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Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate

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ABSTRACT

Quantifying the local crop response to irrigation is important for establishing adequate irrigation management strategies. This study evaluated the effect of irrigation applied with subsurface drip irrigation on field corn (*Zea mays* L.) evapotranspiration (ETc), yield, water use efficiencies (WUE = yield/ETc, and IWUE = yield/irrigation), and dry matter production in the semiarid climate of west central Nebraska. Eight treatments were imposed with irrigation amounts ranging from 53 to 356 mm in 2005 and from 22 to 226 mm in 2006. A soil water balance approach (based on FAO-56) was used to estimate daily soil water and ETc. Treatments resulted in seasonal ETc of 580–663 mm and 466–656 mm in 2005 and 2006, respectively. Yields among treatments differed by as much as 22% in 2005 and 52% in 2006. In both seasons, irrigation significantly affected yields, which increased with irrigation up to a point where irrigation became excessive. Distinct relationships were obtained each season. Yields increased linearly with seasonal ETc ($R^2 = 0.89$) and ETc/ETp ($R^2 = 0.87$) (ETp = ETc with no water stress). The yield response factor (ky), which indicates the relative reduction in yield to relative reduction in ETc, averaged 1.58 over the two seasons. WUE increased non-linearly with seasonal ETc and with yield. WUE was more sensitive to irrigation during the drier 2006 season, compared with 2005. Both seasons, IWUE decreased sharply with irrigation. Irrigation significantly affected dry matter production and partitioning into the different plant components (grain, cob, and stover). On average, the grain accounted for the majority of the above-ground plant dry mass (≈59%), followed by the stover (≈33%) and the cob (≈8%). The dry mass of the plant and that of each plant component tended to increase with seasonal ETc. The good relationships obtained in the study between crop performance indicators and seasonal ETc demonstrate that accurate estimates of ETc on a daily and seasonal basis can be valuable for making tactical in-season irrigation management decisions and for strategic irrigation planning and management.

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1. Introduction

Irrigation water supplies are decreasing in many areas of the US Great Plains due to extended drought periods, decline in groundwater levels, litigation among states related to surface water allocations, and diversion of water from irrigation to environmental and municipal uses (McGuire, 2004; McGuire and Fischer, 1999; Lingle and Franti, 1998). Water shortages have heightened the importance of water in agricultural production in the area and have triggered recent regulations affecting irrigation water use. Such regulations include installation of water meters on pumping stations, moratoriums on drilling new wells, and limitations in groundwater pumping to fixed multi-year water allocations. Under these conditions, it is important to know how much yield can be expected from a given water allocation for each alternative crop, which is especially important for field corn (*Zea mays* L.), the most important irrigated crop in the region.

In the semiarid environment of west central Nebraska, water allocations that result in crop water stress can have a significant impact on corn growth, development, and yield. Knowing how much yield can be expected from a given water allocation, however, is complicated by the fact that corn yield is affected not only by the amount of seasonal irrigation, but also by irrigation timing. Also, yield is affected by other sources of water available to the crop in addition to irrigation. These sources include water stored in the soil profile at crop emergence and effective rainfall occurring during the growing season. Many researchers have shown how corn grain yield can be affected by irrigation timing (Jurgens et al., 1978; NeSmith and Ritchie, 1992; Bryant et al., 1992; Jama and Ottman, 1993). Most of these studies show that corn yield is most affected by water stress when it occurs during the reproductive stages (tasselling, silking, pollination, or grain filling). In Nebraska, the reproductive growth stages coincide with the period of peak crop evapotranspitation (ETc) requirement, making stress during these stages even more significant.

Other studies have linked yields reduction to a reduction in ETc or transpiration, and some researchers have developed different yield versus ETc relationships for different growth stages (Jensen, 1968; Hanks, 1974; Nairizi and Rydzewski, 1977; Barrett and Skogerboe, 1978; Doorenbos and Kassam, 1979; Gilley et al., 1980; Schneekloth et al., 1991; Klocke et al., 2004). Payero et al. (2006b), however, showed that the reported yield versus ETc relationships for corn are not consistent and vary with location, which is likely due to differences in rainfall pattern, soil and crop characteristics, management practices, and weather conditions.

In Nebraska, research on irrigation has previously focused on sprinkler and surface systems (Gilley et al., 1980; Schneekloth et al., 1991; Hergert et al., 1993; Klocke et al., 2004; Payero et al., 2005, 2006a,b; Schneekloth et al., 2006). However, due to the current and expected limited water supplies, interest in subsurface drip irrigation (SDI) systems to irrigate row crops in Nebraska is growing. Although studies with SDI-irrigated corn have been conducted in other states (Ayars et al., 1999; Camp, 1998; Caldwell et al., 1994; Howell et al., 1997; Lamm et al., 1995; Lamm and Trooien, 2003), local information on the response of corn growth, yield and other crop–water dynamics with SDI is very limited. The agronomic response of the crop to irrigation with SDI is needed to be able to evaluate the economic and technical feasibility of using SDI under local conditions and provide scientifically based practical information to the users on best management practices for SDI-irrigated corn. The objective of this study was to evaluate how different seasonal irrigation depths applied with SDI affected the soil water balance, seasonal evapotranspiration, yield, water use efficiency, and dry matter production of corn in the semiarid climate of west central Nebraska.

2. Materials and methods

2.1. Site description

Field experiments were conducted during the 2005 and 2006 growing seasons. The experiments were located at the University of Nebraska-Lincoln West Central Research and Extension Center, in North Platte, Nebraska (41.1°N: 100.8°W: 861 m above sea level). The climate at North Platte is semiarid, with average annual precipitation of approximately 508 mm and reference evapotranspiration of 1403 mm (USDA, 1978).

Table 1 – Seasonal total and monthly irrigation depths (mm) applied to each corn irrigation treatment (T1–T8) during the 2005 and 2006 growing seasons at North Platte, Nebraska

Year	Month	Treatment							
		T1	T2	T3	T4	T5	T6	T7	T8
2005	July	53	61	87	87	107	104	105	106
	August	0	15	15	66	114	150	188	225
	September	0	0	0	0	0	0	13	25
	Total	53	76	102	153	221	254	306	356
2006	June	8	4	8	8	8	8	8	8
	July	13	62	89	121	124	120	123	176
	August	0	0	0	0	39	46	65	41
	September	0	0	0	0	13	0	1	0
	Total	22	66	97	130	184	173	197	226

On average, about 80% of the annual precipitation occurs during the growing season, which extends from late-April to mid-October (USDA, 1978). The soil at the experimental site is a Cozad silt loam (fine-silty, mixed, mesic *Fluventic haplustoll*). From measurements obtained from the experimental plots during this study, it was estimated that the average water contents at field capacity (FC) and permanent wilting point (PWP) in the crop root zone were approximately 0.35 and 0.09 $m^3\ m^{-3}$, respectively.

2.2. Experimental design

The field experiment was conducted using a randomized complete block design with eight irrigation treatments (T1–T8) and four replications. Each treatment received a seasonal irrigation allocation, which ranged from 53 to 356 mm in 2005 and from 22 to 226 mm in 2006 (Table 1). The aim was to develop well-defined crop response functions to irrigation, ranging from near dryland to over-irrigated conditions. A dryland treatment was not included because some irrigation water was needed to apply nitrogen fertilizer. Irrigations were scheduled to avoid or minimize water stress and deep percolation. The target was to keep the percent soil water depletion in the crop root zone below 50% of the total available soil water for as much of the season as possible. Another target was to maintain a soil water depletion of at least 50 mm to store potential rainfall and avoid deep percolation, which was especially important for treatments receiving and excessive allocation. For treatments with a deficient allocation to meet irrigation requirements for the entire season, the strategy was to minimize stress during the peak ETc period (in July), allowing stress later in the season. Once irrigation started, all treatments were irrigated at the same time until the allocation for a given treatment ran out. Irrigations were usually applied two to three times a week. In 2005, irrigations started in mid-July, since rainfall and stored soil water provided adequate moisture for crop development earlier in the season. In 2006, irrigation started in June due to drier soil conditions compared with 2005.

