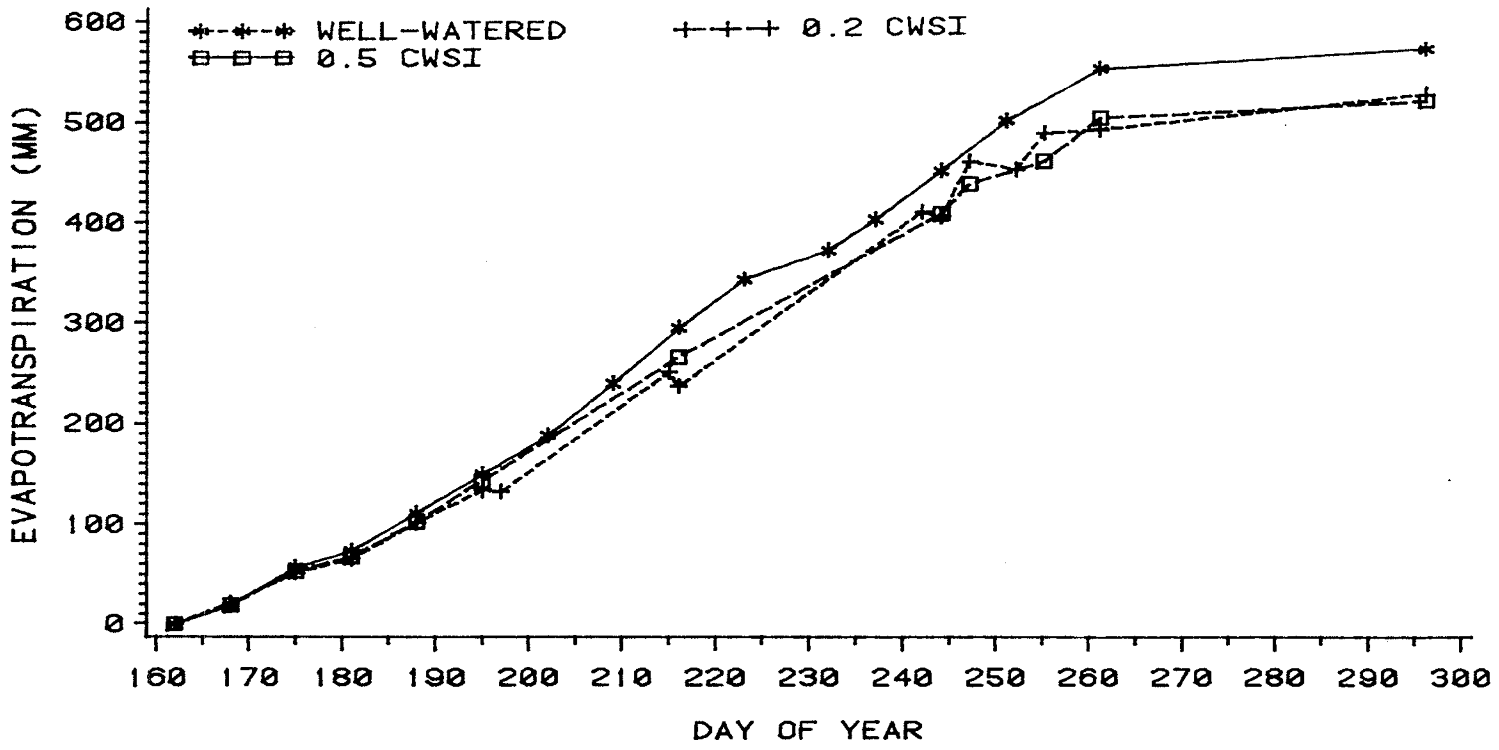


Figure 4.19 Cummulative evapotranspiration for all three treatments, 1986.

were used to evaluate the CWSI method of irrigation scheduling. The well-watered treatment plots were irrigated on the basis of soil moisture status while the 0.2 and 0.5 treatments were irrigated when the calculated CWSI reached or exceeded the assigned threshold level.

The major findings of this study were:

1) Exposed soil greatly influences the Tc measurement. After 85% canopy cover was reached, the standard deviation of Tc was reduced below 1 C.

2) The direction the IRT was aimed produced differences in Tc. North-facing temperatures at 1400 CDT were 0.5 C warmer than east, west or south-facing. This results from the IRT viewing a greater amount of sunlit leaves than would be viewed from other directions.

3) Cloud cover causes drastic changes in Tc and Ta within a few minutes. A 25% decrease in PAR resulted in decreases of 1.8 and 4.0 C for Ta and Tc, respectively.

4) The well-watered baseline for soybeans suggested by Idso, *i.e.* (Tc-Ta) = 1.44 - 1.34 * VPD did not work well. This may be due to the soybean cultivar or the VPD conditions at the experiment location.

5) The regression of Tc-Ta on VPD had a very low R^2. This indicates that an important variable is not accounted for in the Idso CWSI method. This could be Rn which is accounted for by Jackson's (1982a) method.

6) Yield was not affected significantly, but irrigation WUE was greatly enhanced for the CWSI scheduled treatments.

Chapter 5

IRRIGATION SCHEDULING OF CORN, WHEAT AND POTATOES

5.1 Introduction

The primary objectives of the research reported here were: (1) to evaluate the feasibility of scheduling irrigation of corn, wheat and potatoes in Nebraska using the CWSI approach; and, (2) to determine whether or not the baselines established for these crops at other locations are adequate for use in the climatic conditions characteristic of Nebraska.

5.2 Materials and Methods

The study was conducted in 1986 at the University of Nebraska Sandhills Agricultural Laboratory (41° 37° N, 100° 50′ W). Two hard red winter wheat (*Triticum aestivum*) cultivars (Colt and Brule) were planted on September 6, 1985 in 0.30 m rows at a plant population of about 325,000 plants ha^{-1}. Because of certain restraints, the wheat had to be planted into plots where wheat had been grown the previous year. As a result, a serious weed problem arose in 1986 which was impossible to control except by hand-weeding certain plots and, even then, it was not possible to get all the weeds removed from many of the plots because many grassy type weeds closely resembled the wheat plants until seed heads began to develop.

Two hybrids of corn (*Zea mays* L.) *i.e.*, Pioneer 3901 and Golden Harvest 2344, were planted on May 9, 1986 in 0.76 m rows at a population of 67,400 plants ha^{-1}. All corn plots were treated with herbicides and kept weed free. Potatoes (*Solanum tuberosum*), varieties Pontiac and Cobbler, were also planted May 21, 1986 in 0.76 m rows at a plant population of about 50,000 plants ha^{-1}. Row orientation was north-south for all crops.

Because of space and facility limitations, the number of replications for each crop was different. We used a completely random design with the following replications for each crop for each water treatment: corn, two replicates; potatoes, two replicates; and wheat, two to four replicates, depending on whether one or two cultivars were used for each water treatment.

Wheat plots were about 3.5 m wide and 5-8 m long. Plots for all other crops were about 18 m wide and 27 m long. A solid-set irrigation system was located on the east and west borders of all plots - except for wheat where five plots were located between riser rows. Twelve rows 4.6 m long were harvested from each plot - except wheat where four 3.05 m rows were used. Each single row of soybeans was considered to be a separate sample, two rows of wheat and three rows of corn and potatoes were aggregated into a sample. Thus, there were a total of eight corn and potato samples and four wheat samples for each water treatment. Wheat was harvested July 7-9, 1986, potatoes were harvested in late September, and corn and soybeans were harvested October 20-21, 1986.

Canopy temperatures were measured with an infrared thermometer (IRT) during the 1400-1500 CDT period. Measurements were not made when clouds obscured the sun. Plants were allowed to equilibrate for about two minutes following passage of the cloud shadow before readings were resumed. A total of ten measurements - five facing north and five facing south - were taken and averaged to get the canopy temperature values used in the CWSI calculations. The IRT was held abut 1 to 1.5 m above the canopy at an angle of about 30 degrees from horizontal (a zenith view angle of about 60°). All IRT data were recorded with a Polycorder portable data logger. The IRT was calibrated against a portable blackbody reference before and after each day's use to ensure reliable instrument performance. Dry and wet bulb temperatures were measured using a minipsychrometer located about 1 m above the canopy in each plot. Temperatures were measured with a digital thermocouple thermometer.

CWSI values for each crop were calculated using the approach suggested by Idso *et al.* (1981). The equations used for the different crops all take the following forms for the upper limit line (UL) and the well-watered baseline (LL), respectively: $UL = A + B(VPG)$ and $LL = A + B(VPD)$, where VPG is the vapor pressure gradient, VPD is the vapor pressure deficit, A is the y-intercept and B the slope of the Tc-Ta vs. VPD curve. Each crop has a different value for A and B. The values used for A and B for each crop in this study were, respectively: for wheat before heading, 2.88 and -2.11; after heading, 3.38 and -3.25; for corn, 2.67 and -2.06; and for potato, 1.17 and -1.83. When the UL and LL values were determined for a data set, the CWSI was calculated from the equation $CWSI = [(Tc-Ta) - LL] \div (UL - LL)$.

The initiation of an irrigation was dependent on the attainment of a selected CWSI, except for those plots which received either full irrigation or for rainfed plots. The full-irrigation plots were irrigated once each week with sufficient water to refill the soil moisture profile based on neutron probe measurements. The rainfed plots received only natural rainfall. The CWSI values for the different crops for initiation of irrigation were for wheat, CWSI = 0.2; for corn, CWSI = -0.1 (but not more often than once every three days), 0.1, 0.2 and 0.3. Because of space limitations the potatoes had to be interspaced within some of the soybean plots and irrigated only when those plots of soybeans were watered. When the CWSI threshold for a plot was reached, about 25 mm of water was applied to the plot. Irrigations were not scheduled using canopy temperatures until sufficient crop cover had developed to minimize any influence of the soil background radiation on the canopy temperature.

5.3 Results and Discussion

5.3.1 Comparison Baselines

A decision was made at the beginning of the growing season to schedule irrigations based on the Idso baselines values given in the Materials and Methods section. The (Tc-Ta) values as a function of the VPD for the well-watered plots for each of the different crops grown in 1986 along with the lines described by the Idso coefficients are shown in Figs. 5.1-5.3.

The data for wheat suggest that the Idso baseline values were probably acceptable for our wheat (Fig. 5.1). This conclusion, while not apparent from a cursory look at the data, comes from the observation that many of the lower values of (Tc-Ta) fall along the plotted baselines. There are numerous (Tc-Ta) values which fall above these lines, but these values may have been obtained when the wheat crop, in fact, was under some degree of water stress. For wheat, the weekly irrigation may have been inadequate to prevent some stress from occurring. This hypothesis is supported by the cumulative evapotranspiration data for the CWSI of 0.2 vs. the full irrigation treatment (to be discussed later in this report), which shows that the CWSI = 0.2 treatment used about 70 mm more water than the fully irrigated treatment.

The Idso baseline value for corn fits our data very well (Fig. 5.2). The data for the potato shown in Fig. 5.3 likewise suggest that the Idso baseline may have been adequate for our potato crop since the minimum (Tc-Ta) values fall along the baseline, although the general trend was for the (Tc-Ta) values to be greater than would be expected from the Idso baseline. In view of the way in which they were irrigated, that is using the soybean data to irrigate the potato plots, the full irrigation potato plots may not have received enough water to prevent water stress.

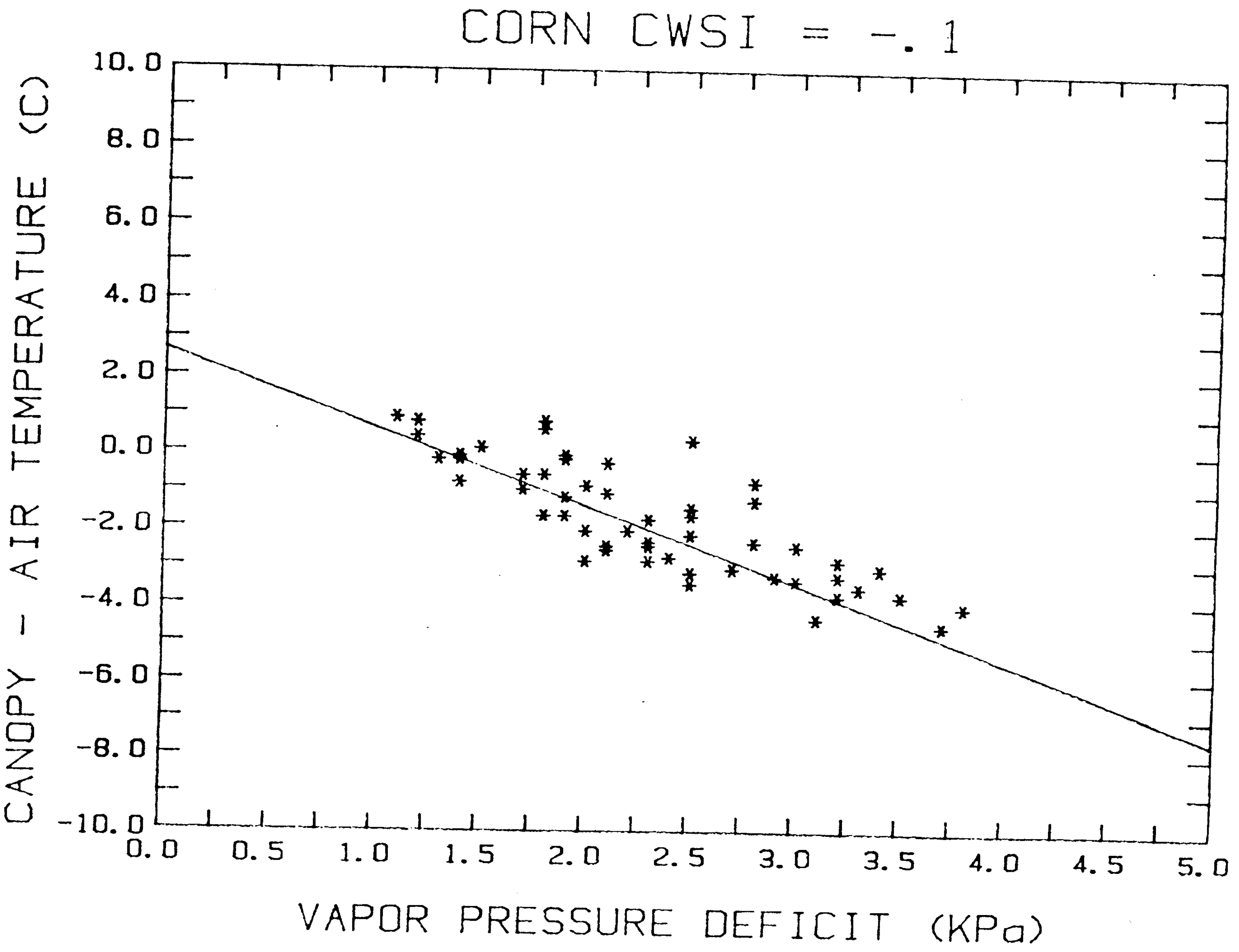


Figure 5.1 Comparison of T_c-T_a data for well-watered corn with the Idso baseline.

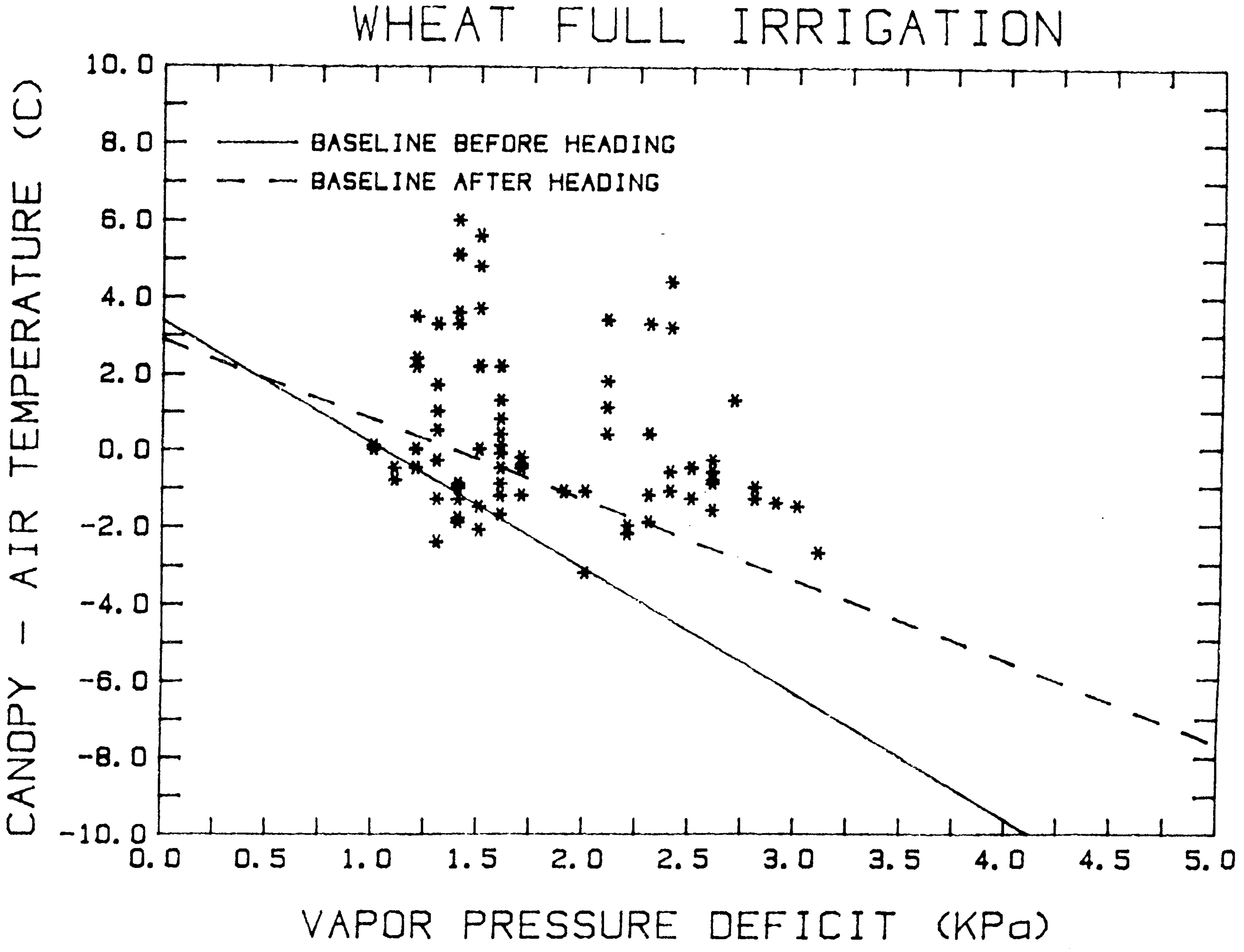


Figure 5.2 Comparison of T_c-T_a data for well-watered wheat with the Idso baseline.

