Response of Soybean to Deficit Irrigation in the Semi-Arid Environment of West-Central Nebraska

J. O. Payero, S. R. Melvin, S. Irmak

Abstract. *Several factors, including multi-year drought, declining aquifer levels, and new water regulations, are contributing to reduced availability of irrigation water in the semi-arid area of west-central Nebraska. Since many farmers in this area do not have enough water to meet the seasonal water requirements of crops like corn and soybean, maximizing yield produced per unit of water under deficit irrigation conditions is becoming increasingly important. This study was conducted to quantify the grain yield response of soybean [*Glycine max *(L.) Merr.] to deficit irrigation, and to determine which seasonal water variables correlated best to soybean grain yield under deficit irrigation. The study was conducted during 2002 at Curtis, and 2003 and 2004 at North Platte, Nebraska. Nine deficit irrigation treatments, including different irrigation amounts and timings, were studied in 2002 and 2003, and eight treatments were studied in 2004. Soybean grain yields across years and sites were best related to the seasonal ratio of the actual crop evapotranspiration and the crop evapotranspiration when soil water was not limiting (ET_d/ET_w), and to the seasonal ratio of actual crop transpiration and crop transpiration when soil water was not limiting (T_d/T_w). Both of these seasonal ratios were linearly related to grain yield with $R^2 = 0.91$ when combining data for all seasons. The crop water productivity (CWP) (yield per unit of seasonal ET_d) linearly increased with both ET_d/ET_w ($R^2 = 0.72$) and T_d/T_w ($R^2 = 0.72$), but was best correlated to the daily positive difference between the actual and the theoretical fraction of total available soil water in the root zone that can be depleted before crop water stress occurred, accumulated for the entire season (seasonal p_{diff}) ($R^2 = 0.77$). A linear relationship between the cumulative ET_w and fraction of season (function of days after emergence) was found. This relationship developed for a given location could be used to extrapolate seasonal ET_w for in-season irrigation management. Poor correlation was found between CWP and other variables such as total irrigation, rain + irrigation, and total water. The results of this study can provide useful information for soybean irrigators to make better management decisions under deficit irrigation conditions.*

Keywords. *Crop water productivity, Deficit irrigation, Evapotranspiration, Limited irrigation, Soybean, Water stress.*

Several factors, including multi-year drought, declining aquifer levels, and new water regulations, are reducing availability of irrigation water in the semi-arid area of west-central Nebraska. Since many farmers in this area now do not have enough water to meet the seasonal water requirements of agronomic crops such as corn and soybean, maximizing the yield produced per unit of water under deficit irrigation conditions is becoming crucial to the long-term viability of the local and state economy. Deficit irrigation has been suggested as an alternative strategy for making better use of irrigation water. For instance, Zwart and Bastiaanssen (2004) reviewed measured crop water productivity (CWP) (yield per unit of seasonal evapotranspiration) for several crops around the world and concluded that the CWP could be significantly increased if irrigation was reduced and crop water deficit was intentionally induced. Similarly, Schneekloth et al. (1991) compared the yields of soybean under dryland, deficit irrigation (limited to 150 mm) and full irrigation at North Platte, Nebraska, using sprinkler irrigation. They found the same yields for the deficit and full irrigation treatments during a three-year study. Deficit irrigation increased dryland yields from 0.4 to 2.8 Mg ha^{-1}, while full irrigation only increased yields by 0 to 0.4 Mg ha^{-1} over the deficit irrigation treatment. Deficit irrigation represented an average seasonal water savings of 119 mm compared with full irrigation. For the same location, Hergert et al. (1993) found that during a field experiment conducted from 1983 to 1991, an allocation of 150 mm of irrigation, which represented 53% of the water applied to a full irrigation treatment, produced an average soybean grain yield of 88% of that obtained using full irrigation.

When water is limited, it is important to maximize storage of rainfall in the soil profile and to use techniques to conserve soil water, such as conservation tillage, terraces (where needed), improved residue management, and effective weed control programs. It is also important to select crops and crop rotations that conserve water, and use irrigation water efficiently by minimizing losses that do not contribute to crop

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yield, such as runoff, deep percolation, wind drift, and soil evaporation. These losses can be minimized by using efficient irrigation systems, and by improving irrigation system management and irrigation scheduling. It is also important to know if there is a time during the growing season when application of a limited amount of water would make the largest contribution to the final marketable yield, so that irrigations can be timed accordingly. The question of whether water stress timing has an impact on crop yield, and the magnitude of the impact, has been the subject of research for decades. For instance, Jensen (1968) proposed that limiting soil moisture during a growth stage would reduce water use during that stage, which would have an effect on marketable crop yield. For a determinate flowering crop, Jensen proposed that the effect of water stress at different stages on crop yield could be explained as:

$$\frac{Y}{Y_o} = \prod_{i=1}^{n} \left(\frac{W_{et}}{W_{oc}} \right)_i^{\lambda_i} \qquad (1)$$

where Y = actual yield (kg ha^{-1}), Y_o = yield when soil water is not limiting (kg ha^{-1}), W_{et} = actual water use (mm), W_{oc} = water use when soil water is not limiting (mm), $(W_{et}/W_{oc})_i$ = relative total evapotranspiration during a given stage of physiological development, λ_i = relative sensitivity of the crop to water stress during the stage of growth *i* (unitless), *n* = number of growth stages, and Π means that the right side of the equation is a product instead of a sum. Jensen, however, only provided λ_i values for grain sorghum. Based on this procedure, Nairizi and Rydzewski (1977) derived λ_i values, which they called the "sensitivity index," and created λ_i curves from planting to harvest for different crops. They found that the magnitude and time of occurrence of peak sensitivity to water stress varied considerably for different crops. For soybean, they found that the sensitivity index curve could be defined by a fifth-degree polynomial function of percent duration of growing season (DGS). The index was low until approximately 50% of DGS and then rapidly increased, peaking at about 87% of DGS, and then dropped rapidly as the crop matured. Several later studies in Nebraska used equation 1 to derive λ_i values, which were called "crop-specific drought index," for several crops including corn (Meyer et al. 1993), sorghum (Paes de Camargo and Hubbard, 1999), and wheat (Xu, 1996).

Similarly, Doorenbos and Kassam (1979) proposed that the effect of water stress on yield could be quantified as:

$$(1 - Y_a/Y_m) = ky(1 - ET_a/ET_m) \qquad (2)$$

where Y_a = actual yield (kg ha^{-1}), Y_m = maximum yield (kg ha^{-1}), ET_a = actual evapotranspiration (mm), ET_m = maximum evapotranspiration (mm), and *ky* = empirical yield response factor that varies depending on the growth stage when water stress occurs (unitless). For soybean, they reported *ky* values of 0.2, 0.8, 1.0 for the vegetative, flowering, and yield formation stages, respectively, indicating that yield was more affected by water stress during the yield formation stage than at any other time. This model suggests that if water is limited, the irrigator should time irrigation to minimize stress during the most sensitive stages.

Other studies supporting the philosophy that stress timing has an impact on soybean yield include that of Sionit and Kramer (1977), who water-stressed soybean at different stages of growth in a controlled environment. They found that soybean grain yield was reduced most by stress during early grain formation and pod filling. However, they did not evaluate the relationship between yield and total seasonal water use. Ashley and Ethridge (1978) also studied the effect of starting irrigation at different stages of growth for soybean and found that the effect of stressing the crop at a given stage varied from season to season. They did not relate yield to total seasonal evapotranspiration either. Korte et al. (1983) and Kadhem et al. (1985) studied the effects of irrigation timing on soybean development and yield in Nebraska. They found significant increases in plant height, nodes per plant, and lodging for indeterminate cultivars when irrigation was applied during the vegetative stage. A single irrigation (gravity irrigation) to refill the crop root zone depth to field capacity was most effective when applied during the period from mid-pod elongation to just before seed enlargement. Korte et al. (1983) found that irrigation timing affected the number of seeds per plant and the 100-seed weight. These studies, however, were conducted in eastern Nebraska, which has a much more humid climate than west-central Nebraska, and there is usually a full moisture profile in the crop root zone at the beginning of the growing season. Therefore, delaying irrigation until the reproductive stage in this environment does not necessarily mean that the crop was under water stress early in the season. These studies did not relate yield to actual water availability and water use. They also applied irrigation at a given stage, regardless of crop needs.

Evans et al. (1990) determined the susceptibility of soybean to wet stress at different growth stages using the following model:

$$SDI = \sum_{i=1}^{n} \left(SD_i \left[\frac{CS_i}{\sum_{i=1}^{n} CS_i} \right] \right) \qquad (3)$$

where SDI = stress-day-index (unitless), SD_i = stress days factor for period *i*, and CS_i = crop susceptibility factor for period *i* (unitless). During a five-year study, Evans et al. (1990) found that soybean was more susceptible to wet stress during pod development and pod fill. They also found that these results were similar to those previously reported for drought stress by Sudar et al. (1979), indicating that this model could also be adapted to quantify crop susceptibility to drought stress conditions.

Other studies, however, suggest that the total amount of seasonal crop evapotranspiration or transpiration is what determines crop yield, and these researchers have paid less attention to stress timing. For instance, Hanks (1974) proposed that crop dry matter yield could be related to water by a function that did not depend on the stage of growth at which stress occurred:

$$Y/Y_p = T/T_p \qquad (4)$$

where Y = actual dry matter yield (kg ha^{-1}), Y_p = potential dry matter yield (kg ha^{-1}), T = actual seasonal transpiration (mm), and T_p = potential seasonal transpiration (mm). It is important to notice that Hanks referred to dry matter yield, while others have referred to grain or marketable yield.

