Report for 2003NE34B: Defining Dynamic Crop-Water-Stress-Index Baselines to Schedule Irrigation Using Infrared Thermometers

There are no reported publications resulting from this project.

Report Follows

Dynamic Crop-Water-Stress-Index Baselines to Schedule Irrigation for Corn and Soybean Using Infrared Thermometers

José O. Payero

Abstract. *In this study, canopy temperature, meteorological, and other supporting variables were measured from corn and soybean plots at North Platte, Nebraska, during the 2004 growing season. The objectives were: (1) to develop transferable upper and lower crop water stress index (CWSI) baselines, and (2) to develop relationships between soil water depletion in the crop root zone and CWSI. Equations to estimate the upper and lower CWSI baseline were developed in this study for corn and soybean (R^2 = 0.76 to 0.94). The lower baselines for both crops were a function of several variables, including plant canopy height, vapor pressure deficit, solar radiation, and wind speed. The lower baselines were only a function of solar radiation for soybean, and solar radiation and plant canopy height for corn. By taking into account all the variables that affect the baselines, it should be possible to apply them at different times of the day and at different locations. The attempt to develop relationships between CWSI and soil water depletion in the crop root zone in this study was not successful. The relationships between the two variables always resulted in very low R^2 values. The new baselines developed in this study should facilitate the application of the CWSI method for irrigation scheduling of corn and soybean, although there is still a need for additional validation of the equations by repeating the experiment in other environments and in other growing seasons.*

Keywords. Crop water stress index, canopy temperature, infrared thermometers, irrigation scheduling, corn, soybean.

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Introduction

Irrigated agriculture is a major component in Nebraska's economy, producing an annual income of about $5 billion. Around 33% of Nebraska's cropland is irrigated (Johnson, 2001), which is above the national average of only 11% (Postel, 1999). Irrigated land area in Nebraska is about 8.1 million acres, which ranks second in the nation following California. The most important irrigated crop in the state is corn, with close to 5 million acres, followed by soybeans, with around 1.5 million acres. Sources of irrigation water include both surface and groundwater. Groundwater is mainly extracted from the Ogallala formation of the High Plains Aquifer, a large aquifer underlying parts of 8 states.

Nebraska is currently facing water quantity and quality challenges. First, in 1998 Kansas filed a lawsuit against Nebraska demanding more water from the Republican River basin. As a result of this lawsuit, the two States have recently agreed upon a settlement in which Nebraska is required, among other things, to establish a moratorium in new irrigation wells. Second, to comply with requirements of the Endangered Species Act, Nebraska is required to transfer considerable amounts of irrigation water from the Platte River to maintain wildlife habitats. At the same time, although Nebraska is rich in groundwater, studies have shown that in some areas, groundwater levels are declining. Alarmingly, high levels of nitrate and pesticides have been detected in groundwater, as a result of excessive applications of nitrogen and pesticides, combined with excessive irrigation. Because of these problems, many farmers in Nebraska are now under a water allocation system in which they are only allowed to pump a fixed amount of groundwater during a given period. Finally, high cost of energy and low commodity prices are imposing economic incentives for farmers to make efficient use of irrigation water. Current conditions require farmers to improve irrigation management practices to conserve water, protect the environment, and increase profitability.

Despite increasing pressure for farmers to use irrigation water more efficiently, most farmers in Nebraska still schedule irrigation empirically, due to tradition, and to the lack of easily applicable and scientifically-based irrigation scheduling methods. A potentially simple way to schedule irrigation is by measuring crop canopy temperature using a portable infrared thermometer. *It is known* that the difference between canopy and air temperatures (Tc-Ta) increases when crops are under water stress. This happens as a response to decreased evapotranspiration, which serves as a cooling mechanism for the crop. It is also known that (Tc-Ta) is lineally related to air vapor pressure deficit (VPD). Although the slope of the line stays nearly constant, its position also changes with soil moisture deficit and solar energy available at the time of measurement. For a crop, a lower and an upper baseline of [(Tc-Ta) versus VPD] can therefore be obtained, which represent non-stressed and maximum water stress conditions, respectively. Based on these baselines, and using actual (Tc-Ta) and VPD for a given day, an index can be calculated, usually known as the Crop Water Stress Index (CWSI), which has been shown to increase with soil moisture depletion and can be used to schedule irrigation. This method of scheduling irrigation, however, is not practical at present because of a few *gaps in the knowledge base*. The most important gap is that it is usually assumed that the solar energy available at the time of measurement is constant if measurements are taken near noon and under clear-sky conditions. This assumption makes this method site-specific, since it is well known that solar radiation changes with location, time of day, and day of year, even under clear-sky

conditions. Because of this assumption, different researchers have found different lower and upper baselines for the same crop. *This is an important problem* since as solar radiation has not been considered to define the baselines, no universal baselines that can be applied from place to place exist. Therefore, to apply this method for a given crop and location, first it is necessary to empirically determine the lower and upper baselines.

Technically sound ways of scheduling irrigation include measuring soil moisture with one of many devices commercially available and /or keeping track of soil moisture budget using crop water use information. Farmers have been slow in adopting these scheduling techniques, mainly because they are labor intensive or require knowledge or tools they do not have. The potential for using infrared thermometers as an easy method for irrigation scheduling has been recognized for a long time, but this potential has not been realized yet because this method is not practical in the present state of knowledge.

Wolpert (1962) was among the first to study the factors affecting canopy temperature, using a theoretical mathematical representation of all the variables important to the heat balance of a plant leaf. Gates (1964) and Linacre (1964) recognized that transpiration was an important factor controlling leaf temperature, as it acts as a cooling mechanism. At that time, canopy temperature was measured using thermocouples embedded in the leaves, which was not very practical for general use. The use of infrared thermometers to measure canopy temperature, however, was becoming feasible (Conaway and van Bavel, 1967; Fuchs and Tanner, 1966). Calson et al. (1972) recognized that canopy temperature provided a measure of the plant response to its environment and suggested that the factors affecting canopy temperature were the same affecting evapotranspiration. These factors included wind speed, solar radiation, air temperature, and vapor pressure deficit, and soil moisture. Linking canopy temperature to soil moisture was particularly important since the potential of using canopy temperature as an indicator of crop water stress and as a tool for irrigation scheduling was then recognized. The basic assumption was that transpiration cools the leaves and as available soil moisture decreases, transpiration is reduced and, therefore, the temperature of the leaves increases. A lot of research followed trying to use canopy temperature as a tool for irrigation scheduling, and many indexes were developed relating canopy temperature to soil moisture depletion (Idso et al. 1977; Jackson et al. 1977; Blad et al. 1981, Ehrler, 1973; Ehrler et al. 1978).

