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Using Soil Water and Canopy Temperature to Improve Irrigation Scheduling for Corn

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Abstract.

With declining well capacities in the Central High Plains resulting from withdrawals exceeding recharge in the Ogallala aquifer, producers will need to adopt advanced irrigation scheduling to maintain productivity with limited water. A study was conducted to assess the effect of irrigation scheduling approaches based on plant water stress sensing, soil water sensing, and climate (ET), or a combination of these methods on corn growth, yield, and water productivity of two hybrids (conventional and drought tolerant), seasonal crop water use, and total irrigation applications. The study involved five irrigation scheduling treatments applying 80% of full irrigation and a control (full irrigation) treatment and two corn hybrids arranged in a split-plot design. Results indicate there were no significant differences in yield among irrigation scheduling methods (p-value=0.38). However, there were significant differences in yield between conventional and drought tolerant corn hybrids (p-value=0.003), on average there was a 20% yield advantage for the conventional hybrid. There were no-significant interactions between irrigation scheduling and corn hybrid (p-value=0.48). Treatment T2 based on crop water stress sensing using the Time Temperature Threshold used 11% more water compared to the standard irrigation scheduling method based on neutron probe monitoring (T1) but resulted in the highest yield for the drought tolerant corn (189 bu/ac). Treatment 3 that triggered irrigation based on soil water sensors resulted in 22% more water applied compared to the standard method, but also resulted in the highest yield (219 bu/ac) for the conventional corn hybrid. Yields appear to have been affected by hail damage that occurred earlier in the season (at growth stage V14) resulting in reduced canopy cover as quantified through leaf area index measurements. Residual soil water effects from a previous study also influenced yields, with treatments located in high water level areas producing higher yields compared to those in low water level locations. Preliminary data indicates that soil-based, plant-based, and/or climate based irrigation scheduling can result in improved crop water productivity particularly under non-ideal growing environments where external abiotic and biotic factors could influence in-season crop water use. Matching irrigation applications with crop use under non-ideal environments could help producers to maintain profitability and conserve water. Integrating soil and plant water status monitoring with the scientifically robust ET-based scheduling could encourage more producers to adopt irrigation scheduling through visual illustrations of root water uptake.

Key words. Irrigation scheduling, soil water, canopy temperature

Introduction

Restrictions in water supplies whether physical (diminished well capacity) or legal (Local Enhanced Management Areas, LEMA), will force many producers to face the prospect of adopting some degree of deficit irrigation. To cope with limited water supplies, producers will have to adjust their irrigation management by adopting strategies such as: reducing irrigated acreage, deficit irrigation of a portion or all acreage, growing crops with different or lower water requirements at different times of the season (e.g., corn and soybean), minimizing water stress during critical reproductive growth stages, crop rotations, reduced tillage and residue management, drought tolerant hybrids, and advanced irrigation scheduling practices. Although it would take an integrated approach to cope with limited water supplies, this study focused on irrigation scheduling approaches involving a 20% reduction in available water as proposed under one LEMA currently operating in Northwest Kansas. Klocke et al. (2011) reported that a 20% reduction in irrigation water applied did not result in significant differences in corn yield. However, it should be noted that curves of yield responses to water are substantially influenced by variations in climate, soil, and other environmental conditions. In addition to pre-season decision making related to allocation of limited water resources to land and crop enterprises, producers have to make tactical in-season water management decisions mainly involving irrigation scheduling. In this study we evaluated water technologies that could improve reliability of irrigation scheduling for corn as the dominant irrigated crop in Kansas.

Traditionally, irrigation scheduling has been based on the producer's perceptions of plant water needs or calendar date irrespective of variation in weather conditions, or fixed crop rotations. Jensen et al. (1970) noted that farmers are reluctant to deviate from traditionally accepted scheduling methods regardless of relative merits of alternative scheduling methods until they are shown that improvements in scheduling results in greater net returns. However, as well capacities dwindle irrigators will need to adopt irrigation scheduling to maintain productivity. Howell and Evett (2005) defined irrigation scheduling as the process of making decisions on the irrigation amount and timing subject to the irrigation water supply constraints and in concert with labor and cultural crop practices with the goal to maximize profits per unit of inputs. Lamm (2014) coined a new definition for irrigation scheduling as being the process of delaying any unnecessary irrigation with the hope that the irrigation season will end before the next irrigation is needed. These definitions highlight the challenges associated with maximizing profitability when irrigating with limited water supplies.

Irrigation scheduling is accomplished using different approaches including: 1) evapotranspiration (ET) also known as ET-based scheduling, 2) measuring a soil water status property using sensors (e.g., dielectric permittivity), and 3) measuring a plant water status property (e.g., canopy temperature) using sensors. The latter is typically used to indicate need for irrigation while 1 and 2 can be used to determine need and amount of irrigation water required. Unfortunately, none of the measurement based methods or soil water balance based irrigation scheduling tools are perfect or without bias. Howell et al. (2012) noted that relying on only one measurement technology can result in mis-diagnosing of abiotic (e.g., soil water stress, wind damage) and biotic stress (e.g., crop damage due to pests, diseases) effects on irrigation scheduling decisions, and recommended using one or more irrigation scheduling methods as a check to avoid over or under irrigation. For example, the ET-based approach works well for near ideal crop conditions, but combining it with soil water sensing and thermometry can help detect abiotic and biotic stresses that could improve reliability of irrigation scheduling decisions. In this study we used the time domain reflectometer based senor to measure soil water content and individually calibrated infrared thermometers to measure canopy temperature.

There are also various types of soil water sensors with varying levels of accuracy. Chavez and Evett (2012) provided a description of various sensor technologies and comparison of various sensors. Their results indicated that the CS655 soil water sensor was one of only two sensors at the time of testing that proved to be accurate compared to gravimetric sampling and TDR measurements. For this study we used the CS655 for continuous monitoring of soil water. In addition to volumetric water content, the CS655 also provides bulk electroconductivity and soil temperature that could be useful for salinity management and planting decisions respectively. They noted that poor installation could affect measured data and that performance of the sensor could be improved by developing linear calibration equations for specific soil types. The CS655 sensor works on a similar principle as a TDR in that the travel time of a reflected electronic pulse is measured using electronics embedded in the sensor head. Unlike the TDR, the CS655 does not capture the wave form of the reflected electronic pulse. Instead, it sends out an electronic pulse along two electrodes that is reflected from the end of the rod. When the sensor head detects the reflected pulse, it sends another pulse and records the frequency of the pulses which it reports as period or inverse of frequency (µs). The period is affected by soil dielectric permittivity which is also influenced by soil water content. The manufacturer provides a calibration equation in the datalogger that relates the period to soil water content (Campbell, 2011). For optimum plant growth, it is desired that soil water is monitored to ensure it is maintained above 50% of plant available water.