Klocke et al. (1989) evaluated the feasibility of starting irrigation at different growth stages at four locations in Nebraska, from sub-humid eastern locations to the semi-arid west-central areas of the state. They found that for the semi-arid region, the best irrigation strategy was to use full-season irrigation to meet crop evapotranspiration. For the sub-humid areas, they found that irrigation could be delayed until flowering in deep, medium to fine-textured soils if there was a full soil water profile at planting. They found that soybean relative yields for all four locations were related to seasonal crop evapotranspiration by a quadratic function ($R^2 = 0.75$) independent of stress timing:

$$Y = a + b(ET) + c(ET^2) \tag{5}$$

where Y = relative yield (%), ET = seasonal evapotranspiration (mm), and *a*, *b*, and *c* are empirical coefficients. Schneekloth et al. (1991) related soybean grain yield to seasonal evapotranspiration by a linear function independent of stress timing:

$$Y = a(ET) + b \tag{6}$$

where Y = yield (kg ha^{-1}), ET = seasonal evapotranspiration (mm), *a* = slope, and *b* = intercept. The R^2 values for this relationship were 0.53, 0.14, and 0.60 during the three years of the study. A similar linear equation was used by Stone (2003) to relate seasonal evapotranspiration to crop yield for soybean. Irmak et al. (2002) also found a linear relationship ($R^2 \geq 0.48$) between plant-available soil water at different times during the reproductive period and yield of rainfed soybean.

The objectives of this study were: (1) to quantify the grain yield response of soybean to deficit irrigation, and (2) to determine which of several water variables correlated best to soybean grain yield under deficit irrigation conditions.

Methods

Site Description

Field data for this study were collected in 2002 at Curtis (40.6° N, 100.5° W, elevation = 784 m), and in 2003 and 2004 at North Platte, Nebraska (41.1° N, 100.8° W, elevation = 861 m). At each site, the experiment was conducted using a randomized complete block design with four replications. Nine irrigation treatments were studied in 2002 and 2003, and eight in 2004. Each year, treatments included a dryland treatment, which received no irrigation. Irrigation treatments consisted of different irrigation timing and target root zone depletions under deficit irrigation conditions (table 1). None of the treatments received irrigation during the vegetative stage, which is a common practice in the area. Soybean growth stages and the number of days needed to reach each stage in Nebraska have been described by Martin (1997). Treatments were designed to create stress at different stages of crop development, and to create a range of seasonal available soil water that was wide enough to develop meaningful quantitative relationships between crop yield and seasonal water variables such as irrigation, rain + irrigation, total water, evapotranspiration, and evaporation, among others.

In 2002, the field experiment at Curtis was conducted at the Nebraska College of Technical Agriculture, University of Nebraska-Lincoln, in a field previously planted to hybrid sorghum-sudan that was harvested for hay. The soil at Curtis is a Hall silt loam, with an average water content at field capacity of 0.32 m^3 m^{-3} and permanent wilting point of 0.11 m^3 m^{-3}. The soybean variety Pioneer 9294 RR was planted in 2002 at 0.76 m row spacing and a depth of approximately 2.5 cm. In 2002, soybean was planted on May 20 and harvested on September 27. The center two rows of each plot were harvested using a plot combine. Plot size at Curtis were 3 m wide by 9 m long, which accommodated four rows per plot.

Plots at Curtis were irrigated using a surface drip irrigation system, which was designed and managed to wet most of the soil surface to simulate a sprinkler-irrigated field. One drip lateral was installed next to each crop row. Drip laterals were 17 mil Typhoon 630 thinwall dripperlines (Netafim USA, Fresno, Cal.) with emitters spaced every 457 mm. The nominal flow rate of the emitters was 3.8 L h^{-1} at a nominal pressure of 69 kPa. Water for this system was pumped from the Ogallala aquifer and was filtered using a 51 mm diameter (120 mesh) disc filter (Netafim USA, Fresno, Cal.). After the filter, the mainline was divided into four sub-mains. Each sub-main had a flowmeter and a pressure regulator. Each sub-main was further divided into two branches with a manual valve on each. Each branch irrigated one treatment (four plots). This arrangement allowed two treatments to share the same flow meter and pressure regulator. PVC pipe was used for the sub-main, and laterals were connected to 25 mm diameter polyethylene tubing. The laterals for all four replications of the same treatment were connected to the same branch. Pressure regulators were adjusted to apply water just fast enough to wet the soil surface without generating runoff.

In 2003 and 2004, the field experiments at North Platte were conducted at the University of Nebraska-Lincoln West Central Research and Extension Center. The soil at North

Table 1. Irrigation treatments applied to soybean at Curtis (2002) and North Platte (2003 and 2004).

Treatment	Irrigation Strategy	Target Root Zone Depletion
T1	Start irrigation at beginning bloom (R1[a])	35%
T2	Start irrigation at beginning bloom (R1)	50%
T3	Start irrigation at beginning bloom (R1), no irrigation at pod development (R3 and R4)	35%
T4	Start irrigation at beginning bloom (R1), no irrigation at pod development (R3 and R4)	50%
T5	Start irrigation at late bloom (R2.5)	35%
T6	Start irrigation at late bloom (R2.5)	50%
T7	Start irrigation at pod development (R3.5)	35%
T8	Start irrigation at pod development (R3.5) in 2002 and 2003, no irrigation (dryland) in 2004	50%
T9	No irrigation (dryland) in 2002 and 2003, not included in 2004	−−

[a] Indicates soybean growth stage (Martin, 1997).

Platte is a Cozad silt loam (Fluventic Haplustolls) with water content at field capacity of 0.29 $m^3\ m^{-3}$ and a permanent wilting point of 0.11 $m^3\ m^{-3}$ (Klocke et al. 1999). The soybean variety Renze 2600 RR was planted at 0.76 m row spacing and a depth of approximately 2.5 cm. In 2003, soybean was planted on May 27 and harvested on October 8. In 2004, soybean was planted on May 21 and harvested on October 5. The center four rows of each plot were harvested using a plot combine. The soybean was irrigated using a solid-set sprinkler system, which was arranged in a 12.2 × 12.2 m grid. At each of the 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.

Water for the system was pumped from the Ogallala aquifer using an electric turbine pump with a capacity of 38 L s^{-1} at 480 kPa of pressure. The mainline at the pumping station was instrumented with two pressure gauges, two flowmeters, a pressure relief valve, a chemigation check valve, and "high" and "low" pressure switches. The flowmeters measured both the instantaneous flow rate and the cumulative volume of water pumped. The irrigation system was turned on and off using an automatic control panel hard-wired to electric valves installed at each plot. Each electric valve controlled the four sprinklers of each plot, which were connected to the same water supply line. This design allowed independent irrigation of individual plots and re-randomization of the plots from year to year to accommodate a particular statistical design. The control panel was also connected to a manual relay panel. This combination allowed both manual and automatic operation of the irrigation system.

Irrigation Scheduling

Irrigation scheduling at both sites was performed with a scheduling spreadsheet that used the calculated daily evapotranspiration (ET) as the input to estimate daily average soil water content in the crop root zone. The spreadsheet estimated daily ET using the single crop coefficient (K_c) approach presented in FAO-56 (Allen et al. 1998). When actual soil water measurements were available, it was possible to adjust the spreadsheet calculations to reflect the actual measurements. Soil water measurements were made approximately every two weeks during the growing season using the neutron scattering method. Soil water readings were taken from 50 mm diameter aluminum access tubes installed at the center of two of the four replications of each treatment. Readings were taken at 0.3 m depth increments to a depth of 1.8 m. Weather data were obtained from an automatic weather station located at each research site, within a distance of 1.5 km. These two weather stations were part of the High Plains Regional Climate Center (HPRCC) weather network. Daily weather data were downloaded from the HPRCC web site (www.hprcc.unl.edu/home.html) and included daily maximum and minimum air temperature, relative humidity, wind speed, rainfall, and solar radiation. Rainfall was also measured at each research site using manual rain gauges.

Data Analyses

The statistical analyses of yield data, which included analysis of variance (ANOVA) and separation of means by the Duncan's new multiple range method, were conducted using the SAS System for Windows statistical software (SAS Institute, Inc., Cary, N.C.). Regression analyses were conducted using Microsoft Excel. A computer program was written in Microsoft Visual Basic to model the daily soil water status and to calculate all of the water variables that were then related to crop yield. Inputs to the program included daily weather data, rainfall, irrigation, soil water 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 rooting depth and the water balance in the crop root zone were calculated on a daily basis.

Grass-reference evapotranspiration (ET_o) was calculated using the procedure presented in FAO-56 (Allen et al. 1998; Wright, 1982). Since this is a long procedure, the details of all computations will not be repeated here and the reader is referred to the original sources for details. According to this procedure, crop evapotranspiration is obtained as the product of the evapotranspiration of a reference crop (ET_o) (grass) and a crop coefficient (K_c). ET_o is calculated using the weather data as the 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 evaporation (E) and transpiration (T). This procedure also linearly reduces crop evapotranspiration when the available soil water in the crop root zone is less than 50%, which is used to quantify the effect of water stress on crop water use. The dual crop coefficient procedure also accounts for the sharp increase of the evaporation component due to a wet soil surface following a rain or irrigation event.

