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LARGE-SCALE ON-FARM IMPLEMENTATION OF SOIL MOISTURE-BASED IRRIGATION MANAGEMENT STRATEGIES FOR INCREASING MAIZE WATER PRODUCTIVITY

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ABSTRACT. *Irrigated maize is produced on about 3.5 Mha in the U.S. Great Plains and western Corn Belt. Most irrigation water comes from groundwater. Persistent drought and increased competition for water resources threaten long-term viability of groundwater resources, which motivated our research to develop strategies to increase water productivity without noticeable reduction in maize yield. Results from previous research at the University of Nebraska-Lincoln (UNL) experiment stations in 2005 and 2006 found that it was possible to substantially reduce irrigation amounts and increase irrigation water use efficiency (IWUE) and crop water use efficiency (CWUE) (or crop water productivity) with little or no reduction in yield using an irrigation regime that applies less water during growth stages that are less sensitive to water stress. Our hypothesis was that a soil moisture-based irrigation management approach in research fields would give similar results in large production-scale, center-pivot irrigated fields in Nebraska. To test this hypothesis, IWUE, CWUE, and grain yields were compared in extensive on-farm research located at eight locations over two years (16 site-years), representing more than 600 ha of irrigated maize area. In each site-year, two contiguous center-pivot irrigated maize fields with similar topography, soil properties, and crop management practices received different irrigation regimes: one was managed by UNL researchers, and the other was managed by the farmer at each site. Irrigation management in farmer-managed fields relied on the farmers' traditional visual observations and personal expertise, whereas irrigation timing in the UNL-managed fields was based on pre-determined soil water depletion thresholds measured using soil moisture sensors, as well as crop phenology predicted by a crop simulation model using a combination of real-time (in-season) and historical weather data. The soil moisture-based irrigation regime resulted in greater soil water depletion, which decreased irrigation requirements and enabled more timely irrigation management in the UNL-managed fields in both years (34% and 32% less irrigation application compared with farmer-managed fields in 2007 and 2008, respectively). The average actual crop evapotranspiration (ET_C) for the UNL- and farmer-managed fields for all sites in 2007 was 487 and 504 mm, respectively. In 2008, the average UNL and average farmer-managed field had seasonal ET_C of 511 and 548 mm, respectively. Thus, when the average of all sites is considered, the UNL-managed fields had 3% and 7% less ET_C than the farmer-managed fields in 2007 and 2008, respectively, although the percentage was much higher for some of the farmer-managed fields. In both years, differences in grain yield between the UNL and farmer-managed fields were not statistically significant (p = 0.75). On-farm implementation of irrigation management strategies resulted in a 38% and 30% increase in IWUE in the UNL-managed fields in 2007 and 2008, respectively. On average, the CWUE value for the UNL-managed fields was 4% higher than those in the farmer-managed fields in both years. Reduction in irrigation water withdrawal in UNL-managed fields resulted in \$32.00 to \$74.10 ha^{-1} in 2007 and \$44.46 to \$66.50 ha^{-1} in 2008 in energy saving and additional net return to the farm income. The results from this study can have significant positive implications in future irrigation management of irrigated maize systems in regions with similar soil and crop management practices.*

Keywords. *Evapotranspiration, Irrigation management, Maize, Soil moisture, Water productivity, Water use efficiency.*

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Irrigated agriculture contributes much of the food and fiber consumed by humans and the grain fed to livestock (Howell, 2001). While agriculture is the largest user of freshwater, accounting for more than 80% of water withdrawals, food production from irrigated systems contributes ~40% of the global supply of cereal production on only about 18% of the land area in crop production. Increasing demand for food, livestock feed, and biofuels coupled with changes in climate variables and competition for water with urban and other sectors will most likely increase competing demands on freshwater resources (Rosegrant et al., 2009). Increasing competition for limited freshwater supplies is already evident in major irrigated cropping systems of the U.S. and the world. Thus, increasing the water productivity in irrigated agriculture will continue to be a vital goal in sustaining the balance between supply and demand of food and fiber production.

Currently, maize is produced on about 160 Mha of land in the world, with a total production of about 820 Tg. Demand for maize for human and animal consumption is projected to increase by nearly 300 Tg by 2030, which does not include the increased demand for biofuel production (FAO, 2010). The five largest maize producers are the U.S., China, Brazil, India, and Mexico. The U.S. is the major producer of maize in the world, with just below a quarter of the world's production. Irrigated maize accounts for 61% of the total maize area in Nebraska and contributes 74% of the total annual maize production of 32 Tg in this state (USDA-NASS, 2007). With approximately 60,000 to 65,000 center pivots and over 110,000 active irrigation wells in Nebraska (Nebraska DNR, 2010), irrigation provides stability in terms of maize yield, especially in years with below-average precipitation, ensuring grain supplies for livestock feed, ethanol plants, corn sweetener, and for grain export. However, below-average rainfall in a majority of the past ten years and poor irrigation management practices have resulted in falling groundwater levels and reduced well outputs in some areas (McGuire, 2004). Likewise, interstate litigation between downstream and upstream water users has placed some restrictions on the amount of water available to farmers for irrigation in some major watersheds (Irmak, 2010). Given these increasing pressures on local and regional water resources available for irrigation, there is a critical need for improving irrigation water use efficiency (IWUE, kg grain m^{-3} applied irrigation) and crop water use efficiency (or crop water productivity) (CWUE, kg grain m^{-3} water used).

Many studies on research fields have emphasized that decreased water use through more efficient irrigation application methods and strategic planning increases water use efficiency through very minimal decreases in yield. However, very few studies have been conducted concerning the practicality of these irrigation methods and strategies on the individual farm level in large-scale applications. Poor irrigation management strategies due to under-utilization of current technologies at the farm level can cause substantial disadvantages in the efforts toward protecting the long-term viability of irrigated agriculture. In many cases, straightforward methods for combining effective irrigation management strategies with more efficient irrigation systems and soil moisture monitoring can lead farmers to become more efficient in utilizing water resources and reduce energy used for irrigation. With the high demand on the water supply, it is increasingly important that agricultural managers combine more efficient irrigation methods with better management strategies. There have been some significant improvements in agricultural water management in the last three decades. For example, the average amount of water applied as irrigation on agricultural land in the U.S. has decreased from 637 mm in 1975 to 502 mm in 2005; comparable figures for Nebraska are 366 mm in 1975 and 335 mm in 2005 (USDA-NASS, 2007). Much of this improvement resulted from conversion of gravity (furrow) irrigation to center pivots. Depending on precision of management and other factors, center-pivot application efficiency (i.e., a measure of the fraction of the total volume of water delivered to the farm or field that is stored in the root zone to meet the crop evapotranspiration) is typically about 75% to 85%, while furrow irrigation is less efficient at 45% to 80% (Irmak et al., 2011). The trend of reduced irrigation application can be further improved with implementation of more conservative and technology-based irrigation management strategies coupled with good agronomical practices implemented at the farm level.

Additional improvements may be possible using limited or deficit irrigation strategies with more efficient irrigation systems and soil water status monitoring. Previous studies conducted on UNL's research station experimental plots showed that it is possible to reduce 25% of irrigation water inputs, as compared with the fully irrigated treatments, through more efficient irrigation application methods and strategic planning of crop rotations, resulting in 25% higher irrigation water use efficiency (IWUE) and only 3% to 6% penalty in grain yield (Irmak and Payero, unpublished research data). To date, however, no studies have been conducted on performance and practicality of soil moisture-based irrigation management in large-scale production fields managed by farmers. The objective of this research was to test the hypothesis that it is possible to reduce irrigation application amounts without significant decrease in maize grain yield in large production fields through use of soil moisture-based irrigation strategies during growth stages when the crop is less sensitive to water stress. The research was conducted in farmers' fields and relied on currently available technologies to determine timing of irrigation in relation to soil moisture depletion thresholds at different crop growth stages, and a crop simulation model to predict when sensitive crop growth stages would occur.

