DEMONSTRATION / VALIDATION OF A DYNAMIC REAL-TIME DECISION SUPPORT SYSTEM FOR IRRIGATION MANAGEMENT

Natural Resources Conservation Service
Conservation Innovation Grant
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-Final Report-

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Grant deliverables / summary of the work performed:

The overall goal of this project was to demonstrate/validate innovative tools and strategies for irrigation management with limited water supply in corn-based cropping systems. Specific steps implemented in this project included:

1. Validate and demonstrate a decision support tool for real-time irrigation scheduling when water supply is limited, in a series of on-farm demonstrations over a three year period.
    - Selected progressive corn producers who were interested in increasing water use efficiency with limited irrigation to conserve water resources and who meet EQIP eligibility requirements.
    - For each selected producer, identified paired fields with pivot irrigation as demonstration sites using satellite imagery, NRCS soil survey maps, digital elevation maps to select fields with similar soil and topographical characteristics.
    - Conducted these demonstrations in different regions of the state to document the validity of the tools/strategies under a variety of soil and climate conditions.
2. Conduct a series of workshops across the state to educate producers, crop consultants, extension educators, and industry professionals about the decision-support tool and results of the on-farm demonstration program.
    - Presented results through various extension and educator workshop, field days and crop clinics (see Appendix A).
    - Prepared and submitted refereed journal articles to disseminate project results/findings in scientific literature.
3. Release the new tool as a software program for use by crop producers, crop consultants, and industry professionals.
    - Validated the robustness of the current model by comparison of model runs versus actual collected field results.

Project Action Plan and Timeline of Activities:

August 1, 2006 – Demonstration project begins

November 2006 – Complete selection of producers for demonstration site participation; quarterly report due.

February 2007 – Conduct training sessions for participating producers; quarterly report due

Spring 2007 – Demonstration projects begin; take soil samples and install soil moisture monitoring equipment; producers work with University specialists to establish field management logs for each field; quarterly report due end of May.

Summer 2007 – Producer-collaborators applies irrigation treatments in consultation with university specialists; continue field monitoring and records of crop management; Quarterly report due end of August.

Fall 2007 – Producer-collaborators will harvest corn from the two treatment fields at their demonstration site and record field yields; university specialists will take the yield validation samples from each field at the demonstration sites.

November 2007 – Assess first-year results to compare water-use efficiencies of the two irrigation treatments across the demonstration sites; analyze and interpret data; select new producers if necessary; quarterly report due.

February 2008 – Make adjustments to implementation of on-farm demonstration protocol as necessary; refine decision-support tool as needed based on results from the first year; conduct training sessions for new participating producers; quarterly report due.

Spring 2008 – Year 2 Demonstration projects begin; take soil samples and install soil moisture monitoring equipment and rain gauge; producers work with University specialists to establish field management logs for each field; quarterly report due end of May.

Summer 2008– Producer-collaborators applies irrigation treatments in consultation with university specialists; continue field monitoring and records of crop management; quarterly report due end of August.

Fall 2008 – Producer-collaborators will harvest corn from the two treatment fields at their demonstration site and record field yields; university specialists will take the yield validation samples from each field at the demonstration sites.

November 2008 – Assess first-year results to compare water-use efficiencies of the two irrigation treatments across the demonstration sites; analyze and interpret data; select new producers if necessary; quarterly report due.

February 2009 – Make adjustments to implementation of on-farm demonstration protocol as necessary; refine decision-support tool as needed based on results from the first year; conduct training sessions for new participating producers; quarterly report due.

Spring 2009 – Year 2 Demonstration projects begin; take soil samples and install soil moisture monitoring equipment and rain gauge; producers work with University specialists to establish field management logs for each field; quarterly report due end of May.

July 31, 2009 – Assess progress so far in Year 3, demonstration project ends; final report due.
November 2009 – October 2010: Educational workshops held for producers, crop consultants, industry professionals, and Extension Educators; release new decision support tool for irrigating with limited irrigation supply by the same outlet as used for the current Hybrid-Maize model

November-December 2010– Final project report preparation

Project Management:

Project oversight and financial management of this project will be the responsibility of the state corn commodity agency, the Nebraska Corn Board. University of Nebraska specialists will oversee the training, implementation, and monitoring of the demonstration sites, and will submit quarterly, written reports to the Nebraska Corn Board to ensure timelines are being met and deliverables are being accomplished. The Nebraska Corn Board will work in concert with University specialists and Extension Educators to conduct outreach efforts to agriculture stakeholders in Nebraska and other states to report the results and success of the project.

- Kelly Brunkhorst – Nebraska Corn Board, Director of Research – Oversight of project, financial management, outreach efforts.
- Dr. Ken Cassman – University of Nebraska, Professor of Agronomy and Horticulture – Co-project director, responsible for overall implementation, coordination, and monitoring of project activities, and for making quarterly and final reports.
- Dr. Haishun Yang – University of Nebraska, Asst. Professor of Agronomy and Horticulture – Responsible for development of the computer decision-support software.
- Dr. Suat Irmak – University of Nebraska, Associate Professor of Biological Systems Engineering – Lead project director, responsible for overall implementation, day-to-day coordination and monitoring of project activities, outreach activities, and preparing quarterly and final reports.
- Dr. William Kranz – Univ. of Nebraska NEREC, Professor of Biological Systems Engineering – Irrigation specialist and will be responsible for overseeing on-farm demonstrations in Districts 4 and 7.
- Dr. Charles Shapiro – Univ. of Nebraska NEREC—Professor of Soil Science – will help oversee implementation of on-farm demonstrations in Districts 4 and 7.
- Dr. Daniel Waters – University of Nebraska, Professor of Soil Science – soil fertility and plant nutrition – will provide leadership for soil and plant sampling to determine soil properties and plant nutritional status in each field.

Note that all team members contributed to the design and implementation of the training workshops throughout the project.

Project Evaluation:

Progress and financial reports were submitted as required by the USDA Natural Resource and Conservation Service. Based on the results from the on-farm demonstrations, we quantified the impact of this project in terms of the:

1. Amount of reduction in applied irrigation water using the real-time decision-support tool
2. Magnitude of increase in water-use efficiency (quantified as bushels of grain per inch of irrigation water applied).
3. Reduction in yield between the optimal irrigation regime and the real-time limited irrigation regime with the goal of minimizing the magnitude of this reduction.
4. The impact on net profit as estimated by the reduction in irrigation cost minus the cost of any yield decrease due to use of limited irrigation with the real-time decision-support tool (clearly the goal here is to minimize any reduction in profit although we would expect there to be some decrease in yield and associated gross return).

In addition, based on a formal survey instrument, we obtained a quantitative assessment from the producer-collaborators and from the workshop participants about the (i) usefulness of the decision-support tool, (ii) the likelihood that they will utilize this tool, (iii) how many irrigated acres they manage, and (iv) the increase in profit per acre they estimate would accrue from using this tool

Environmental Impacts:

As previously described above, this project will have a large potential for positive impact on water quality and conservation of natural resources across the state of Nebraska. The increased water-use efficiency that results from improved irrigation scheduling will reduce leaching volume, and the associated potential for nitrate movement to groundwater. Likewise, the decrease in water use achieved by limited irrigation will allow more water available for other uses, including protection of the integrity of riparian ecosystems and stream flow, which are crucial for conserving several endangered species and natural habitat for wildlife.

DECLARATION OF EQIP ELIGIBILITY

The Nebraska Corn Board through signed memorandums of understanding proclaims that each producer involved with this NRCS-funded water conservation project is EQIP eligible.