Each experimental plot was 9 m × 37 m, which accommodated 12 corn rows. The crop was irrigated with a SDI system that was installed just prior to planting in 2005, in a field that was planted to surface-irrigated soybean in 2004. The SDI laterals were spaced at 1.5 m (every other corn row) and were installed at a depth of 0.4 m between the two crop rows. Laterals were 12.5-mil thin-wall dripper lines (Dripnet PC 1613 F, Netafim USA, Fresno, CA) with inside diameter of 1.6 cm and pressure-compensating emitters spaced every 46 cm. The nominal flow of the emitters was 0.98 $L\ h^{-1}$ (applying 1.5 $mm\ h^{-1}$) at a pressure of 69 kPa. Water for the system was pumped from the Ogallala aquifer and was filtered using a 152-mm diameter screen filter with a 150-mesh screen (model 8060F-MN, Netafim USA, Fresno, CA). Irrigation to each treatment was controlled from a manifold that had eight branches. Each branch had a flow meter (25.4-mm model 36M251T), equipped with a pulse reed switch (model 36RD, Netafim USA, Fresno, CA). It also had a 19-mm electric/manual control valve (model S390-3-0, Dorot Control Valves Inc., Fresno, CA), a pressure regulator (''Standard'' model, 0.22–1.26 $L\ s^{-1}$, 62.1 kPa) (Netafim USA, Fresno, CA), and an air and vacuum relief air vent with shrader valve (''Guardian'' model, Netafim USA, Fresno, CA). Irrigations were controlled manually in 2005, and an automatic controller (model NMC-64; Netafim USA, Fresno, CA) was used in 2006.

2.3. Cultural practices

Corn was planted on May 18 and 11, and matured on September 23 and 20 in 2005 and 2006, respectively. During both seasons, corn with a comparative relative maturity of 112 days (hybrid Kaystar KX-8615Bt) was planted at 0.76-m row spacing and an average seeding rate of 7.6 seeds per m^2. Nitrogen (N) was applied with the starter fertilizer and by fertigating through the SDI system during the growing season. The N application rate was based on soil analysis. All treatments received 11 $kg\ N\ ha^{-1}$ as 10-34-0 with the starter fertilizer. Fertigation with urea ammonium nitrate consisted of 108 $kg\ N\ ha^{-1}$ applied on 15 July 2005, and 213 $kg\ N\ ha^{-1}$ applied on 5 July 2006. In 2005, an estimated 50 $kg\ N\ ha^{-1}$ was supplied by the previous soybean crop.

A herbicide mixture (93.4 $L\ ha^{-1}$) containing Lumax® (3.51 $L\ ha^{-1}$), Banvel® (0.58 $L\ ha^{-1}$), Atrazine 90 DF (1.12 $kg\ ha^{-1}$) and crop oil (1.42 L per 378 L of water) was applied when the crop was at the V4 stage. Target weeds were Kochia (*Kochia scoparia* L.), Common Lambsquaters (*Chenopodium album* L.), Redroot Pigweed (*Amaranthus restroflexus* L.), Field Sandbur (*Cenchrus longispinus* (Hack.) Fern.), Yellow Foxtail (*Setaria glauca* L.) and Puncturevine (*Tribulus terrestris* L.). The insecticide Force® 3G (4.92 $kg\ ha^{-1}$) was applied using a 18-cm T-band in front of the press wheel at planting time. Target insects were the Corn Rootworm Beetle (*Diabrotica virgifera* LeConte) and the European Corn Borer (*Ostrinia nubilalis* (Hübner)). These applications prevented negative effects of weeds and insects on corn growth.

2.4. Yield and dry matter measurements

The center three rows (37 m) of each plot were harvested in early November using a plot combine with a three-row corn head. The combine had a Harvest Data System (model HM-400, Juniper Systems Inc. Logan, Utah), which measured the total mass, water content, and ''*test weight*'' of the harvested grain. The grain yield per plot was calculated both in a ''dry-mass basis'' (0% water content) and in a ''wet-mass basis'' (standard water content of 15.5%).

Eight plants from each plot were also hand-harvested to determine dry matter production and its partitioning into the different plant components (grain, stover, and cob). Plants were cut at ground level and the ears were separated from the stover. The stover samples were weighted, chopped using a tractor-operated plant chopper, and a sub-sample was collected from each plot and weighted. The sub-samples were oven-dried at 70 °C until they reached a constant mass (7 days) and their masses were recorded. The ear samples were placed in a greenhouse to air-dry to a moisture content of approximately 15–16%, and then weighted and shelled by hand. Grain and cob samples were taken, oven-dried at 70 °C until they reached a constant mass (7 days), and weighted.

From this information, the average dry mass per plant and the dry mass and percent of total plant dry mass of the grain, cob, and stover were calculated for each plot.

2.5. Soil water balance and crop evapotranspiration

Daily soil water balance and crop evapotranspiration (ETc) were estimated with a computer program that was written in Microsoft Visual Basic®. The inputs to the program were daily weather data, including rainfall, irrigation date and amounts, initial water content in the soil profile at crop emergence, and crop- and site-specific information such as planting date, maturity date, soil parameters, maximum rooting depth, etc. Similar daily soil water balance models have previously been used by Robinson and Hubbard (1990), Swan et al. (1990), and Bryant et al. (1992). The computer program calculated daily ETc and the water balance in the crop root zone using the procedure described in FAO-56 (Allen et al., 1998). Readers are referred to the original sources for additional details. This procedure obtains ETc as the product of the evapotranspiration of a grass-reference crop (ET_o) 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 K_c approach was used, which separates the two components of ETc, namely evaporation (E) and transpiration (T). For corn, this procedure linearly reduces ETc when the soil water depletion in the crop root zone exceeds 55% (taken from Table 22 in FAO-56) of total available water. Reducing the ETc rate when the crop is under water stress is consistent with the findings of Dwyer and Stewart (1984, 1985), and Gavloski et al. (1992). The dual K_c procedure also accounts for the sharp increases in E due to a wet soil surface following rain or irrigation events. This procedure, therefore, permitted calculation of daily ETc under water-limiting conditions, and when soil water was not limiting (ETp). From the seasonal ETc and ETp values, the ETc/ETp ratio was calculated for each treatment.

Weather data were obtained from an automatic weather station located within 1.5 km from the research site. This 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, solar radiation, reference and crop ET for different crops, including corn. Rainfall data were also collected manually from rain gauges installed at each of the four corners of the field.

The performance of the computer model was evaluated by comparing its soil water content outputs with values measured using the neutron probe method (Evett and Steiner, 1995). Measurements were made at 0.3-m increments to a depth of 1.8 m three times each season on 7 July, 15 August, and 23 September 2005, and on 14 June, 11 August, and 21 November 2006. Gravimetric samples were also taken on 7 June 2005 to a depth of 1.0 m.

2.6. Water use efficiencies

Water use efficiency (WUE, kg m^{-3}) and irrigation water use efficiency (IWUE, kg m^{-3}) were calculated as

$$\mathrm{WUE} = \frac{Y}{\mathrm{ETc}} \quad (1)$$

$$\mathrm{IWUE} = \frac{Y}{I} \quad (2)$$

where Y = yield (g m^{-2}), ETc = seasonal crop evapotranspiration (mm), I = seasonal irrigation (mm).

2.7. Statistical analyses

Analysis of variance (ANOVA) and separation of means were conducted using the GenStat® for Windows® statistical software (VSN International Ltd., Hertfordshire, UK). To evaluate the effect of irrigation treatment, a separate ANOVA was conducted for each year of the experiment. Year was not included as a factor in the ANOVA since irrigation amounts for the different treatments varied with season. Regression analyses were performed with Microsoft Excel®. The root mean square error (RMSE) was used to evaluate the performance of the soil water balance model. The RMSE was calculated as

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{SW_m} - \mathrm{SW_e})^2} \quad (3)$$

where n = number of observations, SW_m = measured soil water (m^3 m^{-3}), and SW_e = estimated soil water (m^3 m^{-3}). Because it is an indication of both bias and variance of the SW_e values with respect to the SW_m values, the RMSE provides an effective measure to evaluate the performance of the model. Lower RMSE values indicate better agreement between SW_e and SW_m values.

3. Results and discussion

3.1. Weather conditions during the growing seasons

Average values of weather variables during the 2005 and 2006 corn growing seasons at North Platte, Nebraska, are shown in Table 2. The seasonal average air temperature was the same (21.8 °C) during both seasons. In 2006, however, temperatures were hotter in May–July, and cooler in August and September, compared with 2005. On average, wind speed and relative humidity were higher in 2005. The average solar radiation, however, was about 5% higher in 2006.