Idso et al (1981). made the seminal observation that canopy minus air temperature (Tc-Ta) was lineally related to air vapor pressure deficit (VPD) and that lower and upper baselines could be established empirically for both non-water-stressed and for non-transpiring crop conditions, respectively. They used these baselines to calculate what they called the Crop Water Stress Index (CWSI), as a measure of crop water stress. This empirical CWSI is calculated as (Idso et al. 1981):

$$\mathbf{CWSI = [(Tc\text{-}Ta)_{m}\text{-}(Tc\text{-}Ta)_{LB}]/[(Tc\text{-}Ta)_{UB}\text{-}(Tc\text{-}Ta)_{LB}]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where the subscripts *m, LB,* and *UB* refer to the (Tc-Ta) values for the measured, lower baseline, and upper baseline, respectively.

Jackson et al. (1981) and Jackson (1982), followed this work by establishing the theoretical basis for the Crop Water Stress Index (CWSI). They showed that the lower baseline is a function of net radiation, crop resistances (both aerodynamic and surface) and vapor pressure deficit, while the upper baseline is a horizontal line that depends on available energy and crop aerodynamic properties. This theoretical approach then required knowledge of crop resistance properties and net radiation, in addition to measured (Tc –Ta) and VPD, which made it difficult to apply in practice. For this reason, most researchers have preferred to use the empirical approach of Idso et al (1981), which have been shown to work well for a given location as long as you have locally calibrated baselines. To establish the lower and upper baselines, however, most researchers have assumed that both the available energy and the wind speed are constant if the required measurements are made close to noon and under clear sky conditions. This assumption, however, is problematic because it is well known that both the available energy and wind speed change, among other things, with location, time of day and day of the year. Because of this, empirical baselines for the same crop will be different under different solar radiation and wind speed conditions as shown by Zolnier et al. (2001) and Jensen et al. (1990). Researchers from different places have used this method for scheduling irrigation, using different baselines. For instance, fig. 1 shows the different lower baselines (non-water-stressed) that researchers have used for corn.

The same type of disagreement is found in defining the upper baseline. For instance, for corn, Shanahan and Nielsen (1987) and Nielsen and Gardner (1987) used a maximum value of (Tc-Ta) = 3ºC as the upper baseline. Steele et al. (1994), however, used 5 ºC, and Irmak et al.(2000) used an average value of 4.6ºC. Sadler et al. (2000), however, reported values of (Tc-Ta) > 10 ºC and Jensen et al (1990), found (Tc-Ta) values for several crops as high as 8 ºC for high levels of solar radiation and values approaching zero or even negative at low levels of solar radiation.

The lack of transferability of the baselines, together with the restriction of having to make required measurements close to noon and under clear sky conditions, are recognized as the major drawbacks of using the CWSI for irrigation scheduling. These problems have prevented farmers for decades from using this method for irrigation scheduling. Transferable baselines that could be used in different locations and using measurements at any time of day can however be developed. All that is needed is to take into account the effect of both available energy and wind speed, which have been identified as the main factors affecting the baselines. However, since it can be assumed that for a given day during the daytime hours, available energy is linearly related to solar radiation, then baselines that change with solar radiation can be developed. An attempt to developed transferable baselines have recently been made by Alves and Pereira (2000), who provided a new definition of the lower baseline based on the difference between the canopy temperature and the wet bulb temperature, instead of the air temperature. This new concept, however, requires almost as much information as the theoretical approach of Jackson et al. (1981), and also requires crop-specific calibration.

The body of work reviewed in this section makes it clear that there is a need to define lower and upper baselines that are transferable to other locations and that will allow measurements to be taken at different times of day. This will make it possible for the CWSI method to be used for irrigation scheduling by farmers without the need to perform site-specific calibration, which has prevented its use for decades. The objectives of this study were: (1) to develop transferable upper

and lower [(Tc-Ta) versus VPD] baselines**,** and (2) to develop relationships between soil water depletion in the crop root zone and crop water stress index (CWSI).

Methods

Site Description

Field data for this study were collected from corn and soybean plots during 2004 at North Platte (41.1˚ N, 100.8˚ W, 861 m above sea level), Nebraska. The field experiment was conducted at the University of Nebraska-Lincoln West Central Research and Extension Center. The soil at North Platte was a Cozad silt loam (*Fluventic Haplustolls*) with field capacity of 0.29 m^3 m^{-3} and permanent wilting point of 0.11 m^3 m^{-3} (Klocke et al. 1999). The corn variety Renze 9363 Bt RR was planted at 0.76-m row spacing. Corn was planted on May 10 and harvested on November 15. The soybean variety Renze 2600 RR, which is in the maturity group 2, was also planted at 0.76-m row spacing and at a depth of approximately 2.5 cm. The soybean was planted on May 21 and harvested on October 5. Both crops were irrigated using a solid-set sprinkler system, which was arranged in a 12.2 m x 12.2 m grid. In each of its four sites, each experimental plot was surrounded by a "border" plot of the same size. The inclusion of "border" plots precluded water from different contiguous irrigation treatments from overlapping within a given experimental plot. Sprinkler heads were installed at the four corners of each plot on 3.35-m risers.

Field Measurements

For each crop, data were collected from four different plots, which received different irrigation treatments, including a dry-land treatment. Measurements included canopy temperature, air temperature, relative humidity, wind speed and direction, solar radiation, and plant canopy height. Daily average canopy heights for each crop were estimated from weekly measurements. For each crop, canopy temperatures were measured from four plots receiving different irrigation treatments. The irrigation treatments were part of a larger experiment that included 9 treatments for corn and 8 for soybean. The four plots were located at the same distance from a center "border" plot (shaded plots in fig. 2).

A tripod was installed at the center of the "border" plot (its location is indicated by and "x" in fig. 2). The tripod supported an environmental enclosure that housed a datalogger and a multiplexer. It also supported an anemometer , a pyranometer, and an air temperature/relative humidity sensor. Power to the system was supplied by a 12-volts car battery. Wind speed and direction were measured using a R.M. Young wind sentry 03101-5 system (Campbell Scientific, Logan, UT). The anemometer was installed at a height of 3.7 m above ground in the corn plots and at a height of 2 m in the soybean plots. Solar radiation was measured using a solar pyranometer (Apogee Instruments, Inc., Logan, UT) that was leveled and installed on the tripod above all other instruments to make sure it was never shaded. Air temperature and relative humidity were measured with a HMP45C sensor (Campbell Scientific, Logan, UT) installed at the same height as the anemometer. The air temperature and relative humidity measurements were used to calculate the vapour pressure Deficit (VPD) of the air as (Allen et al., 1998):

$$e_s = 0.6108*Exp[17.27T/(T + 237.3)] \quad (2)$$
$$e_a = e_s*(RH/100) \quad (3)$$
$$VPD = e_s - e_a \quad (4)$$

where, e_s = saturation vapour pressure (kPa), T = mean air temperature (^oC), RH = relative humidity of the air (%), and VPD = vapour pressure deficit (kPa).