This procedure permitted calculation of the daily crop evapotranspiration and transpiration when soil water is not limiting (ET_w and T_w), and the daily actual crop evapotranspiration, transpiration, and evaporation (ET_d, T_d, and E). Cumulative and seasonal ET_d, ET_w, T_w, T_d, and E values were calculated by adding the daily values. From the seasonal values, the seasonal ET_d/ET_w and T_d/T_w ratios were calculated for each treatment. It was expected that the seasonal ET_d/ET_w and T_d/T_w ratios would be related to the crop yield. Additionally, in the FAO-56 procedure, an equation was presented to estimate p, the fraction of total available soil water in the root zone that can be depleted from the root zone before moisture stress (reduction in ET_d) occurs. This equation estimates a variable p (p_{calc}) as a function of daily ET_w, if ET_w is greater or less than 5 mm, as:

$$p_{calc} = p_{table} + 0.04(5 - ET_w) \qquad (7)$$

where p_{table} = p value taken from table 22 in FAO-56, ET_w is in mm day^{-1}, and $0.1 \leq p_{calc} \leq 0.8$. This equation suggests that if ET_w is less than 5 mm on a given day, it is easier for the crop to sustain ET_w rates, and therefore higher soil water depletion levels could be allowed without yield loss, as previously proposed by Doorenbos and Kassam (1979). This differs from the common procedure of using a fixed p value for a given crop for the entire growing season. In this study, the daily p_{calc} values were calculated, which were taken as the theoretical optimum depletion value for a given day. In addition, a daily actual p (p_{actual}) was calculated as:

$$p_{actual} = D/TAW \quad (8)$$

$$TAW = 1000(\theta_{FC} - \theta_{PWP})Z_r \quad (9)$$

where D = soil water depletion in the crop root zone (mm), θ_{FC} = soil water content at field capacity ($m^3\ m^{-3}$), θ_{PWP} = soil water content at permanent wilting point ($m^3\ m^{-3}$), Z_r = crop rooting depth (m), and TAW = total available soil water in the crop root zone (mm).

In this study, it was expected that p_{diff} (= $p_{actual} - p_{calc}$) accumulated for the entire season (seasonal p_{diff}) only for days when $p_{diff} > 0$ would be a good indicator of the level of crop stress and would, therefore, relate to crop yield. The greater the seasonal p_{diff} for a given treatment, the more stress. Seasonal p_{diff} was therefore calculated for each treatment.

The effect of the different irrigation treatments on crop yield was also evaluated by calculating the crop water productivity (CWP) (Zwart and Bastiaanssen, 2004) as:

$$CWP = Y_a/(\text{seasonal } ET_d) \quad (10)$$

where Y_a = crop yield (kg ha^{-1}), seasonal ET_d is in mm, and CWP is in kg $ha^{-1}\ mm^{-1}$. The effects of several other water variables on soybean grain yields were also evaluated. These variables included seasonal ET_d, T_d, E, irrigation applied, irrigation + rainfall, and total water available to the crop during the growing season.

Results and Discussion

Weather Conditions

Average weather conditions at Curtis and North Platte during the months of June to September from 2002 to 2004 are shown in table 2. The first two years of the study (2002 and 2003) were warmer and drier, while the last year (2004) was cooler and wetter than normal for the area. The 2002 season at Curtis had the highest air temperatures, the lowest air relative humidities, and the highest wind speeds, which resulted in the largest reference evapotranspiration (ET_o) values during the study. Average daily ET_o for Curtis in 2002 was approximately 29% and 39% higher than for North Platte during 2003 and 2004. For North Platte, the average air temperatures during the 2004 growing season were 1.5°C cooler than 2003, which resulted in the lowest ET_o values for the entire study period.

Rainfall

A total of 15, 20, and 31 individual rainfall events occurred during the growing season in 2002 at Curtis and in 2003 and 2004 at North Platte (fig. 1). In-season rainfall supplied approximately 19% and 21% of crop water requirements in 2002 and 2003, but accounted for approximately 56% in 2004. Except for a 56 mm rainfall event that occurred on June 15, 2004, all other individual rainfall events were less than 30 mm, providing little opportunity for rainfall runoff.

Irrigation

During the first two years of the experiment (2002 and 2003), the irrigation strategies described in table 1 were closely followed. In 2004, however, a broken water supply mainline when the first irrigation started at beginning bloom (in mid-July) caused a delay of irrigation of about a week, and rainfalls in mid- to late July further delayed irrigation until early August. By that time, soybean was already in the beginning seed (R5) stage, and irrigations were applied to create different levels of stress among treatments late in the growing season. During the three years of the study, the beginning bloom (R1) stage started in mid-July (July 9 in 2002, and July 13 in 2003 and 2004), when the soybean plants were approximately 0.38 m tall, which triggered the start of irrigation for treatments T1 to T4. The late bloom stage (R2.5) was reached in late July (July 20 in 2002 and July 29 in 2003), which marked the start of irrigation for the T5 and T6 treatments. The pod development stage (R3.5) started in late July in 2002 (July 26) and in early August (August 8) in 2003, which indicated the start of irrigation for treatments T7 and T8. Amounts and timing of individual irrigation events, seasonal irrigation totals, and percents of seasonal ET_w

Table 2. 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 months of June to September at Curtis (2002) and North Platte (2003 and 2004).

Site	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})
Curtis 2002	June	32.5	16.7	24.6	24.9	47.3	4.0	7.5
	July	35.1	18.1	26.6	27.4	45.1	3.4	7.8
	August	31.9	16.6	24.3	21.0	54.0	3.6	6.1
	September	29.9	14.8	22.3	18.6	54.7	3.6	5.4
	Average	32.3	16.5	24.4	23.0	50.3	3.6	6.7
North Platte 2003	June	26.5	11.9	19.2	22.7	71.5	2.3	4.5
	July	33.6	16.3	25.0	24.2	59.3	2.5	6.1
	August	31.9	15.7	23.8	22.4	59.1	2.5	5.5
	September	27.5	9.6	18.6	19.5	56.2	2.6	4.4
	Average	30.3	14.0	22.1	22.6	62.2	2.5	5.2
North Platte 2004	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
	August	27.9	11.8	19.9	21.0	65.9	1.9	4.2
	September	30.9	12.9	21.9	20.5	50.1	3.1	5.5
	Average	28.7	12.6	20.6	21.5	62.4	2.4	4.8

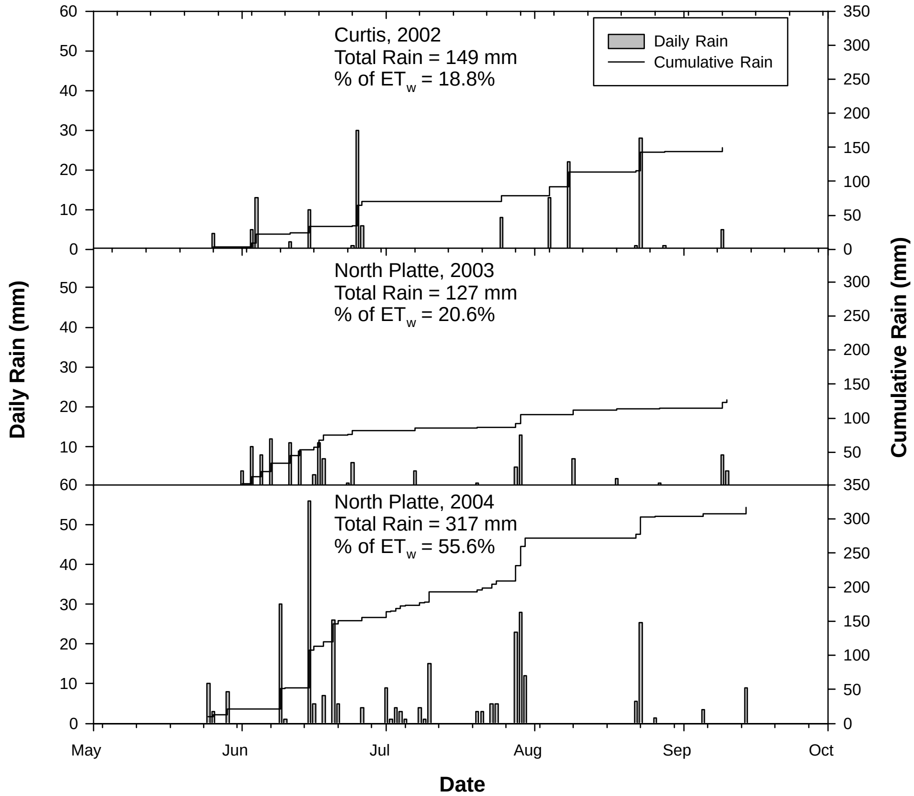

Figure 1. Daily and cumulative rain during the soybean growing season at Curtis (2002) and North Platte (2003 and 2004). The % of ET_w is the percent of seasonal crop evapotranspiration when soil water is not limiting that was supplied by in-season rainfall.

supplied by irrigation, for each treatment during the three seasons, are given in table 3. In 2002 at Curtis, irrigation amounts for the irrigated treatments ranged from 143 to 315 mm, representing between 18% and 40% of ET_w. In 2003 at North Platte, irrigated treatments received between 147 and 255 mm of irrigation, accounting for 24% to 41% of ET_w. In 2004, irrigations ranged from 19 to 162 mm, supplying between 3% and 28% of ET_w.

Table 3. Seasonal irrigation (mm) applied to soybean at Curtis (2002) and North Platte (2003 and 2004) for each irrigation treatment (T1 to T9).