Materials and Methods

The project was conducted in central, south central, and eastern Nebraska to evaluate the performance of a soil moisture-based irrigation management approach to maize productivity. The study area encompasses a rainfall gradient with the highest annual precipitation in the east and the lowest precipitation to the west. The study included eight farms during 2007 and 2008 (fig. 1, table 1). Farmers were selected to achieve reasonable spatial distribution across

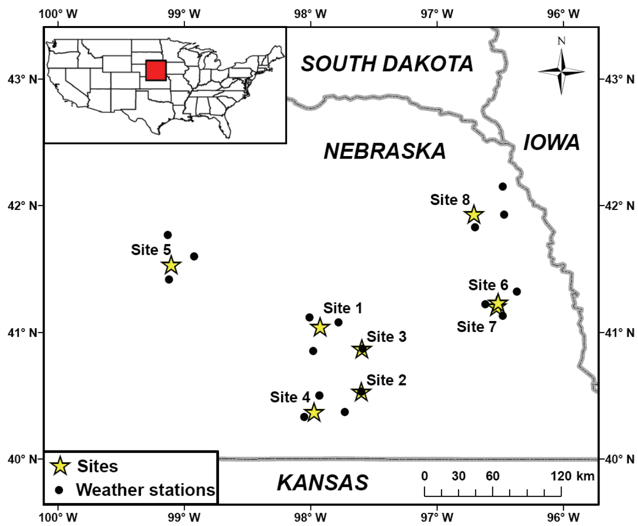

Figure 1. Map of eastern, central, and south central Nebraska. Stars show locations of farmer-irrigated maize fields used in the present study. Solid circles show locations of meteorological stations used. Lines show state boundaries. The location of the study area within the U.S. is shown in the inset.

the eastern half of Nebraska, where maize production is concentrated. Other selection criteria included the farmers' willingness to: (1) manage two center-pivot irrigated fields with the same hybrid and crop management other than irrigation for two years; (2) impose the soil moisture-based irrigation regime on one of the pivots as specified by UNL researchers; (3) provide information on management practices such as fertilizer, seeding rate, hybrid brand and number, dates of planting and maturity, herbicide, pesticide and insecticide applications, and final grain yield. Selected farms had at least two center-pivot irrigated fields with relatively uniform soil properties and slope, and they had flowmeters on each pivot to allow monitoring and reporting of water applications. At each farm, two center-pivot fields within 1.5 km of each other were selected for imposition of irrigation treatments based on similarity of soil type and topography. On each farm (site), center-pivot pairs had similar system pressure, sprinkler nozzles, water application rate, and size (area irrigated) and system capacity. Irrigation in one of the two center-pivot fields was managed by the UNL research team to impose a soil moisture-based irrigation regime, while the other field was managed by the farmer (hereafter called UNL- and farmer-managed fields). Except for irrigation, the two fields at each farm had similar crop management with regard to rotation, planting date, seeding rate, planting direction, maize hybrid and maturity, pest and nutrient management.

Soil samples were taken before planting each year to determine optimal N and P fertilizer rates in each field based on UNL guidelines (www.ianrpubs.unl.edu/epublic/live/ec117/build/ec117.pdf). Fields were divided into four quarters based roughly on compass vectors (NE, SE, NW, and SW). Within each quarter, six soil cores were collected to a depth of 0.90 m. Each of the cores from a quarter was separated into three depths increments (0-0.20, 0.20-0.60, and 0.60-0.90 m) and combined into single samples for each depth. Soil NO_3^- content was determined for the three depths as required for estimating N fertilizer application rates (www.ianrpubs.unl.edu/epublic/live/ec117/build/ec117.pdf), while pH, organic carbon content, and extractable phosphorus were determined only in the 0-0.20 m sample. Samples were air-dried, sieved through a 2 mm screen, and then analyzed by the UNL Department of Agronomy Soil Testing Laboratory, and recommendations were made to the farmer cooperators for each field.

Soil Water Dynamics

Soils at the study sites were dominantly Argiustolls, and soil textures throughout the depth sampled were mostly silt loams and silty clay loams at the eight study sites. These textures are representative of soils used for irrigated agriculture in central, south central, and eastern Nebraska (table 1). Continuous monitoring of soil water status (soil matric potential, SMP) was achieved in farmer- and UNL-managed fields using Watermark granular matrix sensors (GMS) (Armstrong et al., 1985; Thomson and Armstrong, 1987; McCann et al., 1992; Eldredge et al., 1993; Thomson et al., 1996; Irmak and Haman, 2001) and Watermark Monitor dataloggers (Irrometer, Inc., Riverside, Cal.). The GMSs are electrical resistance type sensors and provide SMP in kPa. In practical application, SMP has a negative sign (i.e., more negative SMP values indicate drier soil), but a positive sign is used in this article as an indicator of soil water tension. In each field, GMSs were installed in an area with soil and topography that was most representative of the entire field. Selection of sensor locations was based on aerial photos taken before and during the season, and digital elevation maps (from the USDA-NRCS Web Soil Survey; http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm). An example of the aerial photos that were taken for one of the study sites is given in figure 2. In each field, GMSs were installed at four depths (0.30, 0.60, 0.90, and 1.20 m) in the crop row halfway between two neighboring plants in

Table 1. Site location, coordinates, elevation, and measured soil properties at the research fields. Values are averages for the UNL and farmer-managed fields per site, as both fields had very similar soil physical properties. Average of the soil properties was taken from the 0.23 to 0.38 m soil depth.

Site	Town	Latitude (°)	Longitude (°)	Elevation (m)	Particle Size Distribution (%)			Bulk Density (Mg m^{-3})	Organic Matter (%)	pH
					Sand	Silt	Clay			
1	Hordville	41.05	-97.92	535	12.7	69.0	18.4	1.39	3.0	6.1
2	Mead	41.21	-96.53	366	7.4	64.6	28.0	1.39	3.3	5.9
3	York	40.87	-97.60	490	6.1	70.3	23.7	1.37	2.9	5.7
4	Mead	41.23	-96.52	366	4.8	59.7	35.5	1.44	2.8	5.1
5	Ord	41.54	-99.10	649	25.0	53.2	21.9	1.51	2.3	6.5
6	Edgar	40.37	-97.97	524	5.7	70.3	24.0	1.43	3.1	6.1
7	Geneva	40.53	-97.60	496	5.3	70.1	24.6	1.43	2.9	5.9
8	West Point	41.93	-96.71	430	6.5	68.4	25.2	1.52	2.7	6.6

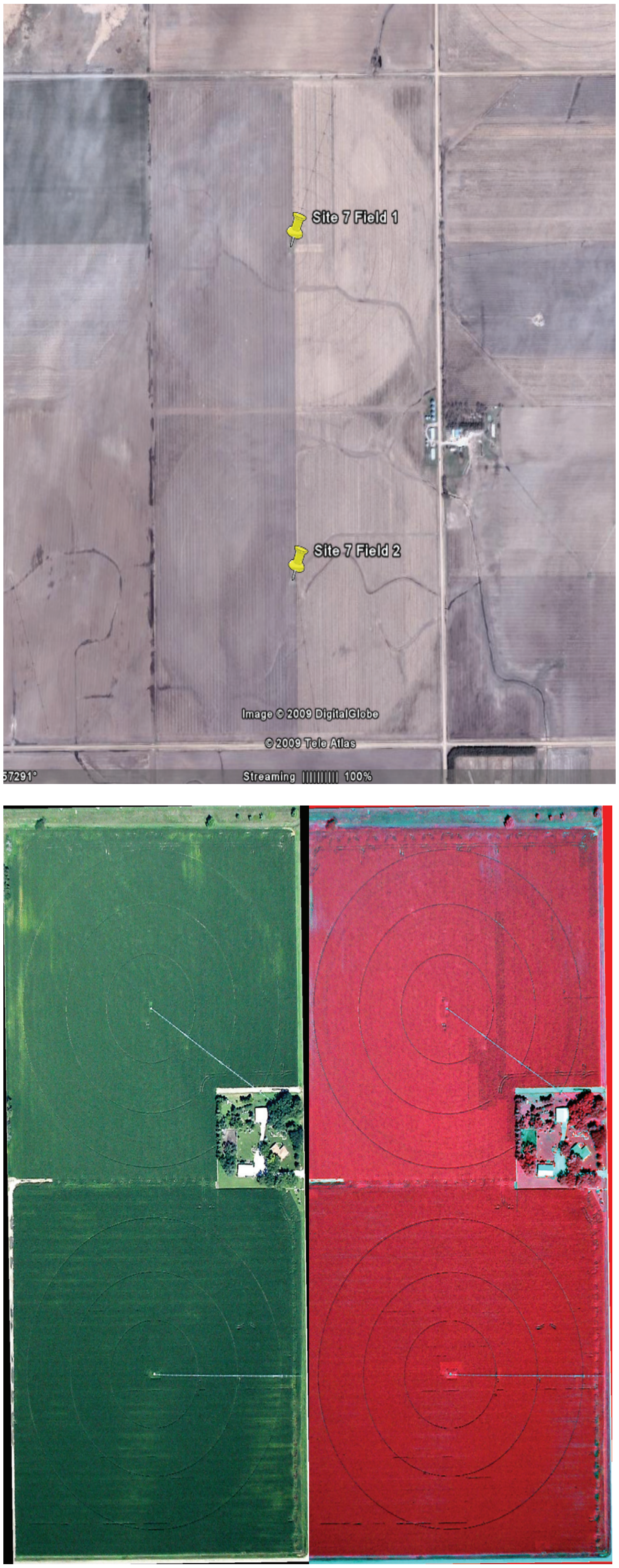

Figure 2. Aerial (upper) and infrared (lower) images taken early in the season to determine the representative locations for soil moisture sensor installation, in-season plant sampling, and harvest locations.

two locations per field to monitor SMP on an hourly basis from the time the equipment was installed until complete physiological maturity or harvest.