The cumulative daily rainfall during 2005, 2006 and 1982–2006 at North Platte are shown in Fig. 1. The two seasons had similar annual rainfalls of 409 and 403 mm for 2005 and 2006, respectively. The rainfall during both seasons was just below the 1982–2006 average of 423 mm. The average rainfall during the last 25 years (1982–2006) was only 83% of the long-term average of 508 mm reported in USDA (1978). Although both

Table 2 – Average weather conditions during the 2005 and 2006 corn growing seasons at North Platte, Nebraska

Year	Month	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	u_2 (m s^{-1})	Rs (MJ m^{-2} d^{-1})	RH (%)	VPD (kPa)
2005	May	21.4	7.9	14.6	2.8	17.9	65.7	0.7
	June	27.6	14.2	20.9	3.2	22.5	69.5	0.9
	July	32.9	16.2	24.5	3.2	24.4	57.0	1.5
	August	29.8	15.2	22.5	2.5	19.8	68.3	1.0
	September	29.4	12.9	21.2	3.2	18.4	59.5	1.2
	Total	29.4	14.3	21.8	3.0	21.2	63.9	1.1
2006	May	30.1	10.8	20.4	2.7	27.1	42.4	1.7
	June	30.5	14.7	22.6	2.8	25.7	54.5	1.5
	July	32.6	17.6	25.1	2.6	24.2	58.1	1.6
	August	29.2	15.6	22.4	2.6	18.3	68.9	1.0
	September	23.6	7.2	15.4	2.2	17.0	68.5	0.7
	Total	29.6	14.0	21.8	2.6	22.4	59.5	1.3
	Grand total	29.5	14.1	21.8	2.8	21.8	61.7	1.2

T_{max} = maximum air temperature, T_{min} = minimum air temperature, T_{avg} = average air temperature, u_2 = wind speed at 2 m height, Rs = solar radiation, RH = relative humidity, VPD = vapour pressure deficit, only data from corn emergence to maturity were included.

seasons had similar rainfall, 2005 followed a wetter-than-normal year (2004), while 2006 followed a year with just-below-normal rainfall. Therefore, there was a higher chance of having more water stored in the soil profile at planting in 2005 compared with 2006.

The monthly distribution of rainfall for 2005, 2006, and the 1982–2006 average for rainfall and alfalfa-reference evapotranspiration (ETr) at North Platte are shown in Fig. 2. ETr values, instead of ET_o, are normally reported by the HPRCC and are used here. However, ETc values in this study were calculated based on ET_o. At North Platte, ETr is normally much higher than rainfall, which explains the need for irrigation. The average annual rainfall for 1982–2006 was 423 mm, while ETr was 1532 mm, therefore, rainfall represented only 27.6% of ETr.

During 2005 and 2006 there was almost twice as much rain in June, which is the wettest month for the area, compared with the long-term average. The total in-season rain was very similar both seasons, with 295 and 282 mm for 2005 and 2006, respectively. However, in 2005 there was considerably more rain in May, making more water available to the crop at planting time and early in the season compared with 2006. In 2006, there was very little rain in May (only 13 mm), which was well below normal. In 2006, there was more rain in September than in 2005. That additional rain in September, however, occurred too late in the growing season to have a significant impact on crop growth and yield, considering that by 1 September 2006 the corn had already entered the R5 growth stage (dent) (Hoeft et al., 2000). During both seasons, rain in July was considerably below normal. This is significant because July had the peak ETr (Fig. 2), and the corn had progressed to the reproductive growth stages. The R1 growth stage (silking) started on 18 July and 11 July in 2005 and 2006, respectively.

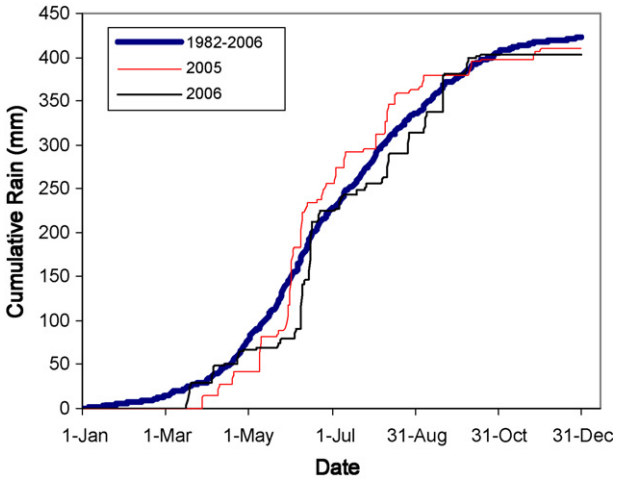

Fig. 1 – Cumulative rain for 2005, 2006 and 1982–2006 at North Platte, Nebraska.

3.2. *Initial soil water*

In 2005, all treatments started with the same soil water profile, since there was abundant rain in May and irrigation treatments were not applied in the experimental plots in 2004. Gravimetric soil sampling in early June (Fig. 3) showed a near uniform soil water content in the top 1 m of soil profile, although later measurements showed considerable water depletion deeper in the soil profile. In 2006, however, due to little rain in May and to the irrigation treatments applied in 2005, there were considerable differences in the initial soil water profiles among treatments (Fig. 3). The treatments that were deficit irrigated in 2005 started the 2006 season with little soil water, especially deep in the profile.

3.3. *Performance of the soil water balance model*

The computer model provided very good estimates of average soil water in the crop root zone compared with neutron probe measurements during both seasons (Fig. 4). On average, the estimated soil water values tended to follow the 1:1 line when compared with measured values during both seasons. Also the measured and estimated values were linearly related with high R^2 values of 0.90 and 0.85 in 2005 and 2006, respectively. The RMSEs calculated between the estimated and measured values were also relatively small with 0.018 and 0.019 m^3 m^{-3} for 2005 and 2006, respectively.

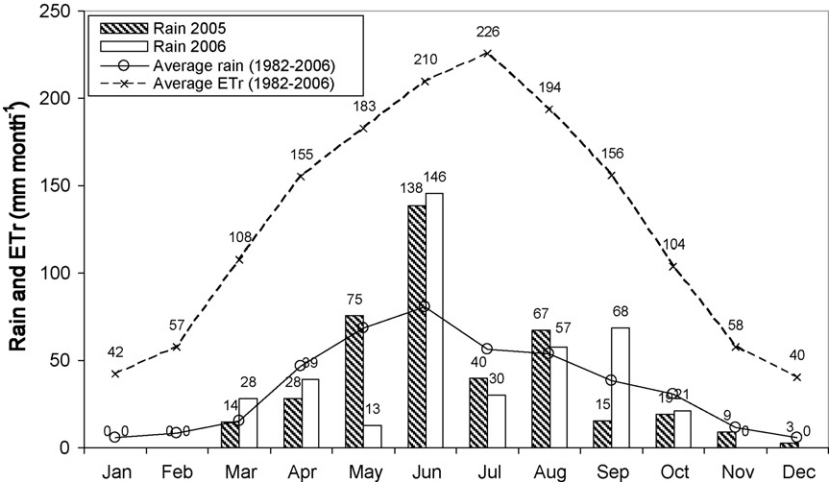

Fig. 2 – Monthly rain for 2005, 2006, and the long-term averages (1982–2006) for rain and alfalfa-reference evapotranspiration (ETr) at North Platte, Nebraska.

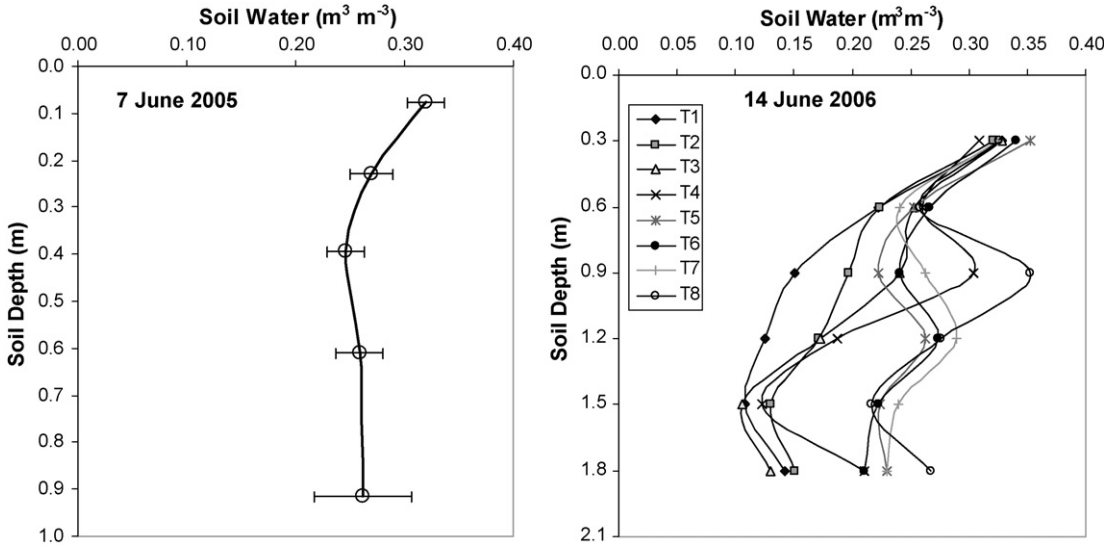

Fig. 3 – Average soil water for all treatments measured from gravimetric samples in June 2005 (error bars are treatment means ± standard deviation), and soil water for the different irrigation treatments (T1–T8) measured with the neutron probe method in June 2006.