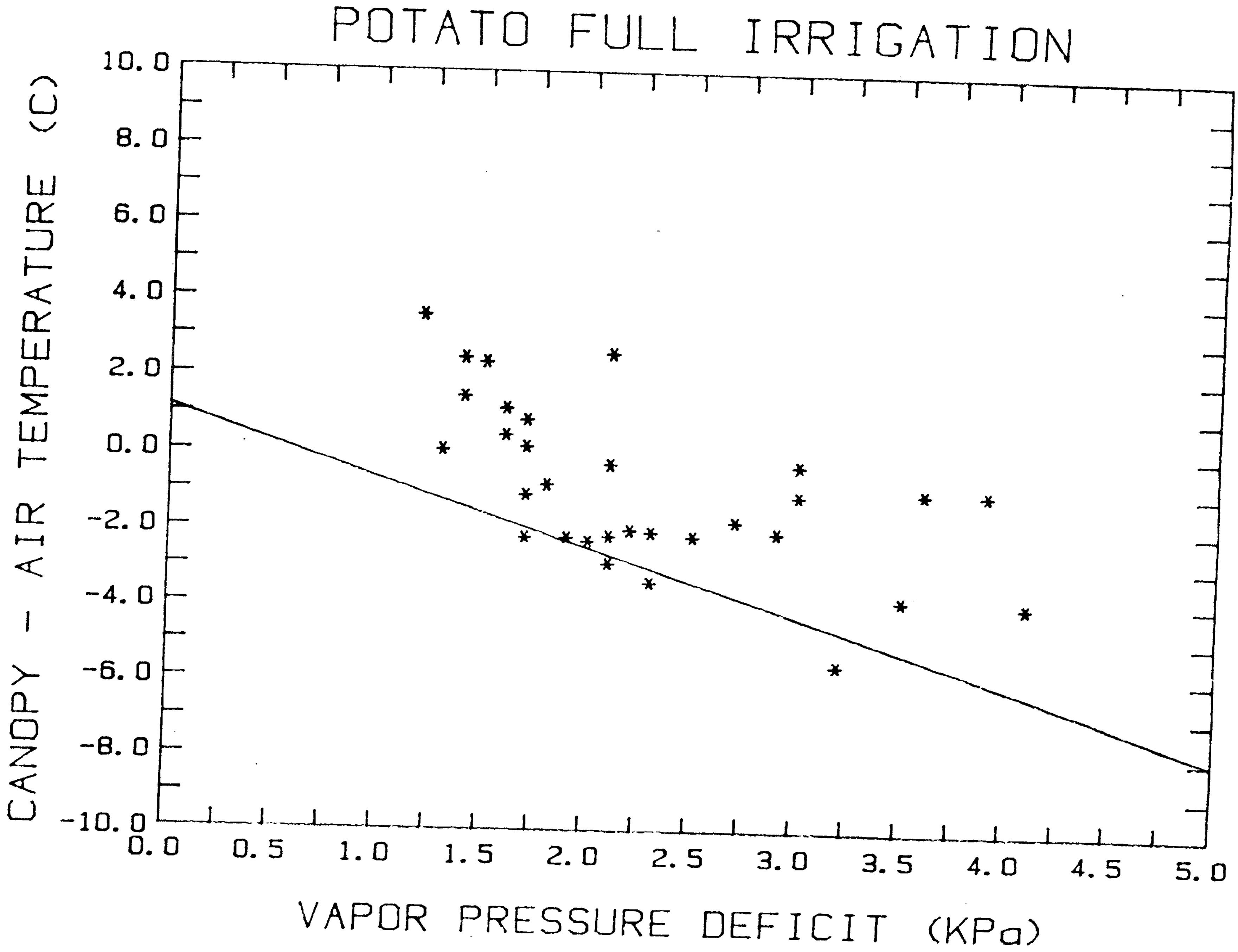


Figure 5.3 Comparison of T_c-T_a data for well-watered potatoes with the Idso baseline.

Our general conclusion from the information shown in Figs. 5.1-5.3 is that the Idso baselines for corn and, probably, wheat and potatoes, were adequate for irrigation scheduling under the environmental conditions at our site.

5.3.2 Seasonal Patterns of CWSI

Collection of CWSI data for corn and potatoes did not begin until day 191 (July 10). Examples of the seasonal progression of CWSI for each of the water treatments in corn are given in Figs. 5.4-5.7. The first irrigation of the corn plots did not commence until about day 197 or 198. All plots were irrigated on that date even though the CWSI = 0.3 treatment had not exceeded the threshold value. This was done because of the unavailability of anyone to make IRT readings over the weekend and because of very hot and dry weather during this period. Therefore, the decision was made to apply 12 mm of water to plot 9.

Initially, the CWSI = -0.1 treatment showed the need to be irrigated almost every day, and a decision was made by about day 208 to irrigate no more frequently than once every three days. A total of 13 different irrigations were made on the CWSI = -0.1 plots, 9 on the 0.1 plots, 6 on the 0.2 plots and only 5 on the 0.5 plot. The distribution of irrigation events for the different treatments presents an interesting picture. The CWSI = -0.1 and 0.1 plots were irrigated periodically throughout the season, but there were no irrigations of the CWSI = 0.2 and 0.3 plots for more than a month. In fact, most irrigations of these plots occurred near the end of the growing season and likely reflected the reduced transpiration rates of the senescing vegetation. Rainfall during the period from about day 210 through day 240 was adequate to prevent the development of other than just minor water stress. The yield data, which will be discussed later, support these findings that severe stress did not occur

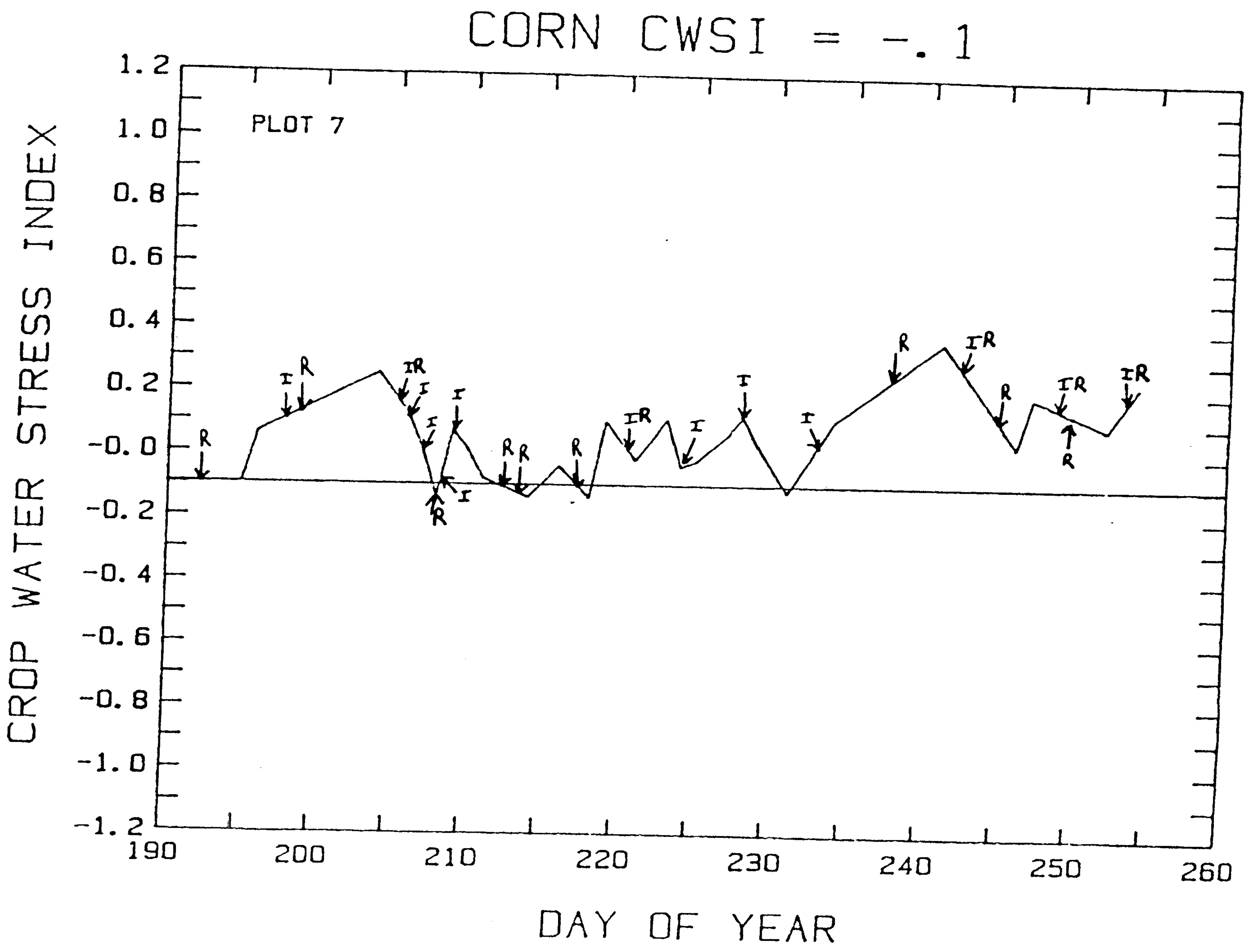


Figure 5.4 Values of CWSI for corn in the water treatment CWSI = -0.1. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

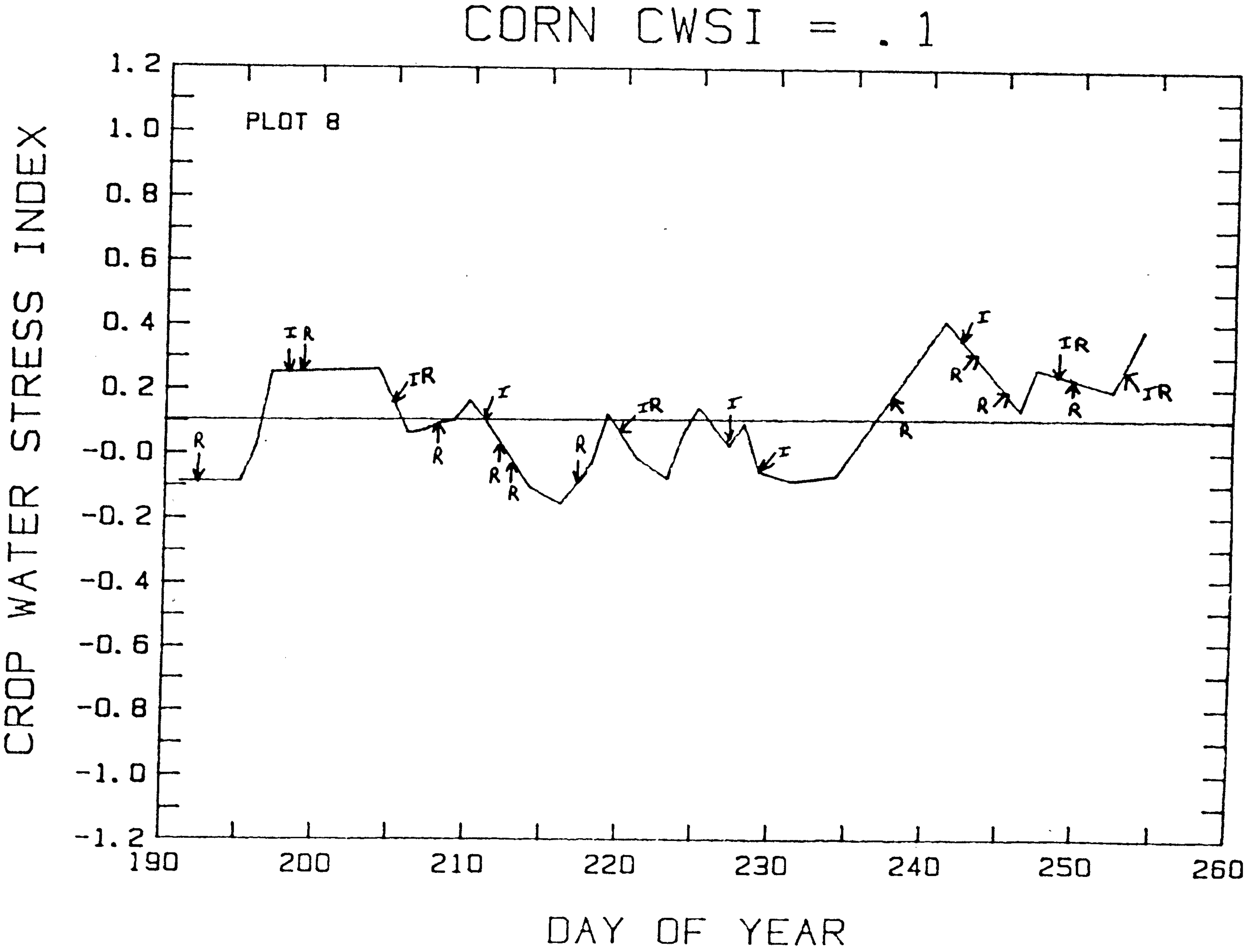


Figure 5.5 Values of CWSI for corn in the water treatment CWSI = 0.1. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

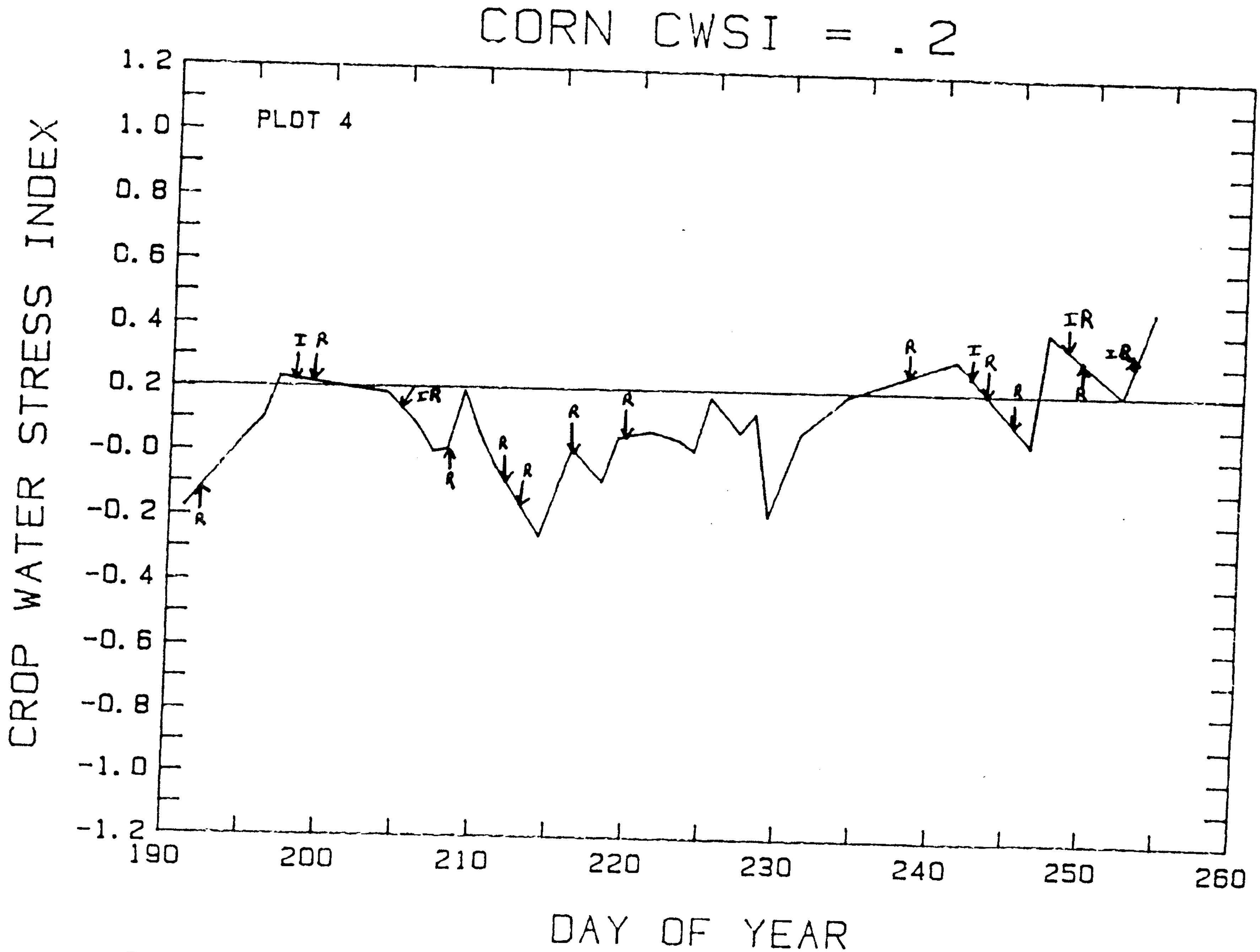


Figure 5.6 Values of CWSI for corn in the water treatment CWSI = 0.2. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

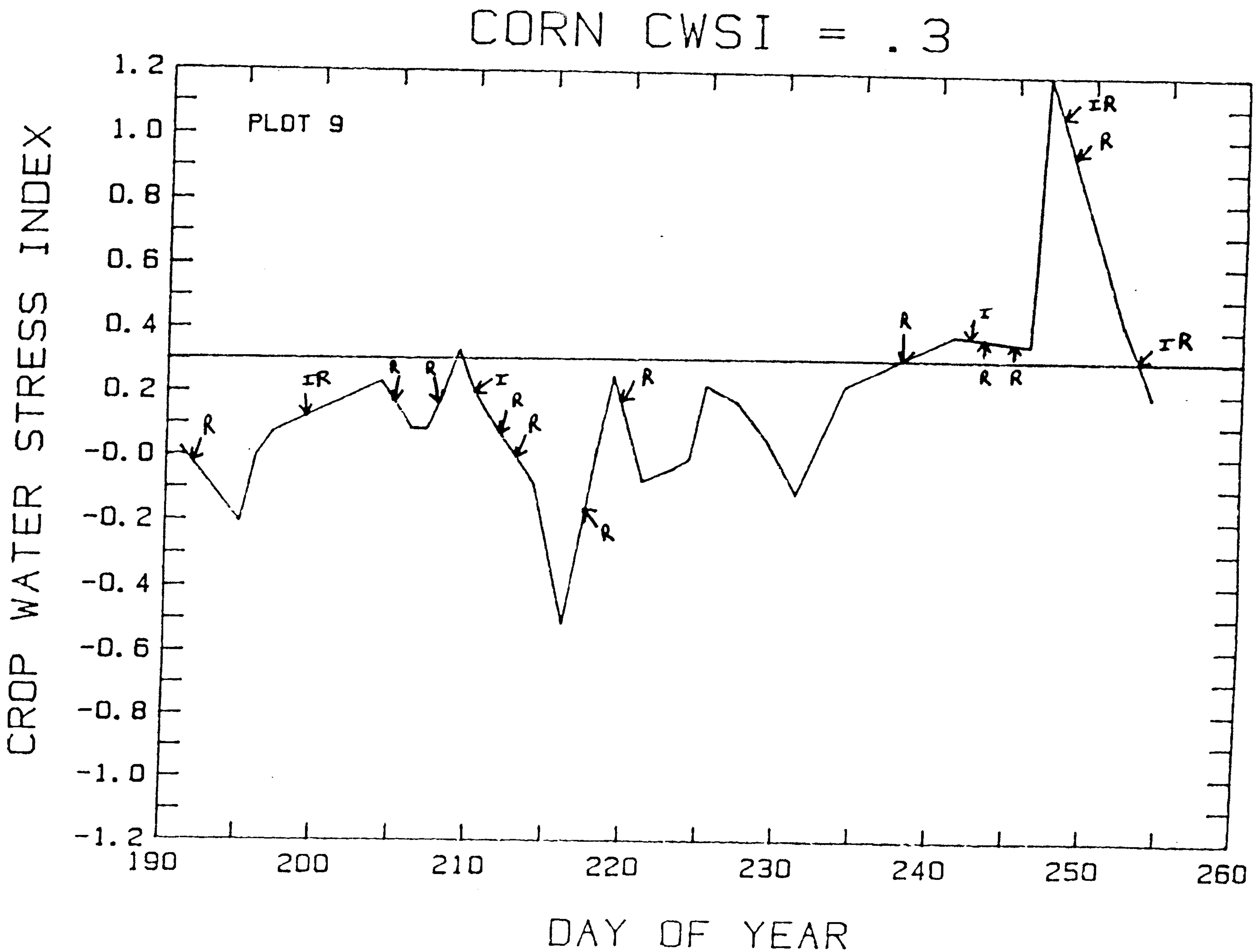


Figure 5.7 Values of CWSI for corn in the water treatment CWSI = 0.3. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

during the pollination and grain-filling growth stages in any of the water treatments.