PROJECT 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 increase water productivity without noticeable reduction in maize yield. Results from previous research at the University of Nebraska-Lincoln (UNL) experiment stations found that it was possible to substantially reduce irrigation amounts, and increase irrigation and crop water use efficiency (IWUE and CWUE) with little or no reduction in yield using an irrigation regime that was more prudent with applied irrigation during growth stages less sensitive to water stress. Our hypothesis was that a soil moisture-based irrigation management approach would give similar results in large productions-scale, center pivot-irrigated fields in Nebraska. To test this hypothesis IWUE, CWUE and grain yield were compared in extensive on-farm research located at eight locations over two years (16 site-years) representing more than 600 ha. In each site-year, two contiguous center pivot-irrigated maize fields with similar topography, soil properties, and crop management received different irrigation regimes: one was managed by UNL researchers ('UNL-managed field') and the other by the farmer at each site ('farmer-managed field'). Irrigation management in farmer-managed fields relied on farmer's visual observations and personal expertise whereas irrigation amount and timing in the UNL-managed fields were based on pre-determined soil water depletion thresholds measured using soil moisture sensors, and 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 scheduling in the UNL-managed fields in both years (34 and 32% less irrigation application compared with farmer-managed fields in 2007 and 2008, respectively). 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 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, respectively. Water savings in UNL-managed fields resulted in $32.00/ha to $74.10/ha and $44.46/ha to $66.50/ha in energy saving and additional net return to the farm income in 2007 and 2008, respectively. The site-year observations included in the study encompass the weather, soil, and management variability expected over a large area of the western U.S. Corn Belt. Therefore, results from this study may have large impact in future irrigation management of irrigated maize systems in the regions with similar soil and crop management practices.

Keywords: Maize, irrigation management, evapotranspiration, water use efficiency.

1. INTRODUCTION

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. Rising demand for food, livestock feed, and biofuels coupled with global climate change and competition with urban sectors, will put increasing pressure on freshwater resources (Rosegrant et al., 2009). Competition for scarce water is already evident in major irrigated cropping systems of the world (Perry et al., 2009). 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 land in the world with a total production of about 820 Mt. Demand for maize for human and animal consumption will increase by nearly 300 Mt by 2030, which does not include the increased demand for bio-fuel production (FAO, 2010). The five largest maize producers are: the United States of America (USA), China, Brazil, India, and Mexico. The United States 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 total maize area in Nebraska and contributes 74% of total annual maize production of 32 Mt in this state (USDA-NASS, 2003-2007). With approximately 60,000 center pivots and over 100,000 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 10 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 critical need for improving irrigation water use efficiency (IWUE, kg grain per m^3 applied irrigation) and crop water use efficiency (CWUE, kg grain per m^3 of water used).

In many cases, straightforward, economical and robust methods for combining limited or deficit irrigation strategies with more efficient irrigation systems and soil moisture monitoring can lead farmers to become substantially more efficient in utilizing water resources. 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 United States has decreased from 637 mm in 1975 to 502 mm in 2005; comparable figures for Nebraska are 366 in 1975 and 335 mm in 2005 (NASS, 2007). Much of this improvement resulted from conversion of gravity (furrow) irrigation to center pivots. Depending on precision of management, center pivot application efficiency (i.e., measure of the fraction of the total volume of water delivered to the farm or field to that which is stored in the root zone to meet the crop evapotranspiration) is typically about 85% while furrow irrigation is less efficient at 40-70%. The trend of reduced irrigation applications 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 3-6% penalty in grain yield (Irmak and Payero, unpublished 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 farmer’s 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.

2. MATERIALS AND METHODS

2.1. Study locations

The project was conducted in central and eastern Nebraska to evaluate performance of a soil moisture-based irrigation management approach on maize. The study area encompasses a rainfall gradient with highest annual precipitation in the east and 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 the eastern half of NE where maize production is concentrated. Other selection criteria included their willingness to: (i) manage two pivot-irrigated fields with the same hybrid and crop management other than irrigation for two years, (ii) impose the soil moisture-based irrigation regime on one of the pivots as specified by UNL researchers, (iii) provide information on management practices such as fertilizer, seeding rate, hybrid brand and number, dates of planting and maturity, and final grain yield. Selected farms had at least two pivot irrigated fields with relatively uniform soil properties and surface relief, and they had flow meters 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), pair center-pivots had similar system pressure, sprinkler nozzles, water application rate, and size and system capacity. Irrigation in one of the two 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, hybrid brand and maturity, pest and nutrient management.

Table 1. Site location, coordinates, elevation, and measured soil properties at the research fields in Nebraska. 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 0.23–0.38 m soil depth.

Site	Town	Lat. (°)	Long. (°)	Elev. (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

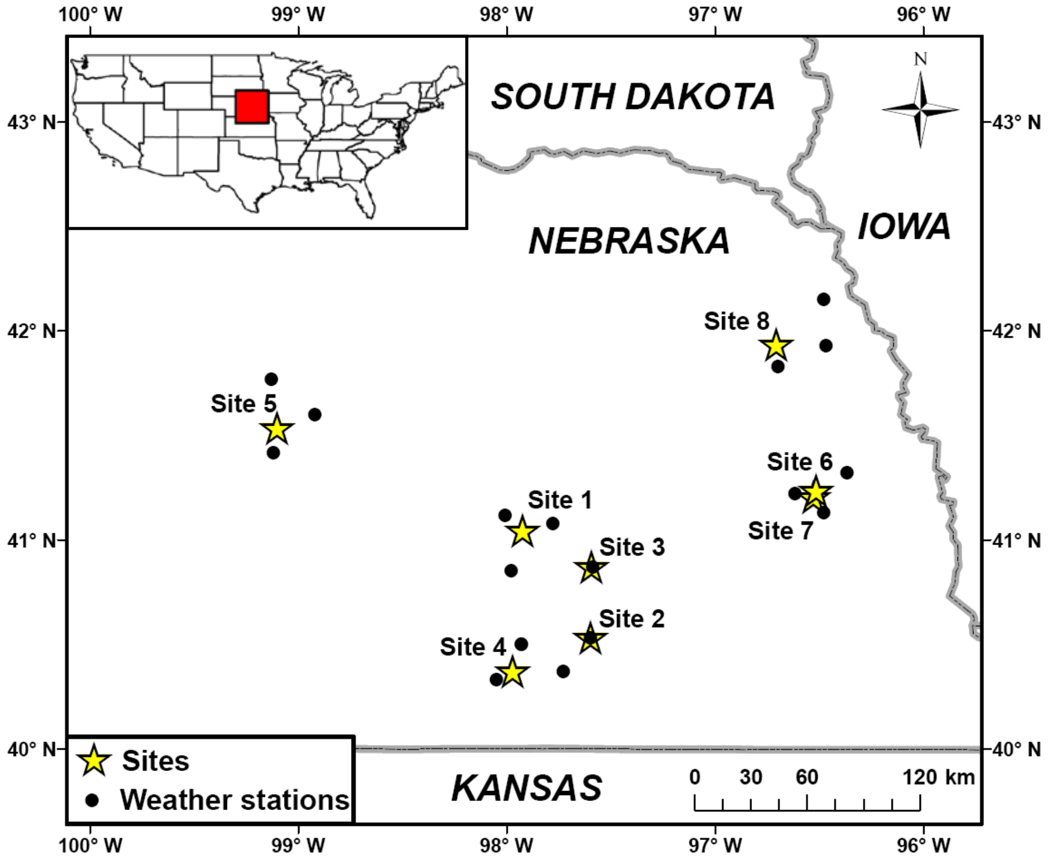

Figure 1. Map of eastern and central Nebraska (USA) showing the location of farmer irrigated maize fields accounted for in the present study (stars). Solid circles indicate location of meteorological stations used. Lines show state boundaries. States are named. Location of the area of study within contiguous U.S. is shown (left upper inset).