Site	Date	T1	T2	T3	T4	T5	T6	T7	T8	T9[a]
Curtis 2002	13 July	70.6	70.6	67.3	67.3	--	--	--	--	--
	19 July	23.6	23.6	--	--	--	--	--	--	--
	20 July	30.0	30.0	29.2	29.2	51.6	51.6	--	--	--
	26 July	16.8	16.8	--	--	28.4	28.4	64.8	64.8	--
	5 August	52.3	26.2	--	--	46.5	31.8	48.0	31.8	--
	10 August	32.0	32.0	32.3	32.3	31.2	31.2	31.5	31.5	--
	14 August	36.3	36.3	33.0	–	--	--	--	--	--
	22 August	53.1	13.2	58.4	27.9	38.6	38.6	32.5	15.0	--
	Total	314.7	248.7	220.2	156.7	196.3	181.6	176.8	143.0	0.0
	% of ET_w[b]	40	31	28	20	25	23	22	18	0
North Platte 2003	14 July	28.2	28.2	28.2	28.2	--	--	--	--	--[a]
	18 July	33.8	24.6	24.6	24.6	--	--	--	--	--
	22 July	35.6	--	--	--	--	--	--	--	--
	26 July	23.6	--	23.6	23.6	--	--	--	--	--
	29 July	35.6	--	35.6	35.6	--	--	--	--	--
	31 July	--	--	--	--	52.1	52.1	--	--	--
	3 August	--	44.7	--	--	--	--	--	--	--
	9 August	--	--	--	--	36.3	--	36.3	36.3	--
	13 August	11.9	--	11.9	11.9	11.9	--	28.4	28.4	--
	14 August	--	--	16.3		16.3	--	34.3	16.3	--
	18 August	--	--	35.1	35.1	--	35.1	35.1	--	--
	19 August	--	--	40.9	40.9	--	40.9	40.9	--	--
	20 August	44.2	--	--	--	--	44.2	--	44.2	--
	26 August	29.7	29.76	15.7	--	45.5	--	15.7	--	--
	2 September	--	21.6	--	21.6	21.6	21.6	--	21.6	--
	3 September	12.4	--	7.6	--	--	--	--	--	--

Table 3 (cont). Seasonal irrigation (mm) applied to soybean at Curtis (2002) and North Platte (2003 and 2004) for each irrigation treatment (T1 to T9).

Site	Date	T1	T2	T3	T4	T5	T6	T7	T8	T9[a]
	Total	255.0	148.8	239.5	221.5	183.6	193.8	190.8	146.8	0.0
	% of ET_w	41	24	39	36	30	31	31	24	0
North Platte 2004	9 August	43.9	−−	−−	−−	−−	−−	−−	−−[a]	−−[c]
	12 August	7.9	16.0	16.0	16.0	16.0	−−	−−	−−	−−
	13 August	−−	13.2	13.2	13.2	13.2	−−	−−	−−	−−
	17 August	35.8	−−	−−	−−	−−	−−	−−	−−	−−
	20 August	−−	−−	−−	18.8	18.8	18.8	18.8	−−	−−
	23 August	26.7	−−	−−	−−	−−	−−	−−	−−	−−
	24 August	−−	27.7	27.7	27.7	27.7	−−	−−	−−	−−
	25 August	−−	−−	11.2	11.2	−−	−−	−−	−−	−−
	7 September	−−	11.2	11.2	−−	−−	11.2	−−	−−	−−
	8 September	47.8	−−	−−	−−	−−	−−	−−	−−	−−
	Total	162.1	68.1	79.2	86.9	75.7	30.0	18.8	−−	−−
	% of ET_w	28	12	14	15	13	5	3	0	−−

[a] Dryland treatment.
[b] % of ET_w is the percent of seasonal crop evapotranspiration when soil water is not limiting that was supplied by irrigation.
[c] Treatment T9 was not included in 2004.

Table 4. Seasonal calculated values of several water variables obtained for soybean at Curtis (2002) and North Platte (2003 and 2004) for each irrigation treatment (T1 to T9).

Site and Treatment	ET_d	ET_w	W_{all}	W_R_I	W_{soil}	E	T_w	T_d	D_p	ET_d/ET_w	p_{diff}	T_d/T_w	CWP
Curtis 2002													
T1	541	801	552	471	81	171	630	382	0	0.68	30.56	0.61	4.4
T2	496	801	486	405	81	171	630	337	0	0.62	36.05	0.54	3.7
T3	452	799	457	376	81	169	630	295	0	0.57	36.62	0.47	4.3
T4	407	796	394	313	81	167	630	251	0	0.51	41.52	0.40	3.9
T5	439	795	433	352	81	166	630	285	0	0.55	38.26	0.45	3.5
T6	426	795	419	338	81	166	630	272	0	0.54	39.32	0.43	4.2
T7	421	793	414	333	81	163	630	270	0	0.53	38.99	0.43	3.4
T8	395	793	380	299	81	163	630	243	0	0.50	41.75	0.39	3.4
T9	261	791	237	156	81	161	630	113	0	0.33	51.18	0.18	2.7
North Platte 2003													
T1	498	641	519	382	137	188	454	310	0	0.78	20.07	0.68	5.6
T2	410	637	417	266	151	183	454	227	10	0.64	28.06	0.50	6.0
T3	482	640	501	366	135	186	454	296	0	0.75	20.72	0.65	5.3
T4	473	636	490	348	142	183	454	290	0	0.74	21.43	0.64	5.9
T5	453	638	501	355	146	184	454	269	0	0.71	20.94	0.59	5.5
T6	404	632	420	267	153	178	454	226	10	0.64	26.52	0.50	4.3
T7	416	623	461	308	153	170	454	246	10	0.67	21.72	0.54	5.0
T8	391	635	411	274	137	181	454	210	0	0.62	28.26	0.46	4.7
T9	262	617	260	127	133	164	454	111	0	0.42	37.99	0.25	2.3
North Platte 2004													
T1	506	585	578	470	108	159	426	347	9	0.86	10.47	0.81	6.0
T2	458	578	485	346	140	152	426	306	39	0.79	15.82	0.72	5.9
T3	465	578	494	393	101	152	426	313	3	0.80	14.99	0.73	6.7
T4	468	572	501	398	104	146	426	322	6	0.82	13.71	0.76	6.4
T5	463	572	499	386	113	146	426	317	6	0.81	14.52	0.74	6.9
T6	430	576	445	335	110	150	426	280	12	0.75	18.93	0.66	7.4
T7	422	570	434	326	108	144	426	278	9	0.74	18.97	0.65	6.8
T8	388	569	413	317	97	143	426	246	0	0.68	22.49	0.58	6.5

ET_d = seasonal actual crop evapotranspiration (mm).
ET_w = seasonal crop evapotranspiration when soil water is not limiting (mm).
W_{all} = water available to the crop from all sources, including irrigation, rainfall and water already stored in the soil at crop emergence (mm).
W_R_I = rainfall plus irrigation water (mm).
W_{soil} = water stored in the soil profile at crop emergence, to a depth equal to the maximum root depth (mm).
E = actual seasonal evaporation (mm).
T_w = seasonal transpiration when soil water is not limiting.
T_d = seasonal actual transpiration (mm).
D_p = seasonal deep percolation (mm).
p_{diff} = daily positive difference between the actual and the theoretical fraction of total available soil water in the root zone that can be depleted before moisture stress occurs, accumulated for the entire season (unitless).
CWP = crop water productivity (kg ha^{-1} mm^{-1}).

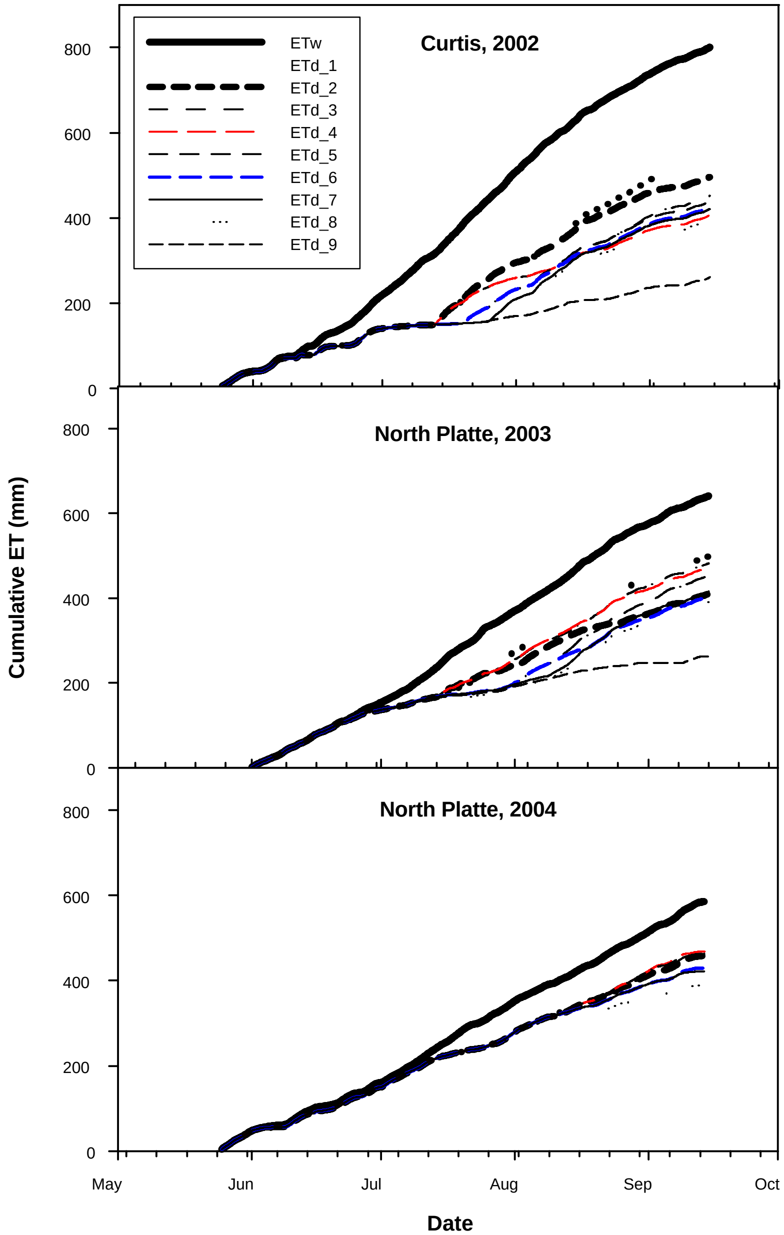

Figure 2. Cumulative soybean evapotranspiration (ET) for the different irrigation treatments at Curtis (2002) and North Platte (2003 and 2004). ET_w is the crop evapotranspiration when soil water is not limiting, and ET_d_1 to ET_d_9 is the actual crop evapotranspiration for treatments T1 to T9.