3.4. *Effect of irrigation on evapotranspiration*

The potential corn evapotranspiration (ETp) (ETp = ETc with no water stress) from emergence to the R6 growth stage (physiological maturity or ''black-layer'') was practically the same during both seasons, calculated at 663 mm. The cumulative ETp was linearly related (except early in the season) to the Fraction of Season[1] (Fs) (Fig. 5). Both seasons, cumulative ETp followed the same straight line after approximately Fs ≥ 0.25 in 2005 and Fs ≥ 0.20 in 2006. Where properly calibrated, this linear relationship between cumulative ETp and Fs can potentially be used to extrapolate and predict ETp during the season and to make in-crop irrigation scheduling decisions. Payero et al. (2005) reported similar linear relationships for soybean at this site.

During both seasons, ETc increased with irrigation up to a point where irrigation became excessive (Fig. 6). No increase in ETc was observed for irrigation amounts above 221 mm (T5) in 2005 and 173 mm (T6) in 2006. There was a steeper increase in ETc with irrigation during 2006 compared with 2005.

The cumulative crop evapotranspiration (ETc) for each treatment and the cumulative ETp are shown in Fig. 7. During both seasons, some of the treatments suffered from water stress, although water supplies were adequate for all treatments early in the season. In 2005, stress for the driest treatment started in mid August. In 2006, however, stress for the driest treatment occurred about a month earlier (in mid July). Stress created differences in seasonal ETc among

[1] Fraction of Season is the ratio of cumulative growing degree days (CGDD) from crop emergence to required CGDD from crop emergence to maturity.

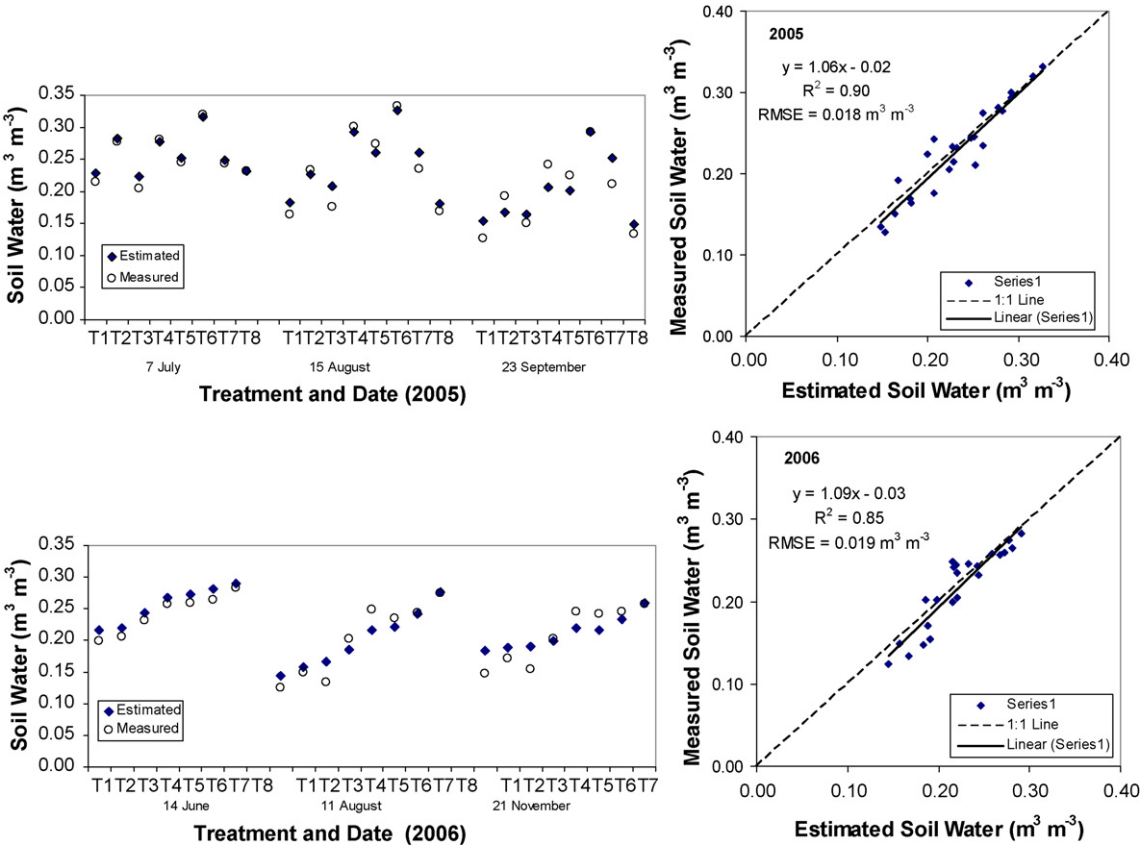

Fig. 4 – Estimated and measured soil water content obtained at North Platte, Nebraska, during the 2005 and 2006 growing seasons. Each data point represents the average soil water content in the crop root zone to a depth of 1.8 m for each treatment (T1–T8), including three sampling dates each year. RMSE is the root mean squared error.

treatments. A wider range of seasonal ETc among treatments resulted in 2006 compared with 2005. The seasonal ETc and ETc/ETp ratios for the different treatments are shown in Table 3. In 2005, seasonal ETc for all treatments averaged 630 mm and ranged from 580–663 mm. The ETc/ETp ratio averaged 0.95 and ranged from 0.87 to 1.00. In 2006, drier soil conditions resulted in a lower seasonal ETc that averaged 600 mm and ranged from 466 to 656 mm. The ETc/ETp ratio averaged 0.90 and ranged from 0.70 to 0.99.

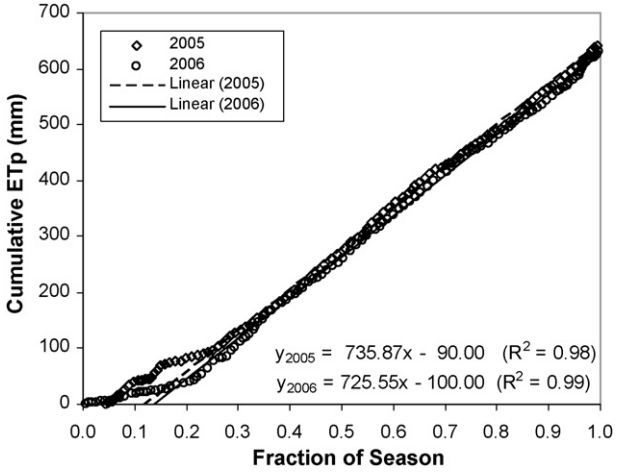

Fig. 5 – Relationships between cumulative ETp and Fraction of season (FS) obtained during the 2005 and 2006 growing seasons at North Platte, NE. ETp = crop evapotranspiration (ETc) with no water stress. FS is the ratio of cumulative growing degree days (CGDD) from crop emergence to required CGDD from crop emergence to maturity.

3.5. *Effect of irrigation on yield and water use efficiencies*

Yield, water use efficiency (WUE), and irrigation water use efficiency (IWUE) for the different treatments are shown in Table 4, both in ''dry-mass basis'' and ''wet-mass basis''. Irrigation significantly affected yields during both years. Yields were higher in 2005 compared with 2006, averaging, in a ''dry-mass basis,'' 968 and 828 g m^{-2} in 2005 and 2006, respectively. In 2005, yields ranged from 844 to 1085 g m^{-2}, a yield difference of 241 g m^{-2} (22%). In 2006, yields ranged from 455 to 957 g m^{-2}, a yield difference of 502 g m^{-2} (52%).