Soil samples were taken before planting each year to determine optimal N and P fertilizer rates in each field based on UNL guidelines (http://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 (http://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 and sieved through a 2 mm screen, then analyzed by the UNL Department of Agronomy Soil Testing Laboratory and recommendations were made to the farmer cooperators for each field.

2.2. 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, and these textures are representative of soils used for irrigated agriculture in 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 (WGM) sensors (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, CA). The WGM sensors are electrical resistance type sensors and provide SMP in kPa. SMP has negative sign (i.e., more negative SMP values indicate drier soil), which is omitted from the data presented in this paper. In each field, WGM sensors were installed in an area with soil and topography that was most representative of the entire field. Selection of such sensor locations was based on aerial photos taken before and during the season, and digital elevation maps (from NRCS WebSoil Survey; http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm). An example of aerial pictures that were taken in one of the study sites is given in fig. 2. In each field, WGM sensors 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 two locations per field to monitor SMP on an hourly basis from the time the equipment was installed until physiological maturity or harvest.

Soil Water Characteristics Software (ver. 6.02.74) by Saxton et al. (1986, 2006) was used to develop soil-water retention curves for converting SMP readings to volumetric water content. Briefly, soil water characteristic equations were developed from 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 water sensors 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 of 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.

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

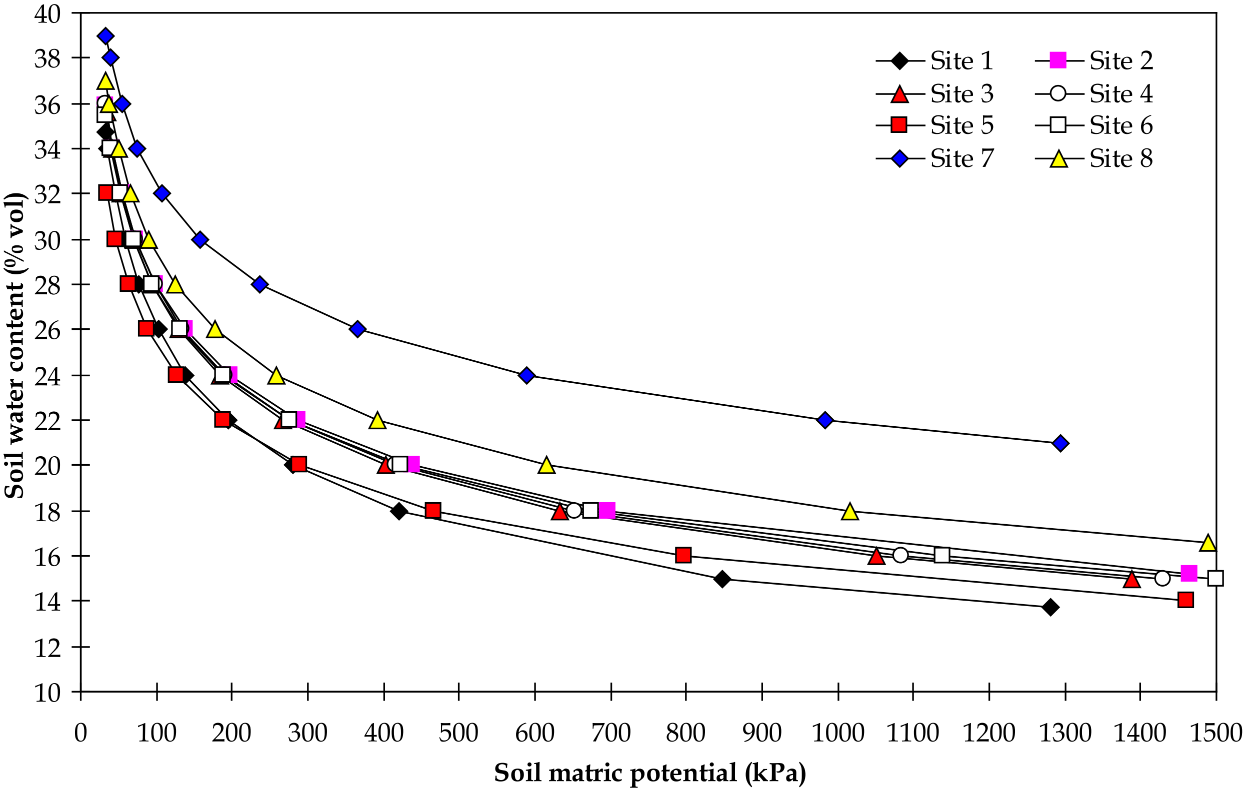

Figure 3. Soil-water retention curves created using Saxton (1986) model for each site to convert soil matric potential data to soil water content.

2.3. Irrigation management

In the farmer-managed fields, irrigation decisions were made by farmers based on their experiences. Farmers' irrigation methods are typically based on a fixed calendar date, visual observation of plant water needs, hand-feel of soil moisture, observing neighbor's irrigation practices, or 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 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 WGM sensor readings equivalent to matric potential between 90-100 kPa [35-40% depletion of available water holding capacity (AWHC) in the root zone for silt loam soils]. 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 day for a complete rotation depending on the well capacity, irrigation system hydraulic design, and several 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 25-35 mm of applied water.

Because maize grain yield is most sensitive to water stress during the critical time pollination 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 was made with the Hybrid-Maized model (Yang et al., 2004 and 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-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, Hybrid-Maize was run each week during the vegetative phase to estimate, in advance, the silking date at each site based on actual sowing dates, real-time and historical weather data obtained from nearby weather stations operated by High Plains Regional Climate Center (http://www.hprcc.unl.edu/). In all cases, weather stations were within 15 km of the study sites.

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 during 2007 and 2008.