There are also various types of infrared thermometers which Mahan and Yeater (2008) classified as industrial quality (e.g., S-111 [Apogee Instrument Inc., Logan, UT] and Exergen model IRt/c.2 type K 27C [Exergen, Watertown, MA]) and consumer quality (e.g., Zytemp model TN901 IRt [Zytemp HsinChu, Taiwan, ROC]). The advantage of the later is low cost and compatibility with wireless configurations. They recommended that for applications where canopy temperature must be precisely and accurately known, currently industrial quality IRts (e.g., from Apogee instruments) would be the best choice. For large scale agricultural applications, inclusion of consumer quality IRts into a wireless network could be advantageous. In this study we used the industrial quality S-111 IRt (Apogee Instrument Inc., Logan, UT). The S-111 measures both surface temperature (canopy temperature) and the sensor body temperature. Calibration equations in the data logger are then used to calculate the correct surface temperature. Plant canopy temperature has long been shown as a useful measure of plant water stress (Idso et al., 1981; Jackson, 1982). Examples of irrigation scheduling studies in which canopy temperature has been used include (Nielsen and Gardner, 1987; Steele et al., 1994; Evett et al., 2002; Lamm and Aiken, 2008; O'Shaughnessy et al., 2011; Schneekloth and Schlegel, 2012). Different indices are used to schedule irrigation based on canopy temperature including the of the crop water stress index (CWSI) and the time temperature threshold (TTT) among others. Maes and Steppes (2012) provided a review of various water stress indices. In this study we used the TTT index and the empirical CWSI to monitor water stress.

The TTT index was developed from observations that plant enzymes are most productive under a very narrow range of temperatures called the thermal kinetic window (Burke, 1993). In the TTT approach, the accumulated time that canopy temperature exceeds the threshold temperature is used as criteria for triggering irrigation. For example, the threshold temperature for corn in the South and Central High Plains was determined by Evett (2002) as 82^{o}C and threshold time was 240 minutes, implying that if corn canopy temperature exceeded 28^{o}C for more than 4 hours irrigation would be triggered. The TTT method is advantageous over the CWSI approach since it does not require determination of lower and upper baselines required to evaluate CWSI (Colaizzi et al. 2012). O'Shaughnessy and Evett (2011) reported that the TTT algorithm appeared to be more responsive to a wide range of meteorological conditions since it was a time-integrating method compared to indices based on measurement's made only once a day. The major advantage of the CWSI over the TTT is that it includes other environmental factors which could affect canopy temperature such as wind speed, solar radiation and vapor pressure deficit.

The ET-based approach was used as the main scheduling method while plant canopy temperature and soil water monitoring were used as a check for reliability or trigger of the need for irrigation. The purpose of this study was to assess the effect of irrigation scheduling methods based on canopy temperature, soil water content, and climate (ET), or a combination of these methods on reducing seasonal water applications while maintaining corn yield and productivity. The specific objectives were to: 1) evaluate the effect of irrigation scheduling method on growth, yield, and water productivity of two corn hybrids, 2) determine total irrigation water applied by each scheduling method, and 3) assess soil water response to the irrigation scheduling methods.

Materials and Methods

Experimental site characteristics

The study was conducted at the Kansas State University Southwest Research and Extension Center Finnup farm (38^{o}01'20.87''N, 100^{o}49"26.95W, elevation of 2910 feet above mean sea level) near Garden City, Kansas. The climate of the area is semi-arid. Summers are hot and generally less humid while winters can vary between warm and very cold. The soil at the study site is a deep well drained Ulysses silt loam (fine ‑ silty, mixed, mesic Aridic Haplustoll) with a slope of 0 to 1%. The soils have an average available water capacity (available water between field capacity and permanent wilting point) of 0.19 to 0.24 in/in. Bulk density ranges between 0.045 and 0.052 lb/in^{3} (or 1.24 and 1.46 g/cm^{3}) while organic matter in the top foot ranges between 1.1 to 1.6% and decreases with increasing depth. A four span (140 feet span width) lateral move sprinkler irrigation system (model 8000, Valmont Corp., Valley, NE) modified as described in Klocke et al. (2003) to apply irrigation water in any desired treatment combination was used. The system has valves to control banks of 9 nozzles along the lateral. Each bank of nine nozzles represented a management zone or experimental plot. The plot sizes were 45 feet wide by 92 feet long.

Irrigation Water Management Treatments

The experimental design was a split-plot randomized complete block design with four replications. Each span represented a replication with six randomized treatments. Irrigation scheduling was the main factor with five levels replenishing 80%ET based soil water, and canopy temperature monitoring and a control treatment replenishing 100%ET intended to quantify the impact on yield of a 20% reduction in irrigation water applied.

Irrigation scheduling treatments were to irrigate by replenishing 80% ET since the last irrigation when: 1) available soil water (ASW) in the top 4 feet of the root zone falls below 60% based on weekly soil water measurements made using a neutron probe (T1), 2) canopy temperature time-temperature-threshold (TTT) exceeds 82^{o}F for more than 240 minutes on a given day (T2), 3) ASW in the top 4 feet of the root zone falls below 60% based on soil water sensor measurements; note: although similar to treatment 1, the goal was to use a soil water sensing technology different from a neutron probe to arrive at an irrigation decision (T3), 4) either CWSI exceeds 0.3 or 60% ASW thresholds are exceeded (T4), 5) both soil water and CWSI thresholds as in T4 have been exceeded (T5), and 6) control treatment replenishing 100% ET or full irrigation (T6). Treatment 1 was used as the scientific standard reference irrigation scheduling method. All irrigation events were designed to provide a net irrigation of 1 inch to minimize evaporation losses which can be significant for small applications under advective environments in the Central Plains. The amount applied during each event was confirmed through a catch can test (data not shown). Irrigation requirements in excess of the 1 inch were transferred to the next irrigation event. Weekly soil water depletions were confirmed using neutron probe measurement. Daily crop water use (ETc) was estimated using alfalfa modified Penman equation (Lamm et al., 1994). Meteorological data for computing ET was obtained from a Kansas Mesonet weather network (http://mesonet.k-state.edu/) located approximately 2.8 miles southeast of the study site.

Soil and Plant Water Status Sensing

Soil water and canopy temperature sensors were installed to serve as checks on the adequacy of the ET-based irrigation schedules and also to indicate need for irrigation. Soil water sensors (CS655; Campbell Scientific Inc., Logan UT, USA) were installed in treatments 3, 4, and 5 in the drought tolerant hybrid. Each set of soil water sensors comprised of three sensors placed at depths of 1, 2, and 3 feet. Data was collected hourly and averaged over 24 hours. Accuracy of the soil water sensors was checked against a field calibrated neutron probe (Campbell Pacific Nuclear, Model 503DR, CPN International Inc., CA, USA) readings in each treatment. Soil water sensors have the advantage of providing soil water data with high temporal resolution and are more adaptable by the farmers compared to the neutron probe although the latter is more accurate.