Relationships relating yield to seasonal irrigation, ETc, ETc/ETp are shown in Fig. 8A–C. It also shows the relative yield decrease with respect to the relative evapotranspiration deficit (Fig. 8D) as proposed by Doorenbos and Kassam (1979). During both seasons, yields tended to increase with irrigation up to the point where irrigation became excessive (Fig. 8A). Although not quantified, excessive irrigation most likely reduced the amount of oxygen in the crop root zone and increased the likelihood of nitrogen leaching, making less of it available for crop uptake. During both seasons yields peaked

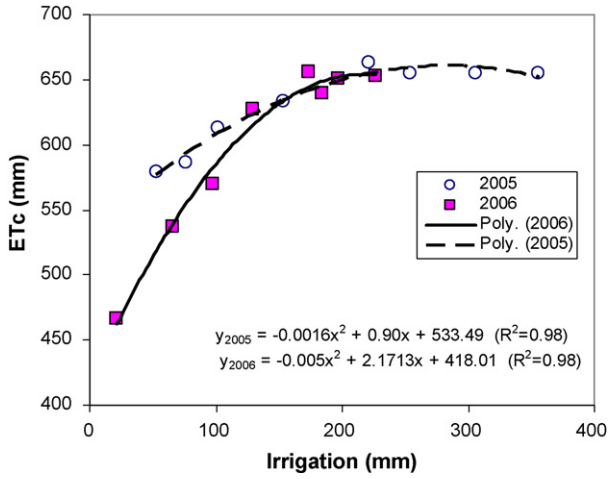

Fig. 6 – Relationship between irrigation and seasonal crop evapotranspiration (ETc) for corn obtained at North Platte, Nebraska, during 2005 and 2006.

with treatment T6, which applied 254 and 173 mm of irrigation in 2005 and 2006, respectively. Different yield versus irrigation functions were obtained each season, with a steeper slope obtained in 2006. When seasonal irrigation was not excessive,

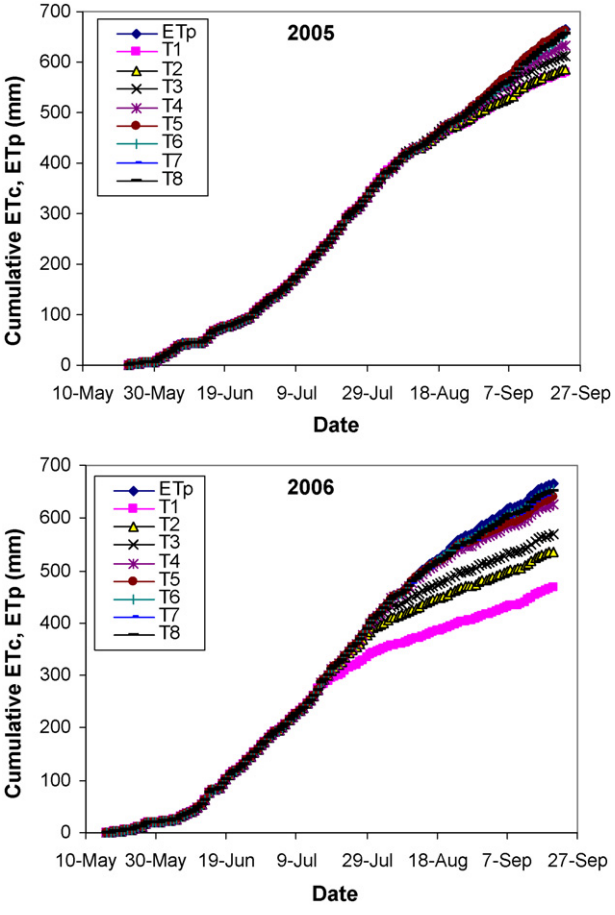

Fig. 7 – Cumulative corn evapotranspiration (ETc) for each irrigation treatment (T1–T8) during the 2005 and 2006 growing seasons at North Platte, Nebraska. ETp = ETc with no water stress.

Table 3 – Seasonal corn evapotranspiration calculated for each irrigation treatment during the 2005 and 2006 growing seasons at North Platte, Nebraska

Treatment	2005 (ETp = 663 mm)		2006 (ETp = 663 mm)	
	ETc (mm)	ETc/ETp	ETc (mm)	ETc/ETp
T1	580	0.87	466	0.70
T2	586	0.88	537	0.81
T3	612	0.92	570	0.86
T4	633	0.96	627	0.95
T5	663	1.00	639	0.96
T6	655	0.99	656	0.99
T7	655	0.99	651	0.98
T8	655	0.99	653	0.99
Average	630	0.95	600	0.90
Minimum	580	0.87	466	0.70
Maximum	663	1.00	656	0.99

ETc = crop evapotranspiration and ETp = ETc with no water stress.

higher yields were obtained with the same amount of irrigation in 2005 compared with 2006. These results are not surprising since the relationship between yield and irrigation is not unique and varies with season and location. On the other hand, yields were linearly related to seasonal ETc (Fig. 8B) and to seasonal ETc/ETp (Fig. 8C), and the relationships practically followed the same line during both seasons.

Good linear relationships between relative evapotranspiration deficit and relative yield decrease were observed in 2006 and combining data from the two seasons (2005–2006) (Fig. 8D). In 2005 the relation was poor probably due to the limited stress observed that year. The slope of the line in Fig. 8D represents the yield response factors (ky) as proposed by Doorenbos and Kassam (1979). The ky = 1.58 was higher than the 1.25 value reported by Doorenbos and Kassam (1979) for stress during the total growing period, but close to the 1.50 value reported for stress during the reproductive stages.

WUE values varied considerably with irrigation treatment, especially during the drier 2006 season (Table 4). Values tended to be higher in 2005, averaging 1.53 and 1.37 kg m^{-3} (dry-mass basis) in 2005 and 2006, respectively. Differences in WUE between the driest and wettest treatment were 12 and 35% in 2005 and 2006, respectively. Irrigation treatments, however, impacted IWUE much more than WUE. Differences in IWUE between the driest and wettest treatment were 82 and 80% in 2005 and 2006, respectively. Fig. 9 shows that WUE increased non-linearly with seasonal ETc and with yield, when combining data from both seasons. Both of these relationships are determined by the observed linear relationship between yield and ETc (Fig. 8B). If the relationship between yield and ETc is linear (yield = slope × ETc − intercept), then for WUE = 0, ETc = (intercept/slope), and yield = 0. The curvilinear function results from the fact that the intercept ≠ 0.

Fig. 10 shows IWUE and WUE as functions of irrigation. IWUE sharply decreased with irrigation, with similar tendencies observed during both seasons. The decreasing tendency of IWUI with irrigation is expected in areas where the dryland yield (yield with no irrigation) is positive. However, in situations when no dryland yield can be obtained without irrigation, IWUE would be expected to increase with irrigation, and in situations when the dryland yield is exactly zero (a rare

Table 4 – Corn yield, water use efficiency (WUE), and irrigation water use efficiency (IWUE) for each irrigation treatment obtained in 2005 and 2006 at North Platte, Nebraska, considering grain yield in both dry-mass and wet-mass basis