Site	Year	Field	Hybrid name (and maturity)[a]	Planting date	Observed silking date	Observed physiological maturity date	Population density (plants/ha)
1	2007	UNL	P33N11 (1524 GDD) and P34B60 (1524 GDD)	4-May	15-Jul	11-Sep	66,765
		Farmer		4-May	15-Jul	10-Sep	66,765
	2008	UNL	DKC63-42 (1559 GDD)	30-Apr	20-Jul	5-Oct	74,809
		Farmer		30-Apr	21-Jul	5-Oct	73,059
2	2007	UNL	P33H26 (1537 GDD)	2-May	14-Jul	6-Sep	68,648
		Farmer		2-May	14-Jul	2-Sep	71,431
	2008	UNL	DK6544VT3 (1586 GDD)	30-Apr	14-Jul	29-Sep	72,387
		Farmer		30-Apr	13-Jul	29-Sep	73,464
3	2007	UNL	DK63-39 (1559 GDD)	21-Apr	7-Jul	2-Sep	74,571
		Farmer		21-Apr	7-Jul	2-Sep	68,918
	2008	UNL	P33H27 (1537 GDD)	30-Apr	16-Jul	28-Sep	82,343
		Farmer		30-Apr	16-Jul	27-Sep	83,420
4	2007	UNL	P32B29 (1578 GDD)	3-May	11-Jul	5-Sep	72,689
		Farmer		3-May	11-Jul	5-Sep	72,150
	2008	UNL	P32T84 (1537 GDD)	30-Apr	14-Jul	21-Sep	78,441
		Farmer		30-Apr	14-Jul	22-Sep	77,500
5	2007	UNL	Renze 6296, 8364 and 3274	5-May	17-Jul	18-Sep	45,497
		Farmer		5-May	17-Jul	18-Sep	52,498
	2008	UNL	Renze 9386YGCB/RR2	7-May	23-Jul	16-Oct	68,621
		Farmer		7-May	23-Jul	16-Oct	67,408
6	2007	UNL	NC+ 5555 (1550 GDD)	23-Apr	5-Jul	6-Sep	69,995
		Farmer	NC+ 5411 (1534 GDD)	23-Apr	5-Jul	4-Sep	71,072
	2008	UNL	NC+ 5225 VT3 (1505 GDD)	29-Apr	15-Jul	20-Sep	73,329
		Farmer		30-Apr	16-Jul	21-Sep	77,366
7	2007	UNL	P34A17 (1457 GDD)	16-Apr	3-Jul	29-Aug	71,342
		Farmer		16-Apr	3-Jul	29-Aug	68,110
	2008	UNL	P34F96 (1484 GDD)	15-Apr	12-Jul	18-Sep	68,755
		Farmer		15-Apr	13-Jul	19-Sep	65,122
8	2007	UNL	DKC61-66 (1531 GDD)	3-May	10-Jul	12-Sep	68,918
		Farmer		3-May	10-Jul	12-Sep	66,227
	2008	UNL	Croplan 6069AS3 (1496 GDD)	23-Apr	19-Jul	1-Oct	62,162
		Farmer		23-Apr	19-Jul	1-Oct	62,026

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

2.4. Crop phenology and grain yield

Two weeks after emergence, within each of the four quarters in each field, two measurement areas of 10 x 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 20-50 m of the second 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 in four contiguous rows in the center of the measurement areas in each quadrant. For grain yield determination, ears were taken from 6 m of two adjacent rows in each measurement area and dried to constant weight at 70°C. Grain yields were adjusted to standard commercial moisture of 0.155 g H_2O g^{-1} for reporting purposes.

2.5. 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) and Howell (2001):

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

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

where yield is in g/m^2, ET_C and irrigation is in mm, and CWUE and IWUE is 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 root zone (ΔTSW) as:

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

where S_{mm} is the available soil water for the previous day, S_{mm+1} is available soil water for the current day, so that (S_{mm}-S_{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 run-off. Depth of active root zone was assumed to be 1.20 m. All components of the water balance are reported in mm. Deep percolation was assumed to be negligible because soil moisture was measured only up to 1.20 m in each field and it was not possible to estimate the deep percolation below the crop root zone. Furthermore, in most cases cumulative ET_C is greater than rainfall where corn 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 WGM sensors 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 the 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.

Surface run-off was calculated using the Soil Conservation Service method (USDA-SCS, 1972), which estimates run-off as a function of soil type, daily precipitation, slope, land use, management practices, and antecedent soil moisture prior to precipitation as:

$$RO = (P - 0.2S_r)^2 / (P + 0.8S_r) \quad (4)$$

$$S_r = (25400 / CN) - 254 \quad (5)$$

where S_r is the initial abstraction or the amount of water before run-off occurs (in mm) and CN is the run-off curve number that correspond to different combinations of soil-cover settings and antecedent soil moisture at each site. UNL- and farmer-managed fields were assumed to have the same run-off since management practices, soil properties, and topography were similar.

The Watermark sensors were installed 4-6 weeks after planting in most of the site-years. The Hybrid-Maize model was used to estimate ET_C from planting until the date when WGM sensors were installed. Hybrid-Maize simulates ET_C based on (i) maximum crop transpiration as estimated from grass-reference evapotranspiration (ET_O) and leaf area index, (ii) rooting depth and soil water potential, which in turn is based on water release characteristics as determined by soil texture, and (iii) direct evaporation from 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 date of start of soil water measurements using Hybrid-Maize model and rest-of-season ET_C calculated using Eq. 3.

2.6. 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 x irrigation treatment, site x year, and site x irrigation treatment x year (errors a, b, and c, respectively, see table 3).

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 eastern Nebraska. *P*-values for the significance of factor effects are shown between brackets.

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

3. RESULTS AND DISCUSSION

3.1. Precipitation and irrigation

The amount and distribution of rainfall varied substantially among sites and years (fig. 4). 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 at 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 growing season 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).

Table 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 (table 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 farmer's records and the research team's ultrasonic flow measurements during irrigation events. 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. In 2007, the average irrigation applied across all sites in the farmer-managed and UNL-managed fields, respectively, were 125 and 82 mm and they were 111 and 75 mm, respectively, in 2008. Thus, soil moisture-based irrigation management strategies and pre-determined SMP threshold in UNL-managed fields resulted in a 34 and 32% less irrigation applications in 2007 and 2008, respectively.

3.2. Seasonal changes in SMP and total 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 figs. 5 and 6 as example datasets. The same datasets were collected for all site-years, but the seasonal patterns of SMP and total 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 fluctuated during the crop growing season as a function of rain and irrigation applications (fig. 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 May 25th the SMP was near 5 kPa and increased gradually thereafter. Near June 5th the SMP at the 0.30 m depth increased greatly from around 30 kPa to 100 kPa within a 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 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 a SMP 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 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 June 27th (total: 33 mm). At this time both the 0.30 m and 0.60 m layers were near the threshold SMP