Crop Evapotranspiration, Evaporation, and Transpiration

The calculated seasonal ET_w and ET_d values for all treatments and seasons are given in table 4. Cumulative values of ET_w for each season and ET_d for each treatment from emergence to maturity are shown in fig. 2. The seasonal ET_w varied from season to season and among treatments within the same season. Small variations in seasonal ET_w among treatments for the same site and season were mainly due to differences in irrigation frequency, which affected the evaporation component of ET_w. Variations among seasons were mainly the result of changes in weather conditions. The highest seasonal ET_w value during the study occurred at Curtis during 2002, which was 801 mm. The lowest seasonal ET_w value occurred at North Platte during 2004, with a maximum of 585 mm. This is a significant difference in ET_w of 216 mm for the same crop between the two site years. The seasonal ET_w values for North Platte were higher than the 500-520 mm previously reported by Klocke et al. (1989) for soybean for the same location. Differences are possibly due to season-to-season variations and to the use of different methodologies to determine ET_w.

Seasonal ET_d under the deficit irrigation conditions of this study varied among treatments and seasons depending on the total water available to the crop and prevailing weather conditions (table 4 and fig. 2). For all seasons, treatment T1 always had the highest ET_d, and the dryland treatment (T9 in 2002 and 2003, and T8 in 2004) had the lowest. Seasonal ET_d varied widely with treatment, from 261 to 541 mm in 2002, from 262 to 498 mm in 2003, and from 388 to 506 mm in 2004. Figure 2 shows that the cumulative ET_d for all treatments started departing from the cumulative ET_w in mid-June in 2002, in late June in 2003, and in early July in 2004. Once the early stress occurred, water inputs later in the

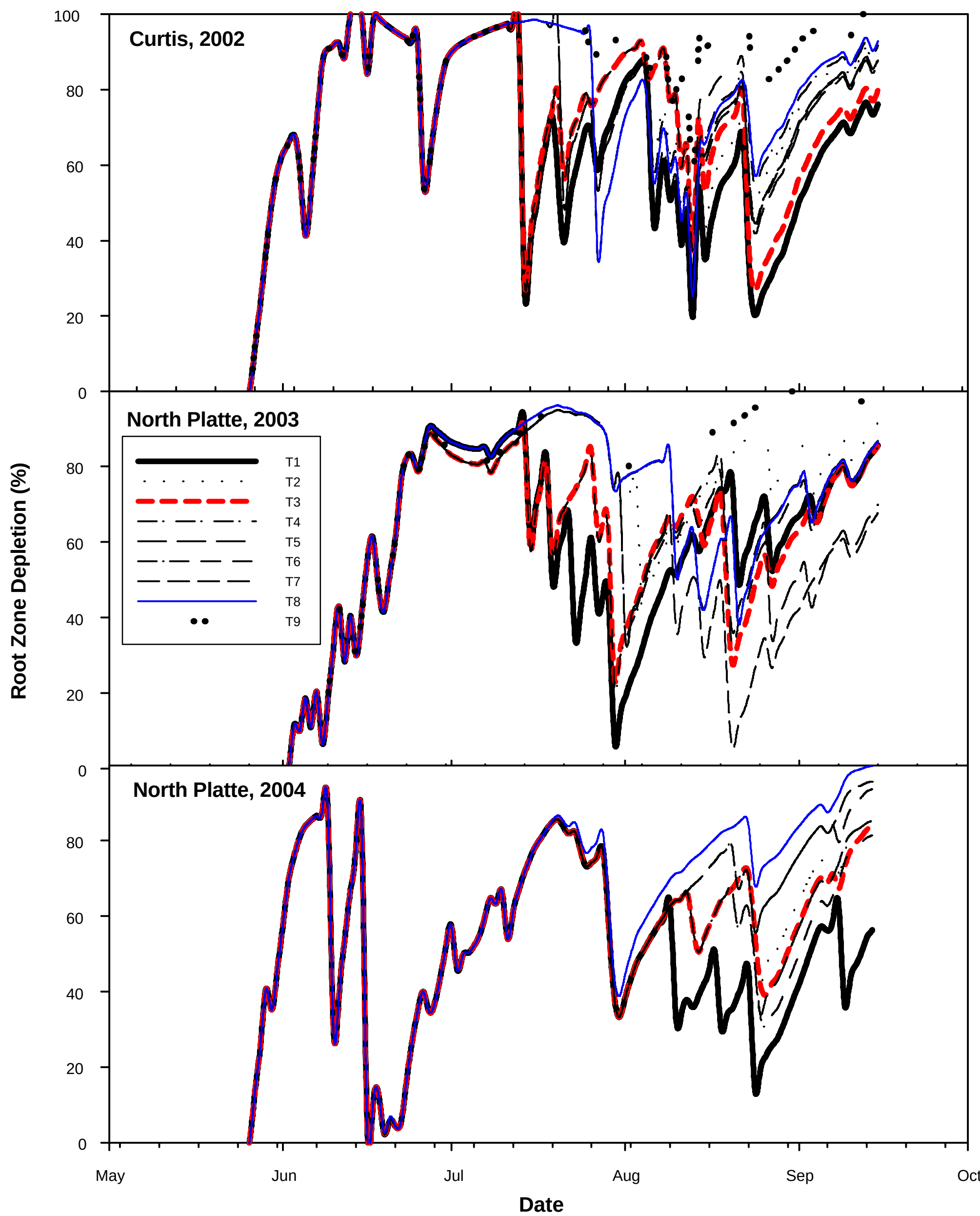

Figure 3. Root zone depletion during each growing season for the different irrigation treatments (T1 to T9) for soybean at Curtis and North Platte, Nebraska. Root zone depletion was calculated as a % of total available water (TAW) in the crop root zone.

season did not bring the cumulative ET_d levels up to match the cumulative ET_w levels for any of the treatments. In general, the largest differences between the cumulative ET_d and ET_w occurred in 2002, resulting in the lowest seasonal ET_d/ET_w and T_d/T_w ratios, and the largest p_{diff} (table 4). Figure 2 also shows that 2004 had the narrowest range of seasonal ET_d values among treatments, while 2002 had the widest range.

Seasonal evaporation (E) varied with season and treatment (table 4). For all seasons and treatments, E was a significant component of ET_d. In 2002, E varied with treatment between 32% and 62% of ET_d. The percentage increased from the wettest to the driest treatment, with an average of 40% for all treatments. In 2003, values ranged between 38% and 63%, with an average of 44%. For 2004, E varied between 31% and 37%, with an average of 33%.

For all treatments and seasons, most of the evaporation occurred early in the season, mostly in the month of June. At this time, evaporation was high compared with transpiration since effective canopy cover had not yet occurred, the soil surface was exposed to sunlight, and the surface was frequently wetted by rainfall. Seasonal transpiration when soil water was not limiting (T_w) was constant for all treatments within a season and varied with season, while the actual transpiration (T_d) varied with treatment and season (table 4). The T_w varied from 426 mm in 2004 to 630 mm in 2002 due to differences in weather conditions, while T_d varied depending on both the weather and the amount of water available to the crop.

Deep Percolation, Total Available Water, and Root Zone Depletion

During 2002 no water was lost to deep percolation from any of the treatments (table 4). In 2003, approximately 10 mm of water deep percolated from treatments T2, T6, and

Table 5. Soybean grain yield obtained at Curtis (2002) and North Platte (2003 and 2004) for each irrigation treatment.

	Grain Yield (kg ha^{-1})[a]		
Treatment	Curtis 2002 [(P>F) < 0.0001]	North Platte 2003 [(P>F) < 0.0001]	North Platte 2004 [(P>F) = 0.0872][b]
T1	2393.55 a	2774.84 a	3010.19 a
T2	1856.95 b	2479.87 ba	2698.04 a
T3	1954.63 b	2548.05 ba	3114.09 a
T4	1567.93 cd	2774.84 a	2981.79 a
T5	1558.04 cd	2500.62 ba	3214.70 a
T6	1784.36 cb	1720.94 c	3167.39 a
T7	1416.35 d	2063.35 bc	2850.92 a
T8	1344.44 d	1857.31 c	2535.32 a
T9	693.96 e	607.74 d	--

[a] For a given year, yields with the same letter are not significantly different.

[b] No significant yield differences due to irrigation were found in 2004.

T7, resulting from rainfall events occurring during the crop emergence period. In 2004, deep percolation occurred in all treatments except for the dryland treatment (T8). Deep percolation in 2004 was due to rainfall events occurring at emergence time and from mid- to late June. No deep percolation during the entire study resulted from irrigation.