Treat	Dry-mass basis						Wet-mass basis					
	2005			2006			2005			2006		
	Yield ($g\ m^{-2}$)	IWUE ($kg\ m^{-3}$)	WUE ($kg\ m^{-3}$)	Yield ($g\ m^{-2}$)	IWUE ($kg\ m^{-3}$)	WUE ($kg\ m^{-3}$)	Yield ($g\ m^{-2}$)	IWUE ($kg\ m^{-3}$)	WUE ($kg\ m^{-3}$)	Yield ($g\ m^{-2}$)	IWUE ($kg\ m^{-3}$)	WUE ($kg\ m^{-3}$)
T1	844 e	15.93	1.46	455 e	21.08	0.98	999 e	18.85	1.72	539 e	24.95	1.16
T2	901 de	11.85	1.54	711 d	10.77	1.32	1066 de	14.03	1.82	842 d	12.74	1.57
T3	932 cd	9.14	1.52	814 c	8.37	1.43	1103 cd	10.81	1.80	963 c	9.90	1.69
T4	935 cd	6.11	1.48	875 cb	6.76	1.40	1106 cd	7.23	1.75	1036 cb	8.00	1.65
T5	1022 ab	4.62	1.54	953 a	5.17	1.49	1209 ab	5.47	1.82	1128 a	6.12	1.76
T6	1085 a	4.27	1.66	957 a	5.52	1.46	1284 a	5.06	1.96	1133 a	6.53	1.73
T7	984 bc	3.21	1.50	927 ab	4.70	1.42	1164 bc	3.80	1.78	1097 ab	5.56	1.68
T8	1040 ab	2.92	1.59	933 ab	4.13	1.43	1231 ab	3.46	1.88	1104 ab	4.88	1.69
Average	968	7.26	1.53	828	8.31	1.37	1145	8.59	1.82	980	9.84	1.62
Minimum	844	2.92	1.46	455	4.13	0.98	999	3.46	1.72	539	4.88	1.16
Maximum	1085	15.93	1.66	957	21.08	1.49	1284	18.85	1.96	1133	24.95	1.76
Difference	241	13.01	0.20	502	16.95	0.51	285	15.39	0.24	594	20.06	0.61
Difference (%)	22%	82%	12%	52%	80%	35%	22%	82%	12%	52%	80%	35%
S.E.M.	26			29			26			29		

WUE = yield/[seasonal crop evapotranspiration], IWUE = yield/irrigation. The "dry-mass basis" and "wet-mass basis" yields were calculated at 0 and 15.5% grain water contents, respectively. Yields with the same letters are not significantly different at the 5% significance level. S.E.M. = standard errors of means.

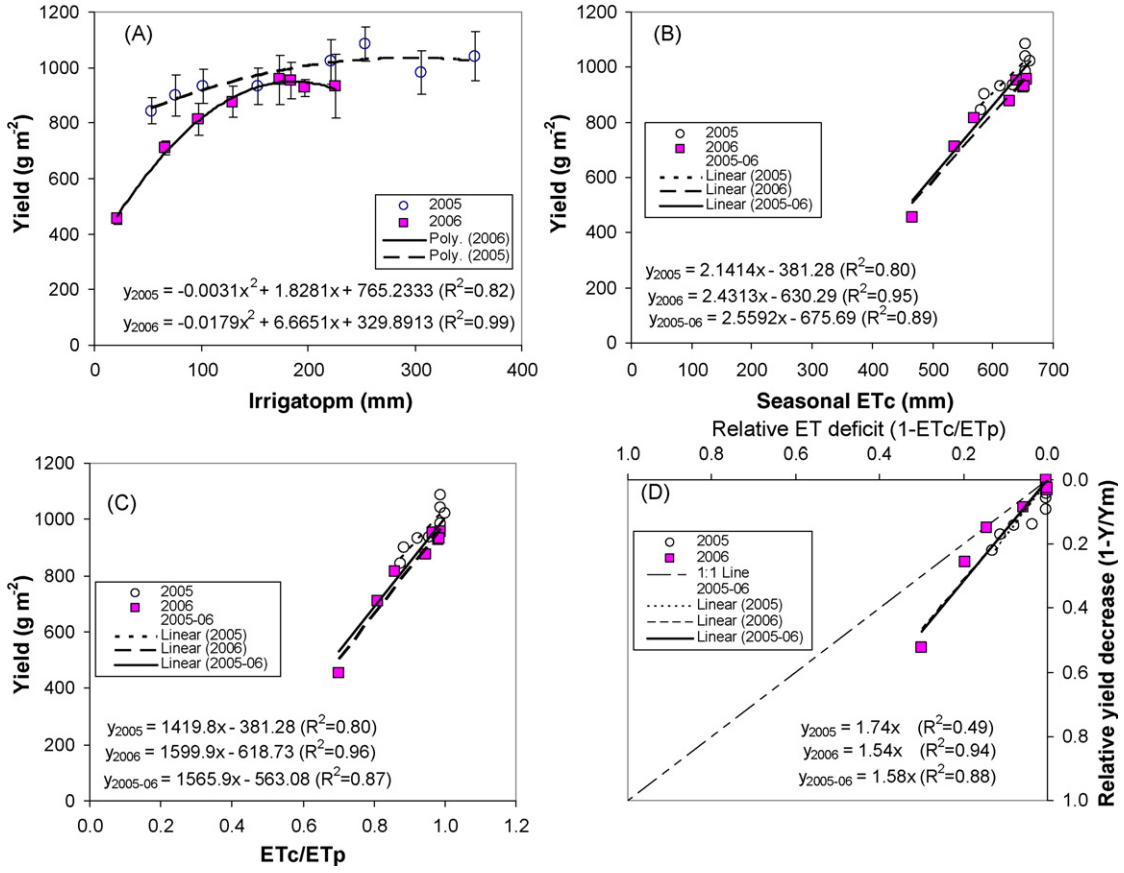

Fig. 8 – Corn yield response to seasonal irrigation, evapotranspiration (ETc) and ETc/ETp obtained during 2005 and 2006 at North Platte, Nebraska. ETp = ETc with not water stress, Y = yield and Y_m = maximum yield. Yields were calculated in a dry-mass basis (0% grain water content). Error bars are treatment means ± standard deviation.

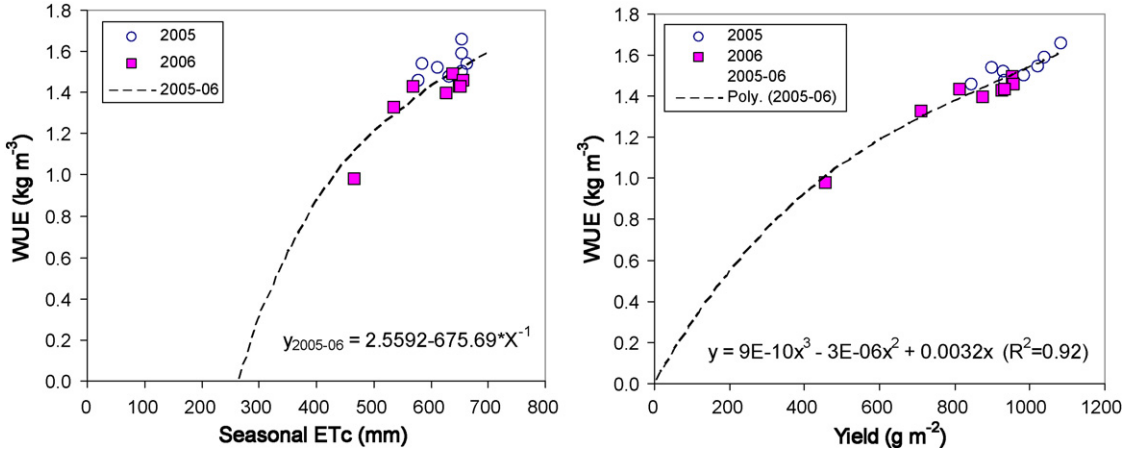

Fig. 9 – Corn water use efficiency (yield/ETc) as a function of seasonal crop evapotranspiration (ETc) and yield obtained during 2005 and 2006 at North Platte, Nebraska. Functions were extrapolated beyond observed values to fit the values dictated by the observed yield versus ETc linear function. Yields were calculated in a dry-mass basis (0% grain water content).

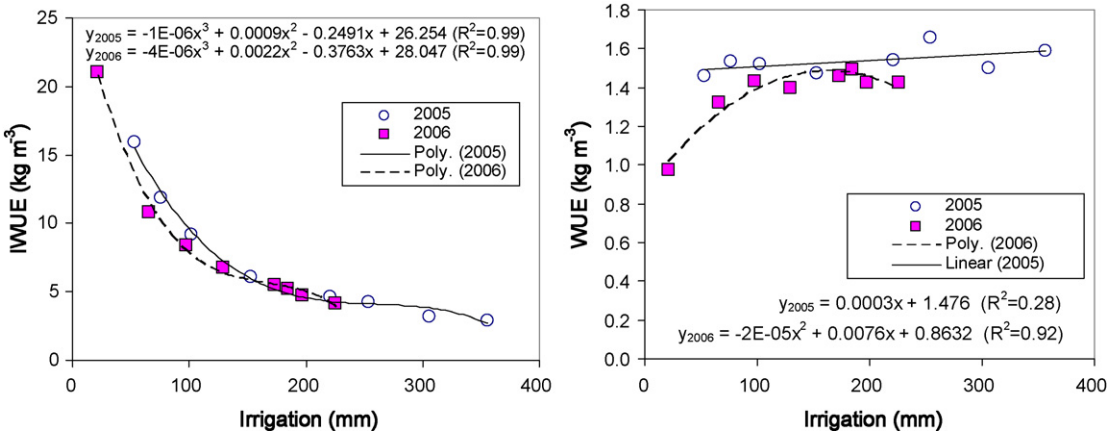

Fig. 10 – Corn water use efficiency (WUE = yield/ETc) and irrigation water use efficiency (IWUE = yield/irrigation) as a function of seasonal irrigation obtained during 2005 and 2006 at North Platte, Nebraska. ETc = crop evapotranspiration. Yields to determine WUE and IWUE were calculated in a dry-mass basis (0% grain water content).

coincidence), IWUE would be constant with irrigation, assuming no over-irrigation. Fig. 10 also shows that WUE varied little with irrigation in 2005, but tended to be well related to irrigation in 2006. In 2006, WUE increased with irrigation up to the point where additional irrigation did not produce additional yield, in a similar fashion as the relationship between irrigation and yield (Fig. 8A). These results show that IWUE and WUE had an opposite behavior with irrigation.