The Soil Water Characteristics Software (ver. 6.02.74) developed by Saxton et al. (1986) and Saxton and Rawls (2006) was used to develop soil water retention curves for converting SMP readings to volumetric water content for various soil types in each study location. The soil water characteristic equations were developed from the USDA soil database based on readily available soil properties including soil texture, bulk density, and organic matter content. Soil samples were collected at the location of each soil water sensor in both years by taking undisturbed core samples at depth increments of 0-0.20, 0.20-0.40, 0.50-0.70, 0.80-1.0, and 1.15-1.30 m. Samples were sent to the laboratory for determination of soil texture, organic matter, pH, and bulk density. Because soil properties were the same or similar in farmer- and UNL-managed fields at the same farm, average values based on values for texture, organic matter, and bulk density values were used as inputs to the Soil Water Characteristics Software to develop soil water retention curves for each site (table 2, fig. 3). Salinity and gravel input fields were left at the default values whereas the compaction input was left at zero because soils at the test sites did not have gravel, did not have salinity problems, and were not compacted.

Irrigation Management

In the farmer-managed fields, irrigation decisions were made by farmers based on their traditional practices and personal experience. Farmers' irrigation methods are typically based on a fixed calendar date, visual observation of plant water needs, hand-feel of soil moisture, observing neighbors' irrigation practices, or a combination of these approaches. These approaches usually do not account for the utilization of the available soil water by the crop. In the UNL-managed fields, monitoring of SMP allowed estimating actual soil water status in the root zone. An irrigation application was triggered when a threshold SMP value was reached. Threshold values for the UNL-managed fields were specified for each field based on soil texture (Irmak et al., 2010). For a silt loam soil, for example, irrigation was initiated when average SMP at 0.30, 0.60, and 0.90 m depth gave GMS readings equivalent to matric potential between 90 and 100 kPa, i.e., approximately 35% to 40% depletion of available water holding capacity (AWHC) in the crop root zone. This SMP trigger point is higher (i.e., less water depletion) than the more widely used traditional threshold value of 50% depletion of AWHC to account for the time required for a center pivot to make one full circle. Most pivots require 3 to 5 days for a complete revolution, depending on the well capacity, water application depth, and other factors. Thus, whenever the threshold value was reached in UNL-managed fields, an irrigation event was triggered. Dates and amounts of irrigation events for both UNL-managed and farmer-managed fields were provided to the UNL team by each farmer. Each irrigation event did not exceed 25 to 35 mm of applied water. This amount is used because it is the most commonly practiced center-pivot water application depth in Nebraska. Although soil water in each field was monitored at 0.30, 0.60, 0.90, and 1.20 m depths, the sensor

Table 2. Actual management practices (seed brand and maturity, sowing date, and plant population density measured at harvest) and dates of silking and physiological maturity for irrigated maize crops in each study field during the 2007 and 2008 growing seasons.

Site	Year	Hybrid Name (and Maturity)[a]	Field Manager	Planting Date	Observed Silking Date	Observed Physiological Maturity Date	Population Density (plants ha^{-1})
1	2007	P33N11 (1524 GDD) and P34B60 (1524 GDD)	UNL	4 May	15 July	11 September	66,800
			Farmer	4 May	15 July	10 September	66,800
	2008	DKC63-42 (1559 GDD)	UNL	30 April	20 July	5 October	74,800
			Farmer	30 Apr	21 July	5 October	73,000
2	2007	P33H26 (1537 GDD)	UNL	2 May	14 July	6 September	68,600
			Farmer	2 May	14 July	2 September	71,400
	2008	DK6544VT3 (1586 GDD)	UNL	30 April	14 July	29 September	72,400
			Farmer	30 April	13 July	29 September	73,500
3	2007	DK63-39 (1559 GDD)	UNL	21 April	7 July	2 September	74,600
			Farmer	21 April	7 July	2 September	68,900
	2008	P33H27 (1537 GDD)	UNL	30 April	16 July	28 September	82,300
			Farmer	30 April	16 July	27 September	83,400
4	2007	P32B29 (1578 GDD)	UNL	3 May	11 July	5 September	72,700
			Farmer	3 May	11 July	5 September	72,200
	2008	P32T84 (1537 GDD)	UNL	30 April	14 July	21 September	78,400
			Farmer	30 April	14 July	22 September	77,500
5	2007	Renze 6296, 8364, and 3274	UNL	5 May	17 July	18 September	45,500
			Farmer	5 May	17 July	18 September	52,500
	2008	Renze 9386YGCB/RR2	UNL	7 May	23 July	16 October	68,600
			Farmer	7 May	23 July	16 October	67,400
6	2007	NC+ 5555 (1550 GDD)	UNL	23 April	5 July	6 September	70,000
		NC+ 5411 (1534 GDD)	Farmer	23 April	5 July	4 September	71,100
	2008	NC+ 5225 VT3 (1505 GDD)	UNL	29 April	15 July	20 September	73,300
			Farmer	30 April	16 July	21 September	77,400
7	2007	P34A17 (1457 GDD)	UNL	16 April	3 July	29 August	71,300
			Farmer	16 April	3 July	29 August	68,100
	2008	P34F96 (1484 GDD)	UNL	15 April	12 July	18 September	68,800
			Farmer	15 April	13 July	19 September	65,100
8	2007	DKC61-66 (1531 GDD)	UNL	3 May	10 July	12 September	68,900
			Farmer	3 May	10 July	12 September	66,200
	2008	Croplan 6069AS3 (1496 GDD)	UNL	23 April	19 July	1 October	62,200
			Farmer	23 April	19 July	1 October	62,000

[a] P = Pioneer, DK = Dekalb, and GDD = reported seed-brand growing-degree days required from planting to maturity (T_{base} = 10ºC). GDD data were not available for Renze hybrids.

readings from 1.20 m depth was not considered in the determination of whether the irrigation trigger point is reached.

Because maize grain yield is most sensitive to water stress during the critical pollination time window around silking (Otegui et al., 1995; Hall et al., 1982), a lower soil water depletion threshold (i.e., about 80 kPa) was used for triggering irrigations in UNL-managed fields from ten days before silking to seven days after. Prediction of when silking would occur for each field was made with the Hybrid-Maize model (Yang et al., 2004, 2006). This simulation model features temperature-driven maize phonological development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. Hybrid-Maize allows in-

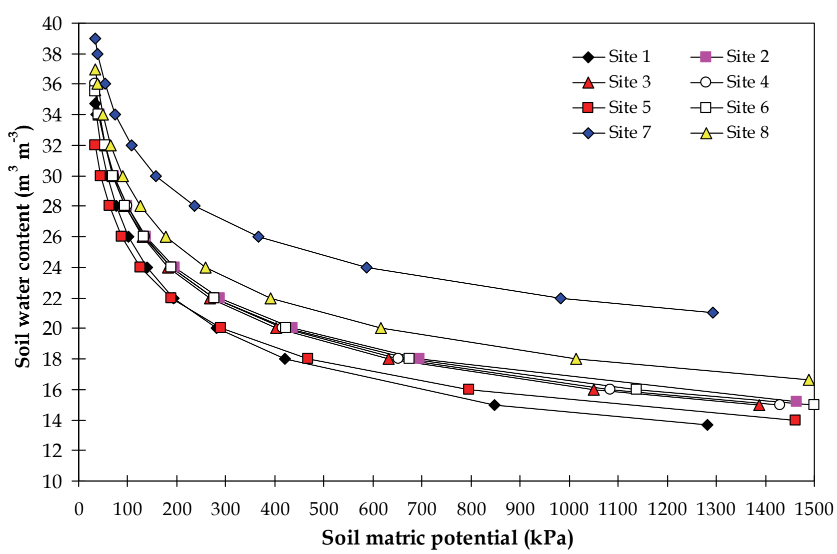

Figure 3. Soil water retention curves created using Saxton (1986) model for each site to convert soil matric potential data to soil water content.

season (or real-time) assessment of maize phenology and growth up to the current date based on the actual weather data up to that point in time, followed by prediction of phenology, growth, and final yield thereafter based on weather data for the remainder of the growing season. Therefore, in the present study, a Hybrid-Maize simulation was made every week for each field during the vegetative phase to estimate, in advance, the silking date at each site based on actual sowing dates, and real-time and historical weather data obtained from nearby weather stations operated by the High Plains Regional Climate Center (HPRCC; www.hprcc.unl.edu). In all cases, the HPRCC weather stations were within 10 to 15 km of the study sites.