Canopy temperature measurements started on July 15, when the crops had reached full cover, to avoid measuring the temperature of the soil background. For each crop, canopy temperature from each of the four plots was measured using two infrared thermometers per plot (model IRTS-P, Apogee Instruments, Inc., Logan, UT). The infrared thermometers were installed approximately one meter above the maximum plant canopy height at a 45 degree angle, one pointing East and the other pointing West. The average of the two sensors was used for analysis. A mount made of 1.9 cm PVC tubing and fittings was constructed to house the two infrared thermometers in each plot and to be able to install them above the canopy (fig. 3). The mount was shaped in form of a "T" and a steel pipe was used as a riser. The riser was supported by a T-post that was driven in the ground. The infrared thermometers were placed inside the PVC tubing for protection and to reduce temperature variations of the body of the sensors, which could affect their accuracy, as reported by Bugbee et al. (1998).

The infrared thermometers were sampled using a 21X datalogger (Campbell Scientific, Logan, UT). The thermometers were connected to the datalogger via an AM16/32 multiplexer (Campbell Scientific, Logan, UT). Both the temperature of the target and that of the body of the sensor were measured from each infrared thermometer using Type K (Chromel-Alumel) thermocouple wires. The temperature from each thermocouple was sampled every minute by measuring the differential voltage between the two thermocouple wires. Data from the infrared thermometers and from all the other instruments were averaged and stored every ten minutes. Data were downloaded from the datalogger to a laptop computer approximately twice a week.

Daily soil water depletion in the crop root zone was estimated using a soil water balance approach. A computer program was written in Microsoft Visual Basic® to model the daily soil water status. Input to the program included daily weather data, rainfall, irrigation, the water content in the soil profile at crop emergence, and crop-specific and site-specific information such as planting date, maturity date, soil parameters, maximum rooting depth, etc. Based on these inputs, the water balance in the crop root zone was calculated daily. The water content in the soil profile at crop emergence was measured using the neutron scattering method. Soil water readings were taken from 50-mm diameter aluminum access tubes installed at the center of the plot in each irrigation treatment. Readings were taken at 0.3-m depth increments to a depth of 1.8 m. Daily crop evapotranspiration was calculated using the procedure presented in FAO-56 (Allen et al. 1998; Wright, 1982). Since this is a very long procedure, readers are referred to the original sources for details. According to this procedure, crop evapotranspiration can be obtained as the product of the evapotranspiration of a reference crop (ET_o) (a grass reference was used in this study) and a crop coefficient (K_c). ET_o is calculated using the weather data as input to the Penman-Monteith equation and the K_c is used to adjust the estimated ET_o for the reference crop to that of other crops at different growth stages and growing environments. In this study, the dual crop coefficient approach was used to separate the two components of evapotranspiration,

namely evapotation (E) and transpiration (T). This procedure also linearly reduced crop evapotranspiration when the available soil moisture in the crop root zone was below 50%, which was used to quantify the effect of water stress on crop water use. The dual crop coefficient procedure also accounts for the sharp increases of the evaporation component due to a wet soil surface following rain or irrigation. Weather data used as input to the program was obtained from an automatic weather stations located near the research plots. The weather station was part of the High Plains Regional Climate Center (HPRCC) weather network. Daily weather data were downloaded from the HPRCC web site (*http://www.hprcc.unl.edu/home.html*), including daily maximum and minimum air temperature, relative humidity, wind speed, rainfall, and solar radiation. The computer program calculated the daily soil water balance for each 0.30 m soil layer and then calculated the daily % root zone depletion on day i ($\%Dep_i$) as:

$$\%Dep_i = (Dep_i/TAW_i)*100 \quad (5)$$

where, Dep_i = soil water depletion in the crop root zone on day i (mm), TAW_i = total available water in the crop root zone on day i (mm).

Calibration of infrared thermometers

The manufacturer of the type of infrared thermometers used in this study recommends correcting the temperatures measured by the infrared sensors to account for differences in sensor body temperature using the procedure proposed by Bugbee et al. (1998) as:

$$CTT = (ATT-SEC) \quad (6)$$

$$SEC = (0.25/P_{sb})*[((ATT - H_{sb})^2)-K_{sb}] \quad (7)$$

where, CTT = corrected target temperature (^oC), ATT = apparent target temperature (^oC), SEC = sensor error correction (^oC), and P_{sb}, H_{sb} and K_{sb} are generic (sensor independent) calibration coefficients that can be calculated as a function of sensor body temperature (SB) (^oC) using second degree polynomials as:

$$P_{sb} = 26.168 + 2.8291(SB) - 0.03329(SB^2) \quad (8)$$
$$H_{sb} = 5.8075 - 0.08016(SB) + 8.49e^{-3}(SB^2) \quad (9)$$
$$K_{sb} = -85.943 + 11.740(SB) + 0.08477(SB^2) \quad (10)$$

In this study, however, to improve accuracy a calibration function was developed for each infrared thermometer. Calibration of the infrared thermometers was performed using a model 1000 calibration source (Everest Interscience Inc., Tucson, AZ). The Blackbody surface of the calibration source had been prepared using high emissivity aluminum oxide, with a configuration that uses re-entrant concentric rings. The calibration was conducted inside a laboratory hood (fig. 4). The temperature inside the hood and that of the blackbody were increased using a portable electric heater. For temperatures below ambient temperature, the calibration source was placed inside a refrigerator until its temperature was just above freezing. The temperature of temperature of the blackbody was then allowed to decrease or increase and readings with the infrared thermometers were taken at different temperatures, ranging between approximately 5 to

45°C, which included the temperatures that would normally occur in the field during the study. Temperatures of the blackbody, and the infrared thermometer readings, including the temperature of the body of the sensors, were recorded. A total of 21 temperature readings were recorded for each infrared thermometer, taking at least 3 readings for each temperature. The same wiring, cable length, and datalogger program actually used in the field was used during the calibration. During the calibration, however, the sampling interval in the datalogger program was changed from one minute to ten seconds, to be able to record the rapid temperature changes of the calibration source.

Statistical Analyses

The statistical analyses, which included summary statistics and regression analysis were conducted using the SAS System for Windows® statistical software (SAS Institute, Inc., Cary, NC).

Data Quality Control

Before analysis, data were validated by identifying and excluding unreasonable values. For instance, data obtained during times when irrigation or rainfall was occurring were excluded. Solar radiation values of less than 100 W m^{-2} were filtered out, which excluded data collected during nighttime, early morning, late afternoon, and severely overcast conditions. Considerable differences between the canopy temperatures measured by the infrared thermometer looking East and that looking West on the same plot were detected during this study (fig. 5). These differences could be due differences in shading of the crop canopy, and differential cooling of the canopy as a result of changes in wind direction. They, however, could also be due to problems with one or both sensors, such as shifts in calibration, improper installation, improper wiring and/or programming, etc. To be conservative, in this study only data with an absolute difference of ≤ 2°C between the canopy temperatures measured by the two sensors in each plot were retained for further analysis. Also values collected after the crops started to mature were excluded.