The CWSI patterns for potatoes are given in Figs. 5.8 and 5.9. Since the potato data were not used to schedule the irrigation, they are only useful to suggest the following. Since the CWSI values were seldom below 0 and almost always above 0.2 even for the full irrigation plot, the potato baseline values of Idso - either or both of the upper and lower limits - were inadequate to give reliable CWSI values or the potatoes needed more water and with considerably more frequent irrigations. Until further research is done with potatoes, our results for potatoes are inconclusive.

Examples of the seasonal patterns of CWSI for the different water treatments and for the two wheat varieties are shown in Figs. 5.10-5.14. The first irrigation was applied on day 134. Although some data were collected during the period preceding day 130, there was insufficient plant cover to prevent a significant contribution of radiation from the soil to the IRT temperature. Cool, damp and rainy weather prevailed through much of the growing season so that IRT data were taken infrequently; and irrigation, even of the full irrigation plots, was infrequent. Only three irrigations of the fully-watered and the CWSI = 0.2 plots were made during the entire season. For both the Colt and Brule varieties the rainfed plots showed slightly more water stress, as indicated by CWSI values, than the fully irrigated plots but differences were not large except before heading (about day 140). CWSI values for the Colt = 0.2 plot were very similar to those of the Colt and Brule dryland plots. Because of the weather conditions experienced during the wheat growing season and the weed problems encountered, we believe that conditions were not favorable for a good test of the use of CWSI to schedule irrigation in wheat.

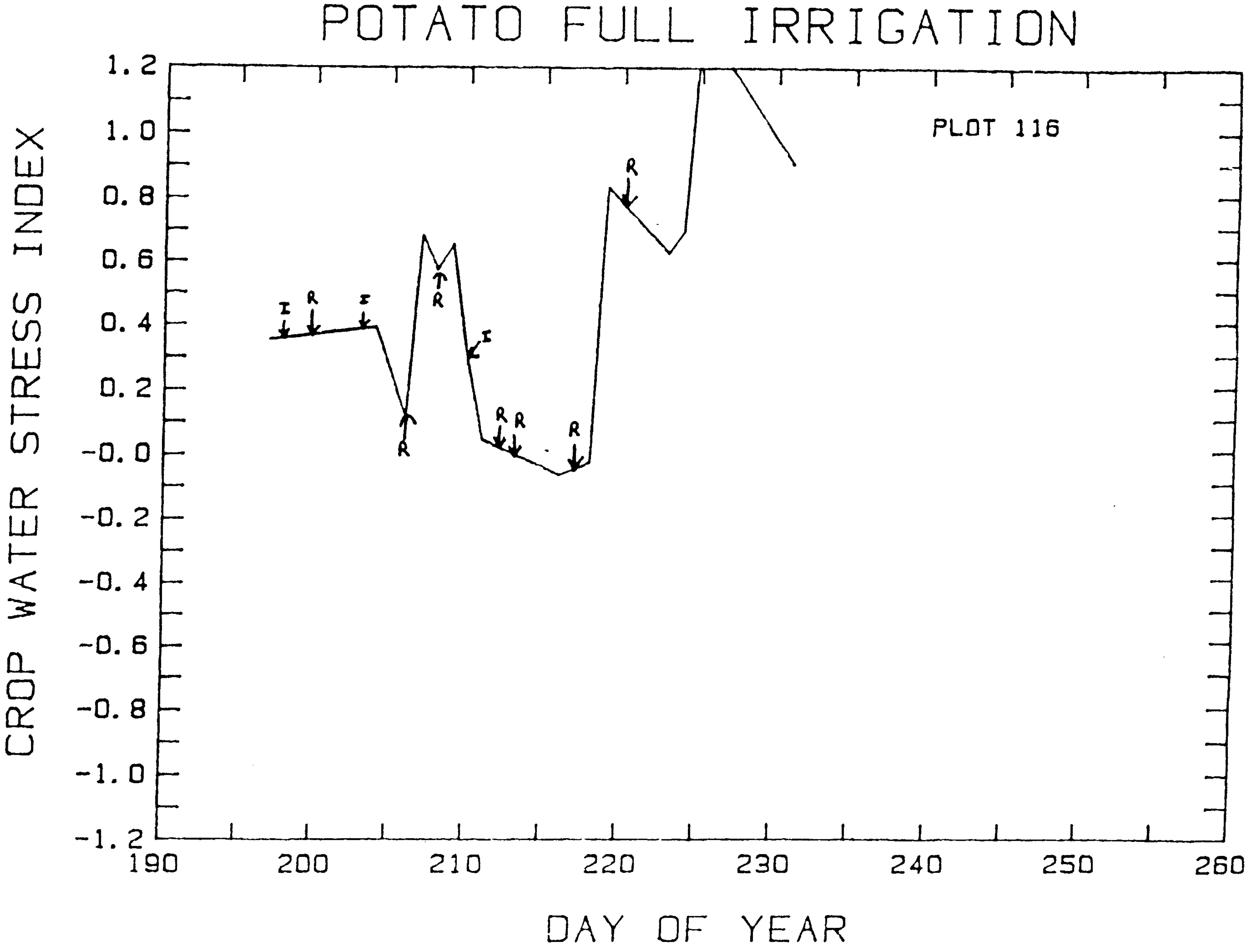


Figure 5.8 CWSI values for full irrigation treatment in potatoes. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

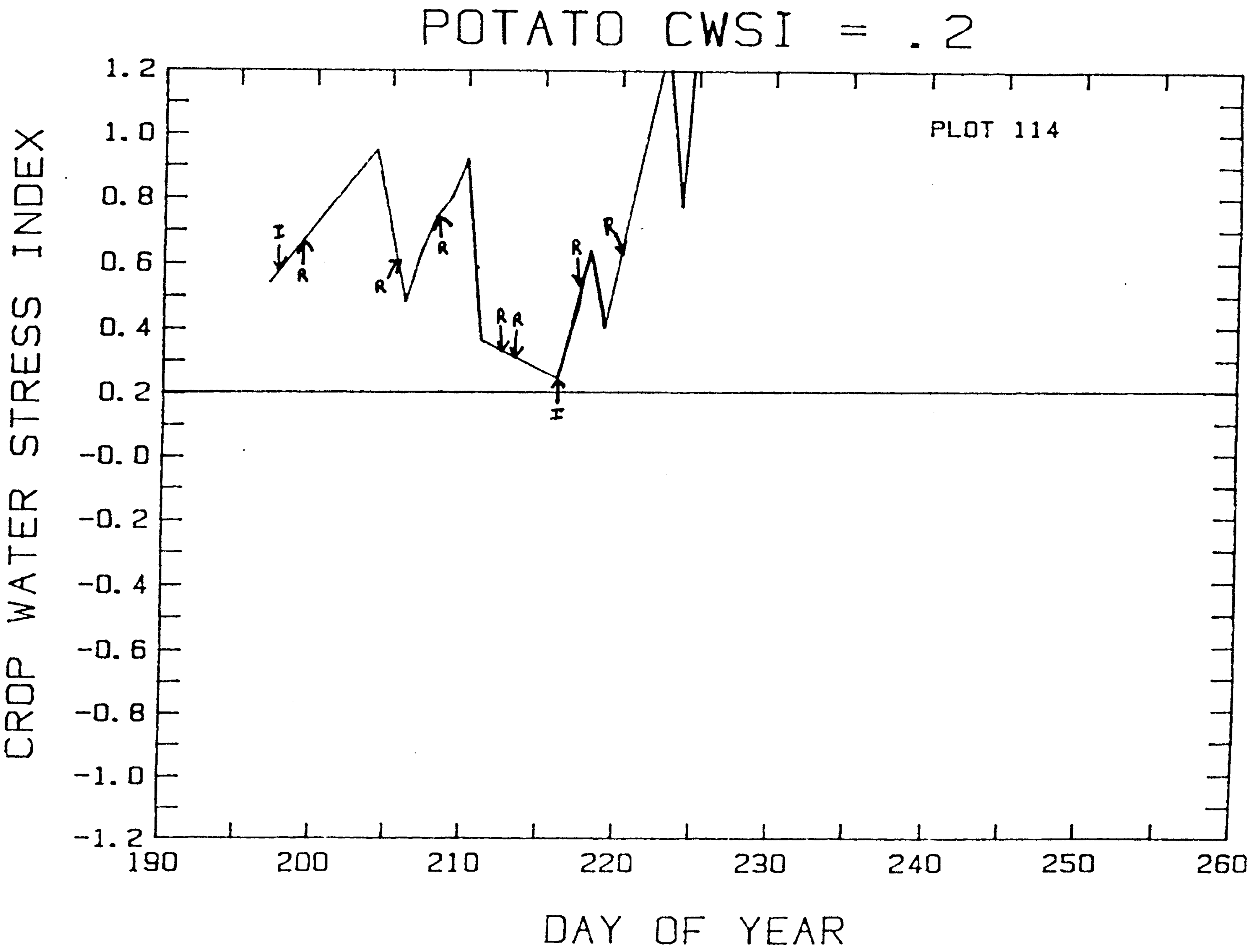


Figure 5.9 CWSI values for CWSI = 0.2 treatment in potatoes. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

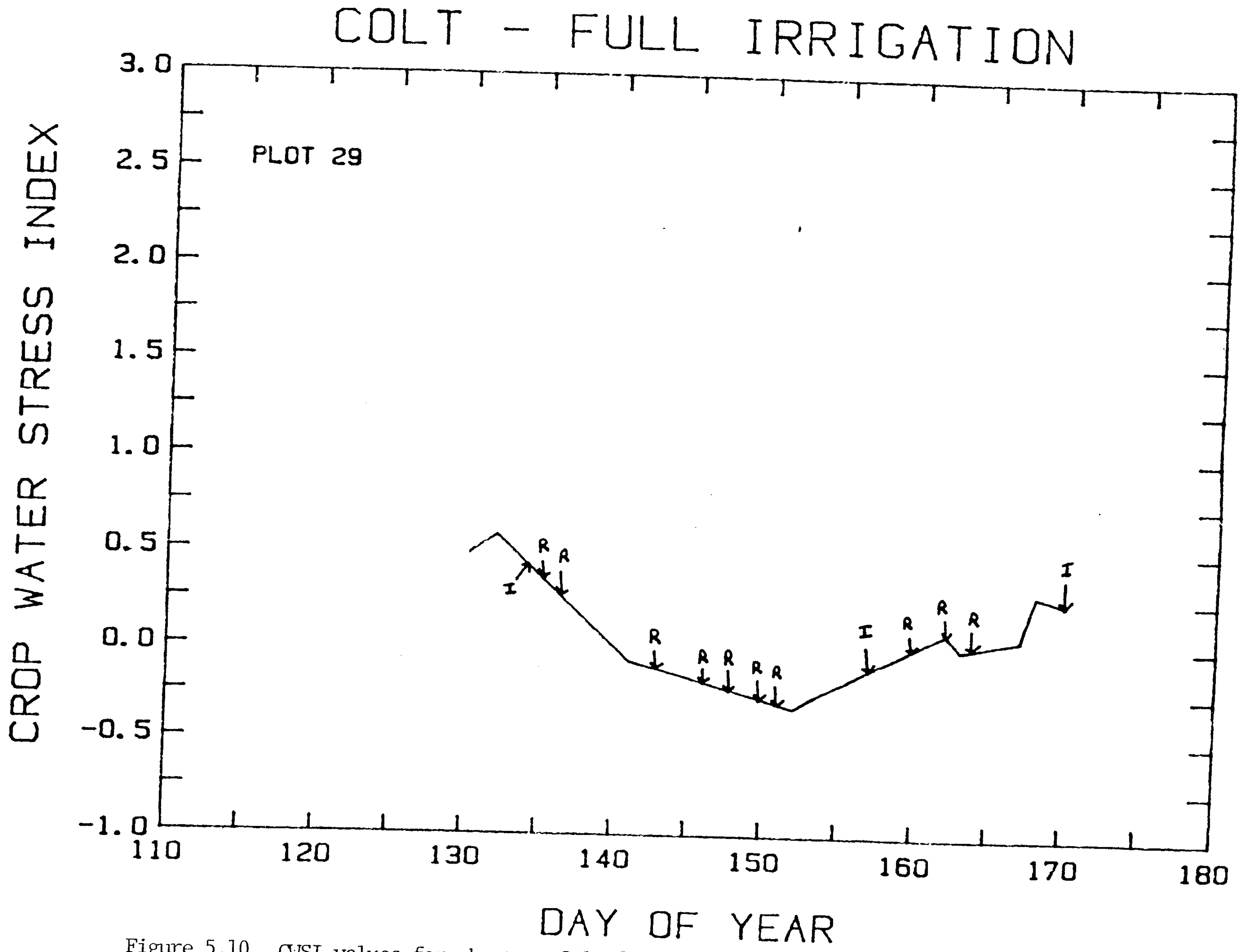


Figure 5.10 CWSI values for wheat cv Colt for full irrigation treatment. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

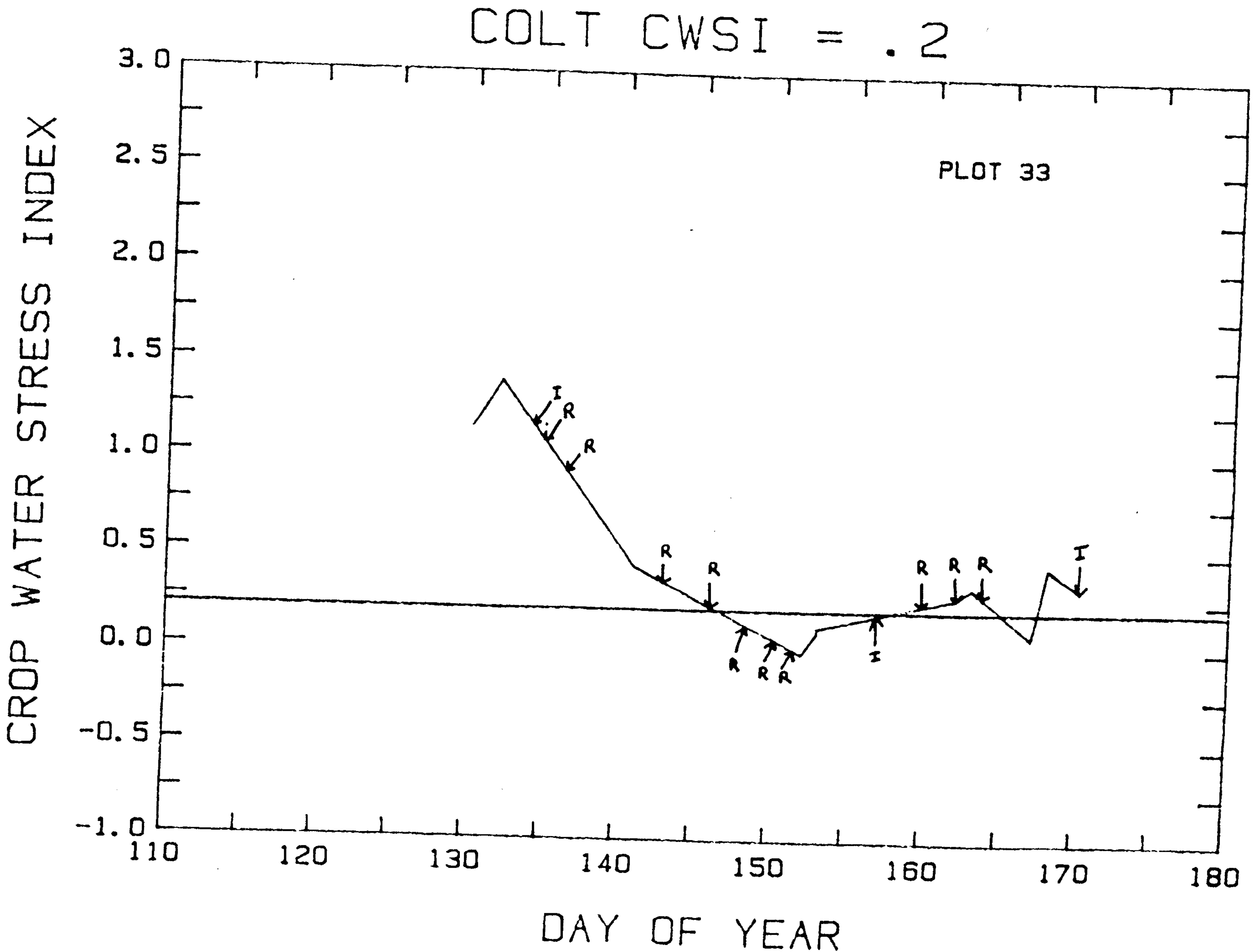


Figure 5.11 CWSI values for CWSI = 0.2 treatment in wheat cv Colt. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