Crop Phenology and Grain Yield

Two weeks after emergence, within each of the four quarters in each field, two measurement areas of 10 × 10 m with uniform emergence were selected for phenology scouting and grain yield determination at maturity. Thus, field means for yield were derived from eight measurement zones. Measurement areas were usually located within 20 to 50 m of the second center-pivot span from the end tower. Crop phenology was scouted on a weekly basis. At harvest, plant population was measured by counting plants from 6 m row segments in four contiguous rows in the center of the measurement areas in each quadrant. During hand-harvesting for grain yield determination, ears were taken from 6 m of two adjacent rows in each measurement area and dried to constant mass at 70°C. Grain yields were adjusted to standard commercial moisture of 0.155 kg H_2O kg^{-1} on a wet weight basis.

Crop Evapotranspiration and Water Use Efficiency

Seasonal crop evapotranspiration (ET_C) from sowing to physiological maturity, total irrigation amount, and grain yield data were used to quantify crop water use efficiency (CWUE, kg m^{-3}) and irrigation water use efficiency (IWUE, kg m^{-3}) of each field. CWUE and IWUE were calculated following Viets (1962):

$$\text{CWUE} = \text{grain yield} / ET_C \tag{1}$$

$$\text{IWUE} = \text{grain yield} / \text{total irrigation applied} \tag{2}$$

where yield is in g m^{-2}, ET_C and irrigation are in mm, and CWUE and IWUE are in kg m^{-3}. Daily ET_C for each field was estimated using precipitation data (obtained from nearby HPRCC weather stations), applied irrigation, and the change in total soil water in the crop root zone (ΔTSW) as:

$$ET_C = (S_{\text{mm}} - S_{\text{mm+1}}) + P + IR - RO \tag{3}$$

where S_{mm} is the available soil water for the previous day, $S_{\text{mm+1}}$ is available soil water for the current day, so that ($S_{\text{mm}} - S_{\text{mm+1}}$) represents the daily change in soil water storage in the crop root zone, P is precipitation, IR is total net irrigation amount, and RO is surface runoff. All components of the water balance are reported in mm. The soil water status was monitored every 0.30 m up to 1.20 m in each field and, in the ET_C calculations, the depth of the active crop root zone of 1.20 m was considered. Deep percolation was assumed to be negligible. In most cases, cumulative ET_C is greater than rainfall where maize is grown in Nebraska. Center-pivot irrigation application efficiency was assumed to be 85% when calculating net irrigation amounts. In the soil water balance, SMP acquired from the GMSs was used to determine changes in soil water over time. Daily average soil moisture tension readings were converted into total available soil water for the soil profile using Saxton's model, as previously described. The difference in total soil water from the previous day to the current day was calculated for the entire period when SMP data were available (early season to harvest). Values were then summed to obtain the seasonal change in total soil water in the crop root zone.

Runoff Estimation

The surface runoff from precipitation and irrigation events for each field was estimated using the USDA Natural Resources Conservation Service (USDA-NRCS, previously known as the Soil Conservation Service, SCS) curve number procedure (USDA-NRCS, 1972). The SCS curve number method relates runoff curve number (CN) to runoff, accounting for initial abstraction losses and infiltration rate of soils. The following equation was used to estimate runoff from each experimental field with the condition that $P > 0.2S$:

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S} \tag{4}$$

where Q is runoff (mm), P is precipitation depth (mm), Ia is initial abstraction (mm), and S is potential maximum watershed retention (mm), which is given by:

$$S = \frac{25400}{\text{CN}} - 254 \tag{5}$$

Initial abstraction (Ia) represents water losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Ia is highly variable, but it is correlated with soil and cover parameters. Through studies of many small agricultural watersheds (USDA-NRCS, 1972), Ia is approximated by the following empirical equation:

$$Ia = 0.2S \tag{6}$$

The curve number is based on the area's hydrologic soil group, land use, treatment, and hydrologic condition. According to the silt loam soil at the site and based on the known land use, slope, and cultivation with conservation tillage, CN = 75 was used, which was obtained from USDA-NRCS (1972, 1985) tables. Since runoff is affected by soil moisture before the precipitation event, or the antecedent moisture condition, prior to estimating precipitation excess for storm events, the curve number was adjusted based on the season and the 5-day antecedent precipitation.

By removing Ia as an independent parameter, this approximation allows the use of the combination of S and P to estimate the runoff amount. After substitution:

Table 3. Analysis of variance and mean squares for maize grain yield, applied irrigation amounts, and crop evapotranspiration (ET_C) during 2007 and 2008 in irrigated maize fields in Nebraska (p-values for the significance of factor effects are shown in parentheses).

Source of Variation	d.f.	Grain Yield	Applied Irrigation	ET_C
Site	7	4,260,420 (p < 0.001)	2,643 (p = 0.01)	22,141 (p = 0.005)
Irrigation treatment	1	8,450 (p = 0.75)	12,724 (p < 0.001)	5,868 (p = 0.18)
Error *a*	7	76,214	403	2,653
Year	1	36,210,050 (p < 0.005)	846 (p = 0.57)	9,720 (p = 0.20)
Error *b*	7	1,794,843	2,332	4,773
Year × Irrigation treatment	1	82,013 (p = 0.47)	124 (p = 0.43)	790 (p = 0.50)
Error *c*	7	142,891	171	1,563

$$Q = \frac{(P - 0.2S)}{(P + 0.8S)} \quad \text{if } P > 0.2S$$
$$Q = 0 \quad \text{if } P \le 0.2S \tag{7}$$

The GMSs were installed 4 to 6 weeks after planting, or earlier, in most of the site-years. The Hybrid-Maize model was used to estimate ET_C from planting until the date when GMSs were installed. Hybrid-Maize simulates ET_C based on (1) maximum crop transpiration as estimated from grass-reference evapotranspiration (ET_O) and leaf area index, (2) rooting depth and soil water potential, which in turn is based on water release characteristics as determined by soil texture, and (3) direct evaporation from the soil surface. Model simulations in the present study were based on actual site-specific management practices, soil properties, and daily weather data interpolated from nearby weather stations. Thus, total ET_C (from planting to physiological maturity) was computed as the sum of simulated ET_C from planting to the start date of soil water measurements using the Hybrid-Maize model and the rest of the season ET_C was calculated using equation 3.

Statistical Analyses

Evaluation of irrigation regime effects on grain yield, applied irrigation amount, and ET_C followed Steel and Torrie (1980). It was not possible to conduct a separate analysis for each site-year because there was one experimental unit (center-pivot irrigated field) assigned to each irrigation treatment. Likewise, sites (two farms per site) were the same across years; thus, site-years could not be considered totally independent from each other. Therefore, our analysis included site, year, and irrigation treatment as sources of variation and accounted for all 32 site-year-irrigation regime observations. Years were treated as repeated measures in the analysis because (center pivot) fields in each site received the same irrigation treatment across years. F-tests were performed using appropriate interactions as error terms: site × irrigation treatment, site × year, and site × irrigation treatment × year (errors *a*, *b*, and *c*, respectively; see table 3).

Results and Discussion

Precipitation and Irrigation

The site-year observations included in the study encompass the weather, soil, and management variability expected over a large area of the Great Plains. The amount and distribution of rainfall varied substantially among sites and years (fig. 4). However, since the paired fields for each site are located very close to each other, the precipitation amount between the UNL-managed vs. farmer-managed field was very similar, and the variability in precipitation was not an issue for the same sites in the water balance analyses when calculating ET_C. The seasonal total rainfall ranged from 211 mm for site 5 to 374 mm for site 1 in 2007 and from 188 mm for site 8 to 523 mm for site 2 in 2008. Total sowing-to-maturity rainfall across all sites averaged 282 and 328 mm in 2007 and 2008, respectively. Despite relatively similar rainfall totals across years, the distribution of rainfall during the two growing seasons was different. Whereas rainfall was distributed evenly before and after silking in 2007 (51% and 49% of total rainfall, respectively), rainfall was concentrated in the pre-silking period in 2008 (72% of total rainfall).