Additional limits on the data were imposed to exclude data that would be unreasonable or abnormal for the area during the period of the study. These limits include the following arbitrary criteria:

- 5% ≤ Relative Humidity ≤100 %
- 0 °C ≤ Air Temperature ≤ 50 °C
- 0 °C ≤ Canopy Temperature ≤ 50 °C
- 0 W m^{-2} ≤ Solar Radiation ≤ 1300 W m^{-2}
- 0.2 m s^{-1} ≤ Wind Speed ≤ 12 m s^{-1}
- 0% ≤ % Soil Water Depletion in the crop root zone ≤100 %

These criteria would not apply to every situation, but were expected to help filter out most of the unreasonable data during this study. These criteria were included in a computer program that was used to validate the data and to make further calculations based on the validated data.

Results

Calibration of infrared thermometers

Results of calibration for each of the infrared thermometers used in this study are shown in figs 6 and 7. Very good correlations were found between the temperature measured by the infrared sensors and the temperature of the blackbody calibration source as indicated by the R^2 values of 1.0 or very close to 1.0 shown in figs 6 and 7. The relationships, however, were better explained by a second order polynomial function rather than a linear function. The good agreement is also indicated by the fact that readings from almost all of the sensors followed the 1:1 lines in figs 6 and 7. There were only three sensors that significantly deviated from the 1:1 line [232(T1)E, 232(T1)W, and 331(T7)E]. The temperatures measured by these three sensors, however, were well-correlated to the temperatures of the calibration source and it was possible to adjust their readings using the calibration equation developed for each of the sensors.

Weather conditions

Daily averages of several weather variables during the 2004 growing season at North Platte, NE, are shown in table 1. It shows considerable variations in weather variables during the growing season. For instance, solar radiation (R_s) was similar during the months of May to September, but decreased considerably during October. Weather variables are also affected by significant diurnal changes. For example, Rs during a clear day in the summer at North Platte can vary between 0 W m^{-2}, just before sunrise or just after sunset, to more than 1000 W m^{-2} during midday. Considerable diurnal variations also occur with the other meteorological variables. These variations could significantly affect the CWSI baselines.

Amounts and timings of rainfall events during the 2004 growing season at North Platte are shown in table 2. A total of 39 rainfall events occurred during the growing season, supplying a total of 414 mm of water, which was enough to meet more than half (54.5%) of the calculated seasonal crop water requirements. These conditions were wetter than normal for the area, but irrigation was still required to match crop water requirements for both crops.

Irrigation

Amounts and timings of irrigation events applied to the different irrigation treatments included in this study are shown in table 3. For corn, seasonal irrigation depths for the irrigated treatments ranged from 39 to 161 mm, enough to meet between 5.1 to 21.2 % of the seasonal crop evapotranspiration calculated assuming that water stress did not limit evapotranspiration (ET_w). For soybean, between 19 and 162 mm of irrigation were applied to the different treatments during the season. These irrigation amounts were enough to meet 3 to 28% of ET_w. The dryland treatments for both crops received no irrigation. Because of considerable rainfall early in the season, it was possible to delay irrigation until early August. The last irrigation to both crops was applied in early September.

Root Zone Depletion

The daily % soil water depletions in the crop root zone for each irrigation treatment during the 2004 growing season for both crops are shown in fig. 8. For soybean, considerable differences in depletion among treatments started in August, while for corn, differences among treatments started much earlier in the season. The difference between the two crops was due to differences in water contents in the soil profile at the beginning of the season, especially for depths greater than the rooting depth of soybean. Figure 8 also shows that a variety of soil water depletion levels were observed for both crops during the study. For both crops, the wetter treatment was T1 and the driest was the dryland treatment (T8 for soybean and T9 for corn). Figure 8 also reflects the fact that soybean started maturing sooner than corn. In 2004 corn maturity was delayed by approximately a month due to weather conditions that were cooler than normal for North Platte.

Upper and Lower CWSI baselines

After validating data using the filtering criteria described above, a total of 9468 and 3315 data points (10-min averages) were retained for corn and soybean, respectively. Summary statistics for the data retained for further analysis are shown in table 4. Statistics include the mean, standard deviation, minimum, and maximum values for nine variables used in the analyses. After data were validated, equations for the upper and lower CWSI baselines were then developed using multiple regression analysis. The equation for the upper baseline was developed by only including data when the % root zone depletion was greater than 85%, which indicated that the crops were under severe water stress. To develop the equation for the lower baseline, only data collected when the % root zone depletion was less than 50%, which is commonly considered as no-water-stress conditions, were included in the analysis. All variables that could have an effect on the baselines were originally included in the multiple regression analysis. However, only those variables that were statistically significant ($p < 0.01$) were included in the final multiple regression equations.

The multiple regression analyses for both crops and for the upper and lower baselines resulted in high R^2 values, which ranged from 0.76 to 0.94 (table 5). The resulting lower baselines were a function of several variables, including plant canopy height, vapor pressure deficit, solar radiation and wind speed. The upper baselines, however, were only a function of solar radiation for soybean, and solar radiation and plant canopy height for corn. The upper and lower baselines for corn and soybean calculated using the equations in table 5 assuming specific values for solar radiation, wind speed, and plant canopy height as a function of vapor pressure deficit are plotted in fig. 9. It shows that the baselines developed in this study are consistent with the theoretical approach of Jackson et al. (1981) and Jackson (1982), in the sense that the lower baseline has a negative slope when plotted as a function of VPD, while the slope of upper baseline is zero. Figure 10 shows the baselines calculated every ten minutes with the equations developed in this study for corn and soybean. It shows that the baselines had significant diurnal variations as a response to the changes in weather conditions that normally occur during the day and from day to day. It shows that for both baselines and crops, a diurnal change in (Tc-Ta) of approximately $5^{o}C$ was typical under the conditions of this study.

Relationship between CWSI and % Root Zone Depletion

The second objective of this study was to develop relationships between CWSI and % root zone depletion ($\%Dep_i$) . To this end, CWSI values were calculated with equation (1) for every 10-minute interval using the measured (Tc-Ta) values and the baselines calculated using the equations developed in the previous section. Then, linear regression analyses were conducted between the CWSI and $\%Dep_i$. The results were disappointing and always resulted in very low R^2 (< 0.15), indicating a poor relationship between these two variables. Part of the problem may have been that there was only one value of $\%Dep_i$ available for a given day, while there were many values of CWSI for the same day and the CWSI values varied considerably during the day. Future work should also automatically collect soil moisture data at the same times as the CWSI data to be able to explain the relationships between these two variables, especially at different times during the diurnal cycle.