Total water available to the crop included irrigation, in-season rainfall, and water stored in the crop root zone at planting time, minus in-season deep percolation. All of these water sources for all treatments and seasons are detailed in table 4. In 2002, water available to the crop including all sources (W_{all}) (table 4) ranged between 237 and 552 mm for the different treatments, enough to meet approximately 30% to 70% of seasonal ET_w, as indicated by the ET_d/ET_w ratios in table 4. In 2003, W_{all} was between 260 and 519 mm, supplying 42% to 78% of ET_w. In 2004, W_{all} ranged from 413 to 578 mm and supplied approximately 68% to 86% of ET_w (fig. 2). Water stored in the soil profile at planting time (W_{soil}) can be a significant source of water to meet seasonal ET_w. W_{soil} represented approximately 10%, 23%, and 19% of ET_w for 2002, 2003, and 2004, respectively. At Curtis, all treatments had the same W_{soil} since no irrigation treatments were applied at this location in the previous year and the research area was planted to the same crop. However, at

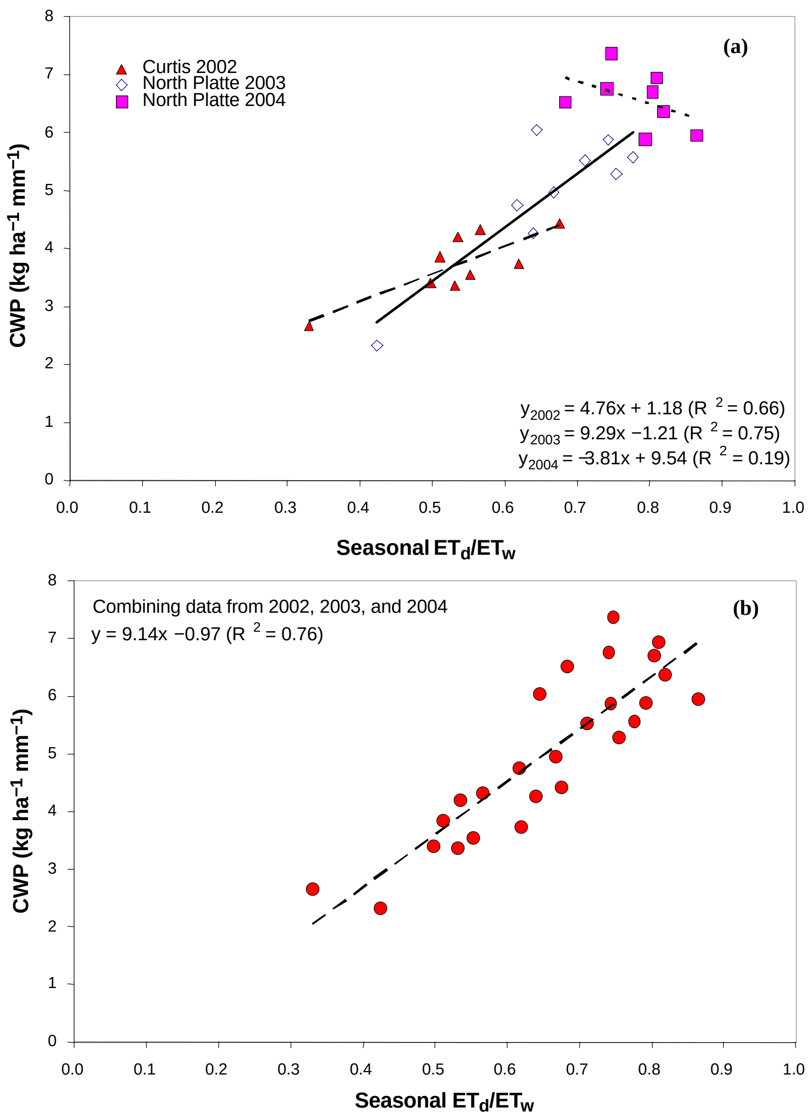

Figure 4. Relationships between the ratio of actual evapotranspiration and the evapotranspiration when soil water is not limiting (ET_d/ET_w) for (a) crop water productivity (CWP) for each season and (b) CWP combining data from all three seasons for soybean at Curtis and North Platte, Nebraska.

North Platte, irrigation treatments were applied to the research plots in the previous year, and therefore treatments had different W_{soil}. At North Platte, there was more W_{soil} in 2003 than in 2004 since plots in 2004 were deficit−irrigated in the previous year and received little precipitation during the off-season.

Daily percent root zone depletions (fig. 3) indicate that high depletion levels occurred early in the season during the three years of the study. Significant rainfall early in the season occurred only in 2004, which reduced depletion levels considerably. Irrigations that created differences in root zone depletion among treatments started in July during the drier 2002 and 2003 seasons, and in August in the wetter 2004 season. Although a high percent of root zone depletion was obtained in this study, especially early in the season, no visible signs of wilting were observed. Soybean is not as susceptible to showing visible signs of water stress, as are other crops like corn, and seems to respond to mild to moderate water stress by slowing down vegetative development instead of wilting.

Grain Yield and Crop Water Productivity

Soybean grain yields were highest during the wettest 2004 season and lowest during the driest 2002 season (table 5). Since all treatments were either dryland or deficit-irrigated, all yields were lower than the yield that would be expected for a fully-irrigated crop, suggesting that water was the main factor limiting yields. Statistically significant yield differences among treatments were only observed in the two driest seasons (2002 and 2003). There were no significant yield differences in 2004, which could be due to the narrow range of seasonal ET_d values among treatments obtained during that season (fig. 2).

Crop water productivity (CWP) obtained during the two driest seasons (2002 and 2003) increased linearly with seasonal ET_d/ET_w (fig. 4a). The relationship between CWP and seasonal ET_d/ET_w was poor in 2004 (R^2 = 0.19), which could have been due to the narrow range of ET_d/ET_w observed among treatments during that season. The pooled data (combining data for all three seasons) resulted in a good linear relationship between ET_d/ET_w and CWP (R^2 = 0.76)

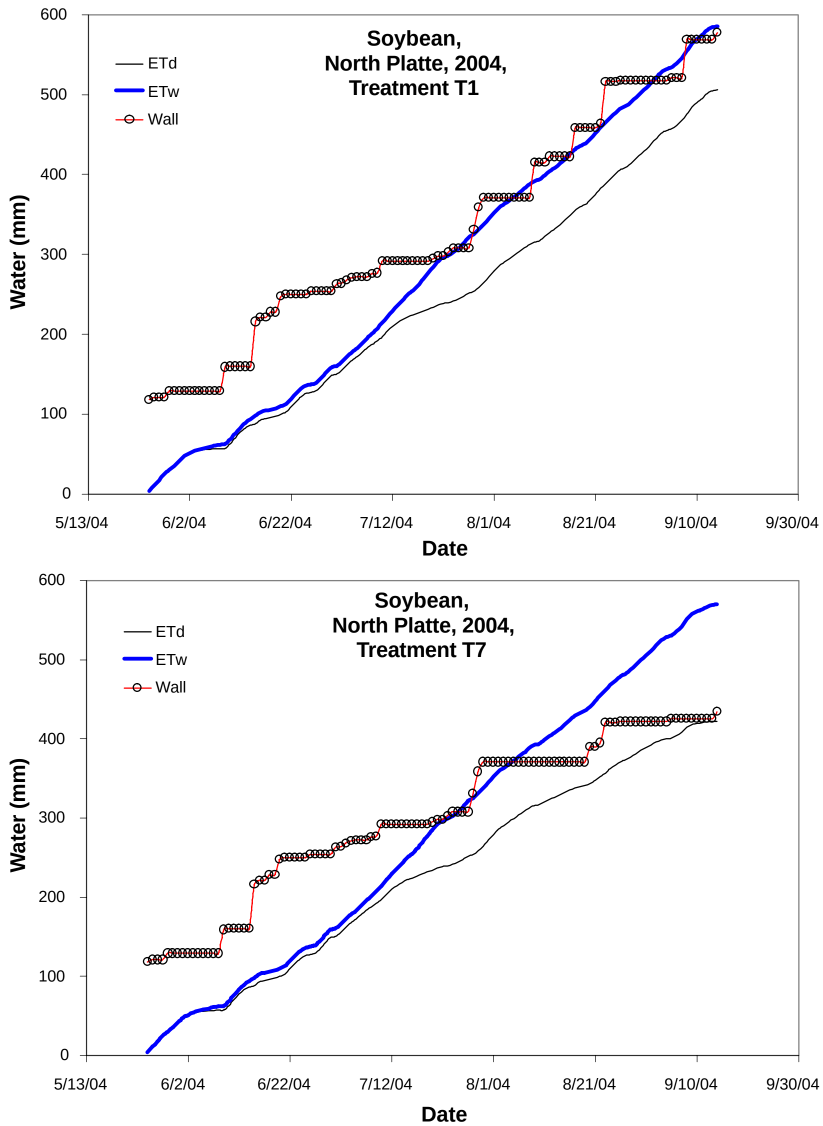

Figure 5. Cumulative values of actual evapotranspiration (ET_d), evapotranspiration when soil water is not limiting (ET_w), and total cumulative water available to the crop from all sources (W_{all}) for treatments T1 and T7 at North Platte, 2004.

(fig. 4b). Similarly, CWP correlated well to T_d/T_w ($R^2 = 0.72$) and correlated best to p_{diff} ($R^2 = 0.77$). The CWP, however, was poorly correlated to seasonal irrigation ($R^2 = 0.04$), W_{all} ($R^2 = 0.36$), and rain + irrigation ($R^2 = 0.22$). The poor correlation of CWP with the latter variables indicates that the crop was not able to utilize some of those water sources in yield production. This point is illustrated in figure 5, which shows cumulative values of ET_d, ET_w, and W_{all} for treatments T1 and T7 from emergence to crop maturity during the 2004 season. For treatment T7, the cumulative W_{all} was equal to the cumulative ET_d at the end of the season, indicating that the crop used all of the available soil water. However, for treatment T1, at the end of the season, the cumulative W_{all} was 72 mm higher than the cumulative ET_d. For this treatment, the crop was not able to use 72 mm of water because that water was applied too late in the season.

Figure 5 shows that for both treatments T1 and T7, differences between the cumulative ET_d and ET_w curves started in July. For treatment T1, the two lines are parallel to each other after that time, indicating that enough water was supplied to that treatment to keep up with ET_w after the initial stress. However, for that treatment, the cumulative ET_d was never able to equal the cumulative ET_w after the initial stress, and therefore the seasonal ET_d was less than the seasonal ET_w, even though the seasonal W_{all} was almost equal to the seasonal ET_w. For treatment T7, starting in July, the difference between cumulative ET_d and cumulative ET_w became larger as the season advanced, indicating that water inputs were not enough to keep up with ET_w. For treatment T7, the limited amount of water was applied early enough for the crop to be able to use it all in yield production before maturing. These results suggest that it is important to apply water early enough in the growing season for the crop to be able to use it.