Tables 4 and 5 summarize the seasonal totals for gross irrigation applications and precipitation for each site and year. Site and irrigation regime had significant impact on applied irrigation amounts (tables 4 and 5). In all site-years, the irrigation amount in UNL-managed fields was less than in farmer-managed fields. Gross irrigation amounts were obtained from a combination of farmers' records and the research team's ultrasonic flow measurements during irrigation events. The research team's portable ultrasonic flowmeter (Great Plains Meter, Inc., Aurora, Neb.) was also used to calibrate and/or validate the existing flowmeter readings in each farmer-managed field. The observation/calculation periods between irrigation events were the same for the UNL-managed and farmer-managed fields for a given site. In 2007, the irrigation amount applied in the farmer-managed fields ranged from 79 mm at site 8 to 178 mm at site 3, whereas the irrigation amounts were less in UNL-managed fields, ranging from 19 mm at site 8 to 127 mm at site 3. The irrigation applications were slightly less in 2008 due to a larger amount of precipitation. The average irrigation amounts applied across all sites in the farmer-managed and UNL-managed fields were 125 and 82 mm, respectively, in 2007 and 111 and 75 mm, respectively, in 2008. Thus, the soil moisture-based irrigation management strategies and pre-determined SMP threshold in the UNL-managed fields resulted in a 34% and 32% less irrigation applications in 2007 and 2008, respectively.

Seasonal Changes in Soil Matric Potential, Soil Water, and Irrigation Management

Daily SMP and total soil water in the 0.30, 0.60, 0.90, and 1.20 m soil layers in farmer- and UNL-managed fields in 2007 and 2008 for site 7 are presented in figures 5 and 6 as example datasets. The same datasets were collected for all site-years, but the seasonal patterns of SMP and total

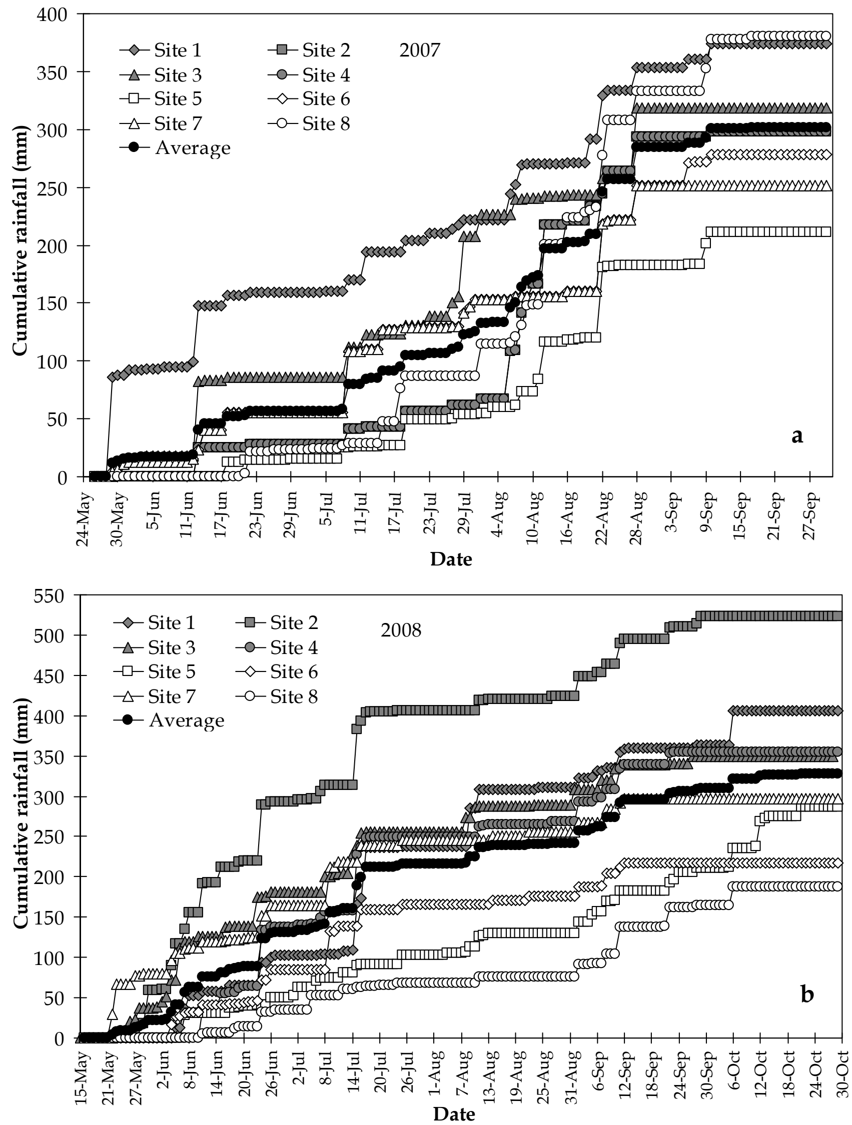

Figure 4. Cumulative rainfall from sowing date to physiological maturity at each site in 2007 and 2008. Rainfall data were obtained from the closest High Plains Regional Climate Center (HPRCC) automated weather station for each site. Average rainfall of all sites is also shown in each figure for comparison.

soil water at site 7 during the 2007 growing season is representative of the major features of soil water dynamics in farmer- and UNL-managed irrigation regimes observed in all site-years. Soil matric potential at site 7 in 2007 fluctu ated during the crop growing season as a function of rain and irrigation applications (figs. 5 and 6). In the farmer-managed field, SMP ranged from around 120 kPa to near 0 for the 0.30 m depth throughout the season. Around 25 May, the SMP was near 5 kPa and increased gradually thereafter. Near 5 June, the SMP at the 0.30 m depth increased greatly from around 40 kPa to 100 kPa within a one-week period as a result of plant water uptake and soil evaporation. Irrigation events and precipitation decreased the SMP at the 0.30 m layer several times throughout the season. The 0.60 m layer shows some depletion at times, but the maximum SMP only reaches 80 kPa. The soil remained relatively wet, and the SMP at the 0.90 m and 1.20 m layers never exceeded 50 kPa. In the UNL-managed field, SMP for the 0.30 m layer reached an SMP value of over 100 kPa twice during the season. The 0.60 m and 0.90 m layers in the UNL-managed field had SMP values that were much greater (more soil water depletion) throughout the season than the farmer-managed field. This was due to the decreased irrigation amounts and proper irrigation timing that were practiced at the UNL-managed fields. The first irrigation event on the UNL-managed field was on 27 June (a total of 33 mm). At this time, both the 0.30 m and 0.60 m layers were near the threshold SMP set forth by UNL of around 90 kPa during the critical growth period of ten days before silking until seven days after silking. However, the sensors did not respond to this irrigation application, likely due to the soil water depletion in the 0.30 m above the first sensor. This is because irrigation water might not have reached the GMSs that were installed at the 0.30 m depth. The bottom of the GMS was at 0.30 m and the sensor has 0.076 m length; therefore, the topsoil (0.30 m – 0.076 m = 0.224 m) was dry enough to hold an extra 42 mm of water (given a water holding capacity of

Table 4. Measured and calculated soil water balance components, including precipitation, runoff, portion of precipitation that infiltrated into the soil profile, change in total soil water (ΔTSW), seasonal average daily ET_C, yield, irrigation water use efficiency (IWUE), and crop water use efficiency (CWUE) for each site for the 2007 growing season. Net irrigation was estimated as 85% of gross irrigation for ET_C calculations.

Site	Precip. (mm)	Runoff (mm)	Effective Precip. (mm)	Treatment	Gross Irrigation (mm)	ΔTSW (mm)	ET_C (mm)	ET_C (mm d^{-1})	Grain Yield (kg ha^{-1})	IWUE (kg m^{-3})	CWUE (kg m^{-3})
1	374	64	310	UNL	44	123	498	3.69	12,740	29	2.56
				Farmer	102	175	599	4.43	12,800	13	2.14
2	298	34	264	UNL	102	165	570	4.32	14,370	14	2.52
				Farmer	159	58	511	3.87	13,930	9	2.73
3	319	60	259	UNL	127	207	626	4.50	14,560	11	2.33
				Farmer	178	146	608	4.37	14,880	8	2.45
4	298	34	264	UNL	104	39	443	3.41	13,430	13	3.03
				Farmer	117	24	439	3.38	12,990	11	2.96
5	211	27	184	UNL	89	117	422	3.27	9,600	11	2.28
				Farmer	102	227	542	4.20	9,670	10	1.78
6	278	39	239	UNL	102	183	549	3.89	14,190	14	2.59
				Farmer	140	92	491	3.48	13,620	10	2.78
7	251	39	212	UNL	66	85	410	2.93	13,870	21	3.38
				Farmer	127	35	412	2.94	13,310	10	3.23
8	224	24	200	UNL	19	56	375	3.57	12,430	65	3.31
				Farmer	79	59	428	4.08	12,930	16	3.02
Average	282	40	241	UNL	82	122	487	3.70	13,150	16	2.75
				Farmer	125	102	504	3.84	13,020	10	2.64

0.19 m^3 m^{-3}). As the effective rooting depth increased throughout the season, the 0.90 m and 1.20 m soil layers experienced an increase in SMP (drier soil). The 0.90 m layer contributed considerably to the maize water uptake, reaching over 90 kPa SMP several times during the season. The average SMP in the top 0.90 m soil profile (average value from the top three sensors installed at 0.30, 0.60, and 0.90 m) reached 90 kPa two times during the season. This value was used to trigger the irrigations.