Conclusions

In this study equations to estimate the upper and lower CWSI were developed for corn and soybean. The lower baseline was a function of several variables, including plant canopy height, vapor pressure deficit, solar radiation, and wind speed. The lower baseline was only a function of solar radiation for soybean, and solar radiation and plant canopy height for corn. By taking into account all the variables that affect the baselines, it should be possible to apply them at different times of the day and at different locations for these crops. The attempt to develop relationships between crop water stress index and soil water depletion in the crop root zone in this study was unsuccessful. The relationships between the two variables always resulted in very low R^2 values. The new baselines developed in this study, however, should facilitate the application of the CWSI method for irrigation scheduling of corn and soybean, although there is still a need for additional validation of the equations by repeating the experiment in other environments and in other growing seasons. There is also a need for further studies to investigate the relationships between CWSI and soil water depletion in the crop root zone in more detail, especially focusing on the diurnal variations of these two variables.

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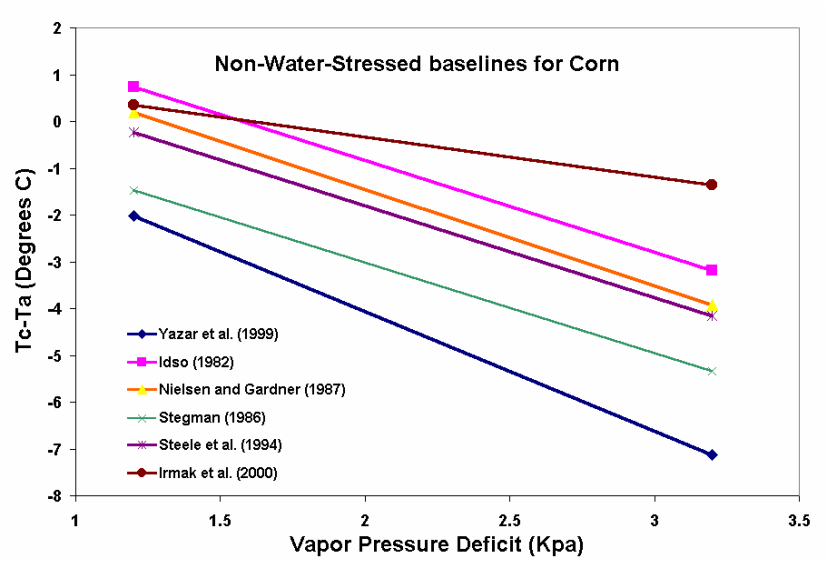

Figure 1. Non-water-stressed baselines reported by several researchers for corn.

236(T2)		**235(T4)**		**234(T3)**
			X	
231(T5)		**232(T1)**		**233(T9)**
230(T6)		229(T7)		228(T8)

Corn

336(T1)		**335(T8)**		**334(T6)**
	X			
331(T7)		**332(T3)**		**333(T1)**
330(T5)		329(T4)		328(T2)

Soybean

Figure 2. Plot layout of field experiment at North Platte. Canopy temperature data for each crop were collected from the shaded plots. The number indicates the plot number and the irrigation treatment is indicated in parenthesis. The plots with no numbers are the "border" plots. The "x" indicates the location of the tripod with the datalogger, multiplexer, and meteorological sensors.

Figure 3. Setup used to install two infrared thermometers above the crop canopy.

Figure 4. Calibration of infrared thermometers.

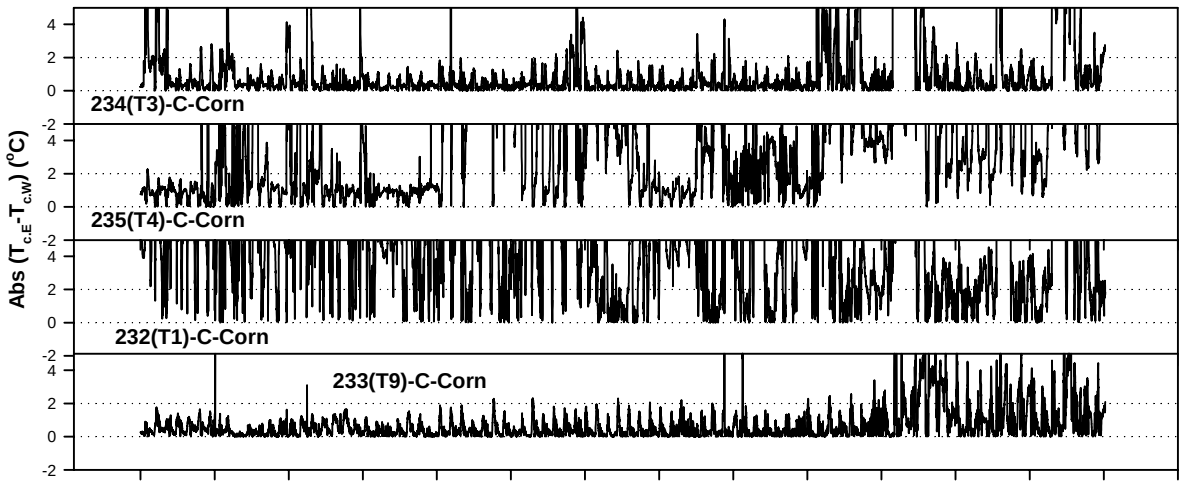

Figure 5. Absolute values of the difference between the canopy temperatures measured with the infrared thermometer looking East ($T_{c.E}$) and West ($T_{c.W}$) over four corn plots at North Platte. The X axis represents time from mid July to mid October. Each data point is a 10-minute average. 234(T3)-C-Corn indicates the plot number (234), the irrigation treatment (T3), "C" means that the readings were corrected using the calibration function developed for each sensor, and "Corn" is the crop.