Some researchers and the general public often refer to "increasing water use efficiency" in general terms as a desirable objective. In some cases they are referring to WUE and in others to IWUE or other measures of water use efficiency such as yield/(total water) (total water = rain + irrigation + soil water). These results show that these terms should not be interchanged and care should be taken to define exactly what it is that they want to increase. The feasibility of increasing either the WUE or IWUE is a decision that needs to be based not only on the biophysical response of the crop but also on economic factors. Often the objective of producers is not to increase yields but to increase profits. If water is the factor limiting production, increasing IWUE (which means decreasing WUE) could be desirable. In instances where water is not the limiting factor, irrigation to produce maximum yield, which will tend to increase WUE but to decrease IWUE could be the most profitable option. Determining the level of irrigation needed to optimize profits can be complex and depends on both biophysical and economic factors (English et al., 2002; Martin et al., 1989; Norton et al., 2000).

3.6. *Effect of irrigation on dry matter production*

The dry matter productions for the entire corn plant and for the different plant components (grain, cob, and stover) obtained during the two seasons are shown in Table 5. Data

Table 5 – Corn dry matter production obtained during 2005 and 2006 with different irrigation treatments at North Platte, Nebraska

Year, treatment	Dry mass (g plant^{-1})				% Of plant dry mass		
	Plant	Grain	Cob	Stover	%Grain	%Cob	%Stover
2005, T1	248 bc	146 bc	22 a	80 a	58.8 ab	9.0 a	32.2 b
T2	244 c	137 c	21 a	86 a	56.2 d	8.6 bc	35.2 a
T3	258 bc	149 bc	22 a	87 a	57.6 bcd	8.6 b	33.7 ab
T4	264 bc	155 bc	23 a	86 a	58.7 ab	8.6 b	32.6 b
T5	281 ab	163 ab	24 a	95 a	57.9 abc	8.5 bc	33.6 ab
T6	307 a	175 a	26 a	106 a	57.0 cd	8.4 bc	34.6 a
T7	262 bc	155 bc	22 a	84 a	59.3 a	8.6 bc	32.1 b
T8	284 ab	162 ab	24 a	98 a	57.2 cd	8.3 c	34.4 a
Average (2005)	268.5	155.3	23.01	90.2	57.9	8.58	33.6
2006, T1	143 a	74 a	10 a	59 a	52.2 a	6.9 a	41.0 c
T2	221 b	131 b	17 b	73 a	59.4 b	7.7 a	32.9 b
T3	240 b	147 b	19 b	74 a	61.2 bc	7.8 a	31.0 ab
T4	246 b	152 b	19 b	75 a	61.6 c	7.6 a	30.8 a
T5	248 b	152 b	18 b	79 a	61.0 bc	7.3 a	31.8 ab
T6	247 b	152 b	18 b	76 a	61.7 c	7.4 a	30.9 a
T7	254 b	157 b	19 b	78 a	61.7 c	7.5 a	30.7 a
T8	262 b	162 b	20 b	80 a	61.8 c	7.5 a	30.7 a
Average (2006)	232.7	140.8	17.5	74.4	60.1	7.5	32.5
Average (2005–2006)	250.6	148.1	20.2	82.3	59.0	8.0	33.0

Means with the same letters within a season were not significantly different at the 5% significance level.

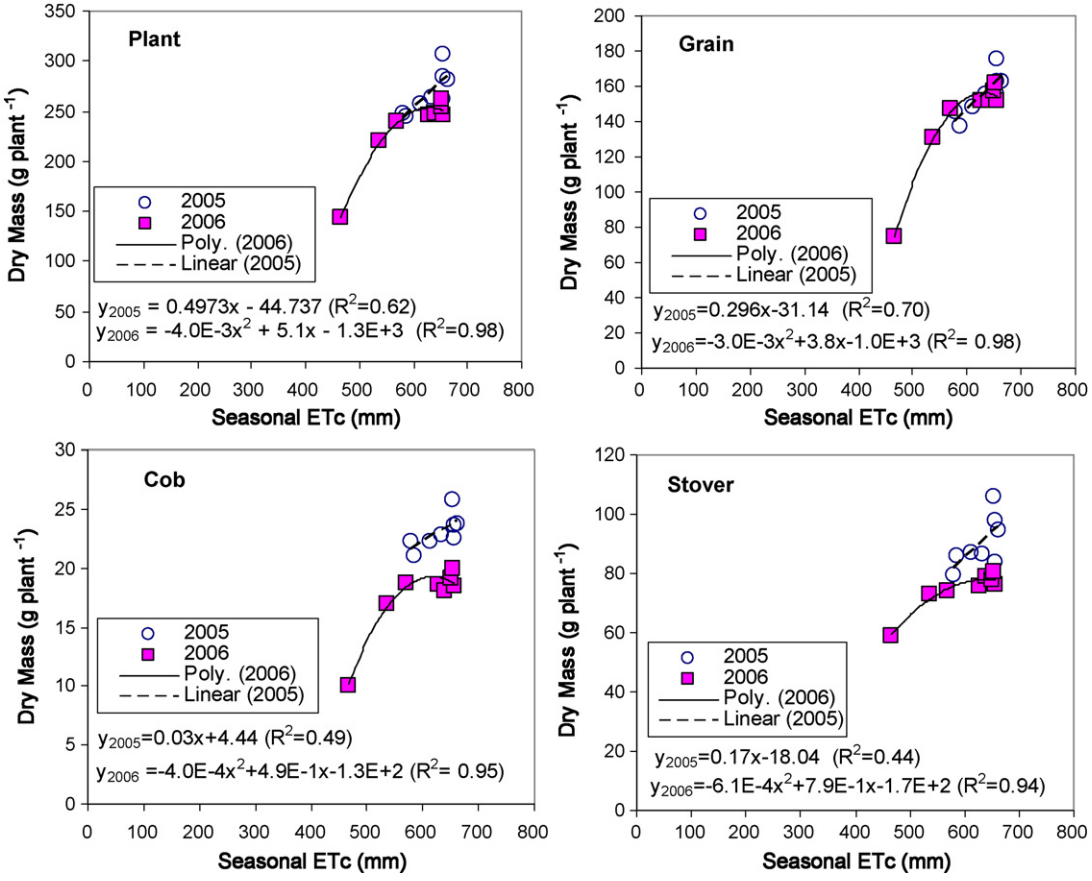

Fig. 11 – Relationships between corn seasonal evapotranspiration (ETc) and the dry mass of the plant, grain, cob, and stover obtained with different irrigation treatments during 2005 and 2006 at North Platte, NE. Differences in dry mass of plant, grain and cob among treatments were statistically significant at the 5% significance level for both seasons, while those of the stover were not.