Another approach to triggering irrigation using a weighted average of soil moisture sensor reading that is practiced, especially in fine-textured soils, is proposed and discussed in detail by Thomson and Fisher (2006). In this approach, the temporal changes in soil water status at each soil depth are determined by the relative contribution of plant water uptake. The change in soil water status at each depth divided by the total change in water status for all zones is then used to determine an approximate percentage contribution of water uptake at each depth (Thomson and Fisher, 2006). Percentage contributions of water uptake at each depth were then multiplied by the value for SMP at that depth. These tension results were then added together to obtain a weighted value at each station (location in the field). Weighted tensions were then averaged across stations to obtain an average value for the field. This approach can have significant positive implications in practical applications, especially for fine-textured soils (i.e., heavy clay soils, silt loam soils), because it encourages crop roots to extract water from deeper soil layers and thus weights the SMP reading to allow more dryness in the upper crop root zones. Depending on the soil type and other factors, sometimes irrigation may not replenish the entire crop root zone (i.e., silt-loam or clay soils). In heavy clay soils, for example, in most cases, irrigation will not replenish the deeper

Table 5. Measured and calculated soil water balance components, including precipitation, runoff, portion of precipitation that infiltrated into the soil profile, change in total soil water (ΔTSW), seasonal average daily ET_C, yield, irrigation water use efficiency (IWUE), and crop water use efficiency (CWUE) for each site for the 2008 growing season. Net irrigation was estimated as 85% of gross irrigation for ET_C calculations.

Site	Precip. (mm)	Runoff (mm)	Effective Precip. (mm)	Treatment	Gross Irrigation (mm)	ΔTSW (mm)	ET_C (mm)	ET_C (mm d^{-1})	Grain Yield (kg ha^{-1})	IWUE (kg m^{-3})	CWUE (kg m^{-3})
1	407	70	337	UNL	57	112	527	3.23	14,810	26	2.81
				Farmer	76	203	633	3.88	15,060	20	2.38
2	523	81	442	UNL	79	102	632	4.03	15,880	20	2.51
				Farmer	109	132	689	4.39	16,760	15	2.43
3	349	18	331	UNL	76	214	631	3.99	15,320	20	2.43
				Farmer	152	178	639	4.04	16,380	11	2.57
4	355	64	291	UNL	84	68	472	3.13	15,320	18	3.24
				Farmer	99	191	609	4.03	15,380	16	2.53
5	287	9	278	UNL	155	67	477	2.86	15,190	10	3.19
				Farmer	155	50	485	2.90	14,440	9	2.98
6	218	16	202	UNL	51	168	442	2.95	15,570	31	3.52
				Farmer	121	55	389	2.59	15,630	13	4.02
7	297	26	271	UNL	0	182	478	2.97	13,620	NA	2.85
				Farmer	51	135	474	2.94	14,190	28	2.99
8	188	8	180	UNL	102	117	431	2.60	14,560	14	3.38
				Farmer	127	135	470	2.83	14,120	11	3.00
Average	328	37	291	UNL	75	129	511	3.22	15,030	20	2.99
				Farmer	111	135	548	3.45	15,240	14	2.86

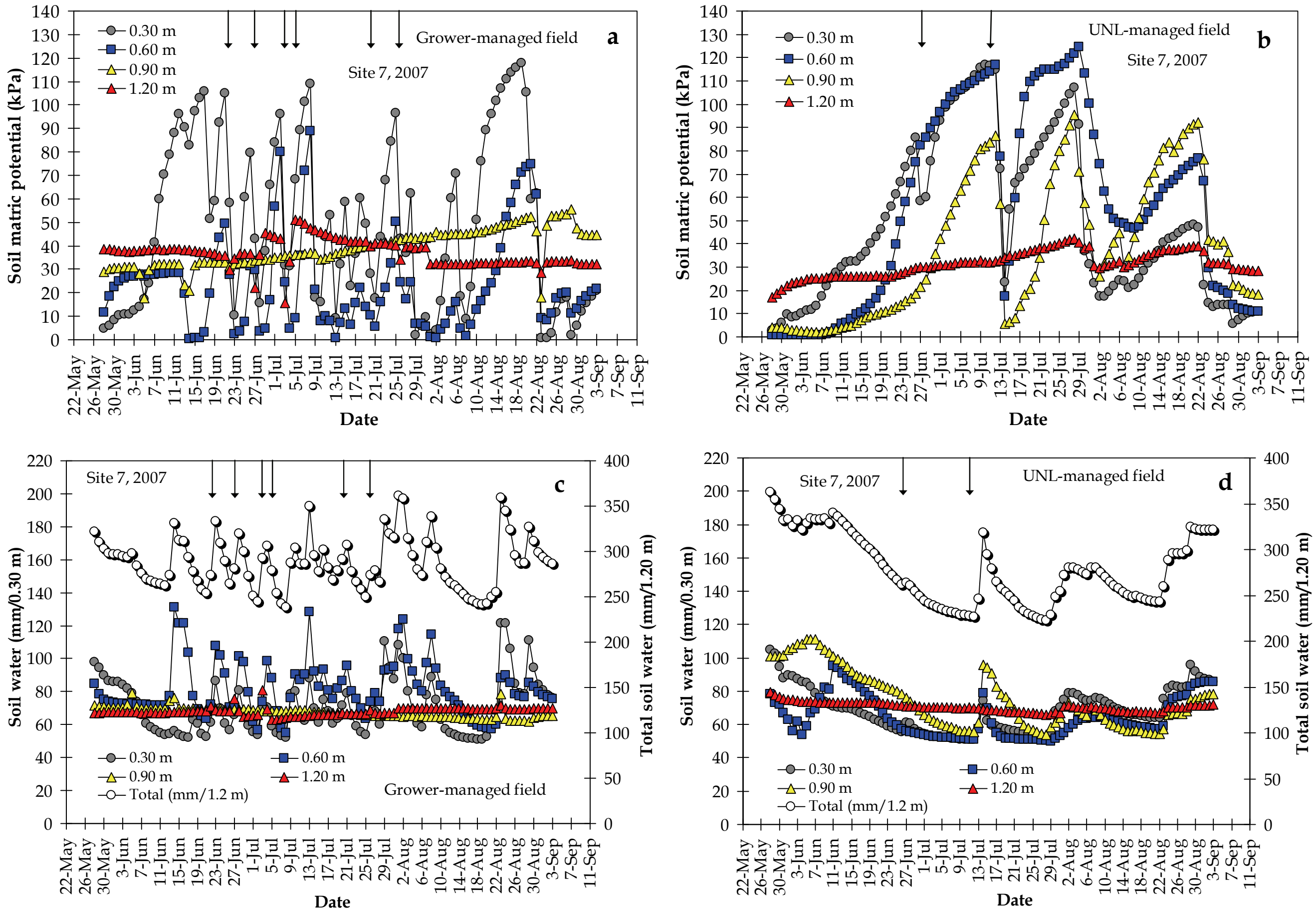

Figure 5. Seasonal distribution of daily soil matric potential at the 0.30, 0.60, 0.90, and 1.20 m soil depths at the (a) grower-managed and (b) UNL-managed field; (c) soil water per 0.30 m depth at the 0.30, 0.60, 0.90, and 1.20 m soil depths; and (d) total soil water in the top 1.20 soil depth at site 7 for 2007 growing season. Arrows along the upper axis represent irrigation events.

soil layers. However, using a weighted average soil water status to obtain a trigger level (according to relative water uptake in the soil profile estimated by the soil water retention curve) as proposed by Thomson and Fisher (2006) is another good option for triggering irrigations.

In this study, for the majority of the year, the SMP was much lower due to precipitation events, and the SMP fluctuated as a function of rain and irrigation applications throughout the season. Less fluctuation occurred except for three major declines in SMP starting on 13 July, 29 July, and 23 August. These declines were due to precipitation. Irrigations after the silking stage were scheduled using the average of the top 0.90 m soil matric potentials. The second irrigation of 33 mm was triggered on 5 July when the average 0.90 m soil matric potential reached 90 kPa. Although the SMP reached 90 kPa on 23 July, irrigation was not triggered due to a forecasted precipitation event in the next one or two days.