After crop emergence, the cumulative ET_w increased almost linearly with time (fig. 5). Time after crop emergence can be expressed in several ways, such as days after emergence or cumulative growing degree days (GDD), or it can be normalized by calculating the fraction of season (F_s), which can be calculated as the ratio of the cumulative GDD since emergence and the GDD the crop needs to reach maturity (Stegman, 1988). Figure 6 shows a linear relationship between the cumulative ET_w and F_s for each of the three seasons, although the slope of the line was greater for Curtis than for North Platte. The linear function developed for a given location could potentially be used to estimate seasonal ET_w for in-season irrigation management, especially when $F_s \geq 0.5$.

Relationship Between Grain Yield and Several Water Variables

Figure 7a shows good linear relationship between grain yield and seasonal ET_d/ET_w during 2002 and 2003, with poor relationship in 2004. However, a very good linear relationship resulted when data for all seasons were combined (fig. 7b). Similarly, good relationships resulted when using the seasonal T_d/T_w ratio (fig. 8) instead of ET_d/ET_w. Both the seasonal T_d/T_w and ET_d/ET_w ratios were the most consistent variables related to soybean grain yield during the three seasons and two sites included in this study.

There was good linear relationship between p_{diff} and grain yield for 2002 and 2003, but not for 2004 (fig. 9a). Although data from North Platte during 2003 and 2004 could be fitted to the same line, a different line was obtained for Curtis in 2002. Therefore, the relationship between seasonal p_{diff} and grain yield was not consistent across the two sites. A good linear relationship was found between p_{diff} and ET_d/ET_w for each site, but the relationship varied from site to site (fig. 9b).

Figures 10 and 11 show the relationships between soybean grain yield and several other variables for all seasons. Variables included seasonal ET_d, total water (same as W_{all}), seasonal irrigation, seasonal irrigation + rain, seasonal T_d, and seasonal evaporation. All variables were poorly correlated to yield in 2004. For the drier 2002 and 2003 seasons, there was a good relationship between grain yield and all the variables. None of these variables, however, were consistent across seasons and sites, which is due to differences in seasonal ET_w between seasons and sites. It may be possible to obtain a unique function between yield and some of these

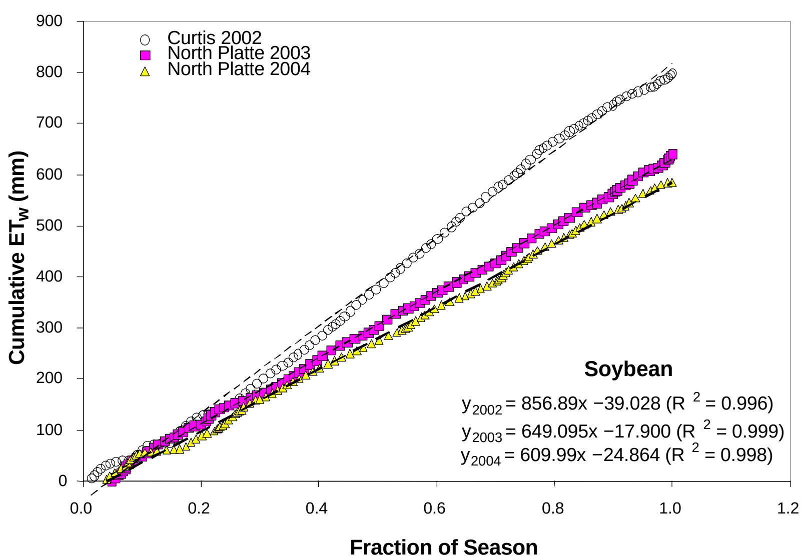

Figure 6. Relationship between cumulative crop evapotranspiration when soil water is not limiting (ET_w) and fraction of season (F_s) for soybean at Curtis and North Platte, Nebraska. The F_s value for a particular day was calculated as the ratio of the cumulative growing degree days (GDD) since emergence and the cumulative GDD at crop maturity. GGD values were calculated using a base temperature of 50°F (10°C) with no upper temperature limit (Stegman, 1988). The dashed line is the regression line.

variables by normalizing yields, as suggested by Klocke et al. (1989), who showed that the relative soybean yields (%) for four different locations in Nebraska were related to crop water use (same as ET_d) by a quadratic function (R^2 = 0.75). In this study, we could not normalize yields because we did not have a fully-irrigated treatment and, therefore, did not know the potential yield when soil water was not limited for each season.

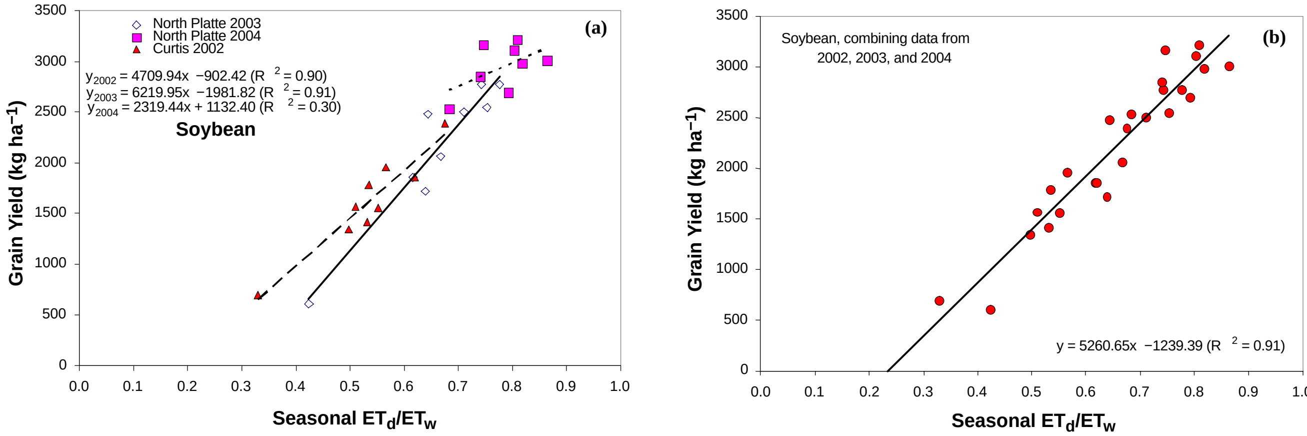

Figure 7. Relationships between the seasonal ratio of actual evapotranspiration and evapotranspiration when soil water is not limiting (ET_d/ET_w) and soybean grain yield: (a) linear regression for each season, and (b) linear regression combining all data obtained at Curtis and North Platte, Nebraska.

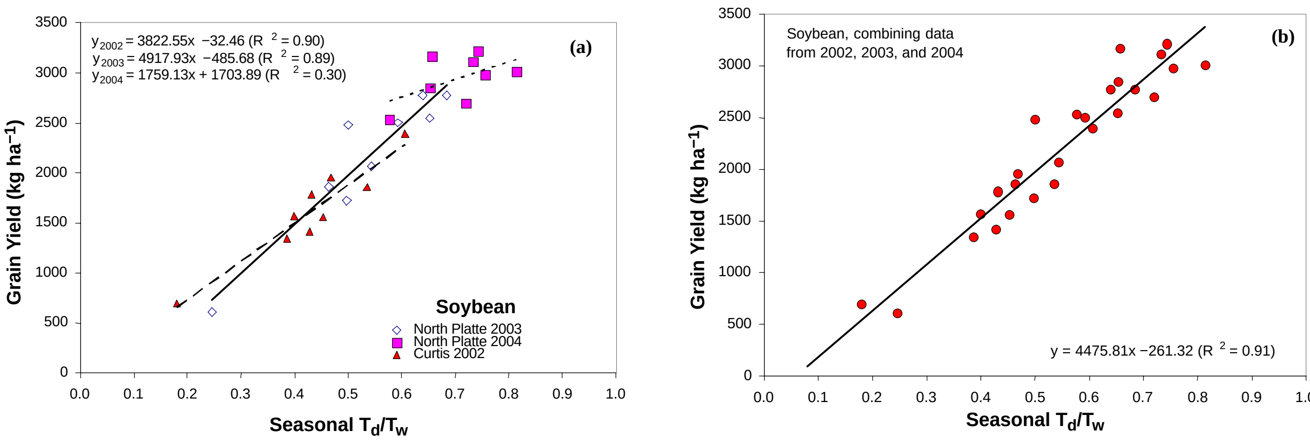

Figure 8. Relationships between the seasonal ratio of actual transpiration and transpiration when soil water was not limiting (T_d/T_w) and soybean grain yield: (a) linear regression for each season, and (b) linear regression combining all data obtained at Curtis and North Platte, Nebraska.

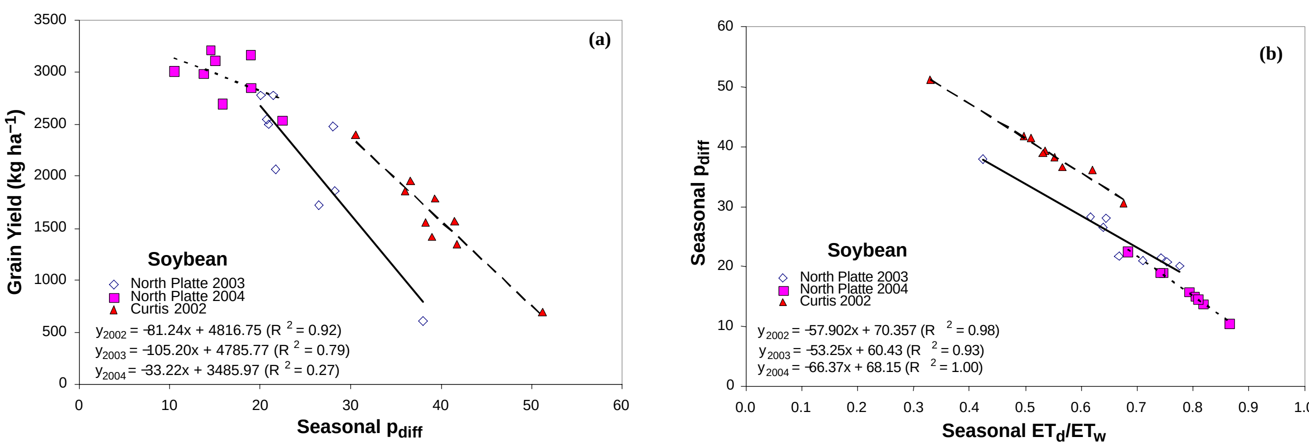

Figure 9. Relationships between (a) soybean grain yield and seasonal p_{diff}, and (b) the ratio of actual evapotranspiration and evapotranspiration when soil water is not limiting (ET_d/ET_w) and seasonal p_{diff}, for three growing seasons at Curtis and North Platte, Nebraska. Seasonal p_{diff} is the daily positive difference between the actual and the theoretical fraction of total available soil water in the root zone that can be depleted before moisture stress occurs, accumulated for the entire season.