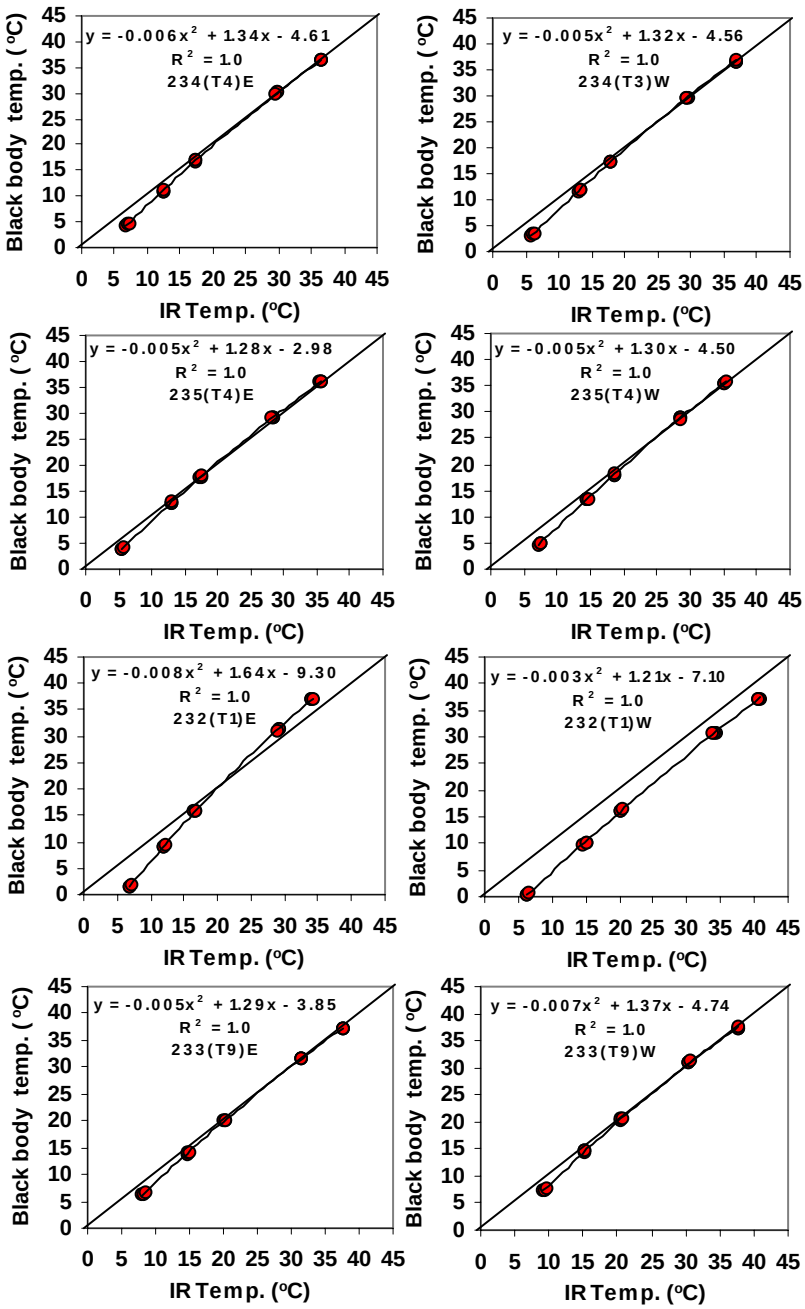

Figure 6. Calibration functions developed for each infrared thermometers used to measured canopy temperature over the corn plots. IR temp is the temperature measured by the infrared thermometer. In "233(T9)E" the number "233" is the plot number, "T9" is the irrigation treatment, and "E" and "W" indicate if the IR sensor was pointing towards the East or West. The straight line is the 1:1 line.

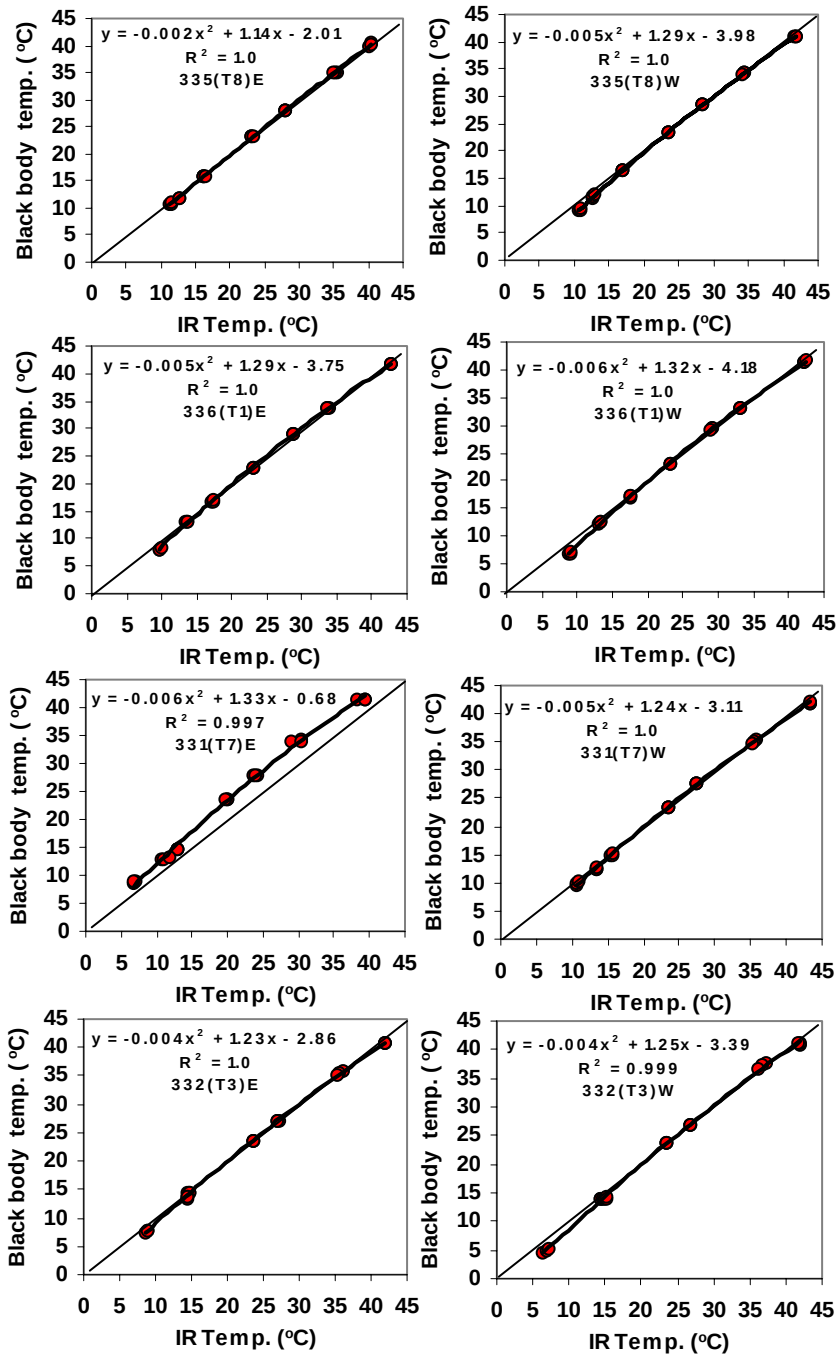

Figure 7. Calibration functions developed for each infrared thermometers used to measured canopy temperature over the soybean plots. IR temp is the temperature measured by the infrared thermometer. In "335(T8)E" the number "335" is the plot number, "T8" is the irrigation treatment, and "E" and "W" indicate if the IR sensor was pointing towards the East or West. The straight line is the 1:1 line.