Infrared radiometers (SI-111: 22^{o} half angle field of view, spectral range 8 to 14 μm, Apogee Instruments Inc., Logan UT, USA) were installed within 3 experimental plots for monitoring canopy temperature in drought tolerant corn hybrids. A total of 12 infrared radiometers were required in treatments 2, 4, and 5 by four replications. The sensors were positioned approximately 3 feet above the crop canopy at a 45^{o} from the horizontal view angle. A VP-3 relative humidity, air temperature, and vapor Pressure sensor with radiation shield (VP-3; Decagon Devices, Inc. Pullman, WA) was installed in the field to monitor the microclimate (relative humidity, temperature and vapor pressure) within the experimental plots during the study. All sensors were connected to a CR1000 data logger (Campbell Scientific Inc., Logan UT, USA) and all cables were put in PVC conduits to prevent rodent damage. Data was manually downloaded at least twice a week and analyzed for possible irrigation triggers before irrigation decisions were made. A program was written in CR Basic and passed to the CR1000 dataloggers to output alarms when TTT and CWSI thresholds were exceeded. The TTT approach was implemented as described in (Colaizzi et al. 2012). The empirical CWSI was estimated using baselines derived for corn in the Central High Plains by Nielsen and Gardner (1987).

Agronomic Management

The experimental field was maintained in a no-till cropping system for over ten years and the previous crop prior to 2014 was corn. Two Monsanto corn cultivars: 1) with transgenic drought tolerant trait [Genuity® DroughtGard, 62-27 DGVT2PRO], and 2) conventional locally adapted hybrid without transgenic DT trait [DeKalb DKC 62-98 VT2PRO] were planted. The hybrids had a relative maturity of 112 days. The planting was done using a no-till planter. Planting depth was 2 inches and seeding rate was 31,500 seeds/acre applied uniformly across all treatments. The no-till planter was equipped with a single coulter preceding a double disc furrow opener, and two rubber-tire closing wheels. The crop row direction was north -south. Fertilizer applications, weed control, and no-till planting are summarized in Table 1 and were applied uniformly to all the treatments following Kansas State University Best Management Practices recommendations. Starter fertilizer was directly delivered to the seed furrow while the side dress was applied in a stream directly behind a coulter in every other pair of corn rows.

Table 1. Agronomic Data

Parameter	2014
Variety	1. DroughtGard, 6227DGVT2PRO 2. DeKalb DKC 62-98 VT2PRO
Population	31,500 seeds/acre
Fertilizer Application	
Starter (10-34-0)	N: 10 (5/05)[1] and P_2O_5:35 (5/05)
Side dress (32-0-0)	N: 272 (6/12)
Herbicide	Rate (Date)
Pre-plant	
Atrazine	1.5 lbs/ac (04/21)
S-Metolachlor	32 oz/ac (04/21)
dicamba	6 oz/ac (04/21)
Isoxaflutole	0.75 oz/ac (04/21)
Fluroxypyr	13 oz/ac (04/21)
Glyphosate	32 oz/ac (04/21)
Post-emergence	Rate (Date)
Glyphosate	36 oz/ac (06/13)
Fluroxypyr	16 oz/ac (06/13)
Pendamethalin	32 oz/ac (06/13)
Atrazine	0.5 lbs/ac (06/13)

[1] Numbers in parentheses are dates of application

Crop Measurements and Water Use Calculations

Corn growth stages were recorded through weekly visits to the experimental plots. Dates of growth stages such as emergence, tasseling, and physiological maturity were recorded. LAI was measured on July 28, 2014 using the non-destructive AccuPAR model LP-80 ceptometer (Decagon Devices, Inc., Pullman, WA). The LP-80 ceptometer uses above canopy radiation measurements, and canopy intercepted PAR (photosynthetically active radiation) to calculate LAI. In this study, an external PAR sensor was mounted on a 6 feet long PVC pipe with a diameter of 1 inch to allow simultaneous measurement of below and above canopy PAR measurements. Grain yield was hand harvested on October 6th, 2014 by taking two 10 feet representative rows. The grain yield data were standardized to 15.5% moisture content to allow for comparison. Measured yield was then used to calculate water productivity, and irrigation water use efficiency as expressed in equations 1 and 2:

$$CWP = \frac{Y}{ET_c} \tag{1}$$

$$IWUE = \frac{Y_i - Y_r}{I} \tag{2}$$

where CWP is the crop water productivity (bu/ac-in) which is a measure of the amount of marketable product per unit volume of water input, *Y* is grain yield (bu/ac), *Yi* is economic yield of irrigated crop, *Yr* is rainfed yield, and *ETc* is actual seasonal crop evapotranspiration (in).

Estimation of Seasonal Evapotranspiration from Soil Water Balance

Soil water was measured weekly to a depth of 8 feet at intervals of 1 foot using the neutron attenuation technique (Evett, 2008). The neutron probe access tube was placed between two plants in a representative row of each hybrid. Seasonal ETc was estimated from the soil water balance equation (3):

$$ET_c = P + I - R - D \pm \Delta SWS \tag{3}$$

where ETc is crop evapotranspiration (in), P is precipitation during the growing period (in), I is applied irrigation (in), R is runoff (in), D is percolation below the root zone; drainage beyond 8 feet was considered as percolation, ΔSWS is the change in soil profile water between the beginning and end of the sampling period (in). *P* was measured using several rain gauges located adjacent to the experimental plots, *I* was estimated as previously described, *R* was observed to be negligible while ΔSWS was estimated from neutron probe readings. ETc between the first neutron probe measurements and emergence was estimated using the WAVE (Water and Agrochemicals in the soil, crop and Vadose Environment) vadose model (Vanclooster et al., 1995; Kisekka et al., 2014). By providing WAVE inputs of planting date, weather data, crop coefficient, estimated LAI and rooting depth, soil water content at emergence was simulated. The difference between soil profile water content at emergence and first neutron probe reading was used to estimate ETc between emergence and first soil water readings. The advantage of WAVE in simulating soil water dynamics is its physical basis; WAVE solves the Richards equations which allows for water movement up or down the soil profile based on hydraulic head differences within the root zone.

Statistical Analysis

Data was statistically analyzed using Proc Mixed procedures in SAS version 10 (SAS Institute Inc., Cary, NC, USA). Where the Irrigation scheduling method was the main factor and corn hybrid was the subplot factor.

Preliminary results

Weather

Rainfall during the 2014 growing season from May 1st to September 30 exceeded normal rainfall (1981-2010) by 6.8 inches. Figure 1 shows daily rainfall totals and cumulative amounts with 2014 growing season rainfall totaling 17.05 inches. About 56% of this coming in the month of June which corresponded to corn vegetative growth stages of V5 to V16. A large rainfall event of 2.7 inches occurred on June 24th in less than 24 hours which could have resulted in runoff. However, the offseason was very dry with only 1.22 inches between January 1 and April 30. Average seasonal maximum temperature was slightly above normal (86.1 versus 85.5°F), while average growing season minimum temperature was also slightly above normal (57.9 versus 57.4°F) as shown in Figure 2. Solar radiation on average was higher during the vegetative growth stages and gradually decreased during reproductive growth stages (Figure 2). Vapor pressure deficit did not show any particular trends during the growing season with a few spikes in June and late July. There were more days of high wind speeds from emergence to late vegetative growth stages than there were during reproductive growth stages, mitigating excessive evaporative demands during the critical growth periods (Figure 2).