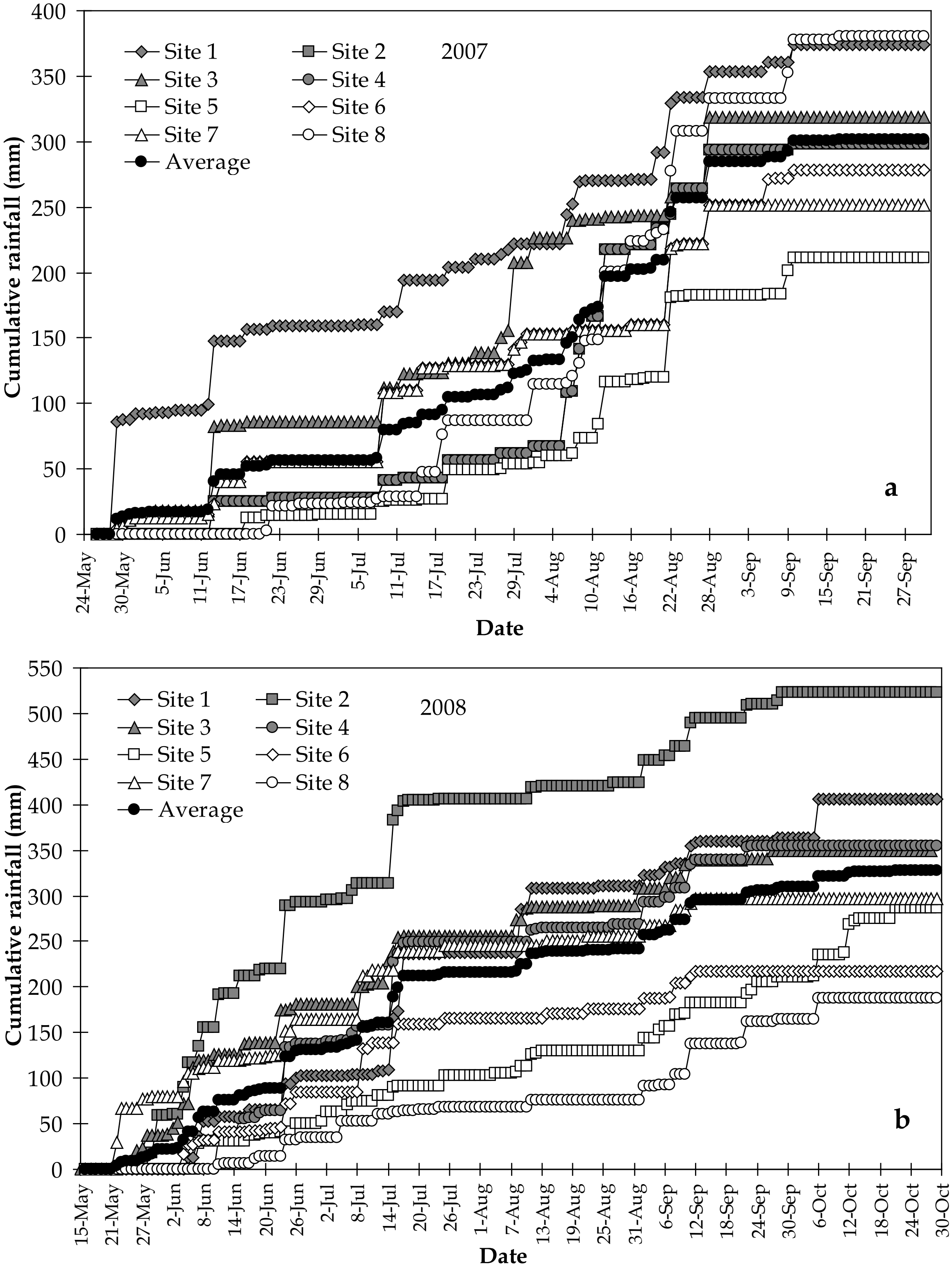

Figure 4. Cumulative rainfall from sowing date to physiological maturity at each site in 2007 and 2008. Rainfall data were obtained from the closest High Plains Regional Climate Center (HPRCC) automated weather station for each site. Average rainfall of all sites is also shown in each figure for comparison.

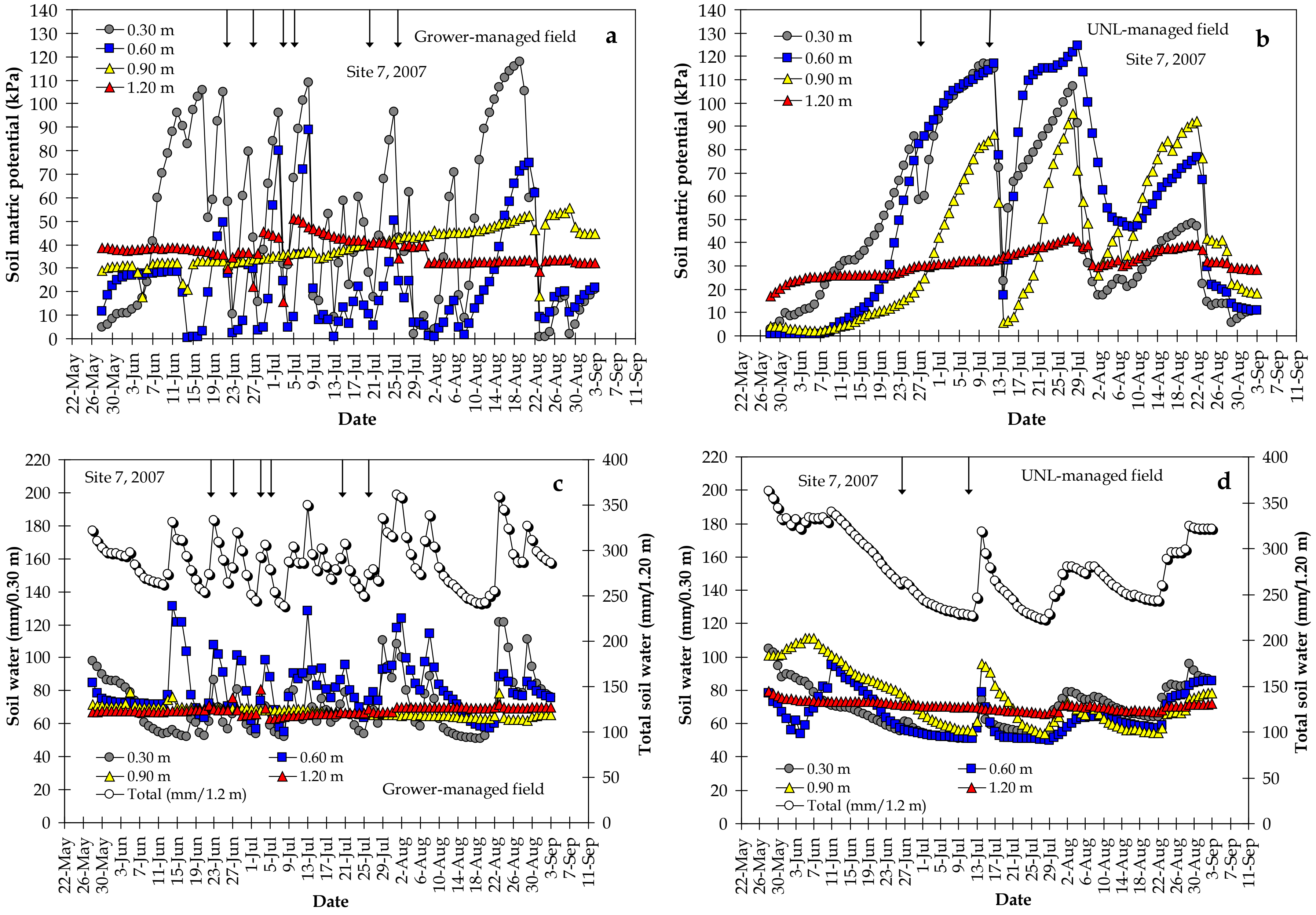

Figure 5. Seasonal distribution of daily soil matric potential in the 0.30, 0.60, 0.90, and 1.20 m soil depths at the grower-managed (a) and UNL-managed field (b); soil water per 0.30 m depth in the 0.30, 0.60, 0.90, and 1.20 m soil depth (c); and total soil water in the top 1.20 soil depth at site 7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