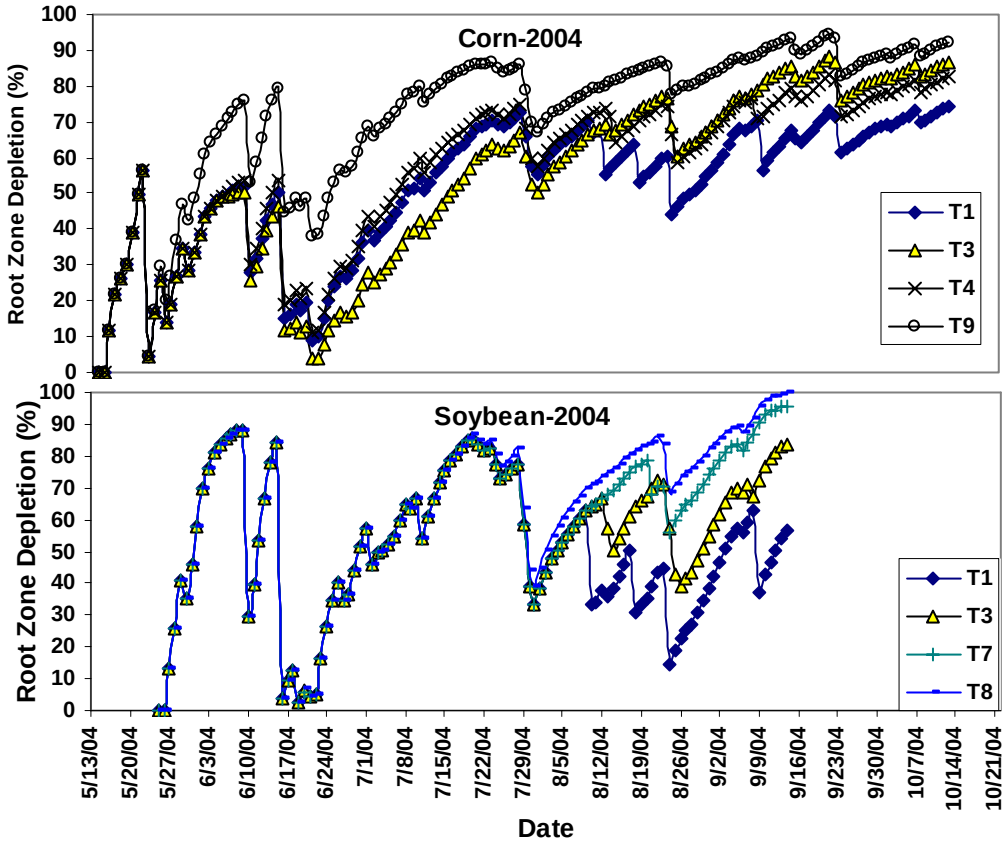

Figure 8. Daily soil water depletion in the crop root zone for different irrigation treatments (T1 toT9) for corn and soybean during the 2004 growing season at North Platte, NE.

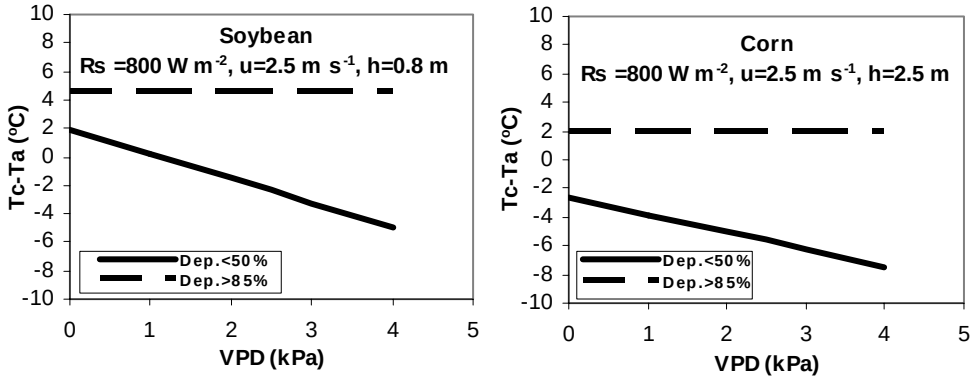

Figure 9. Upper and lower baselines for corn and soybean for the conditions shown, calculated using equations in table 5. Rs = solar radiation, u = wind speed, h= plant canopy height, Dep= % soil water depletion in the crop root zone.

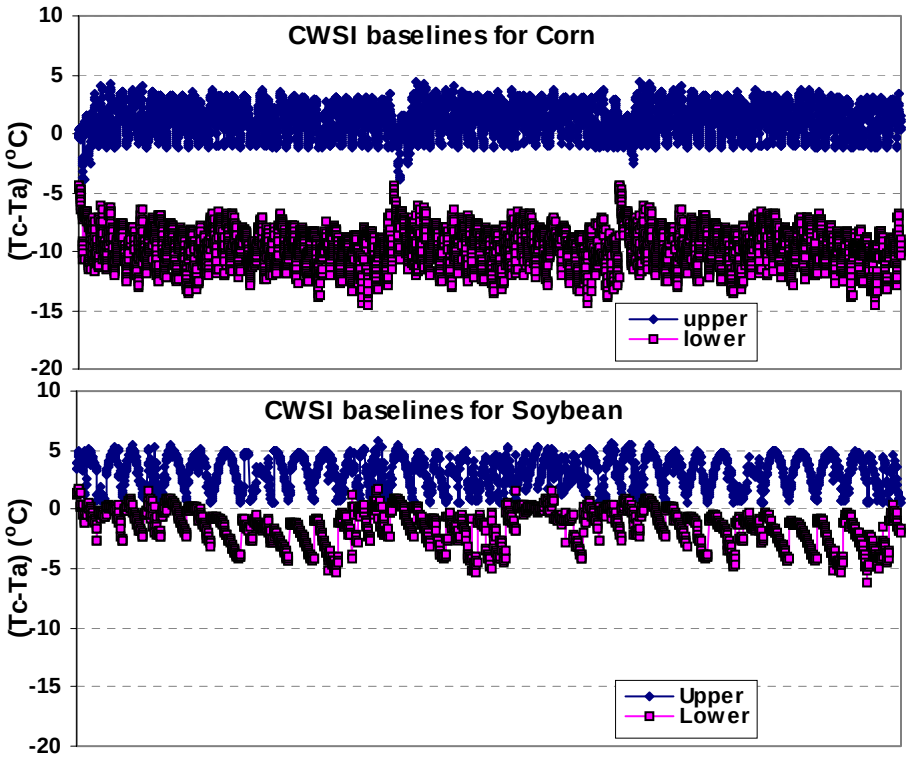

Figure 10. Calculated lower and upper crop water stress index (CWSI) baselines for corn and soybean at North Platte. The X axis represents time from day of year (DOY) 201 to 240 for corn and from DOY 220 to 240 for soybean. During that period, plant canopy height (h) for corn ranged from 2.36-2.74 m, and 0.76-0.84 m for soybean. Each point represents a 10-min average collected during the daytime.