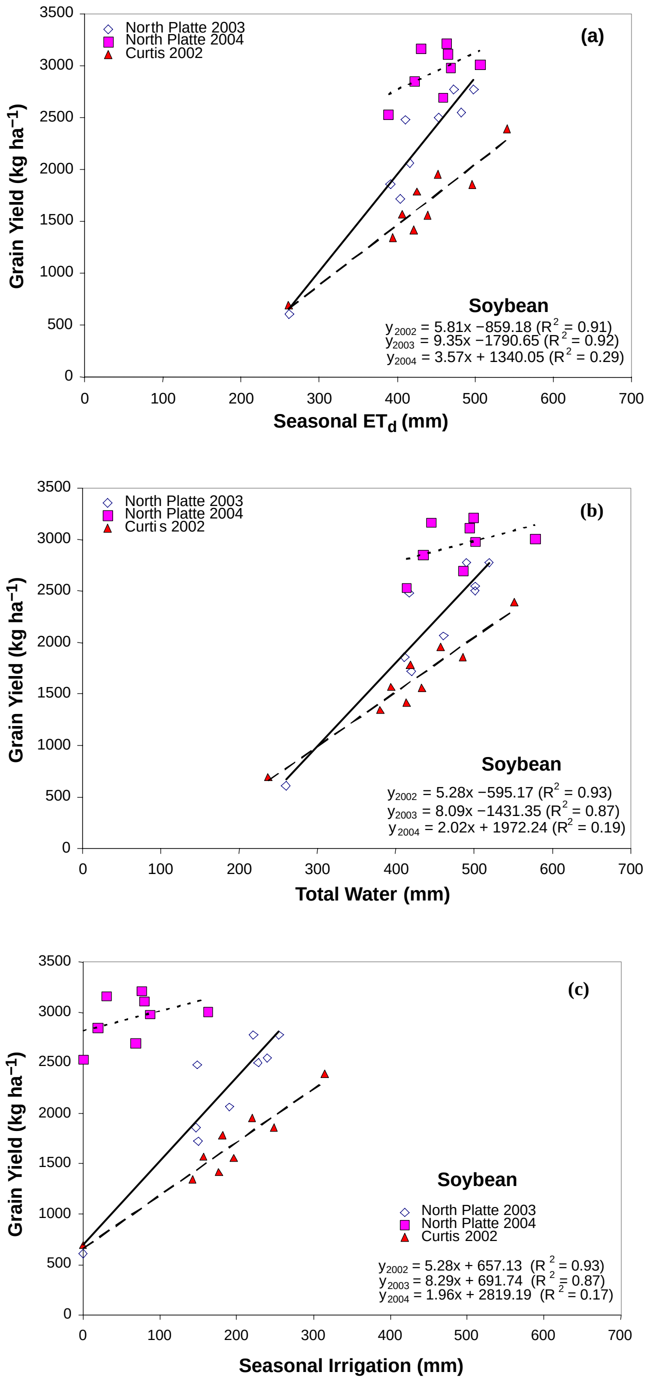

Figure 10. Relationships between soybean grain yield and (a) seasonal actual crop evapotranspiration (ET_d), (b) total water available to the crop during the growing season, and (c) seasonal irrigation at Curtis (2002) and North Platte (2003 and 2004), Nebraska.

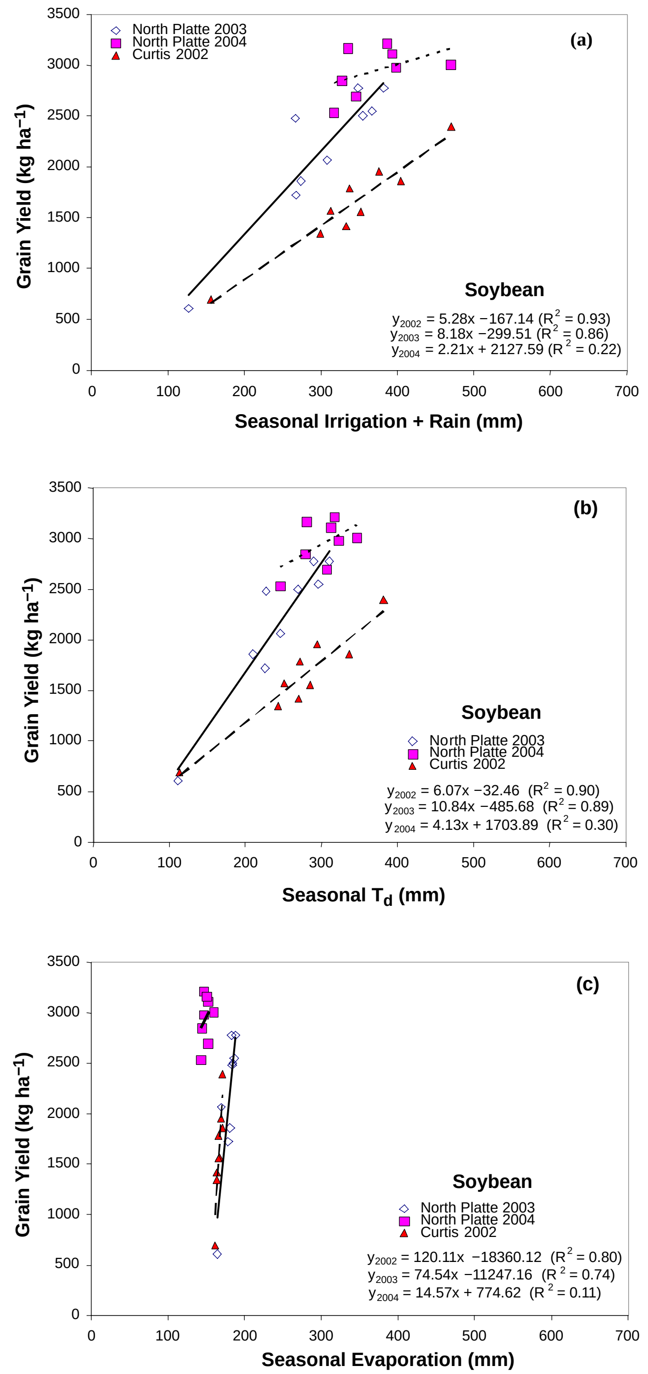

Figure 11. Relationships between soybean grain yield and (a) seasonal irrigation + rain, (b) seasonal actual crop transpiration (T_d), and (c) seasonal evaporation at Curtis (2002) and North Platte (2003 and 2004), Nebraska.

CONCLUSION

Soybean grain yields across years and sites were best related to the seasonal ratio of the actual crop evapotranspiration and the crop evapotranspiration when water was not limiting (ET_d/ET_w), and to the seasonal ratio of actual crop transpiration and crop transpiration when water was not limiting (T_d/T_w). Both of these seasonal ratios were linearly correlated to grain yield with $R^2 = 0.91$ when combining data for all seasons. Other variables such as seasonal ET_d, total water, seasonal irrigation, seasonal irrigation + rain, seasonal T_d, and seasonal E were linearly related to crop yield for each season, except for 2004, but were not consistent across seasons and sites. Normalizing yields could probably improve consistency for some of those variables, but this could not be tested in this study since we did not know the potential yield when soil water was not limited for each season. It is recommended to include a fully-irrigated treatment in future work so that the potential yield can be determined.

The crop water productivity (CWP) (yield per unit of seasonal ET_d) linearly increased with both seasonal ET_d/ET_w

(R^2 = 0.72) and T_d/T_w (R^2 = 0.72), but was best correlated to the cumulative seasonal difference between the actual and the theoretical fraction of total available soil water in the root zone that can be depleted before moisture stress occurs (seasonal p_{diff}) (R^2 = 0.77). Poor correlation was found between CWP and variables such as total irrigation, rain + irrigation, and total water. In this study, delaying irrigation until beginning bloom or later growth stages resulted in early stress, which decreased seasonal ET_d. The fact that seasonal ET_d was linearly related to crop yield for a given season then suggests that stress at any growth stage would reduce yield. Therefore, it is important not to delay irrigation at any stage to the point where seasonal ET_d is reduced, since once seasonal ET_d is reduced, there is no way to bring it back to match seasonal ET_w, and there is no way to recuperate yield that has already been lost by stress occurring earlier in the season.

The results obtained in this study suggest that the greater the value of ET_w when stress occurs, the greater the impact of water stress on soybean yield. This is because seasonal water variables such as ET_d, T_d, and ET_d/ET_w would be reduced most, which could explain some of the effects of stress timing on soybean yield that other researchers have reported. The results also indicate that the larger the amount of water that is available early enough in the growing season to contribute to increase seasonal ET_d, the higher the soybean yield. Therefore, in this study, the irrigation treatments that received more water during a given season and received that water early enough in the growing season for soybean to have time to use it, and before yield components were established, resulted in higher yield.

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