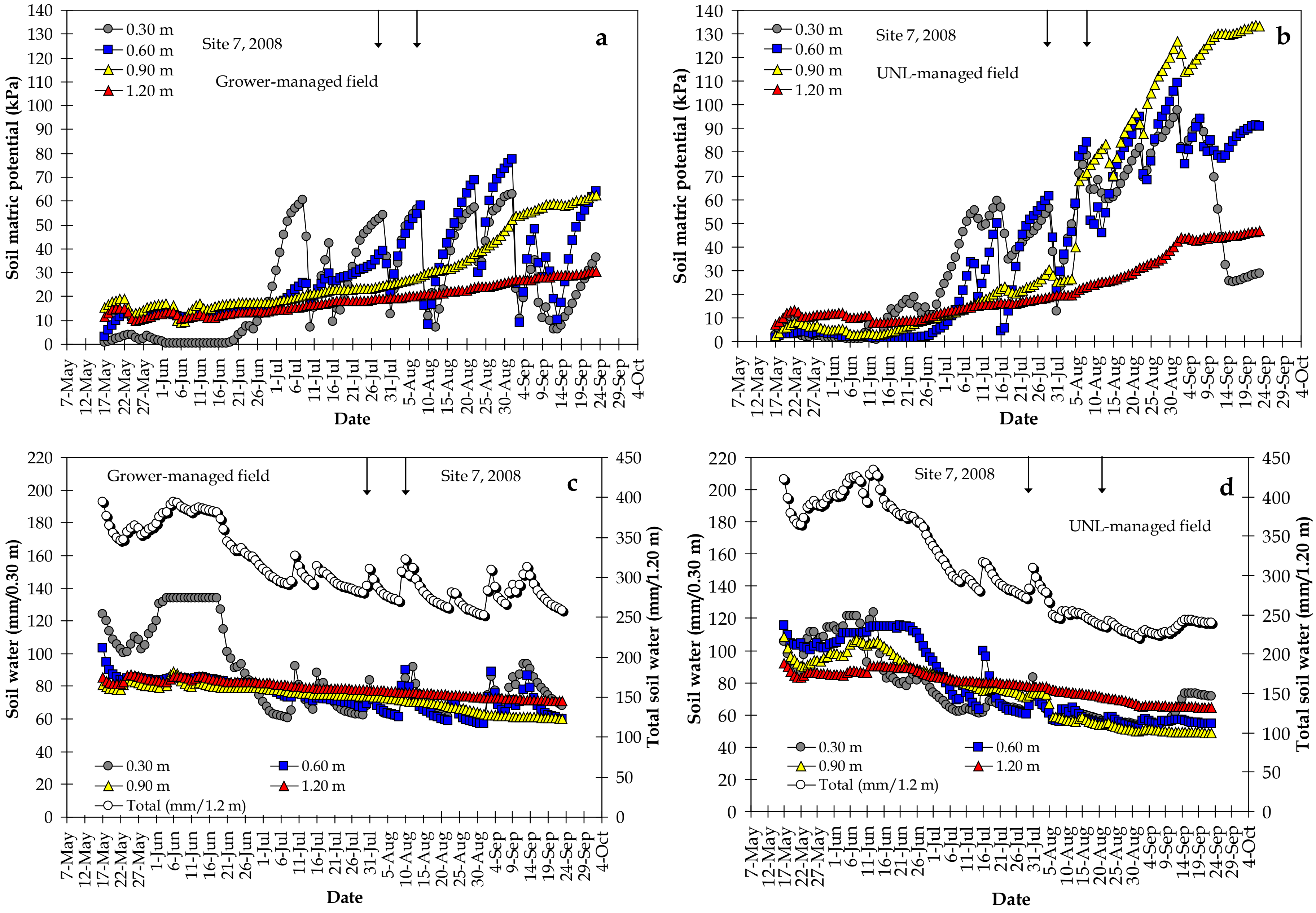

Figure 6. Seasonal distribution of daily soil matric potential in the 0.30, 0.60, 0.90, and 1.20 m soil depths at the grower-managed (a) and UNL-managed field (b); soil water per 0.30 m depth in the 0.30, 0.60, 0.90, and 1.20 m soil depth (c); and total soil water in the top 1.20 soil depth at site 7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

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

Site	Precip. (mm)	Run-off (mm)	Effective precip. (mm)	Treatment	Gross irrigation (mm)	ΔTSW (mm)	ET_C (mm)	ET_C (mm/day)	Yield (kg/ha)	IWUE (kg/m^3)	CWUE (kg/m^3)
1	374	64	310	UNL	44	123	498	3.69	12740	29	2.56
				Farmer	102	175	599	4.43	12800	13	2.14
2	298	34	264	UNL	102	165	570	4.32	14370	14	2.52
				Farmer	159	58	511	3.87	13930	9	2.73
3	319	60	259	UNL	127	207	626	4.50	14560	11	2.33
				Farmer	178	146	608	4.37	14880	8	2.45
4	298	34	264	UNL	104	39	443	3.41	13430	13	3.03
				Farmer	117	24	439	3.38	12990	11	2.96
5	211	27	184	UNL	89	117	422	3.27	9600	11	2.28
				Farmer	102	227	542	4.20	9670	10	1.78
6	278	39	239	UNL	102	183	549	3.89	14190	14	2.59
				Farmer	140	92	491	3.48	13620	10	2.78
7	251	39	212	UNL	66	85	410	2.93	13870	21	3.38
				Farmer	127	35	412	2.94	13310	10	3.23
8	224	24	200	UNL	19	56	375	3.57	12430	65	3.31
				Farmer	79	59	428	4.08	12930	16	3.02
Average	282	40	241	UNL	82	122	487	3.70	13150	16	2.75
				Farmer	125	102	504	3.84	13020	10	2.64

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

Site	Precip. (mm)	Run-off (mm)	Effective precip. mm)	Treatment	Gross irrigation (mm)	ΔTSW (mm)	ET_C (mm)	ET_C (mm/day)	Yield (kg/ha)	IWUE (kg/m^3)	CWUE (kg/m^3)
1	407	70	337	UNL	57	112	527	3.23	14810	26	2.81
				Farmer	76	203	633	3.88	15060	20	2.38
2	523	81	442	UNL	79	102	632	4.03	15880	20	2.51
				Farmer	109	132	689	4.39	16760	15	2.43
3	349	18	331	UNL	76	214	631	3.99	15320	20	2.43
				Farmer	152	178	639	4.04	16380	11	2.57
4	355	64	291	UNL	84	68	472	3.13	15320	18	3.24
				Farmer	99	191	609	4.03	15380	16	2.53
5	287	9	278	UNL	155	67	477	2.86	15190	10	3.19
				Farmer	155	50	485	2.90	14440	9	2.98
6	218	16	202	UNL	51	168	442	2.95	15570	31	3.52
				Farmer	121	55	389	2.59	15630	13	4.02
7	297	26	271	UNL	0	182	478	2.97	13620	NA	2.85
				Farmer	51	135	474	2.94	14190	28	2.99
8	188	8	180	UNL	102	117	431	2.60	14560	14	3.38
				Farmer	127	135	470	2.83	14120	11	3.00
Average	328	37	291	UNL	75	129	511	3.22	15030	20	2.99
				Farmer	111	135	548	3.45	15240	14	2.86

set forth by UNL of around 90 kPa during the critical growth period of 10 days before silking until 7 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 Watermark sensors that were installed in the 0.30 m depth. The bottom of the Watermark sensor 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 0.19 cm^3/cm^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. 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 July 13, July 29, and August 23. 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 July 5th when the average 0.90 m soil matric potential reached 90 kPa. Although the SMP reached 90 kPa on July 23rd irrigation was not triggered due to forecasted precipitation event in the next one or two days.

Seasonal distribution of daily average total soil water per 0.30 m layer (mm/0.30 m) and total soil water (TSW) in the top 1.20 m soil depth for all fields for 2007 are presented in fig. 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 30-33 kPa (near or above field capacity). Total 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 the more soil water was used by the crop, reducing irrigation applications in the UNL-managed field. In 2008, a 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 and utilizing soil water and reducing irrigation requirement. The TSW had a gradual decrease as the season progressed: TSW varied from 170 mm in early June to around 100 mm in mid and late July (fig. 5). There were only two irrigation applications (June 27 and July 5) 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., TWS at the beginning of season minus TSW at maturity) was 122 and 102 mm in UNL- and farmer-managed fields, respectively. An extra-irrigation of 43 mm in 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.