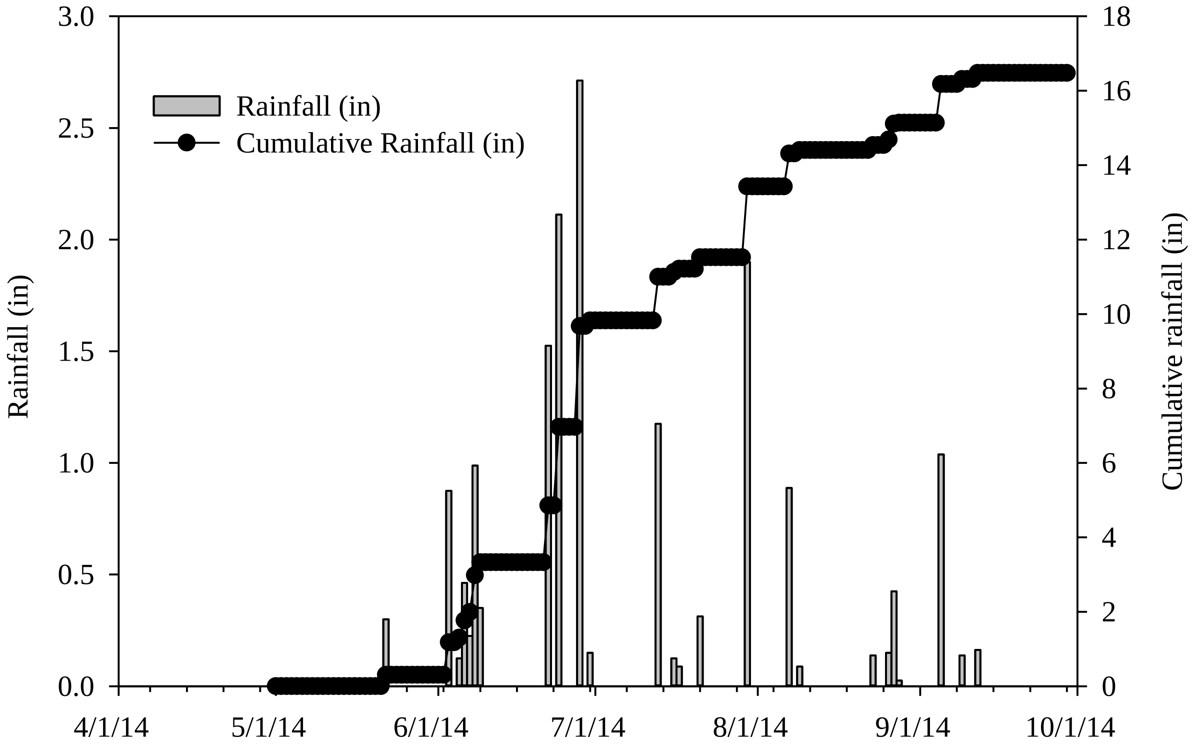

Figure 1. Daily and cumulative rainfall measured at the study site during the 2014 corn growing season.

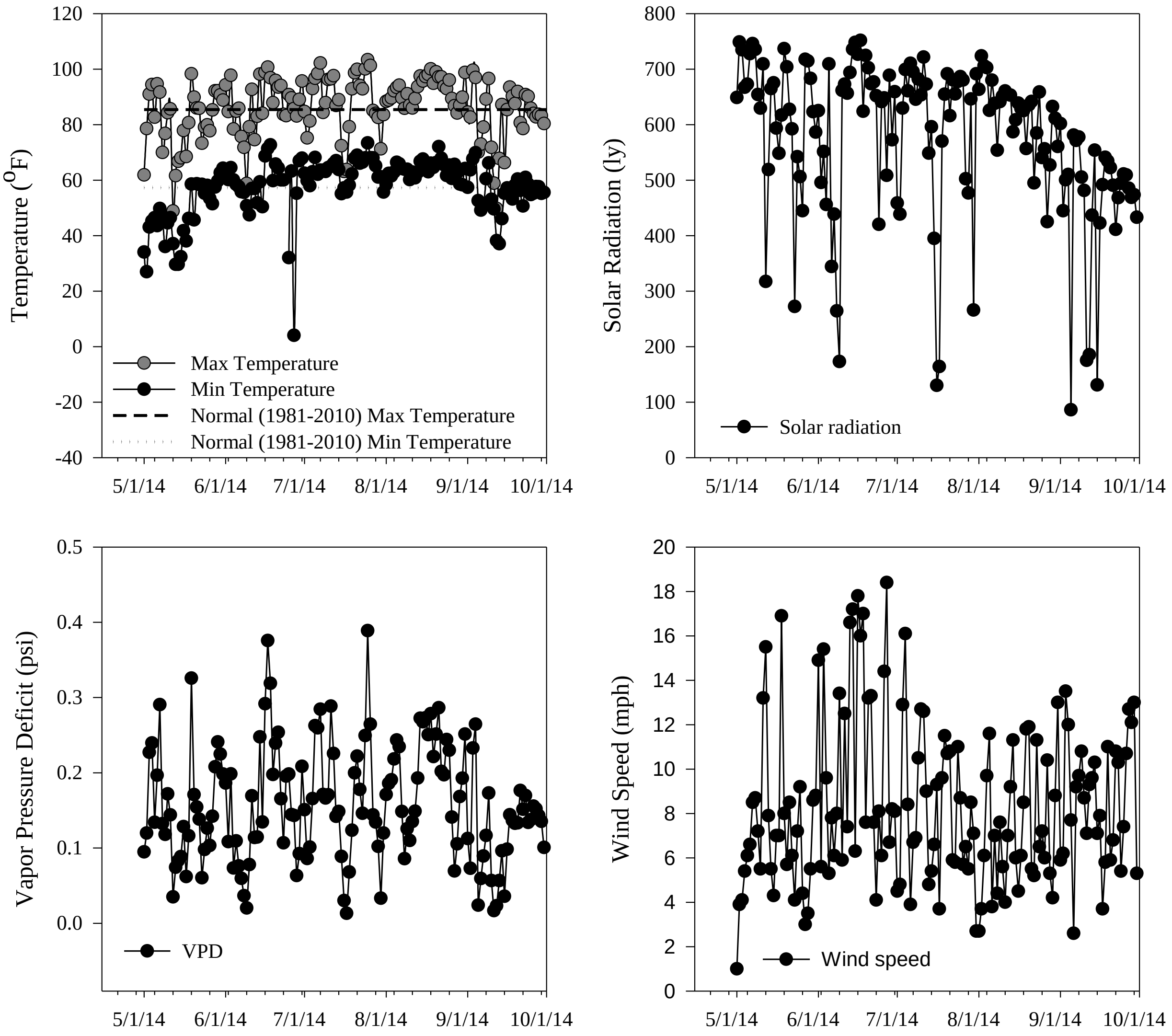

Figure 2. Temperature, solar radiation, vapor pressure deficit (calculated), and wind speed for 2014 growing season measured at the Kansas State University Mesonet located 2.9 miles southeast of the study site in Garden City Kansas.