Seasonal distribution of daily average total soil water per 0.30 m layer (mm per 0.30 m) and total soil water (TSW) in the top 1.20 m soil depth for all fields for 2007 are presented in figure 5. In the farmer-managed field, TSW in the 0.30 m and 0.60 m layers exhibited variation throughout the growing season, while the 0.90 m and 1.20 m layers remained relatively stable, reading around 30 to 33 kPa (near field capacity). The TSW in the top 1.20 m layer fluctuated between 100 and 150 mm throughout the season. There were five irrigation applications, and a total of 127 mm of water was applied, with approximately 25 mm of water application during each irrigation event. In addition to irrigation, a total of 464 mm of precipitation occurred during the growing season, helping to keep the 0.90 and 1.20 m layers wet. Thus, it appears that most of the plant water uptake in the farmer-managed field at site 7 occurred from the 0.60 m soil layer. The total amount of change in soil water in the 1.20 m root zone in the UNL-managed field was 85 mm, whereas it was only 35 mm (table 4) in the grower-managed field, demonstrating that more soil water was used by the crop, reducing irrigation applications in the UNL-managed field. In 2008, the total change in soil water in the root zone was 182 and 135 mm (table 5) in the UNL- and farmer-managed fields, respectively.

Irrigation management in the UNL-managed field at site 7 allowed more timely irrigations, utilizing soil water and reducing irrigation requirements. The TSW had a gradual decrease as the season progressed; TSW varied from 170 mm in early June to around 100 mm in middle and late July (fig. 5). There were only two irrigation applications (27 June and 5 July) of 33 mm each; therefore, applied irrigation water in the UNL-managed field was 61 mm less than in the farmer-managed field. Seasonal change in total available soil water (i.e., TSW at the beginning of season minus TSW at maturity) was 122 and 102 mm in UNL- and

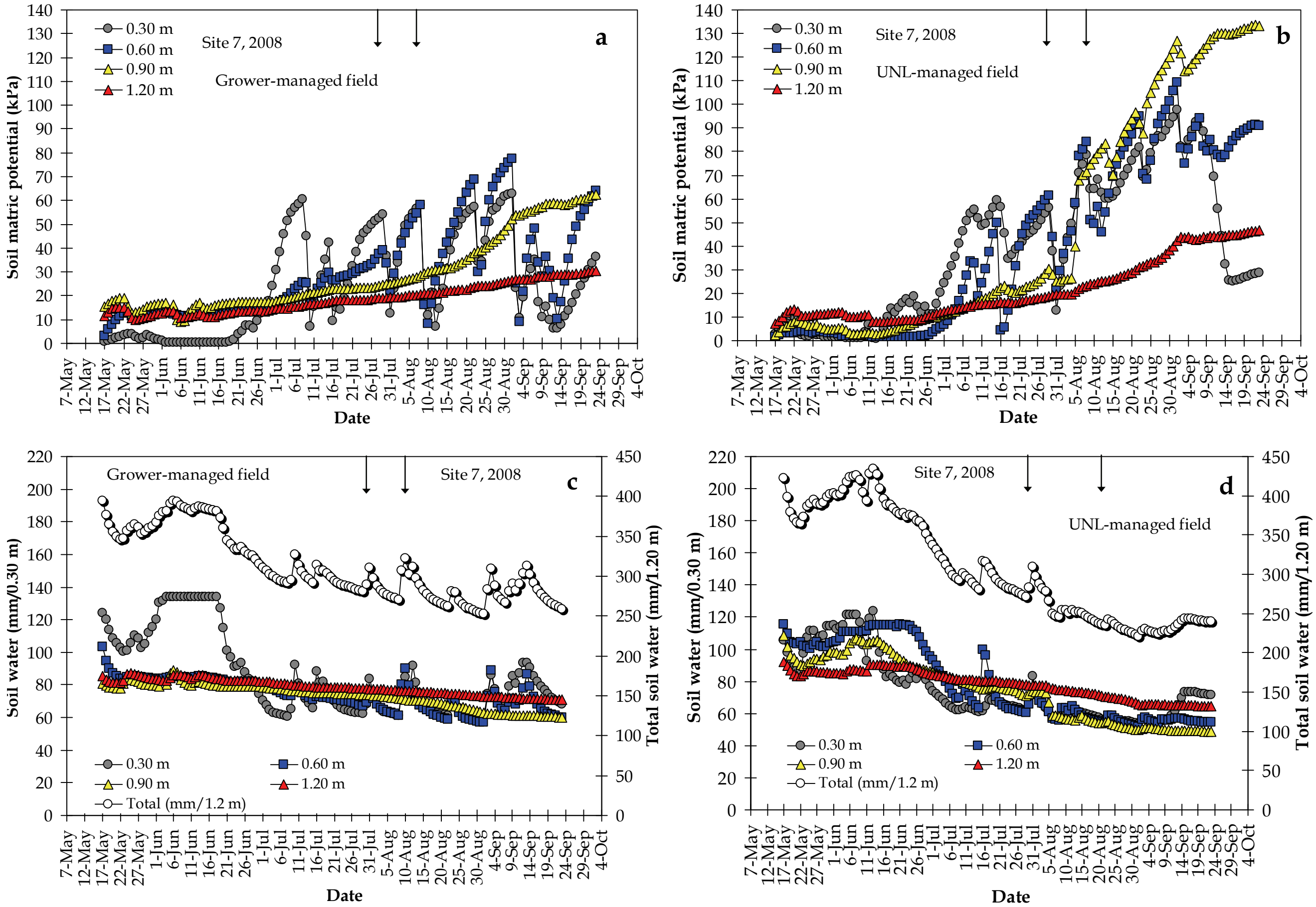

Figure 6. Seasonal distribution of daily soil matric potential at the 0.30, 0.60, 0.90, and 1.20 m soil depths at the (a) grower-managed and (b) UNL-managed field; (c) soil water per 0.30 m depth at the 0.30, 0.60, 0.90, and 1.20 m soil depths; and (d) total soil water in the top 1.20 soil depth at site 7 for 2008 growing season. Arrows along the upper axis represent irrigation events.

farmer-managed fields, respectively. An extra irrigation of 43 mm in the farmer-managed field was partially responsible for the higher TSW at the end of the season. Similar results were found across other site-years. Hence, through proper irrigation management in the UNL-managed fields, more soil water was depleted from the soil profile as compared with the farmer-managed fields, reducing the need for irrigation applications.

Crop Evapotranspiration

The seasonal total ET_C values for each field, as calculated using equation 3, for the 2007 and 2008 growing seasons are presented in tables 4 and 5. In 2007, the seasonal total ET_C ranged from 375 mm for the UNL-managed field at site 8 to as high as about 626 mm for the UNL-managed field at site 3. In 2008, seasonal ET_C values were greater than 2007 due to a longer growing season. In 2008, the average air temperature (data not shown) was cooler than 2007 and the long-term average, which delayed physiological maturity and resulted in a longer growing season and greater seasonal ET_C. Table 2 shows that physiological maturity occurred in early September in 2007 for most sites. In 2008, maturity was delayed to late September and early October. In 2008, ET_C ranged from 389 mm in the farmer-managed fields at site 6 to 689 mm in the farmer-managed field at site 2. Some of the differences in ET_C for the same site between the UNL- and farmer-managed fields were impacted by the irrigation regime, and some of the differences in ET_C between the sites were more likely due to differences in maize hybrid, precipitation amount and distribution, irrigation management, and other soil and crop management practices. The average ET_C for the UNL- and farmer-managed fields for all sites in 2007 was 487 and 504 mm, respectively (table 5). In 2008, the average UNL and average farmer-managed field had seasonal ET_C of 511 and 548 mm, respectively. Thus, when the average of all sites is considered, the UNL-managed fields had 3% and 7% less ET_C than the farmer-managed fields in 2007 and 2008, respectively, although the percentage was much higher for some of the farmer-managed fields. Overall, the ET_C values between the UNL- and farmer-managed fields were not significantly different at the 5% significance level ($p > 0.05$, table 3). There were a total of eight paired ET_C data points for each year, and the analyses were done for the pooled ET_C values for each year. Although it is not statistically significant, greater ET_C would be expected in the farmer-managed fields due to a larger number of irrigation applications than with UNL-management, which would keep surface soil moist for longer periods, as shown by wetter soil moisture status in the farmer-managed fields (figs. 5 and 6), and thus increase soil evaporation. The slight differences in ET_C values between the sites were

mainly due to differences in management practices, climatic conditions, and soil type and also due to the impact of irrigation on water balance components, but the differences in ET_c between the paired fields for the same site are not due to hybrid characteristics because the same hybrid was planted in the paired fields at a given site. The ET_C values being lower in the UNL-managed fields indicate that proper irrigation management practices can aid in reducing consumptive water use by reducing or eliminating unnecessary irrigation and thus reducing surface evaporation losses. Reduction in ET_C by 3% or 7%, while maintaining high yields, can be significant to farmers and can aid in better utilization of water resources through increasing crop water use efficiency. Reduction in ET_C by 3% or 7% can have significant positive implications at a large scale in terms of reduction in irrigation water withdrawals and associated energy savings.