3.3. Grain yield

There was a significant effect of year and site on grain yield (table 3). Each yield data point in table 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 for site 5) had relatively high grain yields (range: 14,430 to 16,760 kg/ha). Yields were higher in 2008 than 2007 due to cooler temperatures and longer duration of the post-silking phase (table 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 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 in 2007 and 15,030 and 15,240 kg/ha in 2008. The lack of difference is notable because 34 and 32% less irrigation was applied to UNL-managed fields in the two years than to fields under farmer’s irrigation management**.**

3.4. Evapotranspiration, irrigation water-use efficiency and crop water-use efficiency

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 higher in 2008 than in 2007 due to longer crop growth duration and slightly lower in UNL- than in farmer-managed fields (3 and 7% less ET_C in 2007 and 2008, respectively). Higher ET_C in farmer-managed fields would be expected due to a larger number of irrigation applications than with UNL-management, which would keep surface soil moist for longer periods and thus increase soil evaporation. The differences in ET_C values between the sites are mainly due to differences in management practices, climatic conditions, and soil type. The main difference in ET_C between UNL and farmer-managed fields in the same site is mainly due to the impact of irrigation on water balance components and not due to hybrid characteristics because same hybrid was planted in the paired fields in a given site.

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.

While the IWUE term is more commonly used by the water management community because of its simplicity since it does not involve a challenging task of determining ET_C, the CWUE is the better 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 (i) not all irrigation water applied to the field is used for ET_C and (ii) stored soil water at plating and planting-to-maturity rainfall also contributed to ET_C. Crop water-use efficiency (CWUE; kg grain per m^3 of ET_C) was more conservative than IWUE across site, years, and irrigation treatments as indicated by their coefficient of variations (64 and 17% for IWUE and CWUE, respectively). Average CWUE in 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 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.

4. 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 favorable environment for maize production in this study was reflected in high yield levels (14.4 to 16.8 t ha^{-1}) with values of water use efficiency (2.1 to 4.0 kg/m^2), which 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 water savings in both years without penalties in grain yield. The irrigation water savings represented, on average, 34% of the irrigation applied in farmer-managed fields. On average, water savings in UNL-managed fields resulted in \$32/ha to \$74/ha and \$45/ha to \$67/ha 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 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 the smaller amount of applied irrigation.

During the life of this two-year project, training sessions and meetings were held with the farmer-cooperators to discuss requirements of the study. Cooperators worked with the project team throughout the growing seasons to manage irrigation and maintain records of all agronomical practices. UNL faculty team members met with 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. 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 crop simulation model, can help farmers achieve significant water and energy savings in high-yield irrigated maize systems without a reduction in yield. At the end of the project, 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. The site-year observations included in the study encompass the weather, soil, and management variability expected over a large area of the western U.S. Corn Belt. Therefore, results from this study may have large impact in future irrigation management of irrigated maize systems in the region.

Through comparisons of the simulated model runs and actual field results, the UNL team members determined that an update of the model was not warranted at this time. The model simulations proved the robustness of the current model, when compared to the actual data collected from collaborator fields.

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APPENDIX A:

List of Educational/Outreach Activities:

The following section lists the extension/education/outreach activities that were performed to disseminate the project findings to growers, crop consultants, state and federal agency personnel, extension educators, and university personnel:

2007

Irmak, S. February 6, 2007. Newer Tools for On-Farm Monitoring of Soil Water Status and Crop Water Use. Mid-Winter Certified Crop Advisors Conference of the Nebraska Agri-Business Association. *Grand Island, NE*.

Irmak, S. February 13, 2007. In-Season Water Management, Evapotranspiration and Soil Water Measurements, Identifying Crop Growth Stages. Irrigation and Energy Conservation Workshop for Corn Growers. *Norfolk, NE*.

Irmak, S. February 13, 2007. In-Season Water Management, Evapotranspiration and Soil Water Measurements, Identifying Crop Growth Stages. Irrigation and Energy Conservation Workshop for Corn Growers. *Cozad, NE*.

Irmak, S. February 13, 2007. In-Season Water Management, Evapotranspiration and Soil Water Measurements, Identifying Crop Growth Stages. Irrigation and Energy Conservation Workshop for Corn Growers. *Geneva, NE*.

Yang, H., S. Irmak and **K. Cassman**. April 18, 2007. Scientific Challenges of Developing a Real-Time Decision Support Tool for Deficit Irrigation for Corn. Spring 2007 Water Seminar Series. *Lincoln, NE*.

Yang, H., **S. Irmak**, **K. Cassman**, D. Tarkalson, and **D. Walters**. November, 2007. Corn Water Use Efficiency with Deficit Irrigation in High Yielding Settings. ASA-CSSA-SSSA 2007 International Annual Meetings. November 4-8. New Orleans, Louisiana.

Irmak, S. Newer technologies to increase on-farm water use efficiency. December 19, 2007. Presented at the Governor's Water Team meeting at the East Campus Union, Lincoln, NE.

2008

Irmak, S. February 11, 2008. Crop evapotranspiration, evaporation, and transpiration. Presented at the UNL Extension, Nebraska Corn Growers Association, and Nebraska Corn Board Statewide Educational Programs. *Clay Center, NE*.

Irmak, S. February 27, 2008. Agricultural water management tools and strategies. Nemaha NRD personnel and area growers. *Tecumseh, NE.*

Irmak, S. February 28, 2008. Challenges and opportunities for water-limited irrigated corn: Making every drop count. Workshop on demonstration and validation of a dynamic, real-time decision support system for irrigation management with limited water supply in corn-based cropping systems. Program by UNL Extension, USDA-NRCS, and NE Corn Board. *Grand Island, NE*.

Irmak, S. March 25, 2008. Southeast Research and Extension Center (SEREC)–research update. Presented to the SEREC faculty. *Lincoln, NE*.

Burgert, M., and **S. Irmak**. Comparison of actual evapotranspiration for corn derived from four methods in Nebraska. Presented at the *ASABE Annual International Meeting*, Rhode Island, Providence, June 29-July 2, 2008.

Irmak, S. September 12, 2008. NAWMDN in-service training for extension educators and NRD personnel. *York*, NE.

2009

Irmak, S. December 5, 2008. Irrigation management strategies to increase water use efficiency using various methods. Producer workshop: Presentation and hands-on demonstration. *Bruning, NE*. 4 hours, 140 people.

Irmak, S. December 18, 2008. Hands-On Workshop for Producers on newer tools/technologies for irrigation water management. *Wilber, NE*. 3 hours, 30 people.

Irmak, S. January 7, 2009. Irrigation management using soil moisture and crop water use data. Crop Protection Clinic Annual Program. *Hastings, NE*. 145 people.

Irmak, S. January 13, 2009.Measurement of soil water status: application of new tools and technologies. Workshop on Soil and Water Management. *Mead, NE*. 41 people.

Irmak, S. January 13, 2009. Measurement of soil water status: application of new tools and technologies. Workshop on Soil and Water Management. *Mead, NE*. 41 people.

Irmak, S. February 26, 2009. On-farm research/demonstration for water management and increasing water use efficiency. Grower and state agency workshop in partnership with UNL Extension/USDA-NRCS/NE Corn Board. *G. Island*, NE. 32 people.

Burgert, M**.**, and **S. Irmak.** April 4, 2009. Large scale implementation of research-based irrigation management tools/strategies for maize. Mid-central ASABE Conference, *Ames, IA*.

Irmak, S. April 30, 2009. Innovations in irrigation technology: Advancements in practical applications and scientific challenges. Sixth Annual Water Law, Policy, and Science Conference. *Lincoln, NE*.

Irmak, S. November 17, 2009. Research update at the South Central Agricultural Laboratory. *Clay Center, NE*, 13 people.

2010

Irmak, S. January 19, 2010. Large scale implementation of irrigation management strategies for increasing water use efficiency of corn. Ag. Update Extension Program, *Central City, NE.* 75 people.