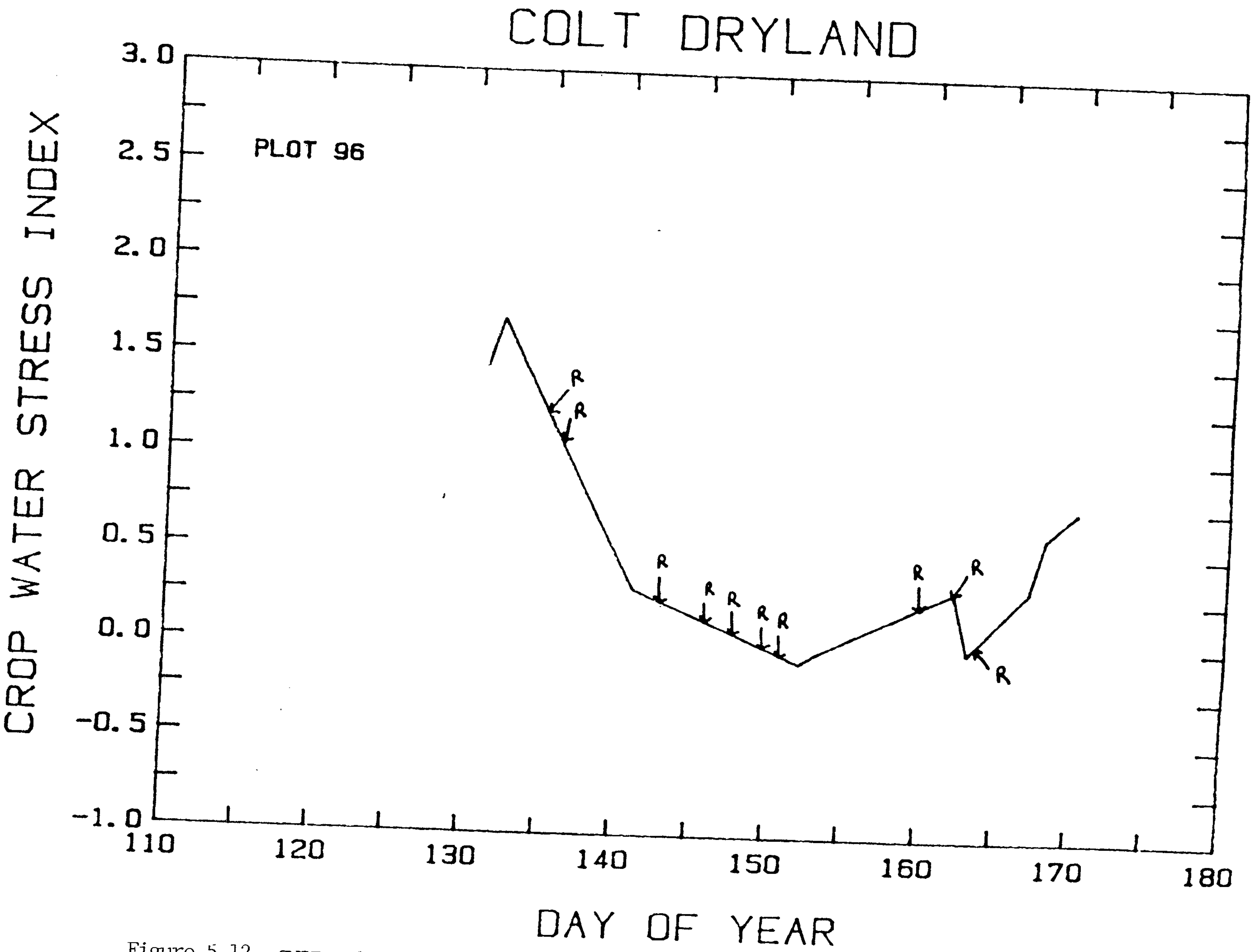


Figure 5.12 CWSI values for dryland treatment in wheat cv Colt. R indicates rainfall of at at least 2.5 mm.

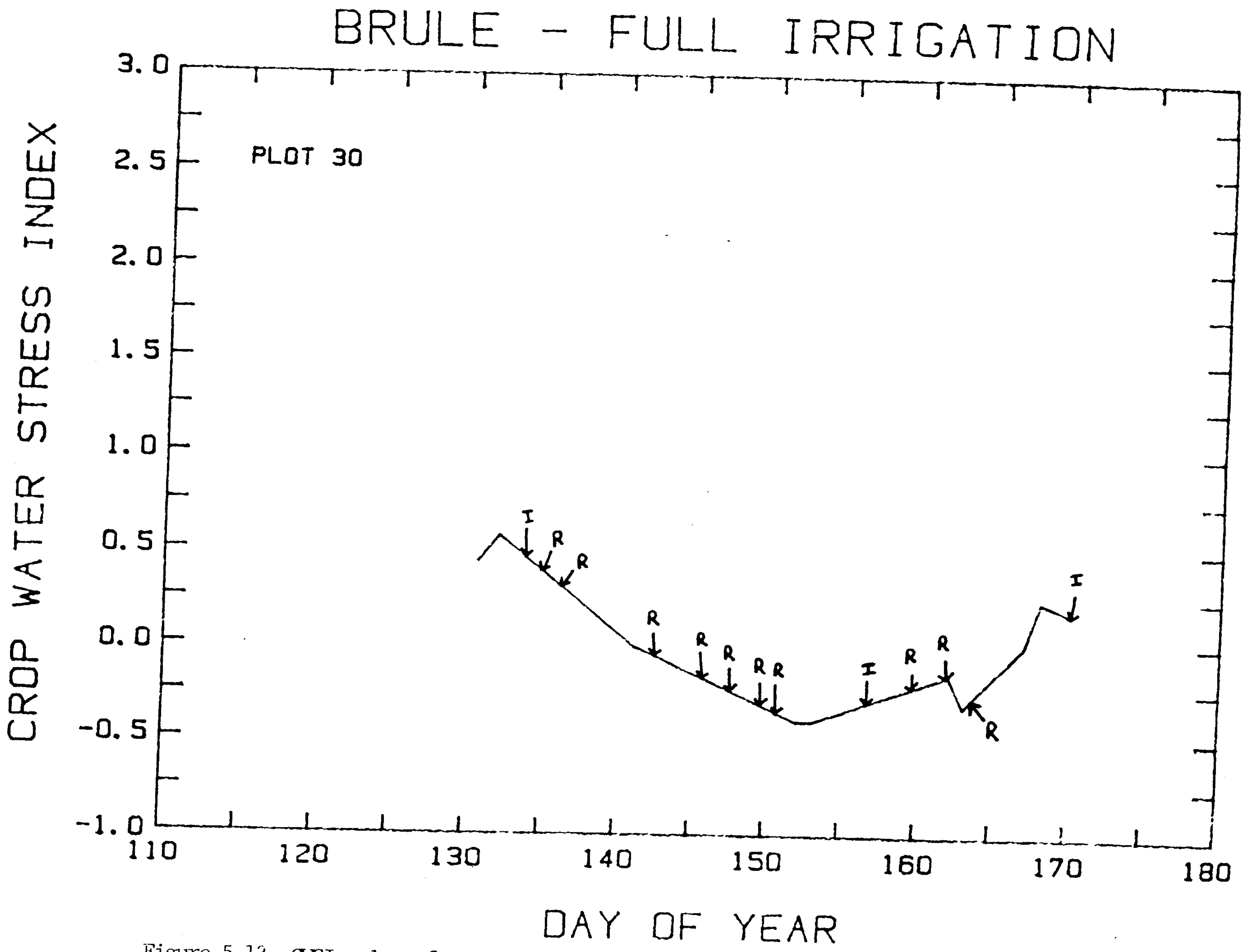


Figure 5.13 CWSI values for Brule cv for full irrigation treatment. I indicates an irrigation event and R indicates rainfall of at least 2.5 mm.

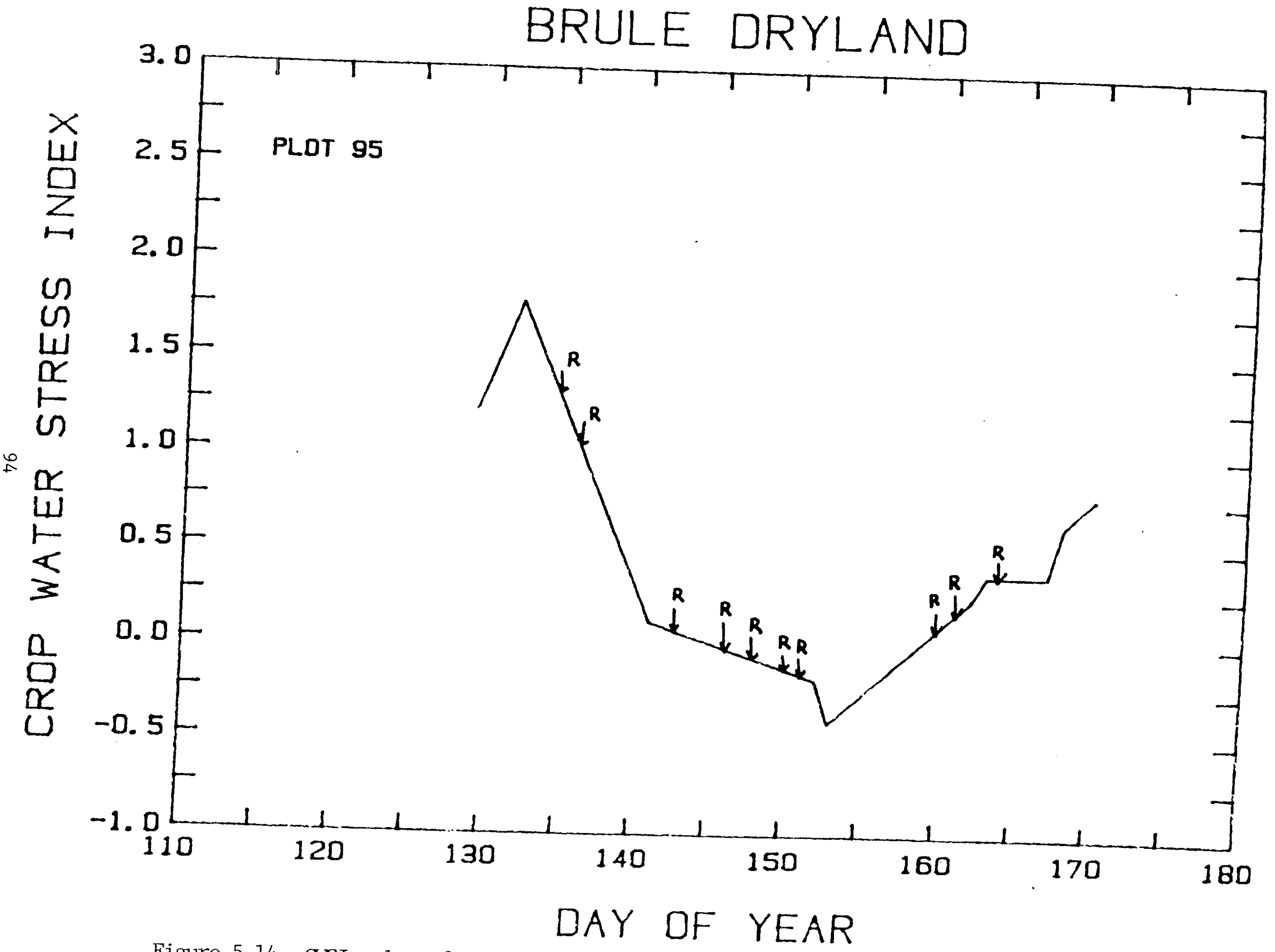


Figure 5.14 CWSI values for Brule cv for dryland treatment. R indicates rainfall of at least 2.5 mm.

5.3.3 Seasonal Water Use

The seasonal water use patterns for all irrigation treatments for the two hybrids of corn are presented in Figs. 5.15 and 5.16. Both hybrids of corn used about equal amounts of water for all water treatments, and the patterns of water use were very similar. The greatest deviation between hybrids occurred for the CWSI = 0.2 treatment. Even for this treatment, the total water use by the end of the season was almost identical to that of the other treatments. The general water use patterns for the different water treatments are about what one might expect, *i.e.*, the greatest ET rates for the CWSI = -0.1 treatment, the next highest rates for CWSI = 0.1, then less water use for the CWSI = 0.2 treatment. The expected pattern changes, however, when comparing the CWSI = 0.2 and CWSI = 0.3 treatments since ET rates from the CWSI = 0.3 treatment are greater than for the 0.2 treatment during most of the season. By the seasons end, however, cumulative ET for the 0.2 and 0.3 treatments were almost identical.

The water use pattern for the Colt variety of wheat is shown in Fig. 5.17. While the water use of the dryland treatment was several mm less than the full irrigation treatment, the major surprise is that about 70 mm more water was used by the CWSI = 0.2 treatment than for the full irrigation treatment during the season. Most of this difference occurred for the data collected on day 147 and that obtained after day 175. Between day 150 and day 175, the ET rates for the full irrigation and CWSI = 0.2 treatments were almost identical since the slopes of the lines are about the same. The reasons for the observed differences are not known, but could relate to poor plant stands and weed problems. As suggested earlier, data collected from the wheat plots are somewhat suspect as to their validity and usefulness.

No water use data were collected for potatoes.

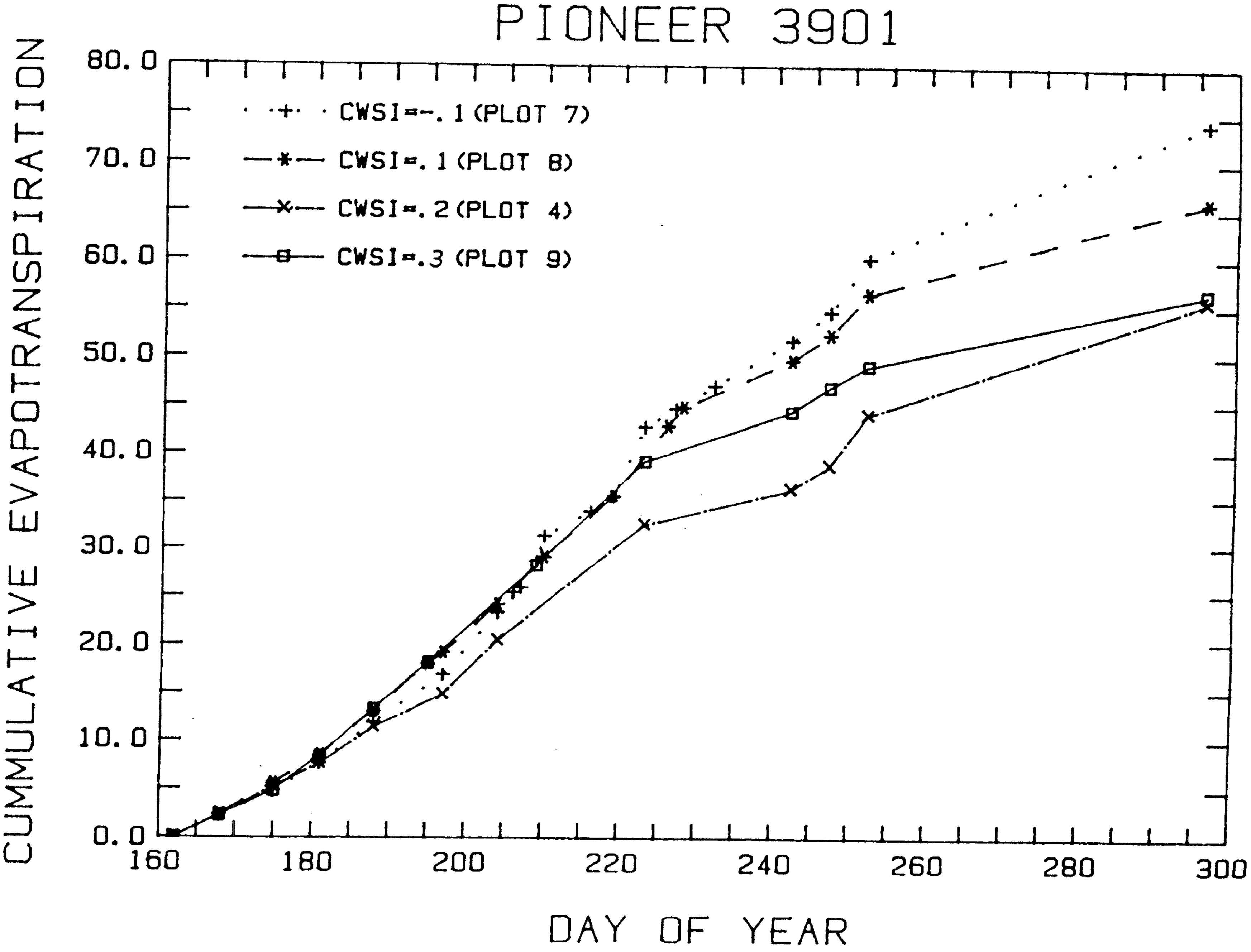


Figure 5.15 Seasonal pattern of cumulative evapotranspiration for corn Pioneer hybrid 3901.

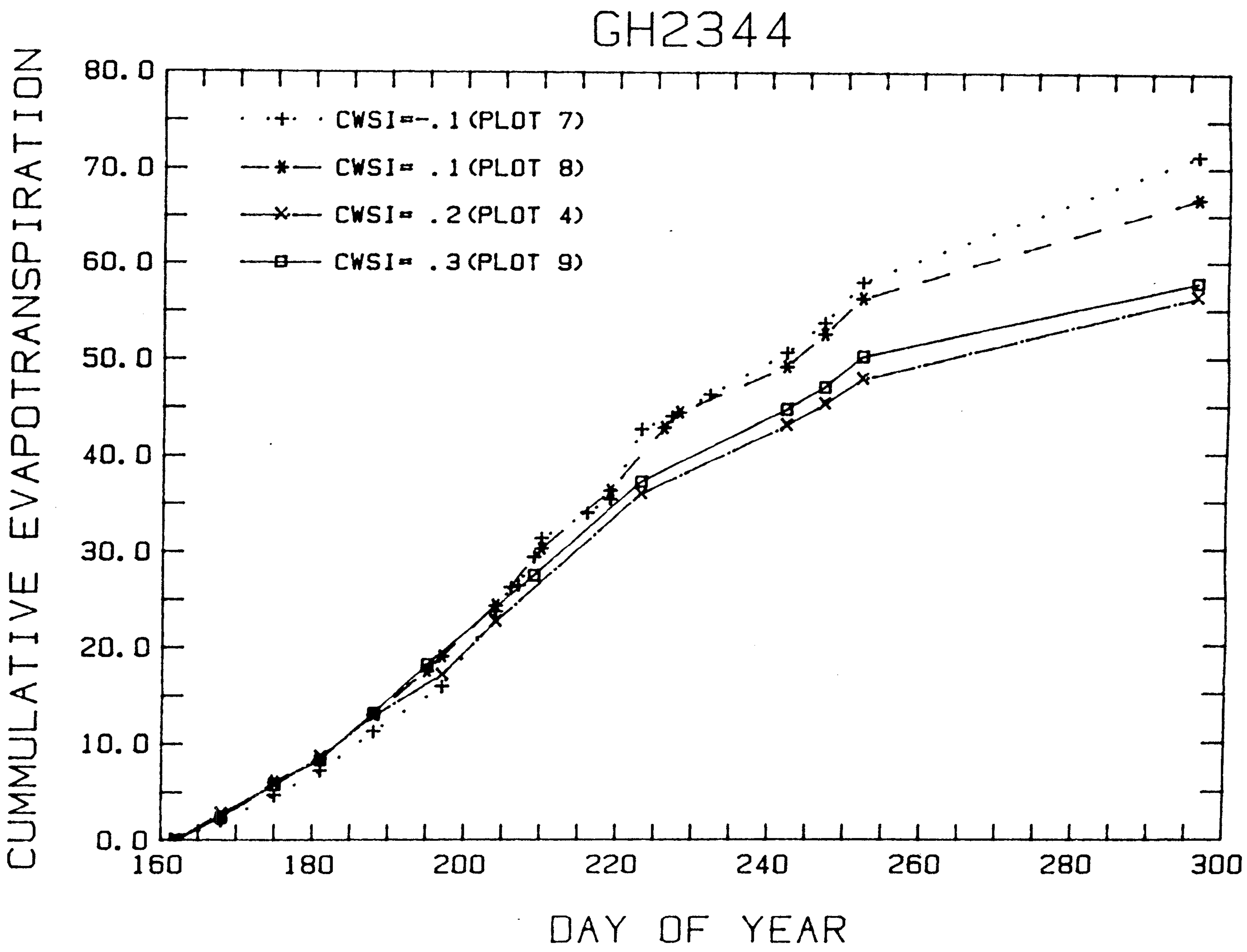


Figure 5.16 Seasonal pattern of cumulative evapotranspiration for corn hybrid GH2344.