Biophysical Measurements

Growth stages were recorded weekly as well as soil water content with the neutron probe. Major growth stages and dates of occurrence are summarized in Table 1. Both the drought tolerant corn hybrid and the conventional corn hybrid reached major growth stages approximately at the same time. However, tassel was reached sooner (3 days earlier) for the fully irrigated treatment compared to the five deficit irrigation scheduling treatments, probably due to external environmental stress. LAI measurements made on July 28 2014 (a week after tassel) indicated that the conventional corn hybrid had higher LAI compared to the drought tolerant corn hybrid particularly for the deficit irrigated treatments 1 to 5 as shown in Figure 3. The observed lower values of below canopy photosynthetically active radiation (data not shown) or PAR (µmol photons $m^{-2}s^{-1}$) suggested reduced leaf growth for the drought tolerant hybrid. Nemali et al (2014) studied physiological responses of a transgenic/biotechnologically derived drought tolerant corn hybrid to different levels of water stress and observed that the hybrid expressing the bacterial cold shock protein B (CspB) for drought tolerance exhibited increased ear growth, decreased leaf area index, and decreased leaf dry weight and sap flow rate during silking under water stress conditions, but no differences were observed under well watered conditions. The lower values of LAI observed in this study compared to values in other studies as high as 5 or larger could be attributed to hail damage that occurred on June 24, and difference planting density among other factors.

Table 2. Growth stages for two corn hybrids and five deficit irrigation scheduling treatments (1 to 5) and a full irrigation treatment (6)

Growth Stage	Date
Planting	05/05/2014
Emergence	05/21/2014
Tassel	07/21/2014 (07/18/2014)*
Black layer	10/01/2014
Harvest	10/06/2014

*Tassel date for treatment 6

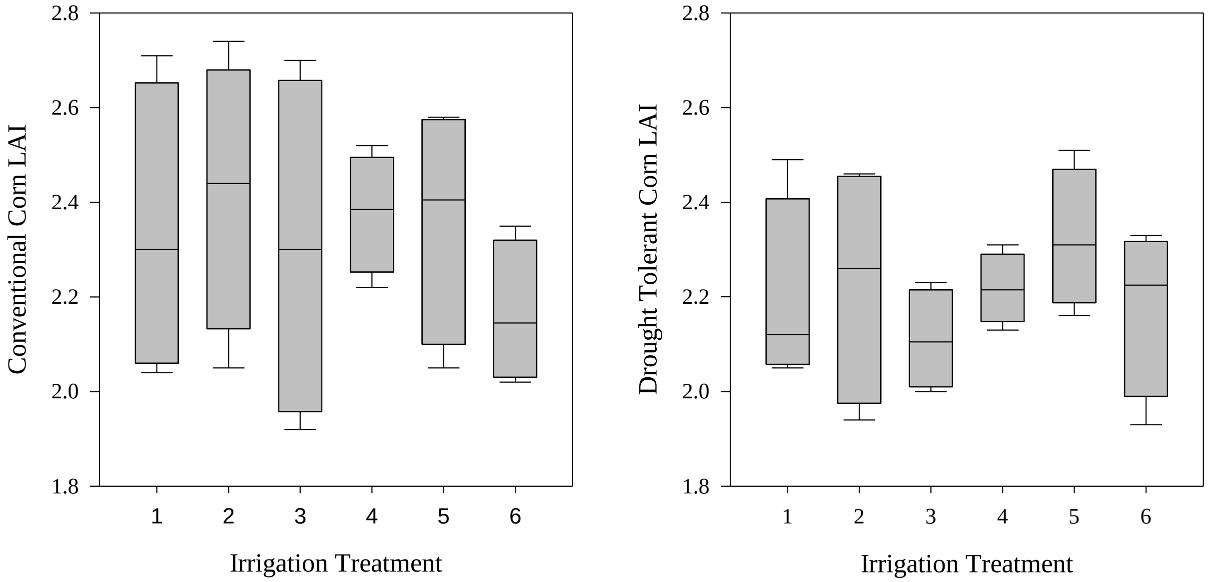

Figure 3. Measured leaf area index (LAI) on July 28, 2014 for Conventional and Drought Tolerant and corn hybrids for all irrigation treatments.

Yield Responses

Average treatment yields and seasonal crop evapotranspiration for the two corn hybrids are summarized in Table 3. Yields did not differ significantly (p-value=0.38) across the five irrigation scheduling treatments. There was also no significant difference between the 100%ET treatment (T6) and the 80%ET treatments T1 to T5. The yield of the fully irrigated treatment (T6) was lower than that for treatments 1, 3, and 5 for the conventional corn hybrid and less than treatments 1 through 5 for the drought tolerant hybrid. This could probably be attributed to the hail storm that occurred early in the season (June 24, 2014) that effected canopy cover as shown by the low LAI, particularly for the conventional hybrid (Figure 3). Treatment 2 based on canopy temperature and the time temperature threshold produced approximately 2% more yield compared to treatment 1 for the conventional hybrid and 4% higher yield for the drought tolerant hybrid. Treatment 3 based on calibrated CS655 soil water sensors produced 5% higher yield than T1 for the conventional hybrid and 1% higher yield for the drought tolerant hybrid. Treatment 4 that triggered irrigation events based either soil water or plant stress thresholds being exceeded produced yields that were 12% lower for the conventional hybrid and 3% higher for the drought tolerant hybrid compared to treatment1. Yields for treatment 5 that triggered irrigation only if both soil water and plant water stress (CWSI=0.3) thresholds were exceeded produced yields that were lower than those for treatment 1, 9% for conventional hybrid and 4% for the drought tolerant hybrid.

However, there were significant differences between drought tolerant and conventional corn hybrids (p-value=0.003). There was no-significant interaction between irrigation scheduling and corn hybrid (p-value=0.45). With the exception of treatment 4, the conventional hybrid out yielded the drought tolerant hybrid on average 20%. Again these observations could be attributed to reduced canopy cover from hail damage, particularly in the drought tolerant hybrid, which also unfortunately lead to increased weed pressure in these plots due to more direct solar radiation reaching the ground surface. From Table 3, it appears seasonal ETc did not differ substantially between the two hybrids despite the fact that the drought tolerant hybrid had less canopy which could have contributed to reduced water use. This could probably be attributed to an increase in soil evaporation as transpiration reduced.

Table 3. Yield response to irrigation scheduling method and corn hybrid during the 2014 growing at Garden City Kansas.