In 2007, site 8 had low seasonal ET_C values as compared with other sites because the ET_C calculation period only covered 3 May through 16 August. This is because the soil moisture dataloggers did not log any data after 16 August due to a programming problem. Thus, the period of 3 May through 16 August was short, resulting in low ET_C values. The seasonal average daily ET_C was also less in the UNL-managed fields in both years (3.70 and 3.84 mm d^{-1} in 2007 for UNL- and farmer-managed fields, respectively) (table 4). The seasonal average daily ET_C was lower in the UNL- and farmer-managed fields in 2008 than in 2007 (table 5). In 2007, the greatest daily average ET_C was observed in the UNL-managed field at site 3 as 4.5 mm d^{-1}, whereas the greatest seasonal average daily ET_C occurred in the farmer-managed field at site 2 as 4.4 mm d^{-1} in 2008. When the average of all sites is considered, the runoff estimated using equation 4 was similar for both years (40 mm in 2007 and 37 mm in 2008), although it varied considerably between sites. In 2007, site 1 had the largest runoff (64 mm) and site 8 had the least estimated runoff (24 mm). In 2008, site 2 had the largest runoff (81 mm) and, again, site 8 had the least amount of runoff (8 mm).

Grain Yield

There was a significant effect of year and site on grain yield (table 3). Each yield data point in tables 5 and 6 is an average of four yield data points for each field. Grain yield was related to the amount of incident solar radiation during the grain filling at each site-year ($r^2 = 0.67$, $p < 0.001$) (data not shown), which is consistent with a previous analysis of the most sensitive weather parameters affecting maize productivity in the western Corn Belt (Grassini et al., 2009). All site-years (except site 5) had relatively high grain yields (range: 14,430 to 16,760 kg ha^{-1}). Yields were greater in 2008 than in 2007 due to cooler temperatures and longer duration of the post-silking phase (tables 2 and 4). Furthermore, in both years, maize crops in most study locations did not experience water or heat stress during the most critical growth stage for maize, which is the tasseling-silking stage. Remarkably, there was no difference in grain yields between UNL- and farmer-managed fields ($p = 0.75$). Average grain yield in the UNL- and farmer-managed fields was, respectively, 13,150 and 13,020 kg ha^{-1} in 2007 and 15,030 and 15,240 kg ha^{-1} in 2008. The lack of difference is notable because 34% and 32% less irrigation was applied to the UNL-managed fields in the two years than to fields under farmers' irrigation management**.**

Irrigation Water Use Efficiency and Crop Water Use Efficiency

It is important to note that the IWUE and CWUE values measured in this study may be greater than the values typically reported in the literature because the rainfed yields were not accounted for when calculating the IWUE and CWUE values in this study. There was a significant effect of site on ET_C that can be attributed to differences in evaporative demand, soil type, and tillage practices across sites (table 3). ET_C was not different across years or irrigation management regimes. It was slightly greater in 2008 than in 2007 due to longer crop growth duration and slightly lower in UNL-managed than in farmer-managed fields (3% and 7% less ET_C in 2007 and 2008, respectively). Irrigation water use efficiency was largely affected by year, site, and irrigation management (table 4). On average, IWUE in farmer- and UNL-managed fields, respectively, were 11 and 22 kg m^{-3} in 2007, and 15 and 19 kg m^{-3} in 2008. Thus, on-farm implementation of irrigation management strategies resulted in 38% and 30% increase in IWUE in the UNL-managed fields in 2007 and 2008, respectively.

While the IWUE term is more commonly used by the water management community because of its simplicity, since it does not involve the challenging task of determining ET_C, the CWUE is a more effective term when quantifying the efficiency of a crop production system because it directly reflects the amount of grain yield produced per amount of water used rather than per depth of water applied, which is the case with the IWUE. This is because (1) not all irrigation water applied to the field is used for ET_C, and (2) stored soil water at planting and planting-to-maturity rainfall also contribute to ET_C. Crop water use efficiency (CWUE; kg grain m^{-3} ET_C) was more conservative than IWUE across sites, years, and irrigation treatments, as indicated by the coefficients of variation (64% and 17% for IWUE and CWUE, respectively). Average CWUE values in the UNL- and farmer-managed fields, respectively, were 2.6 and 2.7 kg m^{-3} in 2008 and 3.0 and 3.1 kg m^{-3} in 2007 (table 4). These values are comparable with measured CWUE for maize in previous studies (e.g., Hanks et al., 1978; Eck, 1984; Musick and Dusek, 1980; Wenda and Hanks, 1981; Stegman, 1982; Howell et al., 1995). While the previous reported values for CWUE were based on studies conducted at research stations, the CWUE values from the present study were obtained from commercial-scale production fields where crops received good management practices and achieved high yield levels. Remarkably, many of the CWUE values shown in table 4 approached the maximum CWUE of 3.7 kg m^{-3} for maize reported by Grassini et al. (2009) based on crop model simulations in the western U.S. Corn Belt and measured CWUE in several maize-growing regions around the world.

CONCLUSIONS

The production-scale fields included in this study provide good representation of the variation in weather, soil, and management that is typical of maize systems in the western U.S. Corn Belt. The present research differs from previous studies on irrigation management strategies because it was conducted in commercial-scale high-yielding fields where management, microclimate, and soil water balance components differ substantially from small-plot experiments. Excellent farmer management skills and a favorable environment for maize production in this study was reflected in high yield levels (14.4 to 16.8 Mg ha^{-1}) with values of crop water use efficiency (2.1 to 4.0 kg m^{-3}) that are in the upper range of values reported in the literature. Irrigation management strategies practiced by the UNL team, based on soil water depletion thresholds and crop phenology, resulted in significant reduction in irrigation water withdrawals in both years without penalties in grain yield. The reduction in irrigation water withdrawals in the UNL-managed fields represented, on average, 34% of the irrigation applied in farmer-managed fields. On average, reduction in irrigation water withdrawals in UNL-managed fields resulted in \$32 to \$74 ha^{-1} and \$45 to \$67 ha^{-1} in energy saving and additional net return to the farm income in 2007 and 2008, respectively.

On-farm implementation of irrigation management strategies resulted in 38% and 30% increase in irrigation water use efficiency (IWUE) in the UNL-managed fields in 2007 and 2008, respectively. In contrast, average crop water use efficiency (CWUE) was only 4% higher in UNL-managed fields than in farmer-managed fields in both years. This is because there was no significant effect on ET_C despite the substantial reduction in applied irrigation water under UNL management. Lack of difference in ET_C resulted from greater soil water use under the UNL-managed irrigation regime, presumably from deep soil layers, which compensated for the smaller amount of applied irrigation.

During the life of this two-year project, training sessions and meetings were held with the participating farmers to discuss the requirements of the study. The farmers worked with the project team throughout the growing seasons to manage irrigation and maintain records of all agronomic practices. UNL faculty team members met with the farmers on a regular basis to assess progress. The Hybrid-Maize crop simulation model (www.hybridmaize.unl.edu) was utilized to estimate critical maize growth stages to aid in water management strategies. The farmers were provided training sessions about how to run and interpret the simulation results and incorporate them into their farming practices. This project successfully demonstrated that simple, but accurate, soil water status measurement devices, coupled with research-based decision making and a crop simulation model, can help farmers achieve significant reduction in water withdrawals and energy savings in high-yield irrigated maize systems without a reduction in yield. At the end of the project, the participating farmers were surveyed and results showed that all farmers benefited from the project by learning proper irrigation management strategies. As a result, they changed their behavior by adopting UNL management strategies in their irrigation practices. While the results from this study may potentially have a large impact in future irrigation management of irrigated maize systems in the region, the study was conducted only for two years, and the weather patterns may have potentially favored one strategy over another. Thus, additional years of research or perhaps the integration of long-term model simulations might be able to better assess the long-term impacts and/or implications of the irrigation management strategies studied in this research.

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