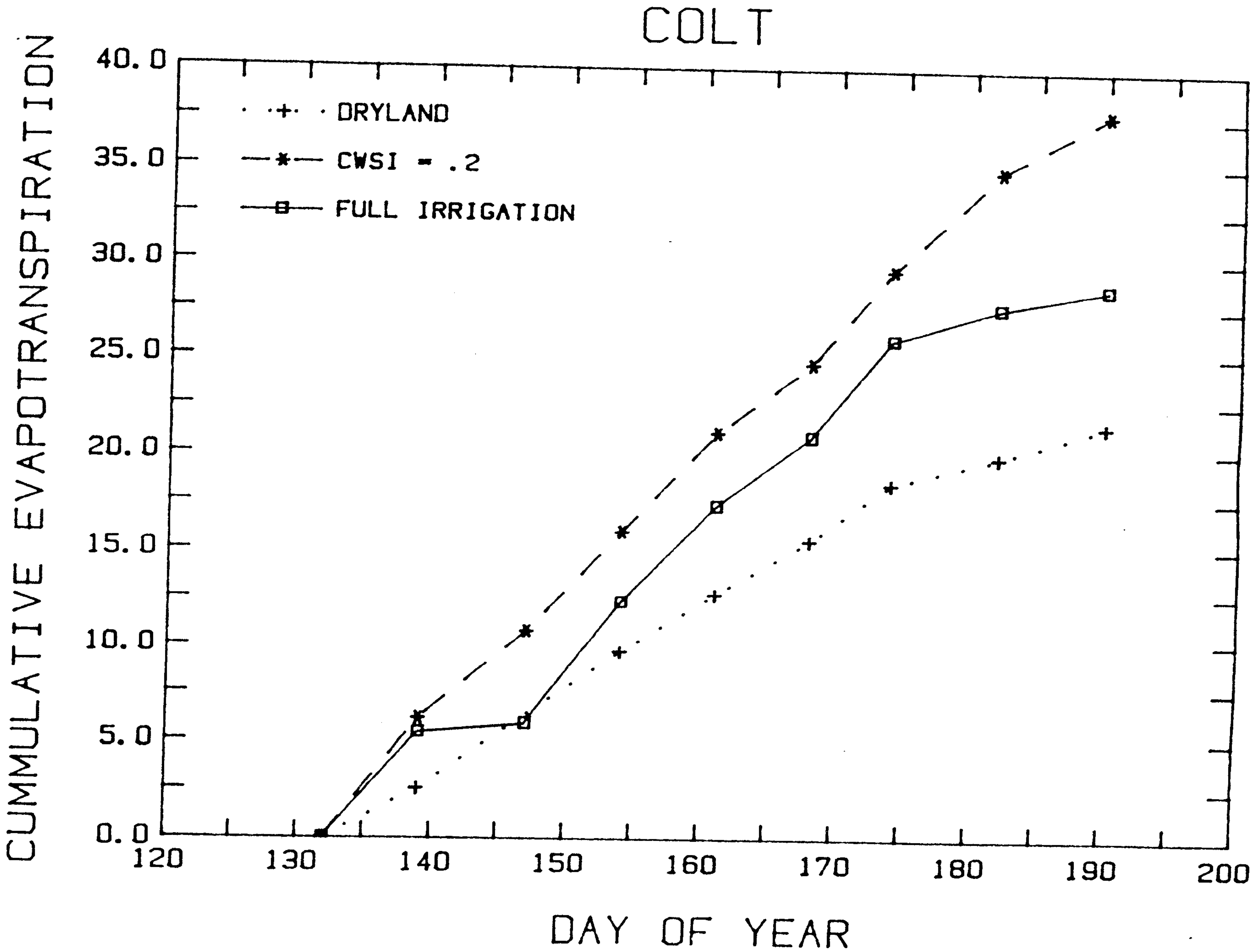


Figure 5.17 Seasonal pattern of cumulative evapotranspiration for wheat cv Colt.

5.3.4 Yields and Water Use Efficiency

Information pertaining to yields, total cumulative water use, and water use efficiencies is summarized in Table 5.1 for all crops and all water treatments. The water use efficiency data presented in the table were calculated on the basis of grain yields, or tuber yields in the case of potatoes. Two kinds of WUE were calculated. WUE_t is based on the total cumulative ET for the season while WUE_i is based only on the amount of water applied through irrigation.

In general, the GH2344 corn hybrid outyielded the Pioneer 3201 hybrid for all water treatments, but, only for the CWSI = -0.1 were the differences in yield large enough to have statistical significance. Overall, there were no statistically significant differences due to the water treatments for corn. The yield data suggest that water stress reduced yields in the GH2344 hybrid more than they did in Pioneer 3901. The highest water use efficiency values were obtained when the corn plants were allowed to experience some degree of water stress, *i.e.*, for CWSI treatments 0.2 or 0.3.

Although there appears to be fairly large differences in wheat yields as a function of water treatment, the statistical analysis of the data indicated that differences were not significant. This probably results from having only two yield samples for each water treatment in wheat. The WUE values for the dryland and fully-irrigated wheat were not very different, but were both slightly lower than for the CWSI = 0.2 treatment.

5.4 Conclusions

Although research was done on corn, wheat and potatoes, only the results for corn should be considered as definitive. Problems with stands, weeds and considerable periods of inclement weather severely restricted the quality and amount of data collected from wheat. Space limitations at the site made it

Table 5.1 Grain yields, total cumulative evapotranspiration (CET), and water use efficiencies for all crops and all water treatments. WUE_t is the water use efficiency for grain yield based on total CET. WUE_i is water use efficiency based on total amount of irrigation.

Crop	Cultivar or Hybrid	Water Treatment	Average Yield (kg ha^{-1})	CET (cm)	WUE_t (kg ha^{-1} cm^{-1})	WUE_i (kg ha^{-1} cm^{-1})
Corn	GH2344	-0.1	8,800 ± 207	73.7 ± 3.5	119.3	252.8
	P3901	-0.1	7,337 ± 109	75.0 ± 1.1	97.8	208.6
	GH2344	0.1	7,742 ± 115	66.1 ± 0.8	117.1	314.4
	P3901	0.1	7,173 ± 107	64.2 ± 2.5	111.6	302.9
	GH2344	0.2	7,388 ± 449	57.1 ± 1.0	129.5	460.3
	P3901	0.2	7,762 ± 885	57.0 ± 1.8	136.2	485.0
	GH2344	0.3	7,509 ± 1,889	55.0 ± 4.1	136.5	624.7
	P3901	0.3	6,841 ± 879	53.5 ± 4.4	127.9	582.7
Wheat	Colt	Full	2,238 ± 523	28.6	78.2	204.0
		0.2	1,977 ± 661	37.8	52.4	136.5
		Dry	1,575 ± 790	21.4	73.6	-----
	Brule	Full	2,285 ± 946	26.7	85.6	208.7
Potatoes	Cobbler	Full	28,703 ± 6,494	N/A	-----	-----
	Cobbler	0.2	24,972 ± 6,591	N/A	-----	-----
	Pontiac	Full	32,052 ± 4,897	N/A	-----	-----
	Pontiac	0.2	27,699 ± 2,435	N/A	-----	-----

impossible to treat the potato crop independently from some of the soybean plots, therefore, the water use data and CWSI values used to schedule the irrigations for soybeans were used to irrigate the potatoes both in terms of timing and the amount of water to be applied.

Scheduling of irrigation in corn using the CWSI approach based on the baseline equations suggested by Idso was quite successful. Our well-watered data for corn fit the Idso baseline very well. We found that using the CWSI value of -0.1 did not work well since this approach dictated that irrigation was needed almost every day. We, therefore, decided to irrigate no more frequently than once every three days in the -0.1 plots. Although precipitation was quite abundant during the 1986 growing season at SAL, sufficient water stress occurred to initiate the scheduling of some irrigations of corn at the CWSI threshold values of 0.1, 0.2 and 0.3. There was a slight tendency for grain yield reductions at the 0.2 and 0.3 levels, but differences were not statistically significant. The highest water use efficiencies were obtained for the CWSI treatments of 0.2 and 0.3. This suggests that, in cases when water is limited for irrigation, the CWSI approach could be used to make the application of the water as efficient as possible.

We believe that the CWSI approach to scheduling irrigation works well, although more research is warranted to establish the correct baseline or to determine if apparent differences in baselines for a given crop reported by different researchers can be explained by differences in environmental parameters such as net radiation. We feel that the CWSI approach can be used to schedule irrigations to minimize or prevent water stress from occurring, and that, in cases where water for irrigation is limited, it can provide a rational basis for helping to allocate the available water.

Chapter 6

SUGGESTIONS FOR FUTURE RESEARCH

While irrigation scheduling based on the CWSI has been demonstrated to be feasible, more research should be conducted in order to evaluate the method of calculating the CWSI. The energy balance method proposed by Jackson (1982b) and Idso *et al.* (1986) requires rc and ra values. Jackson notes that rc probably changes with growth. Thus research is needed to determine how rc changes through the growing season for specific crop varieties.

More field tests of the energy balance-CWSI irrigation scheduling method are needed. An experiment with sufficient replications of several CWSI threshold levels must be conducted to determine the effect of each threshold on yield and WUE of soybeans.

Since the CWSI does not indicate the amount of water required for the crop, an experiment using a modified Penman equation to calculate ET concurrent to the CWSI should be conducted to determine if the combination of the two methods can be a useful irrigation scheduling tool.

Stomatal resistance, and osmotic and xylem pressure potential measurements coupled with various CWSI threshold treatments would help characterize the degree of water stress imposed by the different threshold values.

The problems posed by cloud cover needs to be addressed by researchers. It is difficult to gather the data necessary, so the first step is to devise a system of collecting concurrent, instantaneous Rn, Tc, Ta and Wb measurements throughout a partly cloudy period. Then it can be determined if a relationship exists between Tc, Ta, Wb and Rn. If a relationship exists between Rn and Tc, an equation to predict Tc given Rn would be beneficial to the utility of the CWSI.

The use of the CWSI as an irrigation scheduling tool seems to have a promising future. The idea of creating an irrigation scheduling and application system based on infrared thermometry appears to be feasible. Placing all the equipment necessary to calculate a CWSI on an irrigation system could be done given the small size of current microprocessors. Of course, development of a self-contained system also requires more research regarding the effect of a disease or nutrient deficiency on canopy temperature.

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APPENDIX I

Daily Weather Summary

SAL 1985

DATE	THI	TLO	TAV	RH	WIND	MAX1	SOIL	SOLAR	PRECIP	ETPOT	GDD	
	C	C	C	%	M/S	MIN	C	MJ/M2	MM	MM	(4)	(10)
5/ 1	30.E	12.E	19.0	60.3	4.7	0.0M	12.9	19.2	0.	9.	14	11
5/ 2	25.E	8.E	16.5	48.8	3.8	0.0M	13.2	25.3	1.	8.	12	7
5/ 3	21.E	1.E	12.3	48.2	3.8	0.0M	12.0	25.3	0.	7.	8	6
5/ 4	23.E	6.E	15.5	66.4	2.6	0.0M	15.0	23.7	0.	6.	10	7
5/ 5	27.E	10.E	19.2	66.9	6.7	0.0M	16.6	24.5	0.	9.	13	8
5/ 6	29.E	13.E	20.8	66.7	4.4	0.0M	18.3	22.2	0.	8.	15	11
5/ 7	30.E	15.E	21.8	55.9	3.7	0.0M	19.9	22.3	0.	8.	15	12
5/ 8	15.E	10.E	12.6	81.7	7.0	0.0M	15.0	7.2	34.	3.	8	3
5/ 9	17.E	7.E	11.8	59.6	3.5	0.0M	12.4	22.7	5.	6.	7	4
5/10	8.E	5.E	6.7	87.7	6.9	0.0M	9.1	3.4	17.	2.	2	0
5/11	15.E	4.E	10.0	66.1	6.6	0.0M	9.1	18.3	0.	6.	5	3
5/12	20.E	4.E	12.2	51.9	6.1	0.0M	11.4	28.7	0.	9.	8	5
5/13	21.E	5.E	12.7	49.3	4.7	0.0M	13.8	28.8	0.	9.	9	6
5/14	22.E	2.E	12.8	52.9	2.1	0.0M	15.9	28.8	0.	7.	9	6
5/15	22.E	4.E	14.6	54.9	3.6	0.0M	17.0	27.8	0.	8.	9	6
5/16	27.E	8.E	16.9	59.2	3.1	0.0M	18.9	27.9	0.	8.	12	8
5/17	22.E	6.E	15.0	53.4	2.6	0.0M	19.4	29.0	0.	7.	10	6
5/18	24.E	4.E	15.2	58.7	2.4	0.0M	19.0	25.2	0.	7.	10	7
5/19	27.E	7.E	17.8	50.3	2.1	0.0M	20.1	26.9	0.	7.	12	9
5/20	27.E	10.E	18.8	45.2	2.2	0.0M	20.8	26.6	0.	8.	13	9
5/21	28.E	8.E	18.5	55.8	2.3	0.0M	20.6	29.0	0.	8.	12	9
5/22	33.E	11.E	22.2	41.8	3.5	0.0M	22.7	28.4	0.	11.	14	11
5/23	26.E	10.E	17.1	71.2	3.5	0.0M	21.3	19.5	19.	7.	13	8
5/24	17.E	11.E	14.3	81.1	4.0	0.0M	17.1	11.3	0.	3.	10	4
5/25	27.E	12.E	19.6	71.2	5.5	0.0M	18.6	26.4	1.	8.	14	9
5/26	27.E	14.E	20.0	60.5	3.3	0.0M	21.3	28.4	13.	8.	15	10
5/27	23.E	10.E	16.8	55.0	5.5	0.0M	18.3	25.4	0.	9.	12	7
5/28	23.E	8.E	16.3	46.1	4.3	0.0M	18.4	29.5	0.	9.	11	7
5/29	20.E	10.E	15.8	53.6	5.7	0.0M	19.7	29.1	0.	9.	11	5
5/30	24.E	6.E	14.6	68.9	3.7	0.0M	18.1	25.3	10.	8.	11	7
5/31	19.E	9.E	13.8	70.5	4.1	0.0M	16.6	22.0	6.	6.	10	5
6/ 1	17.E	10.E	12.9	78.3	3.1	0.0M	15.6	13.7	0.	4.	9	3
6/ 2	17.E	11.E	14.3	82.8	4.2	0.0M	15.9	12.6	0.	3.	10	4
6/ 3	31.E	14.E	20.7	65.6	4.5	0.0M	20.4	26.5	0.	10.	15	12
6/ 4	35.E	12.E	24.4	52.5	2.1	0.0M	23.5	29.4	0.	9.	14	11
6/ 5	32.E	16.E	24.1	38.3	4.4	0.0M	24.4	29.4	0.	13.	16	13
6/ 6	25.E	13.E	19.7	35.5	4.4	0.0M	23.6	28.0	0.	11.	15	9
6/ 7	24.E	11.E	17.7	56.6	6.9	0.0M	22.2	20.7	0.	10.	13	7
6/ 8	16.E	6.E	11.4	58.3	6.5	0.0M	18.4	19.1	0.	8.	7	3
6/ 9	19.E	5.E	11.5	55.2	4.4	0.0M	17.8	27.5	0.	8.	8	4
6/10	29.E	7.E	18.3	51.3	4.0	0.0M	20.0	27.4	0.	10.	12	10
6/11	26.E	11.E	19.3	55.6	3.6	0.0M	21.6	23.7	0.	8.	14	9