Treatments	Yield (bu/ac)		Yield (bu/ac)		Seasonal ETc (in)	
	Conventional	Std.[1]	Drought Tolerant	Std.	Conventional	Drought Tolerant
T1	206	32	181	18	22 (2)[2]	21 (2)
T2	209	13	189	13	25 (1)	26 (1)
T3	219	23	179	23	25 (2)	24 (2)
T4	182	26	186	17	24 (1)	24 (0)
T5	192	12	173	22	23 (1)	23 (2)
T6	189	8	173	32	25 (1)	25 (1)

[1] Standard Deviation

[2] Numbers in parentheses are standard deviations

Irrigation and Water Use

The number of irrigation events, irrigation frequency and total irrigation is summarized in Table 4. The fully irrigated treatment (T6) received 42%, 33%, 25%, 17% and 25% more water compared to treatments T1 through T5, which were designed to replenish only 80% of full irrigation. As explained earlier, despite the large amount of irrigation applied to treatment 6, its yields were lower than all other treatments with the exception of treatment 4. All treatments received 2 inches of pre-irrigation prior to emergence to allow for germination and plant establishment since only 1.25 inches of rainfall had been received since January 01, prior to planting on May 05. Of all the treatments, the standard irrigation scheduling method based on monitoring soil water using the neutron probe and a threshold of 60% plant available water required the least amount of water. Treatment 2 based on the TTT required 11% more water, while treatments 4 and 5 required 33% and 11% more water compared to treatment 1 respectively. Treatment 3 based on using a calibrated CS655 soil water sensor required 22% more water compared to treatment 1, this treatment also resulted in the highest yield for the conventional corn hybrid.

Average crop water productivity (CWP) and irrigation water use efficiency (IWUE) are summarized in Table 5. The conventional corn hybrid had higher crop water productivity compared to the drought tolerant hybrid. All deficit irrigation scheduling treatments had higher crop water productivity compared to the fully irrigated treatment since the high ET (25 inches) for treatment 6 was not proportionally related to yield as would be expected under conditions with no external abiotic stresses. Treatment 3 based on calibrated soil water sensor had the highest water productivity. Overall the CWP did not vary substantially among irrigation scheduling methods.

Irrigation Water Use Efficiency (IWUE) was higher for conventional versus drought tolerant corn. The fully irrigated treatment resulted in the lowest IWUE again probably due to external abiotic stresses since not all water applied was beneficially used to produce economic yield. Some water could have been used in producing non-economic yield like weeds. The reference irrigation scheduling treatment T1 had the highest IWUE followed by treatment T2 based on canopy temperature. These results highlight the need for integrated monitoring of the soil water, and plant stress (both abiotic and biotic) when growing crops under non ideal environments. For example, the fully irrigated treatment designed to replace 100 % ET did not account for reduced water use resulting from canopy damage caused by hail and ended up applying more than 4 inches of water than would be required given the reduced yield potential. This suggests that irrigation water management without feedback from monitoring could result in reduced profitability. Unfortunately in the Central Plains, in addition to water stress there are many other external factors that lower yield potential (e.g., hail, temperatures, pests and diseases).

Table 4. Irrigation applications, frequency and total irrigation applied to five deficit irrigation scheduling treatments (80% of full irrigation) and control (full irrigation)

Treatment	Number of Irrigation Events	Irrigation Frequency (days)	Pre-irrigation[1] (in)	In-season Irrigation[2] (in)	Total Irrigation (in)
T1	7	6.7	2	7	9
T2	8	6.0	2	8	10
T3	9	5.4	2	9	11
T4	10	5.6	2	10	12
T5	8	6.0	2	8	10
T6 (Full)	12	4.5	2	12	14

[1] Irrigation applied before crop emergence

[2] Irrigation applied between emergence and harvest

Table 5. Crop Water Productivity and Irrigation Water Use Efficiency for 5 deficit irrigation scheduling methods and a control (full irrigation)

Treatments	CWP (bu/ac-in)		IWUE (bu/ac-in)	
	Conventional	Drought Tolerant	Conventional	Drought Tolerant
T1	12.4 (2.1)	10.6 (1.1)	29.5 (4.5)	25.8 (2.6)
T2	12.9 (0.9)	10.7 (0.8)	26.2 (1.6)	23.7 (2.6)
T3	13.0 (1.7)	10.7 (1.3)	24.3 (2.6)	19.9 (1.7)

T4	11.3 (1.2)	10.7 (1.4)	18.2 (2.6)	18.6 (1.7)
T5	12.0 (0.7)	10.7 (1.0)	24.0 (1.5)	21.7 (2.7)
T6 (Full)	11.1 (0.3)	9.7 (2.4)	15.8 (0.7)	14.4 (2.7)

[1] Standard Deviation

[2] Numbers in parentheses are standard deviations

Soil Water Analysis

The first neutron probe soil water content measurement was made on July 10, 2014, due to practical issues such as wet field conditions that prohibited installation of the neutron probe access tubes earlier in the season. Soil water measurements were taken at different depth in increments of 1 foot down to 8 feet. The soil water data indicates that residual soil water effects from a prior study had significant effect on soil profile water content as shown in Figures 4 and 5. Prior to July 10, all treatments were managed the same, receiving only two pre-irrigations to support germination and plant establishment. Treatments 1, 2, and 3 were in the high water plots in the previous study while treatments 4, 5 and 6 were in the locations of low irrigation levels. Soil water measurements in the top 4 feet on DOY191, corresponding to July 10, indicated that soil water content was less than 50% depleted (based on 0.33 =0% depleted and 0.15=100% depleted) in treatments 1 to 3 while treatments 4 and 5 were between 50 to 75% depleted. Treatment 6 was very dry ranging from approximately 70% to 100% in the top 4 feet. Since the study was conducted under no-till system, the high water plots from the previous study also tended to have high crop residue cover.

The neutron probe readings were taken approximately 11 days before tassel which is a sensitive stage to water stress. These data could also explain the differences in yields between treatment sets 1 to 3 and 4 to 6. It appears the full irrigation treatment was not able to restore soil water content in the top 4 feet to less than 50% depleted by tassel (DOY 202 or July 21). This could also explain why this treatment tasseled earlier than other treatments. These results underscore the need to have sufficient soil profile water at planting, since the irrigation system might not catch up with plant water use during the season.