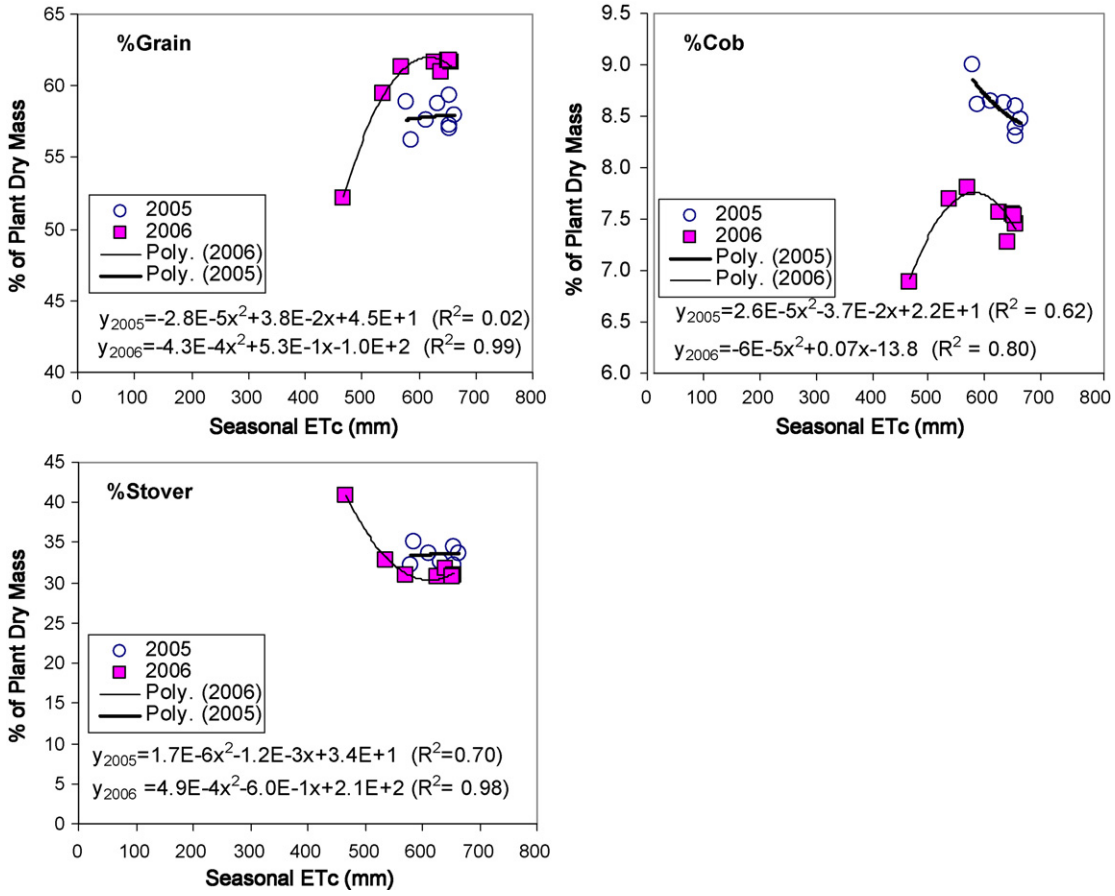

Fig. 12 – Relationships between corn seasonal evapotranspiration (ETc) and the % of dry mass partitioned into grain (%Grain), cob (%Cob) and stover (%Stover) obtained with different irrigation treatments during 2005 and 2006 at North Platte, NE. Except for %Cob in 2006, differences among treatments in all variables were statistically significant at the 5% significance level.

are presented as dry mass per plant and as a percentage of total plant dry mass (%Grain, %Cob, and %Stover). On average for all treatments, dry matter production (dry mass) for the plant and for each of the plant components was higher in 2005 than in 2006. In a percentage basis, however, the %Grain was higher, while the %Cob and %Stover were lower in 2006. In 2005, irrigation treatments significantly affected all dry matter variables, except for the dry mass of the cob and the stover. In 2006, all variables were significantly affected by irrigation treatments, except for the dry mass of the stover and the %Cob.

Combining data for both seasons, crop yield (dry-mass basis, $g\,m^{-2}$) was linearly related to the plant dry mass ($g\,plant^{-1}$) ($R^2 = 0.93$) as

$$\text{yield} = 4.09\ (\text{plant dry mass}) - 127.57 \quad (4)$$

A linear relationship for corn was also reported by Howell et al. (1997). This is not surprising because on average for both seasons, the grain accounted for about 59% of the plant dry mass, the stover for about 33%, and the cob for about 8%. The proportion of grain dry mass to total above-ground plant dry mass is usually known as the harvest index (HI), which is a value commonly used in crop modeling (Stockle and Campbell, 1985; Bryant et al., 1992). Stockle and Campbell (1985) indicated that the HI was a function of crop water stress and estimated it using empirical linear functions of a stress coefficient. Similarly, Bryant et al. (1992) estimated the HI by multiplying the ETc/ETp ratio by a potential HI values. They assumed a potential HI value for corn of 0.50 (50%), which was much lower than the values obtained in this study. Traore et al. (2000) found that HI was affected by water stress only when the stress occurred at anthesis. Under non-stress conditions they obtained HI values as high as 0.59 (59%), which were similar to the values obtained in this study for the fully irrigated treatments. The maximum HI obtained in this study was approximately 0.62 (61.77% for treatment T8 in 2006). For plants stressed at or after tasseling, however, they obtained HI values as low as 0.28 (28%).

The relationships between corn dry matter production and seasonal ETc, in terms of dry mass and in a percentage basis, are shown in Figs. 11 and 12, respectively. The dry mass of the whole plant and for each of its components increased with seasonal ETc during both seasons, although better relationships were obtained in 2006 due to the wider range in seasonal ETc among treatments. In a percentage basis, %Grain was poorly related to seasonal ETc in 2005, but a very good

relationship was obtained in 2006. In 2006, %Grain increased with seasonal ETc and then tended to level off for seasonal ETc above about 580 mm. The %Cob was well related to seasonal ETc during both seasons. In 2005, it decreased with ETc for ETc above about 580 mm. The same tendency was observed in 2006, but %Cob increased with ETc when ETc was below about 580 mm. The %Stover was very well related and decreased with seasonal ETc in 2006 for those treatments with seasonal ETc of less than about 580 mm. Since in 2005 all treatments had seasonal ETc of 580 mm or higher, the %Stover was relatively constant with seasonal ETc.

4. Conclusions

This study evaluated the effect of different seasonal irrigation depths on corn evapotranspiration, yield, water use efficiency, and dry matter production in the semiarid climate of west central Nebraska during 2005 and 2006. During both seasons, some of the irrigation treatments resulted in crop stress, which reduced seasonal ETc. In 2005, seasonal ETc for all treatments averaged 630 mm and ranged from 580 to 663 mm. In 2006, drier growing conditions resulted in a lower seasonal ETc that averaged 600 mm and ranged from 466 to 656 mm.

The differences in seasonal ETc among treatments significantly affected crop yields. In 2005, yields (dry-mass basis) averaged 968 g m^{-2} and ranged from 844 to 1085 g m^{-2} (a difference of 22%). In 2006, yields averaged 828 g m^{-2} and ranged from 455 to 957 g m^{-2} (a difference of 52%). During both seasons, irrigation significantly affected yields, which increased with irrigation up to the point where irrigation became excessive. Different yield versus irrigation functions were obtained each season, with a steeper slope obtained in 2006. Yields increased linearly with seasonal ETc ($R^2 = 0.89$) and ETc/ETp ($R^2 = 0.87$), with similar relationships observed both seasons. The average yield response factor (ky) (Doorenbos and Kassam, 1979), which indicates the effect of water stress on reducing crop yield, averaged 1.58 over the 2 years. This value was higher than the 1.25 value reported by Doorenbos and Kassam (1979) for stress during the total growing period, but close to the 1.50 value reported for stress during the reproductive stages.

Combining the data for both seasons, WUE increased nonlinearly with seasonal ETc and with yield. IWUE sharply decreased with increasing irrigation amount, with similar trends observed during both seasons, while WUE tended to increase as irrigation amount increased.

On average for all treatments, the dry mass for the plant and for each of the plant components (grain, cob, and stover) was higher in 2005 than in 2006. In a percentage basis, however, the %Grain was higher, while the %Cob and %Stover were lower in 2006. In 2005, irrigation treatments significantly affected all dry matter variables, except for the dry mass of the cob and the stover. In 2006, all variables were significantly affected by irrigation treatments, except for the dry mass of the stover and the %Cob. The grain accounted for the majority of the above-ground plant dry mass (≈59%), followed by the stover (≈33%) and the cob (≈8%). The good relationships obtained in the study between seasonal ETc and crop performance indicators (such as yield, WUE, IWUE, and dry matter) demonstrate that accurate estimates of ETc in a daily and seasonal basis can be valuable for making tactical in-crop irrigation management decisions and for long-term and pre-season strategic irrigation planning.

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