SAL			1985									
DATE	THI	TLO	TAV	RH	WIND	MAX1	SOIL	SOLAR	PRECIP	ETPOT	GDD	
	C	C	C	%	M/S	MIN	C	MJ/M2	MM	MM	(4)	(10)
6/12	31.E	7.E	20.5	50.6	3.1	0.0M	22.0	27.9	0.	9.	11	10
6/13	32.E	11.E	22.4	41.5	4.9	0.0M	23.5	29.2	0.	13.	14	11
6/14	26.E	9.E	18.5	37.5	5.2	0.0M	22.2	29.3	0.	12.	13	8
6/15	21.E	7.E	14.9	37.0	6.0	0.0M	20.5	28.7	0.	12.	10	6
6/16	26.E	4.E	16.9	46.9	3.5	0.0M	20.8	30.3	0.	9.	10	8
6/17	35.E	11.E	24.1	35.4	2.8	0.0M	23.2	26.2	0.	10.	13	10
6/18	24.E	8.E	18.4	46.6	6.0	0.0M	22.6	25.4	0.	10.	11	7
6/19	33.E	6.E	20.6	41.1	3.5	0.0M	22.0	30.1	0.	12.	11	10
6/20	31.E	12.E	24.1	51.8	3.9	0.0M	23.9	29.5	0.	10.	14	11
6/21	34.E	16.E	25.5	54.0	6.6	0.0M	25.4	28.3	0.	14.	16	13
6/22	26.E	11.E	19.1	66.0	7.8	0.0M	23.4	20.9	8.	10.	13	8
6/23	14.E	7.E	11.4	80.3	6.0	0.0M	15.6	8.4	0.	3.	6	2
6/24	24.E	6.E	14.7	53.5	3.9	0.0M	15.5	29.5	0.	9.	10	7
6/25	28.E	5.E	17.1	52.7	2.6	0.0M	18.7	30.2	0.	8.	10	9
6/26	29.E	10.E	19.5	63.8	3.5	0.0M	21.4	27.7	0.	9.	13	9
6/27	27.E	14.E	20.8	66.2	4.0	0.0M	23.0	26.2	0.	8.	15	10
6/28	30.E	13.E	21.9	57.5	2.7	0.0M	23.8	27.3	1.	8.	15	12
6/29	31.E	14.E	22.0	52.0	2.3	0.0M	23.5	27.7	0.	8.	15	12
6/30	35.E	13.E	24.7	39.1	2.6	0.0M	24.2	27.3	0.	10.	15	12
7/ 1	31.E	11.E	23.6	30.3	4.4	0.0M	24.4	29.7	0.	12.	14	11
7/ 2	31.E	8.E	21.0	41.6	1.9	0.0M	23.5	29.7	0.	9.	12	10
7/ 3	34.E	9.E	23.1	43.0	3.5	0.0M	24.3	27.4	0.	11.	13	10
7/ 4	37.E	16.E	26.6	34.5	3.2	0.0M	25.3	27.6	0.	11.	16	13
7/ 5	37.E	18.E	27.7	39.1	3.4	0.0M	25.7	25.2	0.	11.	17	14
7/ 6	35.E	16.E	26.0	39.5	2.7	0.0M	25.7	26.4	0.	10.	16	13
7/ 7	36.E	13.E	24.3	47.0	2.7	0.0M	23.1	24.7	24.	9.	15	11
7/ 8	38.E	13.E	27.0	39.6	2.5	0.0M	22.7	27.2	0.	10.	14	11
7/ 9	35.E	20.E	28.5	26.6	2.5	0.0M	24.4	26.3	6.	10.	18	15
7/10	33.E	17.E	26.1	41.8	3.5	0.0M	23.2	27.9	7.	10.	17	14
7/11	32.E	13.E	21.4	59.5	3.4	0.0M	22.2	26.8	0.	10.	15	11
7/12	27.E	11.E	20.3	59.3	3.1	0.0M	21.9	26.3	3.	7.	13	9
7/13	31.E	18.E	25.1	51.4	5.0	0.0M	22.9	26.7	0.	11.	17	14
7/14	34.E	20.E	26.3	59.4	5.3	0.0M	24.6	25.2	2.	11.	18	15
7/15	34.E	20.E	26.3	59.4	5.3	0.0M	24.6	25.2	2.	11.	18	15
7/16	26.E	17.E	21.4	68.5	3.0	0.0M	21.8	15.8	1.	5.	16	12
7/17	25.E	16.E	19.5	79.6	2.3	0.0M	20.8	12.8	16.	4.	16	10
7/18	32.E	15.E	22.5	62.5	1.9	0.0M	21.8	23.4	0.	7.	16	13
7/19	29.E	16.E	22.2	72.4	2.9	0.0M	22.3	21.9	0.	6.	16	12
7/20	29.E	17.E	22.6	70.0	4.4	0.0M	22.7	22.6	6.	8.	17	13
7/21	27.E	15.E	21.3	66.8	2.9	0.0M	21.7	25.0	9.	7.	16	11
7/22	28.E	15.E	21.4	57.9	2.9	0.0M	20.8	27.9	1.	8.	15	12
7/23	29.E	13.E	21.7	57.7	3.8	0.0M	20.2	23.4	0.	8.	15	11
7/24	30.E	14.E	22.8	49.7	3.5	0.0M	21.1	27.5	0.	9.	15	12
7/25	24.E	16.E	20.4	66.4	3.0	0.0M	20.5	13.9	3.	5.	16	10
7/26	18.E	14.E	16.8	83.2	3.0	0.0M	18.3	3.4	1.	1.	12	6
7/27	26.E	14.E	18.5	78.1	2.7	0.0M	18.1	14.1	0.	5.	15	10
7/28	22.E	13.E	17.1	78.7	3.0	0.0M	18.3	12.0	1.	4.	13	8
7/29	23.E	14.E	18.2	78.3	3.5	0.0M	18.6	17.5	0.	5.	14	9
7/30	21.E	17.E	18.4	81.9	4.7	0.0M	18.4	6.0	0.	3.	15	9
7/31	31.E	14.E	23.3	59.7	2.5	0.0M	20.1	22.3	0.	7.	15	12

SAL			1985									
DATE	THI	TLO	TAV	RH	WIND	MAX1	SOIL	SOLAR	PRECIP	ETPOT	GDD	
	C	C	C	%	M/S	MIN	C	MJ/M2	MM	MM	(4)	(10)
8/ 1	31.E	12.E	21.6	56.7	2.3	0.0M	19.9	26.8	0.	7.	14	11
8/ 2	32.E	14.E	21.1	68.0	2.1	0.0M	20.4	22.8	0.	7.	15	12
8/ 3	29.E	14.E	21.7	64.8	1.8	0.0M	20.1	25.1	0.	6.	15	12
8/ 4	30.E	14.E	21.6	67.8	3.4	0.0M	20.3	21.0	0.	7.	15	12
8/ 5	32.E	17.E	24.8	63.6	4.0	0.0M	21.0	26.3	0.	8.	17	14
8/ 6	32.E	18.E	25.2	58.0	4.5	0.0M	21.5	25.8	0.	9.	17	14
8/ 7	25.E	8.E	19.9	54.3	4.4	0.0M	5.1	26.2	0.	6.	12	8
8/ 8	29.E	13.E	20.6	71.1	5.1	0.0M	-0.2	17.5	0.	5.	14	11
8/ 9	24.E	11.E	18.3	67.2	2.6	0.0M	-0.2	21.8	1.	3.	13	7
8/10	23.E	10.E	16.8	61.6	3.5	0.0M	-0.2	23.8	0.	5.	12	7
8/11	19.E	9.E	14.5	63.3	2.4	0.0M	0.5	10.9	0.	2.	10	4
8/12	24.E	7.E	15.9	76.2	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/13	24.E	7.E	15.9	76.2	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/14	24.E	7.E	15.9	76.2	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/15	24.E	7.E	15.9	76.2	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/16	24.E	7.E	15.9	76.2	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/17	24.E	7.E	15.9	76.2	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/18	24.E	7.E	15.9	75.5	3.5	0.0M	14.5	16.3	0.	5.	11	7
8/19	31.E	15.E	22.5	69.9	2.2	0.0M	14.5	22.4	5.	5.	16	13
8/20	26.E	14.E	19.9	63.1	2.5	0.0M	12.2	23.6	6.	5.	15	10
8/21	22.E	9.E	15.4	66.8	3.1	0.0M	15.9	20.3	0.	5.	11	6
8/22	25.E	7.E	16.3	67.8	1.7	0.0M	15.9	24.3	0.	5.	12	8
8/23	29.E	10.E	19.5	68.7	3.4	0.0M	15.9	23.2	0.	7.	13	10
8/24	29.E	7.E	20.1	64.8	3.4	0.0M	14.9	13.0	0.	5.	12	9
8/25	8.E	0.E	3.1	62.3	3.0	0.0M	-1.9	12.7	0.	3.	2	0
8/26	8.E	0.E	3.1	58.7	2.1	0.0M	-1.9	14.3	0.	2.	2	0
8/27	8.E	0.E	3.1	62.7	3.2	0.0M	-1.9	13.9	0.	3.	2	0
8/28	8.E	0.E	3.1	53.8	3.0	0.0M	-1.9	13.0	0.	3.	2	0
8/29	8.E	0.E	3.1	57.8	4.4	0.0M	-1.9	9.4	0.	3.	2	0
8/30	8.E	0.E	3.1	55.6	3.2	0.0M	-1.9	13.1	1.	3.	2	0
8/31	8.E	0.E	3.1	55.4	2.0	0.0M	-1.9	13.8	0.	2.	2	0
9/ 1	8.E	0.E	3.1	63.7	1.6	0.0M	-1.9	9.1	1.	2.	2	0
9/ 2	8.E	0.E	3.1	53.0	2.3	0.0M	-1.9	13.8	0.	3.	2	0
9/ 3	8.E	0.E	3.1	46.9	2.0	0.0M	-1.9	14.0	0.	3.	2	0
9/ 4	8.E	0.E	3.1	53.7	2.0	0.0M	-1.9	15.8	0.	3.	2	0
9/ 5	8.E	0.E	3.1	64.7	4.2	0.0M	-1.9	15.3	0.	3.	2	0
9/ 6	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/ 7	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/ 8	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/ 9	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/10	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/11	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/12	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/13	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/14	8.E	0.E	3.1	64.6	2.8	0.0M	-1.9	12.7	0.	2.	2	0
9/15	8.E	0.E	3.1	56.1	2.8	0.0M	-1.9	8.5	0.	2.	2	0
9/16	8.E	0.E	3.1	38.3	5.2	0.0M	-1.9	0.0	0.	4.	2	0
9/17	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/18	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0

SAL DATE	THI C	TLO C	1985 TAV C	RH %	WIND M/S	MAX1 MIN	SOIL C	SOLAR MJ/M2	PRECIP MM	ETPOT MM	GDD (4)	 (10)
9/19	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/20	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/21	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/22	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/23	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/24	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/25	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/26	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/27	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/28	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0
9/29	8.E	0.E	3.1	38.0	2.9	0.0M	-1.9	0.0	0.	3.	2	0

1986 JUL DATE /TIME	MAX TEMP C	MIN TEMP C	MAX WIND SPEED	TIME OF MAX	AV VAPOR PRESSURE	VAP PRES DEFICIT	PRECIP MM
121/2400	18.790	1.056	6.059	1310.000	0.672	0.704	0.000M
122/2400	21.420	5.297	10.670	1250.000	0.982	0.689	0.000M
123/2400	27.470	8.940	7.580	1407.000	1.316	0.907	0.000M
124/2400	29.490	12.270	9.810	2330.000	1.406	1.315	0.000M
125/2400	22.330	6.426	10.900	1455.000	0.514	1.352	0.000M
126/2400	22.920	5.919	8.940	2243.000	0.723	1.127	0.000M
127/2400	29.850	11.060	16.280	1934.000	1.240	1.002	0.000M
128/2400	20.150	10.210	10.120	1439.000	1.369	0.320	0.000M
129/2400	19.780	3.170	8.420	1535.000	0.942	0.564	0.000M
130/2400	23.910	3.131	6.006	2328.000	0.949	0.836	0.000M
131/2400	29.910	5.530	9.770	2206.000	1.147	1.168	0.000M
132/2400	21.460	8.780	10.420	800.000	0.787	1.016	0.000M
133/2400	23.160	2.285	4.849	2400.000	0.840	0.869	0.000M
134/2400	26.750	7.280	10.280	1712.000	1.070	1.132	0.000M
135/2400	24.530	6.661	8.420	2351.000	1.100	0.628	0.000M
136/2400	9.300	3.209	10.760	855.000	0.812	0.161	0.000M
137/2400	17.460	-0.055	7.840	1055.000	0.760	0.462	0.000M
138/2400	23.610	-1.780	7.150	1411.000	0.951	0.511	0.000M
139/2400	21.180	3.401	6.764	1718.000	1.139	0.486	0.000M
140/2400	22.570	6.544	8.340	1256.000	1.302	0.488	0.000M
141/2400	23.020	8.700	9.770	1422.000	1.421	0.501	0.000M
142/2400	13.510	6.192	7.300	2007.000	1.071	0.087	0.000M
143/2400	20.340	3.864	4.942	2224.000	0.924	0.631	0.000M
144/2400	23.610	7.200	5.979	1018.000	0.972	0.861	0.000M
145/2400	19.280	4.406	5.820	1333.000	0.998	0.448	0.000M
146/2400	15.900	3.980	8.620	1337.000	1.047	0.147	0.000M
147/2400	16.630	3.286	7.600	2001.000	1.096	0.121	0.000M
148/2400	15.430	7.990	7.560	1303.000	1.178	0.125	0.000M
149/2400	22.230	6.387	6.525	1559.000	1.266	0.216	0.000M
150/2400	24.780	3.170	2.841	1230.000	1.289	0.453	0.000M
151/2400	26.540	7.010	4.942	1425.000	1.380	0.719	0.000M
152/2400	29.190	6.075	5.181	1654.000	1.422	1.029	0.000M
153/2400	27.310	8.740	6.392	1451.000	1.689	0.628	0.000M
154/2400	27.190	9.220	5.527	1459.000	1.720	0.597	0.000M
155/2400	26.540	11.950	8.730	1719.000	1.768	0.413	0.000M
156/2400	23.110	7.090	5.341	548.000	1.433	0.315	0.000M
157/2400	32.020	9.970	12.770	1711.000	1.713	0.665	0.000M
158/2400	27.530	9.690	6.378	943.000	1.462	0.885	0.000M
159/2400	26.590	11.790	8.280	1417.000	1.546	0.818	0.000M
160/2400	24.120	11.180	9.980	1448.000	1.715	0.381	0.000M
161/2400	23.360	9.610	10.480	1657.000	1.477	0.284	0.000M

1986 JUL DATE /TIME	MAX TEMP C	MIN TEMP C	MAX WIND SPEED	TIME OF MAX	AV VAPOR PRESSURE	VAP PRES DEFICIT	PRECIP MM
162/2400	26.100	10.290	6.086	1422.000	1.357	0.859	0.000M
163/2400	32.350	6.348	6.937	1859.000	1.500	1.311	0.000M
164/2400	27.470	14.420	9.570	1057.000	1.635	0.835	0.000M
165/2400	29.140	11.180	8.040	125.000	1.733	0.906	0.000M
166/2400	34.920	15.860	7.420	459.000	1.857	1.405	0.000M
167/2400	31.330	13.420	8.040	1559.000	1.916	1.160	0.000M
168/2400	32.670	15.770	9.010	1459.000	1.806	1.498	0.000M
169/2400	31.140	17.720	9.070	1735.000	1.868	1.381	0.000M
170/2400	34.640	17.990	10.540	1731.000	2.022	1.016	0.000M
171/2400	31.700	15.900	5.421	340.000	2.073	0.887	0.000M
172/2400	32.870	14.840	11.520	1938.000	1.949	1.275	0.000M
173/2400	28.440	11.060	8.660	124.000	1.193	1.257	0.000M
174/2400	32.090	11.750	10.870	1526.000	1.742	0.755	0.000M
175/2400	29.910	8.980	7.560	1341.000	1.786	0.933	0.000M
176/2400	32.810	18.920	9.010	1350.000	1.894	1.478	0.000M
177/2400	31.140	17.760	7.900	26.000	1.866	1.332	0.000M
178/2400	35.410	14.510	5.421	2354.000	1.779	1.750	0.000M
179/2400	36.280	18.430	6.831	2314.000	1.973	1.890	0.000M
180/2400	36.140	16.290	7.540	1713.000	2.060	1.620	0.000M
181/2400	27.250	12.970	10.060	2321.000	1.938	0.371	0.000M
182/2400	31.510	10.010	5.288	1317.000	1.550	1.227	0.000M
183/2400	32.540	16.670	7.540	634.000	2.020	1.065	0.000M
184/2400	37.790	14.760	10.200	1618.000	1.550	2.506	0.000M
185/2400	37.250	21.130	9.420	2145.000	2.109	2.215	0.000M
186/2400	28.320	16.850	8.420	46.000	1.589	1.357	0.000M
187/2400	27.190	15.430	6.299	1829.000	1.291	1.190	0.000M
188/2400	30.700	10.980	8.080	1538.000	1.810	1.053	0.000M
189/2400	32.740	13.300	5.687	1348.000	1.796	1.252	0.000M
190/2400	24.370	9.850	6.844	1804.000	1.725	0.287	0.000M
191/2400	32.940	6.153	10.680	1859.000	1.517	0.859	0.000M
192/2400	29.190	8.660	8.930	1918.000	1.771	0.658	0.000M
193/2400	30.090	12.110	6.219	157.000	1.477	1.220	0.000M
194/2400	30.760	18.160	8.200	933.000	2.149	1.046	0.000M
195/2400	33.740	16.420	7.780	37.000	2.124	1.435	0.000M
196/2400	36.280	20.850	7.840	1759.000	1.975	2.064	0.000M
197/2400	36.210	20.760	8.210	1926.000	1.843	2.263	0.000M
198/2400	36.950	19.420	6.432	29.000	2.009	1.868	0.000M
199/2400	36.650	16.460	9.700	2107.000	2.203	1.406	0.000M
200/2400	28.500	14.630	6.365	1615.000	1.842	0.842	0.000M
201/2400	27.250	9.930	6.804	1721.000	1.551	0.754	0.000M
202/2400	26.920	10.660	8.520	1345.000	1.535	0.925	0.000M
203/2400	31.010	16.590	9.660	1746.000	1.856	1.244	0.000M
204/2400	35.560	18.650	8.330	1328.000	1.787	1.970	0.000M
205/2400	31.390	14.130	9.550	1943.000	1.864	0.900	0.000M
206/2400	31.700	8.540	10.620	1931.000	1.565	1.194	0.000M
207/2400	35.270	16.240	11.970	1954.000	1.757	1.475	0.000M
208/2400	33.670	17.590	6.591	316.000	1.962	1.334	0.000M
209/2400	37.560	18.160	4.929	1003.000	1.871	1.989	0.000M