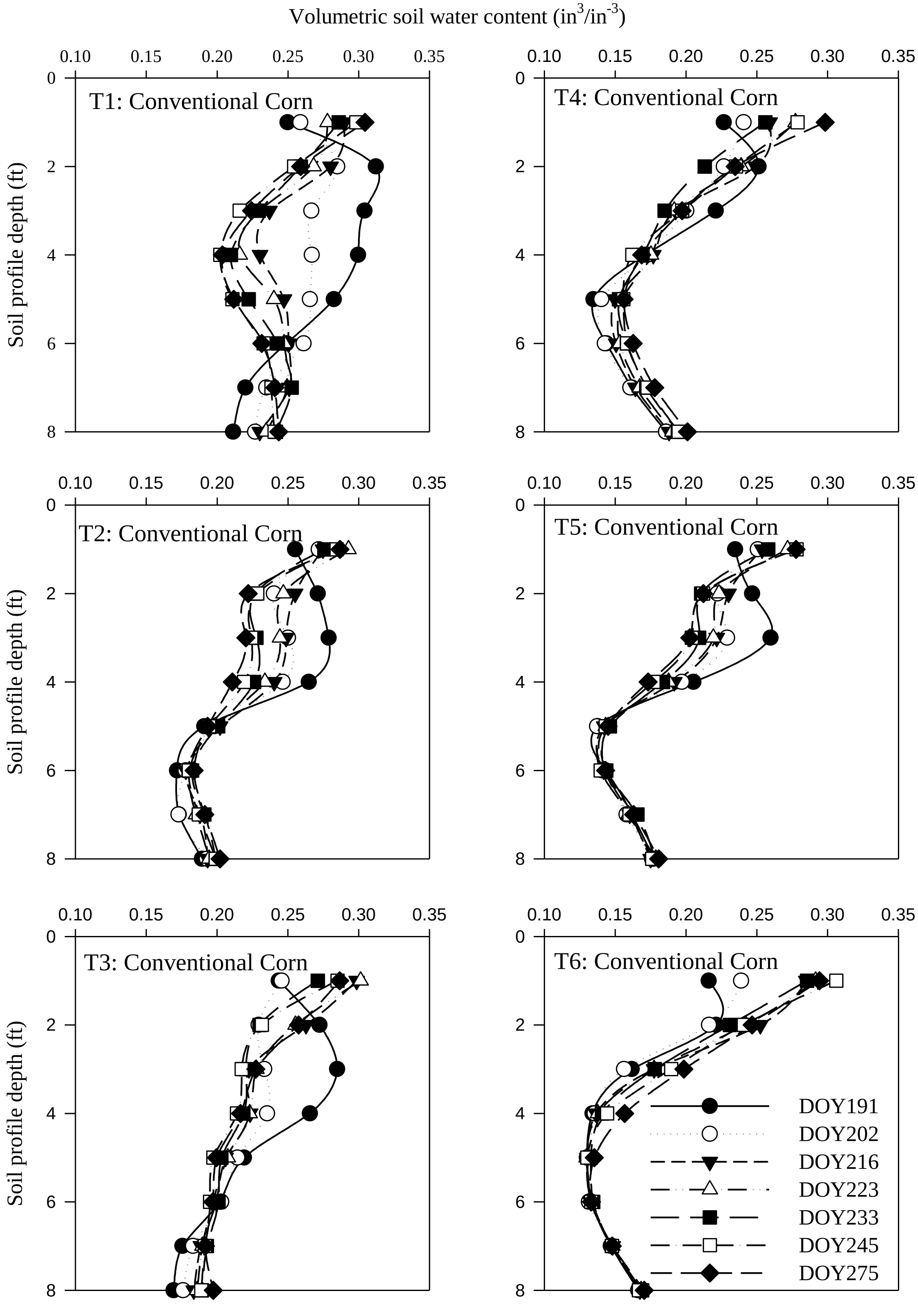

Figure 4. Soil profile water content taken at different depth using a neutron during the 2014 growing season in the conventional corn plots at Garden City Kansas.

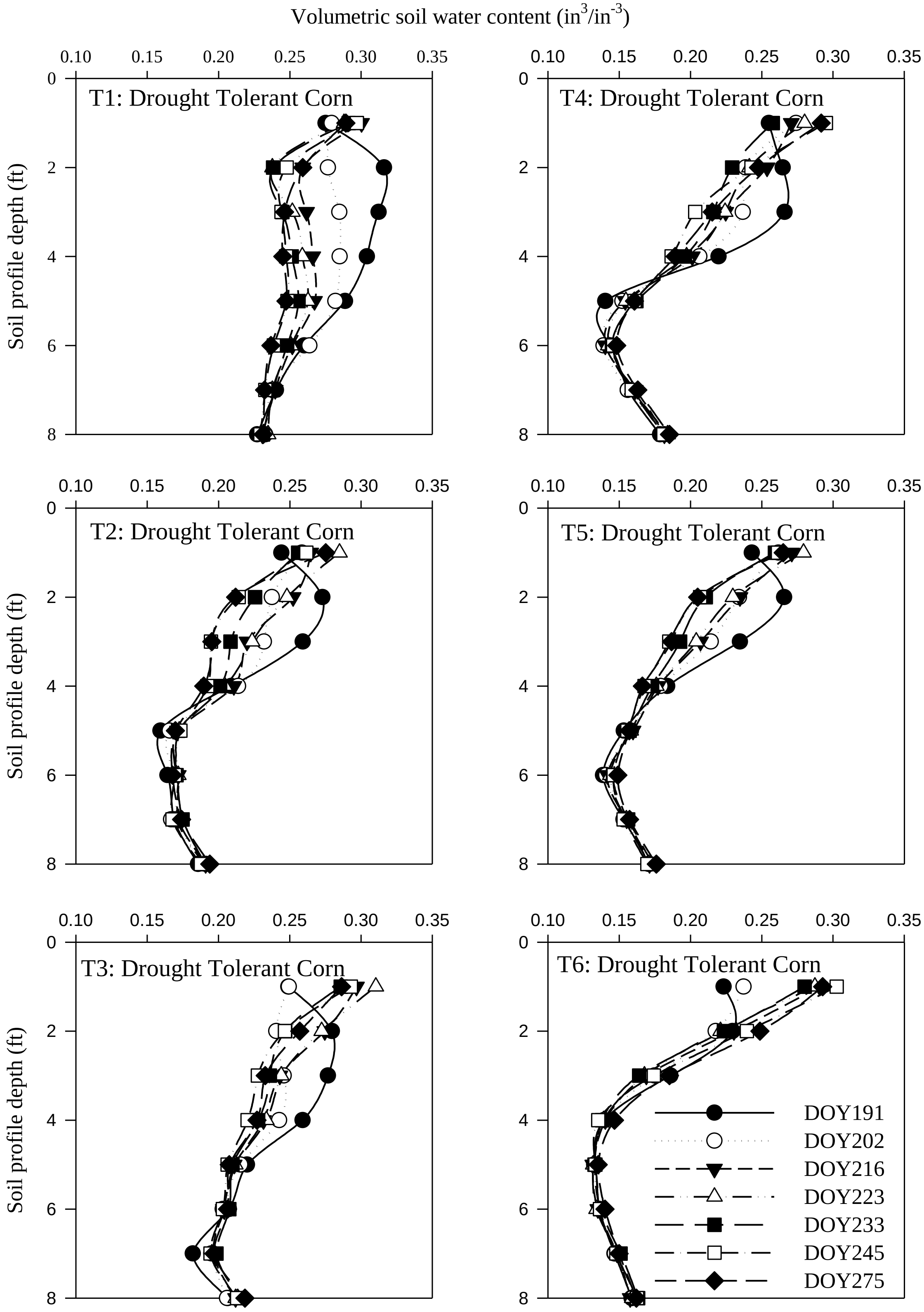

Figure 5. Soil profile water content taken at different depth using a neutron during the 2014 growing season in the drought tolerant corn plots at Garden City Kansas.

Soil water measurements from the CS655 soil water sensors were calibrated using neutron probe measurements. Prior to calibration, the sensor was over estimating soil water under wet conditions. However, after calibration using a simple linear regression (Y=0.1991X+0.2081, R^2=0.89), the sensors were able to accurately measure soil water. The soil water sensors were to track wetting (from irrigation or rainfall) and drying cycles as shown in Figure 6 and root water uptake during the day and near zero transpiration during the night as shown in Figure 7. These figures indicate that in addition to bulk soil electroconductivity and soil temperature data these types of multi parameter sensors provide, they could also be used to determine rooting depth; which could be useful in characterizing soil water extraction patterns of different hybrids. This data on root zone water use may increase the confidence of users of ET-based scheduling.