Irmak, S. January, 27, 2010. Sensor-based irrigation management. 2010 Annual NEATA (Nebraska Agricultural Technologies Association) conference and Trade Show. *Grand Island, NE.* 40 people.

Irmak, S. March 17, 2010. Large scale implementation of research-based irrigation management tools/strategies for maize. Hamilton County NAWMDN program. *Aurora, NE*. 46 people.

Irmak, S. March 19, 2010. Large sacel implementation of irrigation management tools for corn and soybean production. Producer Workshop. *York, NE*. 40 people.

Irmak, S. March 30, 2010. Research and extension projects update. *Clay Center, NE*. 17 people.

Irmak, S. May 4, 2010. Research and educational programs related to agricultural water management: Highlights from Nebraska. Second Annual UNL Water for Food Conference. *Lincoln, NE*. 320 people.

Irmak, S. August 2, 2010. Newer tools/technologies for agricultural water management. *Alma, NE*. 25 people.

Irmak, S. August 30, 2010. New technologies for monitoring soil water status and crop water use. SCAL-NE Corn Board-NE Corn Growers Association-UNL Extension Field Day on Irrigation and Energy Conservation (**repeated four times**). *Clay Center, NE*. 162 people.

Irmak, S. December 3, 2010. Large scale implementation of irrigation management strategies to increase maize water productivity. Presented at the Nebraska Agribusiness Association Annual Conference. *Lincoln, NE*. 60 people.

APPENDIX B:

Project pictures

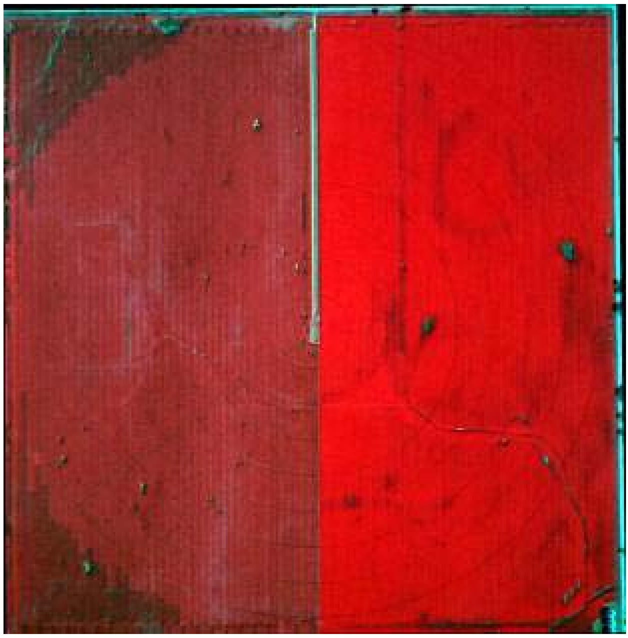
Examples of Project Fields

NRCS Web Soil Survey

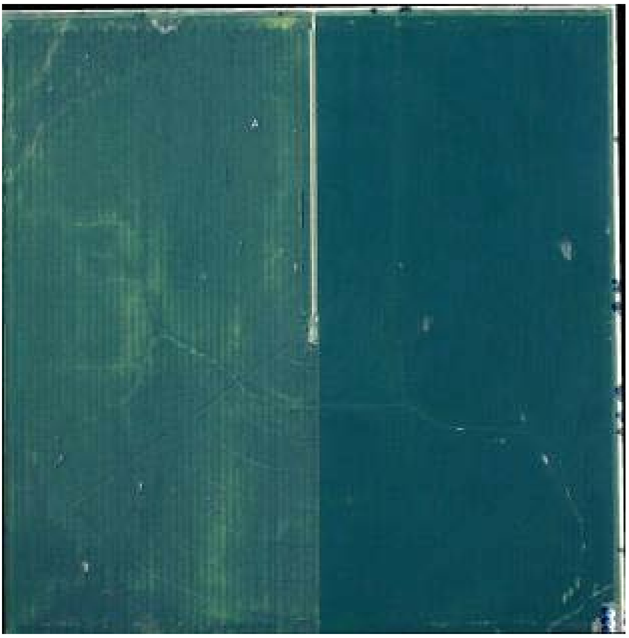
Aerial

Infrared

Infrared



Aerial



Sampling Areas within Project Fields

- Plant sampling locations were determined as soon as possible after emergence.

- When possible the sampling areas were positioned in each of the four quadrants of the field.

- The areas that were selected had uniform emergence. These areas also were representative of the entire field in terms of soils and topography.

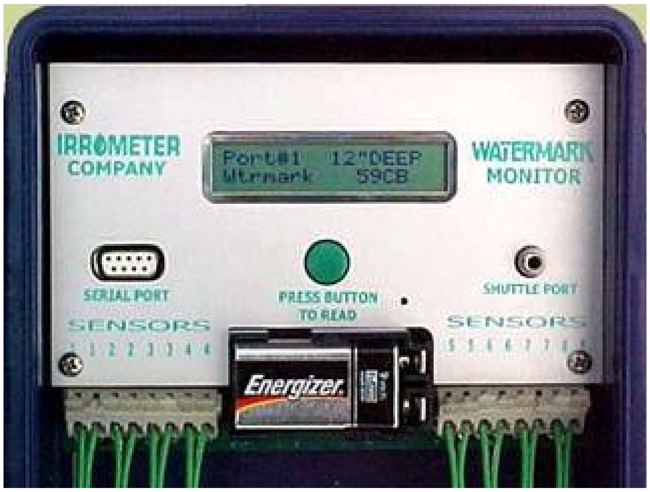
- Sampling areas were 30ft x 30ft.

- All agronomic yields and measurements were taken in these sampling areas.

Measurements, sampling of soil and plant parameters, harvest and other field demonstration components

Watermark Soil Moisture Sensors

- **Watermark® 200SS granular matrix sensors are practical and accurate tools that have been developed to allow for monitoring of soil water status at different depths in the soil profile.**
- **These sensors were employed in our project to quantify soil water status by measuring soil matric potential on an hourly basis for the entire growing season.**
- **Watermark sensors were attached to Watermark Monitor model (900M) datalogger (Irrometer, Co., Riverside, CA).**

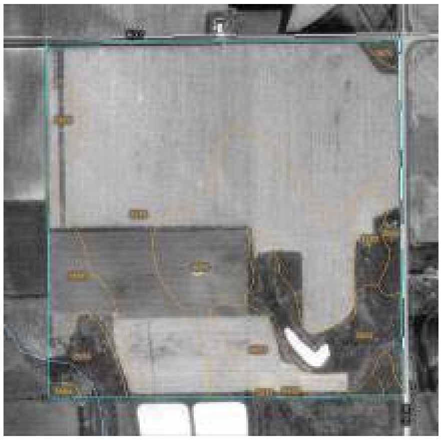



WATERMARK
MONITOR

Soil Moisture Sensor Installation

- Installed as soon as possible after corn was completely emerged.
- Measured soil moisture tension throughout entire growing season for 1, 2, 3, and 4 foot depths.
- When UNL managed fields met a threshold soil moisture tension cooperators were instructed to irrigate the field.
- Threshold value was lowered around the silking stage due to potential yield loss from crop water stress.

Soil Sampling



- Performed in the spring of 2007 and 2008 before planting by UNL project members.
- Fields were sampled for soil physical and chemical properties that influence soil water use and movement.
  - Nutrient analysis samples were taken to evaluate soil nutrient levels to confirm all were at levels were at levels for optimum production (N, P, K, pH, OM).