1986 JUL DATE /TIME	MAX TEMP C	MIN TEMP C	MAX WIND SPEED	TIME OF MAX	AV VAPOR PRESSURE	VAP PRES DEFICIT	PRECIP MM
210/2400	37.790	14.300	6.338	1753.000	1.782	2.163	0.000M
211/2400	33.270	19.150	6.259	1043.000	1.909	1.423	0.000M
212/2400	26.000	14.670	10.140	723.000	1.722	0.651	0.000M
213/2400	27.980	11.790	7.240	552.000	1.564	0.675	0.000M
214/2400	27.140	11.140	4.729	1308.000	1.623	0.822	0.000M
215/2400	29.610	11.260	7.720	1358.000	1.603	1.037	0.000M
216/2400	31.640	14.710	8.780	1953.000	1.680	1.049	0.000M
217/2400	31.010	10.740	4.516	1301.000	1.700	0.960	0.000M
218/2400	33.880	11.340	9.260	1644.000	1.705	1.383	0.000M
219/2400	30.030	11.300	5.554	1331.000	1.486	1.135	0.000M
220/2400	32.020	10.980	12.850	2302.000	1.659	1.001	0.000M
221/2400	30.760	11.300	10.740	1641.000	1.700	0.881	0.000M
222/2400	26.970	9.810	5.168	1748.000	1.435	0.795	0.000M
223/2400	29.190	15.010	8.970	641.000	1.882	0.883	0.000M
224/2400	30.270	16.420	7.410	724.000	2.037	0.753	0.000M
225/2400	32.150	11.540	5.008	1704.000	1.739	1.002	0.000M
226/2400	30.520	10.090	5.221	1820.000	1.505	0.970	0.000M
227/2400	32.350	11.460	7.700	2332.000	1.592	1.461	0.000M
228/2400	37.330	16.370	7.380	1116.000	1.690	1.913	0.000M
229/2400	28.150	13.920	6.804	1750.000	1.829	0.705	0.000M
230/2400	28.040	15.730	5.647	1304.000	2.039	0.464	0.000M
231/2400	32.870	14.250	8.520	2322.000	1.890	1.147	0.000M
232/2400	24.680	14.880	10.110	948.000	1.787	0.765	0.000M
233/2400	22.770	10.530	6.884	2157.000	1.406	0.492	0.000M
234/2400	29.970	9.650	6.831	1123.000	1.384	1.180	0.000M
235/2400	27.030	5.491	7.230	1520.000	1.116	1.016	0.000M
236/2400	33.340	16.720	8.000	606.000	1.707	1.479	0.000M
237/2400	33.610	14.880	6.724	1149.000	1.736	1.553	0.000M
238/2400	21.890	8.820	7.240	1314.000	1.514	0.385	0.000M
239/2400	24.320	5.258	7.560	1606.000	1.264	0.420	0.000M
240/2400	22.090	7.950	10.320	2349.000	1.134	0.549	0.000M
241/2400	32.090	9.690	10.670	51.000	1.395	1.376	0.000M
242/2400	32.540	14.000	7.980	810.000	1.805	1.215	0.000M
243/2400	27.530	14.590	7.570	31.000	1.723	0.522	0.000M
244/2400	19.880	14.800	6.086	207.000	1.589	0.349	0.000M
245/2400	24.420	12.810	5.354	2057.000	1.590	0.410	0.000M
246/2400	30.330	7.990	4.463	2054.000	1.388	1.061	0.000M
247/2400	26.540	8.350	5.660	2220.000	1.193	0.957	0.000M
248/2400	26.640	13.010	7.960	241.000	1.666	0.704	0.000M
249/2400	15.050	6.231	8.580	436.000	0.970	0.176	0.000M
250/2400	17.460	6.739	4.649	1646.000	0.868	0.485	0.000M
251/2400	16.240	7.830	7.250	1547.000	1.150	0.264	0.000M
252/2400	29.430	6.935	6.219	243.000	1.511	0.606	0.000M
253/2400	26.370	10.210	6.565	402.000	1.315	0.694	0.000M
254/2400	25.040	8.310	6.977	1130.000	1.032	0.908	0.000M
255/2400	30.270	10.370	6.831	1619.000	1.093	1.329	0.000M
256/2400	19.510	9.060	7.770	1219.000	1.154	0.425	0.000M
257/2400	29.610	10.490	9.500	1736.000	1.573	0.763	0.000M

1986

JUL DATE /TIME	MAX TEMP C	MIN TEMP C	MAX WIND SPEED	TIME OF MAX	AV VAPOR PRESSURE	VAP PRES DEFICIT	PRECIP MM
258/2400	11.990	7.050	7.240	1503.000	0.980	0.141	0.000M
259/2400	27.190	8.230	10.120	2111.000	1.422	0.308	0.000M
260/2400	23.810	11.870	6.791	141.000	1.562	0.406	0.000M
261/2400	14.130	7.750	7.190	813.000	1.041	0.152	0.000M
262/2400	24.070	3.363	7.050	2247.000	1.270	0.427	0.000M
263/2400	25.680	11.700	6.631	5.000	1.630	0.401	0.000M
264/2400	22.870	13.010	6.059	128.000	1.584	0.395	0.000M
265/2400	17.240	12.190	5.820	239.000	1.370	0.250	0.000M
266/2400	25.250	11.340	6.644	2001.000	1.471	0.468	0.000M
267/2400	28.040	10.610	13.050	1835.000	1.366	0.883	0.000M
268/2400	27.080	6.270	7.170	1457.000	0.595	1.550	0.000M
269/2400	25.940	5.025	4.330	1426.000	0.732	1.120	0.000M
270/2400	24.580	1.708	4.663	2358.000	0.692	1.013	0.000M
271/2400	23.310	8.900	7.290	224.000	0.934	0.888	0.000M
272/2400	20.570	7.010	5.274	54.000	0.790	0.782	0.000M
273/2400	21.990	3.363	5.527	1611.000	0.883	0.716	0.000M

APPENDIX II

Weather Information at the Times of IRT Measurements

1985 JUL DATE /TIME	AIR TEMP C	REL HUM %	SOIL TMP C	WIND SP M/SEC	WIND VEC M/SEC	VECT DIR	VECT SD	RAD W/M2	PRECIP MM	SH BAND DIFFUSE
198/1300	25.900	40.110	25.390	4.066	0.182	24.360	79.200	0.000	0.000	0.000e
198/1400	26.870	39.490	26.270	4.167	0.115	19.410	79.900	0.000	0.000	0.000e
198/1500	27.610	39.060	27.210	4.873	0.143	348.900	79.800	0.000	0.000	0.000e
199/1300	29.560	46.160	25.850	7.450	0.330	43.160	79.200	0.000	0.000	0.000e
199/1400	30.780	42.460	26.560	7.150	0.075	25.180	80.600	0.000	0.000	0.000e
199/1500	31.710	39.250	27.320	7.340	0.145	4.571	80.200	0.000	0.000	0.000e
200/1400	32.900	41.280	27.160	8.760	0.367	308.700	79.300	0.000	0.000	0.000e
200/1500	34.800	36.120	28.150	8.420	0.303	206.100	79.500	0.000	9.000	0.000e
201/1400	23.687E	74.542E	23.060E	5.003E	4.804E	178.757E	15.264E	531.078E	0.000	0.000
201/1500	24.702E	71.045E	23.366E	4.951E	4.751E	182.823E	15.659E	571.753E	0.000E	0.000e
202/1400	32.066E	28.842E	27.425E	2.679E	2.259E	106.919E	29.080E	875.916E	0.000E	0.000e
202/1500	32.683E	25.858E	28.566E	2.204E	1.869E	105.185E	32.461E	760.976E	0.000E	0.000e
203/1400	20.800	90.600	23.080	3.647	0.088	75.100	80.000	387.000	0.000E	0.000e
203/1500	22.620	82.600	23.310	4.085	0.173	206.500	79.300	430.200	0.000	834.000
204/1400	30.900	36.700	24.340	1.891	0.027	172.800	80.400	733.000	0.000	900.000
204/1500	31.690	33.560	25.340	2.284	0.063	199.700	79.900	900.000	0.000	1299.000
205/1400	28.350	58.020	25.180	4.684	0.084	257.900	80.300	808.000	0.000	1299.000
205/1500	28.780	53.040	25.900	4.875	0.128	170.200	79.900	774.000	0.000	1299.000
206/1400	29.400	48.320	25.690	6.961	0.127	168.100	80.300	805.000	0.000	1299.000
206/1500	29.790	47.380	26.470	7.780	0.197	191.000	80.000	737.000	0.000	1299.000
207/1400	26.550	48.820	24.210	5.072	0.121	111.100	80.000	955.000	0.000	1299.000
207/1500	27.540	42.380	25.130	5.194	0.244	174.800	79.100	949.000	0.000	1299.000
208/1400	27.610	36.630	25.220	4.831	0.133	143.700	79.900	981.000	0.000	1299.000
208/1500	28.590	33.440	26.830	4.537	0.096	102.500	80.100	973.000	0.000	1299.000
209/1400	28.760	38.580	25.940	7.480	0.180	14.860	80.000	934.000	0.000	1299.000
209/1500	29.000	38.120	27.020	6.910	0.236	147.700	79.600	708.000	0.000	1299.000
210/1400	29.780	33.270	26.390	5.113	0.061	18.950	80.500	974.000	0.000	1299.000
210/1500	30.740	32.040	27.840	4.766	0.193	53.180	79.300	981.000	0.000	1299.000
211/1400	23.200	57.960	24.140	4.402	0.058	123.600	80.500	237.900	0.000	514.300
211/1500	23.830	55.630	24.260	5.336	0.061	46.230	80.500	404.400	0.000	855.000
212/1400	17.350	94.700	21.320	2.062	0.005	66.620	80.900	60.130	10.000	159.800
213/1400	6.609	0.000	0.000	1.667	0.048	106.000	79.800	0.000	0.000	0.000
213/1500	8.000	0.000	0.000	2.433	0.027	297.600	80.600	0.000	0.000	0.000
214/1400	17.225E	90.119E	20.825E	6.407E	6.261E	160.344E	12.081E	161.526E	0.000E	1299.000e
214/1500	18.378E	88.591E	20.996E	6.444E	6.297E	154.616E	10.598E	202.045E	0.000E	1299.000e
215/1400	30.808E	36.406E	25.376E	4.436E	3.979E	234.793E	30.994E	860.913E	0.000E	1299.000e
215/1500	31.220E	32.934E	26.383E	4.493E	4.033E	240.969E	31.732E	701.185E	0.000E	1299.000e
216/1400	29.947E	35.500E	25.360E	3.698E	3.444E	288.059E	22.241E	904.171E	0.000E	1299.000e
216/1500	30.716E	32.162E	26.523E	3.930E	3.572E	286.193E	23.992E	835.482E	0.000E	1299.000e
217/1400	33.811E	37.389E	27.402E	2.559E	1.936E	85.557E	39.358E	769.707E	0.000E	1299.000e
217/1500	33.838E	33.689E	28.304E	3.183E	2.363E	130.903E	41.318E	589.622E	0.000E	1299.000e

1985 JUL DATE /TIME	AIR TEMP C	REL HUM %	SOIL TMP C	WIND SP M/SEC	WIND VEC M/SEC	VECT DIR	VECT SD	RAD W/M2	PRECIP MM	SH BAND DIFFUSE
218/ 900	22.105E	68.969E	21.667E	2.983E	2.728E	77.989E	25.221E	441.042E	0.000E	586.200e
218/1000	23.743E	63.719E	22.232E	3.082E	2.759E	50.556E	26.584E	617.854E	0.000E	985.000e
218/1100	26.076E	56.462E	23.018E	3.097E	2.533E	45.296E	33.701E	818.558E	0.000E	1299.000e
218/1200	27.652E	51.570E	24.006E	2.883E	2.451E	59.089E	30.916E	882.904E	0.000E	1299.000e
218/1300	28.804E	47.771E	25.131E	2.718E	2.323E	70.644E	30.697E	898.452E	0.000E	1299.000e
218/1400	29.474E	45.424E	26.362E	2.974E	2.442E	81.989E	32.387E	861.141E	0.000E	1299.000e
218/1500	29.856E	43.530E	27.346E	2.948E	2.532E	79.840E	28.909E	773.107E	0.000E	1299.000e
218/1600	29.984E	42.424E	28.159E	2.700E	2.383E	87.394E	28.249E	638.585E	0.000E	1299.000e
218/1700	29.769E	42.232E	28.695E	2.698E	2.453E	84.846E	25.476E	470.843E	0.000E	1299.000e
218/1800	28.858E	43.333E	28.833E	2.805E	2.676E	80.916E	17.750E	284.646E	0.000E	1138.000e
219/ 800	15.494E	92.794E	22.111E	2.816E	2.515E	158.466E	30.898E	197.443E	0.000E	217.100e
219/ 900	18.223E	88.827E	22.086E	3.746E	3.342E	144.140E	26.447E	256.447E	0.000E	586.200e
219/1000	21.449E	80.235E	22.331E	5.035E	4.802E	141.500E	16.655E	557.430E	0.000E	985.000e
219/1100	26.697E	63.123E	22.812E	6.779E	6.614E	153.518E	14.006E	752.032E	0.000E	1299.000e
219/1200	28.614E	58.878E	23.493E	7.206E	6.907E	165.663E	15.702E	864.261E	0.000E	1299.000e
219/1300	29.912E	53.656E	24.340E	7.381E	7.181E	165.507E	14.215E	885.148E	0.000E	1299.000e
219/1400	30.811E	49.726E	25.278E	7.379E	7.179E	161.252E	13.381E	858.801E	0.000E	1299.000e
219/1500	31.433E	46.079E	26.115E	7.808E	7.573E	156.855E	13.798E	764.129E	0.000E	1299.000e
219/1600	30.967E	43.708E	26.812E	7.617E	7.351E	158.139E	12.932E	514.579E	0.000E	1299.000e
219/1700	30.132E	44.463E	27.234E	6.965E	6.834E	158.730E	11.984E	283.112E	0.000E	1299.000e
219/1800	26.661E	54.123E	27.283E	7.224E	6.330E	172.580E	23.409E	96.445E	0.000E	1138.000e
220/ 700	21.511E	72.802E	20.680E	6.361E	6.159E	182.400E	14.718E	146.730E	0.000E	15.830e
220/ 800	22.295E	71.589E	20.622E	6.011E	5.862E	188.434E	13.781E	353.022E	0.000E	217.100e
220/ 900	23.491E	69.963E	20.885E	6.526E	6.347E	194.182E	13.926E	531.749E	0.000E	586.200e
220/1000	24.986E	67.881E	21.277E	6.374E	6.148E	195.634E	15.554E	700.058E	0.000E	985.000e
220/1100	26.970E	64.062E	21.922E	5.705E	5.504E	196.190E	15.158E	822.611E	0.000E	1299.000e
220/1200	28.984E	58.613E	22.641E	5.206E	4.980E	192.408E	16.888E	895.225E	0.000E	1299.000e
220/1300	30.718E	52.413E	23.576E	4.969E	4.764E	194.664E	17.173E	913.830E	0.000E	1299.000e
220/1400	32.009E	47.914E	24.557E	4.962E	4.836E	185.289E	13.903E	878.738E	0.000E	1299.000e
220/1500	32.963E	45.047E	25.446E	4.846E	4.693E	179.636E	14.831E	787.571E	0.000E	1299.000e
220/1600	33.343E	41.589E	26.197E	4.808E	4.682E	174.598E	14.415E	648.867E	0.000E	1299.000e
220/1700	33.182E	40.079E	26.733E	5.477E	5.351E	163.800E	11.914E	479.314E	0.000E	1299.000e
220/1800	32.034E	42.162E	26.915E	5.647E	5.570E	160.745E	10.393E	287.616E	0.000E	1138.000e
220/1900	29.817E	50.074E	26.752E	5.354E	5.307E	158.832E	9.272E	109.296E	0.000E	791.000e
221/1400	21.712E	50.620E	23.296E	7.932E	6.985E	139.176E	26.726E	718.012E	0.000E	1299.000e
221/1500	22.524E	49.314E	24.120E	7.915E	7.307E	138.801E	20.877E	661.227E	0.000E	1299.000e
222/ 900	17.797E	69.717E	18.155E	5.024E	4.823E	195.586E	15.495E	482.643E	0.000E	586.200e
222/1000	20.412E	58.907E	18.683E	4.980E	4.784E	185.659E	16.474E	651.110E	0.000E	985.000e
222/1100	25.950	61.610	21.870	7.780	0.947	29.760	75.900	664.000	0.000	164.400
222/1200	26.760	60.610	22.630	7.460	7.290	224.000	12.180	766.000	0.000	330.700
222/1300	27.610	60.270	23.390	6.598	6.448	222.200	12.190	825.000	0.000	198.300
222/1400	29.200	57.640	24.520	5.947	5.778	220.500	13.660	868.000	0.000	49.750
222/1500	30.690	52.880	25.680	5.796	5.621	217.900	14.050	859.000	0.000	49.670
222/1600	31.920	46.200	26.760	5.655	5.508	203.400	13.050	798.000	0.000	152.200
222/1700	32.510	43.340	27.770	5.516	5.357	196.800	13.750	681.600	0.000	517.400
223/1500	17.040	60.440	23.830	9.050	8.940	3.559	8.920	342.000	0.000	273.800
224/1100	18.610	53.120	17.860	5.516	5.388	215.000	12.350	590.200	0.000	222.200

1985 JUL DATE /TIME	AIR TEMP C	REL HUM %	SOIL TMP C	WIND SP M/SEC	WIND VEC M/SEC	VECT DIR	VECT SD	RAD W/M2	PRECIP MM	SH BAND DIFFUSE
224/1200	20.760	50.480	19.280	5.304	5.129	198.600	14.720	726.000	0.000	55.010
224/1300	22.450	43.920	21.010	5.992	5.810	188.900	14.120	818.000	0.000	52.330
224/1400	24.020	40.930	22.800	6.063	5.921	182.600	12.390	855.000	0.000	57.750
224/1500	25.010	38.040	24.490	6.571	6.385	180.000	13.610	845.000	0.000	57.450
225/1500	27.700	64.480	24.060	7.490	7.340	166.500	11.620	634.300	0.000	315.600
226/1500	22.130	52.570	23.580	6.047	5.774	302.000	17.230	775.000	0.000	108.300
227/1500	21.980	48.630	24.380	6.569	6.340	32.490	15.140	832.000	0.000	51.030
228/1500	18.440	49.980	20.640	2.925	2.633	48.770	25.600	472.700	0.000	404.200
231/1500	22.700	47.030	23.770	25.000E	25.000E	359.100	20.520	904.000	0.000	888.000
232/1500	19.310	59.140	21.880	25.000E	25.000E	149.000	13.970	397.900	0.000	352.500
233/1500	23.880	66.280	24.760	25.000E	25.000E	161.800	18.780	811.000	0.000	766.000
234/1500	21.260	91.200	21.060	25.000E	25.000E	141.500	13.680	340.800	0.000	302.300
235/1500	29.780	62.190	26.450	25.000E	25.000E	173.600	18.570	770.000	0.000	730.000
236/1500	28.030	60.270	26.190	18.370	15.460	301.500	32.240	885.000	0.000	868.000
238/1500	20.910	48.520	23.370	6.585	6.414	343.400	13.090	607.400	0.000	329.100
239/1500	24.220	49.810	25.340	2.316	1.823	158.000	37.380	887.000	0.000	38.640
240/1500	27.380	53.920	25.140	6.176	5.988	192.000	14.120	864.000	0.000	55.820
241/ 800	15.680	94.000	20.520	2.756	2.703	179.200	11.240	44.740	0.000	42.930
241/ 900	17.670	91.400	20.240	4.345	4.237	191.700	12.740	202.400	0.000	120.800
241/1000	20.380	83.700	20.210	6.576	6.433	200.600	11.950	386.100	0.000	93.500
241/1100	22.920	73.100	20.720	6.929	6.792	208.200	11.390	578.200	0.000	69.880
241/1200	25.160	65.710	21.830	4.451	4.050	217.500	24.300	725.000	0.000	75.100
241/1300	27.230	59.740	23.400	4.027	3.815	198.900	18.610	838.000	0.000	114.600
241/1400	28.700	54.730	25.190	5.081	4.819	183.500	18.380	831.000	0.000	239.400
241/1500	29.210	51.490	26.750	5.953	5.745	172.500	15.130	766.000	0.000	263.100
241/1600	29.670	48.240	27.890	6.525	6.344	165.700	13.500	649.900	0.000	270.800
242/1500	25.830	66.500	26.980	4.268	4.132	170.400	14.480	477.500	0.000	294.500
243/1500	35.700E	26.075E	27.530E	3.437E	3.062E	43.102E	27.537E	677.953E	0.000E	294.500e
244/1400	29.240	60.030	26.660	5.900	5.790	170.900	11.070	851.000	0.000	237.400
244/1500	30.980	53.090	28.000	5.958	5.757	185.000	14.880	836.000	0.000	125.100
245/1400	34.110	21.520	26.690	4.146	3.980	20.460	16.210	805.000	0.000	309.200
245/1500	35.050	19.670	28.210	4.218	4.023	31.880	17.410	852.000	0.000	154.400
246/1400	23.690	55.300	24.150	6.389	6.197	98.200	14.070	674.500	0.000	432.700
246/1500	24.840	45.430	25.100	6.440	6.237	95.400	14.390	758.000	0.000	287.400
247/1500	30.400	43.880	27.360	6.363	6.100	215.800	16.460	513.000	0.000	351.800
248/1400	29.300	35.720	25.020	3.372	3.153	16.090	20.630	825.000	0.000	560.800
248/1500	30.120	32.000	26.470	2.323	1.457	11.350	49.450	777.000	0.000	388.500
249/1500	29.730	42.360	27.060	4.362	3.866	311.100	27.300	531.700	0.000	332.600
250/1500	30.670	33.470	25.220	4.524	4.256	252.700	19.730	839.000	0.000	533.300
252/1000	21.610	70.100	20.450	1.967	1.173	8.790	51.480	374.700	0.000	49.990
252/1100	25.380	54.180	20.990	4.041	3.898	344.200	15.270	555.700	0.000	237.600
252/1200	27.840	43.460	22.140	3.636	3.475	9.860	17.070	707.000	0.000	582.800
252/1300	30.270	34.550	23.590	3.952	3.717	31.670	19.730	799.000	0.000	776.000
252/1400	31.370	30.570	25.190	4.112	3.853	57.200	20.320	849.000	0.000	818.000
252/1500	32.040	27.980	26.730	4.087	3.793	62.820	21.730	826.000	0.000	684.100
252/1600	32.460	29.320	28.060	3.741	3.415	78.900	23.910	740.000	0.000	302.400
253/1100	14.850	78.900	21.900	7.110	6.993	340.000	10.570	515.400	0.000	303.300
253/1200	16.860	69.900	22.350	6.794	6.570	343.700	14.700	701.000	0.000	627.700
253/1300	18.540	64.170	23.240	6.154	5.973	345.100	13.890	797.000	0.000	781.000
253/1400	20.450	59.040	24.370	5.371	5.148	356.500	16.510	826.000	0.000	809.000