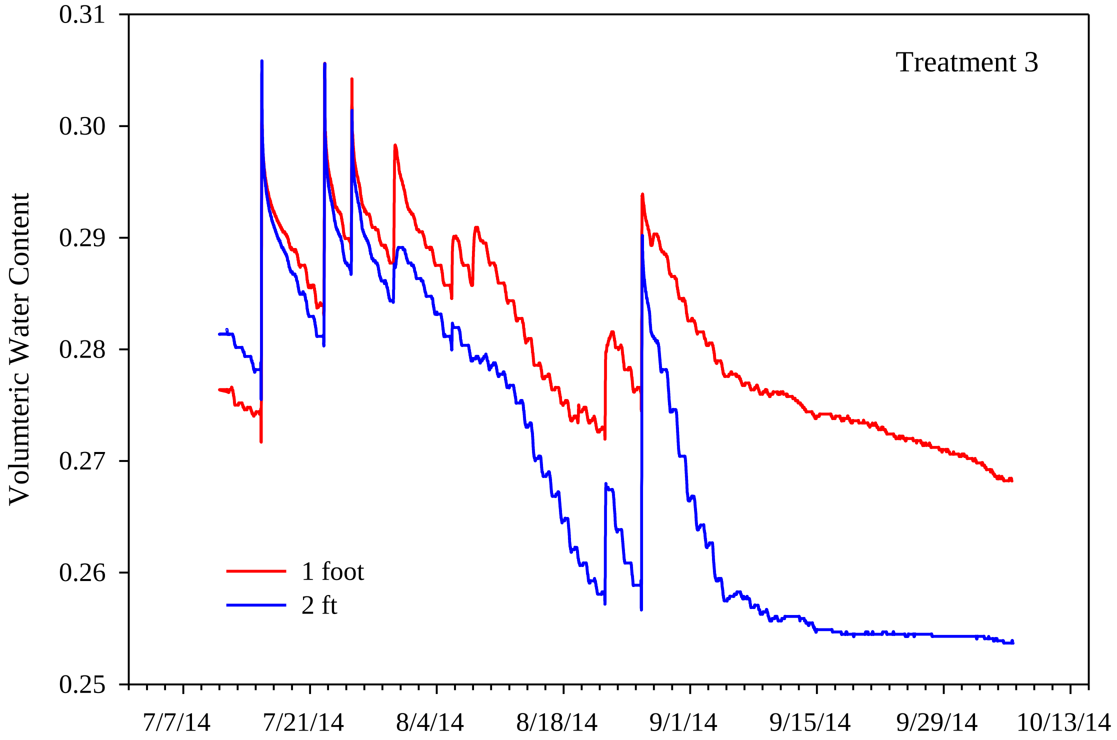

Figure 6. Soil water measurements at two different depths over time made by the CS655 soil water during the 2014 corn growing season Garden City Kansas.

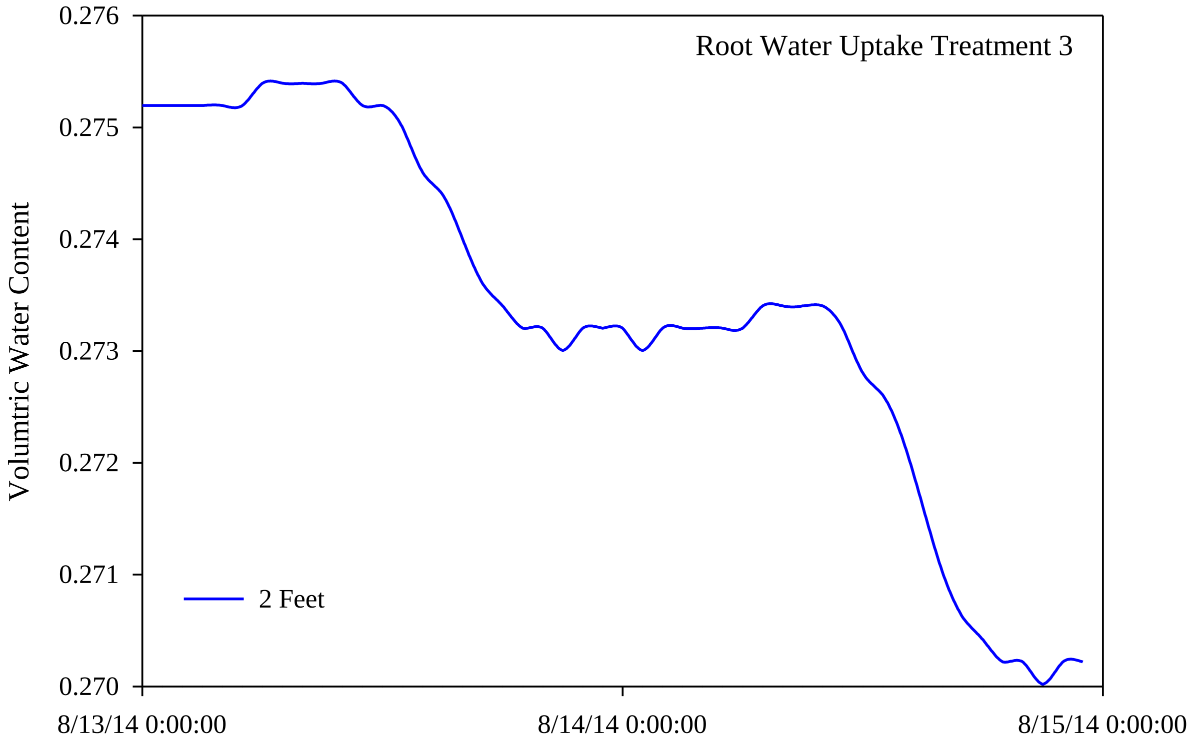

Figure 7. Illustration of root water uptake during the day and close to zero uptake during the night.

Conclusion

As well capacities continue to decline, producers will need to adopt advanced irrigation scheduling to maintain productivity with limited water supplies. Five irrigation scheduling approaches based on plant water stress sensing, soil water sensing, and climate (ET), or a combination of these methods were assessed. Preliminary data indicates that all irrigation scheduling methods could be effectively used to manage irrigation water. However, combining more than one irrigation scheduling method might increase reliability and adequacy of irrigation scheduling. Locally adapted conventional hybrids out yielded the drought tolerant hybrid in this study, although hail damage that occurred earlier in the season could have confounded the results. The study also underscored the potential impact of low soil water at planting on corn yield. Continuous soil water sensing using a calibrated CS655 sensor provided useful insights into root water update at night and during daylight hours. Integrating soil and plant water status monitoring with the scientifically robust ET-based scheduling could result in more reliable irrigation scheduling decisions, especially under nonideal growing conditions where external abiotic and biotic factors influence crop water use. Integrated irrigation scheduling technologies could also encourage more producers to adopt the practice thereby optimizing profitability while conserving water.

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