Table 1. Average of daily values of maximum air temperature (T_{max}), minimum air temperature (T_{min}), average air temperature (T_a), solar radiation (R_s), relative humidity (RH), wind speed at 2-m height (u_2), and grass reference evapotranspiration (ET_o) for the month of May to October at North Platte, NE during 2004.

Month	T_{max} (°C)	T_{min} (°C)	T_a (°C)	R_s (MJ m^{-2} d^{-1})	RH (%)	u_2 (m s^{-1})	ET_o (mm d^{-1})
May	24.9	8.6	16.7	23.7	58.3	2.9	4.9
June	26.0	11.0	18.5	21.8	64.2	2.5	4.7
July	29.8	14.8	22.3	22.6	69.3	2.1	4.9
Aug.	27.9	11.8	19.9	21.0	65.9	1.9	4.2
Sept.	30.9	12.9	21.9	20.5	50.1	3.1	5.5
Oct.	18.5	4.1	11.3	11.0	71.7	2.1	1.8
Average	**26.3**	**10.5**	**18.4**	**20.1**	**63.3**	**2.4**	**4.3**

Table 2. Rainfall events during the growing season at North Platte during 2004.

Date	Rain (mm)
5/14/04	1
5/15/04	2
5/22/04	40
5/25/04	10
5/26/04	3
5/29/04	8
6/9/04	30
6/10/04	1
6/15/04	56
6/16/04	5
6/18/04	7
6/20/04	26
6/21/04	5
6/26/04	4
7/1/04	9
7/2/04	1
7/3/04	4
7/4/04	3
7/5/04	1
7/8/04	4
7/9/04	1
7/10/04	15
7/20/04	3
7/21/04	3
7/23/04	5
7/24/04	5
7/28/04	23
7/29/04	28
7/30/04	12
8/22/04	6
8/23/04	25
8/26/04	1
9/5/04	4
9/14/04	9
9/15/04	6
9/21/04	4
9/22/04	31
10/1/04	3
10/6/04	10
Total	**414**
% of ET_w §	**54.5**

(§) % of ET_w is the percent of seasonal crop evapotranspiration when soil water is not limiting that was supplied by in-season rainfall.

Table 3. Irrigation (mm) applied to soybean and corn at North Platte during 2004 for each irrigation treatment (T1 to T9).

Soybean				
Date	**T1**	**T3**	**T7**	**T8**
8/9/04	43.9	-	-	-
8/12/04	7.9	16.0	-	-
8/13/04	-	13.2	-	-
8/17/04	35.8	-	-	-
8/20/04	-	-	18.8	
8/23/04	26.7	-	-	-
8/24/04	-	27.7	-	-
8/25/04	-	11.2	-	-
9/7/04	-	11.2	-	-
9/8/04	47.8	-	-	-
Total	**162.1**	**79.2**	**18.8**	**0.0**
% of ETw¢	**28%**	**14%**	**3%**	**0%**
Corn				
Date	**T1**	**T3**	**T4**	**T9**
8/9/04	11.7	-	-	-
8/11/04	39.1	-	-	-
8/12/04	-	10.4	10.4	-
8/13/04	-	-	22.6	-
8/17/04	35.8	-	-	-
8/19/04	-	-	-	-
8/23/04	26.7	-	-	-
8/24/04	-	28.2	28.2	-
8/25/04	-	-	-	-
9/7/04	-	-	18.8	-
9/8/04	47.8	-	5.6	-
Total	**161.0**	**38.6**	**85.6**	**0.0**
% of ET_w¢	**21.2%**	**5.1%**	**11.3%**	**0.0%**

(¢) % of ET_w is the percent of seasonal crop evapotranspiration when soil water is not limiting that was supplied by irrigation.

Table 4. Summary statistics (n=9468 for corn and 3315 for soybean). Variables are canopy temperature (T_c), air temperature (T_a), vapor pressure deficit (VPD), canopy height (h), solar radiation (Rs), wind speed at 2-m height (u_2), and soil water depletion in the crop root zone (%Dep_i).

Corn					
Variable	**Units**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
T_c	^oC	24.36	5.18	4.53	36.5
RH	%	56.99	16.65	22.71	98.3
VPD	kPa	1.5	0.91	0.03	4.45
h	m	2.65	0.23	1.77	2.74
Rs	W m^{-2}	531.14	257.21	100.1	1126
u_2	m s^{-1}	2.31	1.36	0.2	7.31
T_a	^oC	24.59	5.31	7.95	36.69
%Dep_i	%	71.35	9.92	44	88
(T_c-T_a)	^oC	-0.23	1.73	-7.63	7.8
Soybean					
Variable	**Units**	**Mean**	**Std Dev**	**Minimum**	**Maximum**
T_c	^oC	21.45	4.65	4.82	34.55
RH	%	57.76	16.38	29.98	97.4
VPD	kPa	1.25	0.73	0.04	3.22
h	m	0.81	0.03	0.74	0.84
Rs	W m^{-2}	524.83	254.08	100.1	1030
u_2	m s^{-1}	3.1	1.41	0.45	6.74
T_a	^oC	22.07	4.84	7.61	31.79
%Dep_i	%	58.16	17.52	15	86
(T_c-T_a)	^oC	-0.62	1.85	-5.1	10.19

Table 5. Upper and lower baselines for corn and soybean determined at North Platte during 2004. The baselines were determined by multiple regression analysis. Variables and units are canopy temperature (Tc, ^{o}C), air temperature (Ta, ^{o}C), vapor pressure deficit (VPD, kPa), canopy height (h, m), solar radiation (Rs, W m^{-2}), and wind speed (u, m s^{-1}). RMSE is the root mean square error, and n is the number of values used in the analysis.

Baselines	Depletion (%)	Equations for Corn	n	R^2	RMSE
Upper Baseline	>85	Tc-Ta = -22.42+7.56h+0.0055Rs	975	0.76	0.93
Lower Baseline	<50	Tc-Ta = 20.40-11.44h-1.21VPD+0.0059Rs-0.135u	50	0.94	0.34
		Equations for Soybean			
Upper Baseline	>85	Tc-Ta = 0.0056Rs	84	0.94	0.44
Lower Baseline	<50	Tc-Ta = 12.23-16.20h-1.73VPD+0.003Rs+0.108u	784	0.80	0.67