1985 JUL DATE /TIME	AIR TEMP C	REL HUM %	SOIL TMP C	WIND SP M/SEC	WIND VEC M/SEC	VECT DIR	VECT SD	RAD W/M2	PRECIP MM	SH BAND DIFFUSE
253/1500	21.180	55.540	25.540	5.422	5.254	343.300	14.270	738.000	0.000	652.400
254/1200	16.250	76.900	20.570	3.066	2.825	72.900	22.730	598.700	0.000	536.500
254/1300	18.890	66.650	21.530	2.795	2.531	81.400	24.890	784.000	0.000	752.000
254/1400	20.090	63.750	22.830	3.307	3.078	112.700	21.340	763.000	0.000	722.000
254/1500	21.470	60.610	24.130	3.949	3.706	128.200	20.080	718.000	0.000	620.700
255/1500	15.920	94.500	20.460	3.690	3.608	103.400	12.110	106.500	0.000	97.400
256/1500	15.890	95.200	18.730	4.632	4.539	138.600	11.440	90.400	0.000	84.200
257/1500	20.600	89.300	19.300	5.214	5.074	172.500	13.270	589.400	0.000	537.300
258/1500	22.200	57.940	22.960	2.800	2.528	96.800	25.260	796.000	0.000	787.000

1986 JUL DATE /TIME	AIR TEMP C	REL HUM %	SOIL TMP C	WIND SP M/SEC	WIND VEC M/SEC	VECT DIR	VECT SD	RAD W/M2	PRECIP MM	SH BAND DIFFUSE
191/1300	29.090	49.530	27.630	0.447	0.404	247.300	25.160	883.000		
191/1400	30.600	38.760	28.830	0.447	0.422	268.000	19.210	852.000	0.000	174.500E
195/1400	32.930	43.230	33.650	5.358	5.168	154.300	15.250	888.000	0.000	303.500E
196/1400	35.730	36.720	34.010	4.319	4.033	190.700	20.830	878.000	0.000	73.600E
197/1400	34.500	37.550	33.700	5.844	5.520	198.400	19.060	884.000	0.000	75.000E
198/1400	35.510	30.130	34.500	1.778	1.216	326.100	45.540	622.600	0.000	51.780E
200/1400	27.500	49.780	29.840	4.833	4.650	21.870	15.750	726.000	0.000	45.190E
203/1400	29.090	52.800	30.660	6.644	6.393	174.700	15.720	808.000	0.000	171.900E
204/1400	33.210	36.720	32.310	6.170	5.952	192.600	15.260	767.000	0.000	128.800E
206/1100	27.040	59.910	25.810	4.609	4.455	196.300	14.790	850.000	0.000	194.000E
206/1400	29.980	43.050	31.140	5.816	5.465	194.500	19.920	815.000	0.000	32.270E
207/1400	33.510	23.270	32.270	3.311	2.692	265.300	35.020	885.000	0.000	37.610E
208/1400	32.080	31.850	32.590	5.278	4.886	278.300	22.080	871.000	0.000	29.360E
209/1400	36.920	10.590	33.280	4.151	3.735	321.500	25.650	927.000	0.000	318.000E
210/1000	32.910	40.990	26.700	6.527	6.406	220.200	11.030	801.000	0.000	197.900E
210/1100	34.660	35.380	28.470	6.782	6.535	220.700	15.470	901.000	0.000	107.300E
210/1200	35.890	31.930	30.240	6.637	6.327	222.100	17.500	949.000	0.000	68.010E
210/1300	37.180	23.830	31.900	6.296	6.029	225.700	16.670	937.000	0.000	57.270E
210/1400	37.880	18.400	33.330	6.110	5.929	215.000	13.940	831.000	0.000	59.540E
210/1500	35.300	19.770	34.110	3.704	3.624	228.800	11.900	230.700	0.000	58.970E
210/1600	37.230	17.760	33.780	5.048	4.729	202.200	20.360	500.200	0.000	61.480E
211/1300	31.320	41.460	31.680	4.450	4.093	356.200	22.930	910.000	0.000	89.600E
211/1400	32.230	34.870	33.300	4.834	4.473	349.900	22.130	875.000	0.000	79.000E
212/1400	18.520	90.300	24.670	2.252	1.906	352.300	31.770	575.843E	0.000	74.000E
214/1400	25.110	49.810	29.140	3.654	3.381	80.500	22.150	773.000	0.000	266.200E
216/1400	30.070	38.540	27.440	2.560	2.194	171.100	30.630	854.000	0.000	101.100E
218/1400	31.080	48.300	30.070	6.012	5.796	163.000	15.360	832.000	0.000	278.500E
219/ 900	22.870	56.630	22.300	4.327	4.144	8.610	16.660	624.500	0.000	310.300E
219/1000	24.180	48.520	24.220	3.949	3.536	359.600	26.180	776.000	0.000	68.810E
219/1100	25.150	43.790	26.470	3.821	3.485	355.500	24.040	877.000	0.000	382.600E
219/1200	25.970	41.320	28.710	4.155	3.970	336.300	17.100	923.000	0.000	482.500E
219/1300	26.810	40.020	30.730	4.095	3.859	351.800	19.450	912.000	0.000	445.700E
219/1400	27.420	39.030	32.330	4.289	3.893	350.700	24.620	850.000	0.000	393.100E
219/1500	27.900	38.220	33.460	4.033	3.732	351.200	22.130	734.000	0.000	377.900E
219/1600	28.110	37.390	34.030	3.994	3.719	342.900	21.280	571.100	0.000	422.900E
221/1400	29.200	42.640	29.980	6.016	5.839	359.300	13.900	843.000	0.000	461.700E
223/1400	28.130	58.930	30.160	5.395	5.182	193.900	16.070	821.000	0.000	114.100E
224/1400	28.390	56.440	32.110	4.277	4.110	147.700	16.030	725.000	0.000	79.700E
225/1100	27.840	59.910	28.380	3.909	3.598	323.700	22.850	854.000	0.000	307.200E
225/1400	29.370	53.470	33.760	3.908	3.642	345.600	21.140	729.000	0.000	155.100E
226/1400	28.740	39.920	30.950	2.539	1.824	336.700	42.990	765.000	0.000	173.200E
227/1400	31.500	31.220	31.250	4.366	4.230	172.500	14.290	835.000	0.000	391.600E
228/1400	35.790	20.500	31.480	4.612	4.417	194.000	16.640	818.000	0.000	263.400E
229/1400	26.600	60.230	29.460	6.229	6.052	99.700	13.650	807.000	0.000	102.300E
231/1400	31.090	53.570	28.900	5.902	5.671	167.000	16.040	795.000	0.000	353.300E

1986 JUL DATE /TIME	AIR TEMP C	REL HUM %	SOIL TMP C	WIND SP M/SEC	WIND VEC M/SEC	VECT DIR	VECT SD	RAD W/M2	PRECIP MM	SH BAND DIFFUSE
232/ 900	21.240	81.700	24.340	10.610	10.450	5.712	10.000	229.154E	0.000	351.200E
232/1000	21.340	80.800	24.530	10.240	9.990	5.882	12.820	254.714E	0.000	412.900E
232/1100	22.380	74.400	24.880	10.590	10.430	8.610	10.210	623.900	0.000	405.600E
232/1200	23.440	66.410	25.680	10.310	10.110	11.010	11.340	819.000	0.000	370.300E
232/1300	23.800	58.860	26.850	10.220	9.930	9.980	13.690	878.000	0.000	174.200E
232/1400	23.120	53.570	27.880	10.150	10.030	4.718	9.000	607.000	0.000	238.800E
232/1500	20.870	54.430	28.210	8.570	8.330	3.552	13.540	302.637E	0.000	260.100E
233/ 900	16.14	65.3	20.54	3.425	3.316	131.2	14.42	342.8	0.0	132.600e
233/1400	20.260	68.990	24.640	4.858	4.697	105.400	14.780	638.882E	0.000	370.000E
233/1500	20.040	71.100	25.040	5.270	5.136	108.000	12.900	594.545E	0.000	328.700E
234/1400	27.400	35.140	28.410	6.356	6.075	349.800	17.020	809.000	0.000	203.000E
238/ 900	19.180	84.000	21.680	8.090	7.930	18.450	11.410	417.400	0.000	77.700E
238/1000	18.750	81.300	22.250	7.760	7.640	18.780	9.970	334.500	0.000	98.300E
238/1100	17.790	83.200	22.390	6.655	6.539	24.420	10.670	148.800	0.000	231.600E
238/1200	17.410	85.700	22.170	5.540	5.445	31.920	10.590	155.000	0.000	248.900E
238/1300	19.070	79.300	22.120	6.002	5.780	23.350	15.600	368.400	0.000	89.500E
238/1400	19.666E	72.833E	21.914E	5.208E	4.701E	18.098E	24.528E	427.799E	0.000E	0.000E
241/1400	28.580	44.600	24.830	4.714	4.534	178.900	15.850	839.000	0.000	97.100E
242/1400	30.680	45.400	26.640	5.810	5.621	188.300	14.610	839.000	0.000	342.000E
246/1400	28.280	33.690	25.110	3.571	3.157	326.500	27.560	854.000	0.000	220.200E
251/1400	12.880	88.200	14.510	6.070	5.902	177.600	13.440	512.546E	0.000	197.100E
252/1400	28.410	37.660	22.200	1.778	1.203	160.400	46.050	810.000	0.000	306.000E
254/1400	23.090	33.920	23.120	9.330	9.150	324.000	11.330	808.000	0.000	166.500E

APPENDIX III

FORTRAN Program used to Calculate CWSI

```
C**********************************************************************
C*                CROP WATER STRESS INDEX PROGRAM
C*                    FOR SOYBEANS AND CORN
C*          WRITTEN BY: V. BOYD SAMSON AND C. HAYS
C*                          MAY 1986
C**********************************************************************
C    IDSO BASELINE = 1.44 - 1.34 (VPD)  FOR SOYBEANS, BASELINE FOR
C    CORN IS 2.67 - 2.059 (VPD).  UPPER LIMIT IS BASED ON INTERCEPT
C    AND AIR TEMPERATURE.  ATC = AVERAGE CANOPY TEMPERATURE
C    FOR NORTH AND SOUTH TEMPERATURES COMBINED.
C
C
      CHARACTER*12 FNAME,FNAME2, FNAME3
      CHARACTER*1 DIR1,DIR2
      INTEGER PLOT,TIME,REP,DATE
      REAL NORTH
      E= 2.718282
      SB=1.44
      SM=-1.34
      CB=2.67
      CM=-2.059
      OPEN(6,FILE='LPT1')
      WRITE(*,10)
 10   FORMAT(1X,'ENTER INPUT FILE NAME-')
      READ(*,20)FNAME
 20   FORMAT(A)
      WRITE(*,30)
 30   FORMAT(1X,'ENTER OUTPUT FILE NAME FOR SOYBEANS-')
      READ(*,20)FNAME2
      WRITE(*,35)
 35   FORMAT(1X,'ENTER OUTPUT FILE NAME FOR CORN-')
      READ(*,20)FNAME3
      OPEN(3,FILE=FNAME,STATUS='OLD')
      OPEN(4,FILE=FNAME2,STATUS='NEW')
      OPEN(2,FILE=FNAME3,STATUS='NEW')
 36   TEMPN= 0
      TEMPS= 0
      NORTH= 0
      SOUTH= 0
      DO 45  I=1,5
 40   READ(3,42,END=900)DATE,TIME,PLOT,REP,DIR1,T1,DIR2,T2
 42   FORMAT(2X,I3,1X,I4,1X,I3,1X,I2,1X,A1,2X,F5.3,1X,A1,2X,F5.2)
      TEMPN=T1+TEMPN
      TEMPS=T2+TEMPS
 45   CONTINUE
      NORTH= TEMPN/5
      SOUTH= TEMPS/5
      ATC= (NORTH + SOUTH)/2
```

```
C
C  CALCULATE TEMPERATURE DIFFERENCE (TD)
  46   WRITE(*,50)PLOT
  50   FORMAT(1X,'ENTER AIR TEMPERATURE FOR PLOT ',I3/)
        READ(*,*)TA
        TD= ATC - TA
        WRITE(*,55)PLOT
  55   FORMAT(1X,'ENTER WET BULB TEMPERATURE FOR PLOT ',I3/)
        READ(*,*)WBULB
C
C  CALCULATE SATURATED AND ACTUAL VAPOR PRESSURE
        POWER= (17.26939 * TA)/(TA +237.3)
        SVP= 0.61078 * E**POWER
C
C  ACT. VP= AVP  CALCULATIONS:
        DT= (17.26939 * WBULB)/(237.3 + WBULB)
        A2= 0.61078 * E**DT
C  G= PSYCHROMETRIC CONSTANT  IN KPa
        G= (64.549  + (0.0647 * TA))/1000
        R= 0.001 * WBULB
        S= 1.15 * R
        T= S + 1
        U= T * (TA - WBULB)
        AVP = A2 - (G * U)
C
C  CALCULATE VAPOR PRESSURE DEFICIT (VPD)
        VPD= SVP - AVP
C
C ***CALL SUBROUTINES FOR RESPECTIVE CORN OR SOYBEAN PLOTS *****
C
        IF((PLOT.EQ.4).OR.(PLOT.EQ.7).OR.(PLOT.EQ.8))THEN
           GOTO 85
        ELSE
        IF((PLOT.EQ.9).OR.(PLOT.EQ.10).OR.(PLOT.EQ.11))THEN
           GOTO 85
        ELSE
        IF((PLOT.EQ.12.).OR.(PLOT.EQ.13)) THEN
          GOTO 85
        ELSE
        IF((PLOT.EQ.1).OR.(PLOT.EQ.2).OR.(PLOT.EQ.3)) THEN
           GOTO 70
        ELSE
        IF((PLOT.EQ.5).OR.(PLOT.EQ.6).OR.(PLOT.EQ.14)) THEN
           GOTO 70
        ELSE
        IF((PLOT.EQ.15).OR.(PLOT.EQ.16).OR.(PLOT.EQ.17)) THEN
           GOTO 70
        ELSE
        GOTO 70
        ENDIF
        ENDIF
        ENDIF
        ENDIF
```

```
          ENDIF
          ENDIF
C
C CALCULATE VAPOR PRESSURE GRADIENT (VPG) FOR SOYBEANS
C
   70  EXPON= (17.26989 * (TA +SB))/(TA +SB + 237.3)
          VAP= 0.61078 * E**EXPON
          VPG= SVP - VAP
C
C CALCULATE UPPER LIMIT FOR SOYBEANS
C
          UPLIM= SB + (SM * VPG)
C
C CALCULATE WELL WATERED BASELINE  FOR SOYBEANS
C
          BLINE= SB + (SM * VPD)
C
C  CALCULATE CWSI AND WRITE TO FILES
C
         CWSI= (TD - BLINE)/(UPLIM - BLINE)
         WRITE(4,75)DATE,TIME,PLOT,NORTH,SOUTH,ATC,TA,TD,WBULB,VPD,CWSI
   75  FORMAT(1X,I3,1X,I4,1X,I2,7(1X,F4.1),1X,F6.2)
         WRITE(6,80)DATE,PLOT,CWSI
   80  FORMAT(1X,I3,1X,'FOR PLOT ',I3,3X,'CWSI= ',F6.2)
         GOTO 36
C
C    CALCULATE VAPOR PRESSURE GRADIENT FOR CORN
C
  85   EXPON= (17.26989 * (TA +CB))/(TA+CB + 237.3)
         VAP= 0.61078 * E**EXPON
         VPG= SVP - VAP
C
C        CALCULATE UPPER LIMIT FOR CORN
C
         UPLIM= CB + (CM * VPG)
C
C   CALCULATE WELL-WATERED BASELINE FOR CORN
C
         BLINE= CB + (CM * VPD)
C
C CALCULATE CWSI AND PRINT TO FILES
C
        CWSI= (TD - BLINE)/(UPLIM - BLINE)
        WRITE(2,90)DATE,TIME,PLOT,NORTH,SOUTH,ATC,TA,TD,WBULB,VPD,CWSI
  90   FORMAT(1X,I3,1X,I4,1X,I2,7(1X,F4.1),1X,F6.2)
        WRITE(6,95)DATE,PLOT,CWSI
  95   FORMAT(1X,I3,1X,'FOR PLOT ',I3,3X,'CWSI= ',F6.2)
        GOTO 36
  900  WRITE(6,100)
  100  FORMAT('1')
        STOP
        END
```