



Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr



High-yield irrigated maize in the Western U.S. Corn Belt: II. Irrigation management and crop water productivity

Patricio Grassini^a, Haishun Yang^b, Suat Irmak^c, John Thorburn^d, Charles Burr^e, Kenneth G. Cassman^{a,*}

^a Department of Agronomy and Horticulture, University of Nebraska-Lincoln, P.O. Box 830915, Lincoln, NE 68583-0915, USA

^b Monsanto Company, 800 N Lindbergh Blvd, St. Louis, MO 63167, USA

^c Department of Biological Systems Engineering, University of Nebraska-Lincoln, 241 L.W. Chase Hall, Lincoln, NE 68583-0726, USA

^d Tri-Basin Natural Resources District, 1723 N Burlington, Holdrege, NE 68949, USA

^e University of Nebraska-Lincoln Phelps County Extension Office, P.O. Box 2803, 2nd St, Holdrege, NE 68949-2803, USA

ARTICLE INFO

Article history:

Received 6 July 2010

Received in revised form

14 September 2010

Accepted 18 September 2010

Keywords:

Zea mays L.

Maize

Irrigation

Water productivity

Irrigation water-use efficiency

Simulation model

ABSTRACT

Appropriate benchmarks for water productivity (WP), defined here as the amount of grain yield produced per unit of water supply, are needed to help identify and diagnose inefficiencies in crop production and water management in irrigated systems. Such analysis is lacking for maize in the Western U.S. Corn Belt where irrigated production represents 58% of total maize output. The objective of this paper was to quantify WP and identify opportunities to increase it in irrigated maize systems of central Nebraska. In the present study, a benchmark for maize WP was (i) developed from relationships between simulated yield and seasonal water supply (stored soil water and sowing-to-maturity rainfall plus irrigation) documented in a previous study; (ii) validated against actual data from crops grown with good management over a wide range of environments and water supply regimes ($n = 123$); and (iii) used to evaluate WP of farmer's fields in central Nebraska using a 3-y database (2005–2007) that included field-specific values for yield and applied irrigation ($n = 777$). The database was also used to quantify applied irrigation, irrigation water-use efficiency (IWUE; amount of yield produced per unit of applied irrigation), and the impact of agronomic practices on both parameters. Opportunities to improve irrigation management were evaluated using a maize simulation model in combination with actual weather records and detailed data on soil properties and crop management collected from a subset of fields ($n = 123$). The linear function derived from the relationship between simulated grain yield and seasonal water supply, namely the *mean WP function* (slope = $19.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$; x -intercept = 100 mm), proved to be a robust benchmark for maize WP when compared with actual yield and water supply data. Average farmer's WP in central Nebraska was ~73% of the WP derived from the slope of the mean WP function. A substantial number of fields (55% of total) had water supply in excess of that required to achieve yield potential (900 mm). Pivot irrigation (instead of surface irrigation) and conservation tillage in fields under soybean–maize rotation had the greatest IWUE and yield. Applied irrigation was 41 and 20% less under pivot and conservation tillage than under surface irrigation and conventional tillage, respectively. Simulation analysis showed that up to 32% of the annual water volume allocated to irrigated maize in the region could be saved with little yield penalty, by switching current surface systems to pivot, improving irrigation schedules to be more synchronous with crop water requirements and, as a fine-tune option, adopting limited irrigation.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Agriculture is the largest user of freshwater accounting for about 75% of current withdrawals (Wallace, 2000; Howell, 2001). Food production from irrigated systems represents ~40% of the global total and uses only about 18% of the land area allocated to food

production (Fereser and Connor, 2004). Rising demand for food, livestock feed, and biofuels coupled with global climate change will put increasing pressure on freshwater resources (Falkenmark et al., 1998; Rosegrant et al., 2009). Competition for scarce water is already evident in major irrigated cropping systems of the world (Postel, 1998; Perry et al., 2009; Rosegrant et al., 2009). Water productivity (WP) offers a quantifiable benchmark to assess crop production in relation to available water resources (Bouman et al., 2005; Passioura, 2006). WP can be defined in several ways depending on the temporal and spatial scales of concern and study objectives. At the field level during a single crop growing season, WP can be quantified as the ratio of grain yield to either total crop

* Corresponding author at: Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Plant Science 387, Lincoln, NE 68583-0915, USA.
Tel.: +1 402 472 5554; fax: +1 402 472 7904.

E-mail address: kcassman1@unl.edu (K.G. Cassman).

transpiration, evapotranspiration (ET_C), or water supply (including available soil water at sowing plus sowing-to-maturity rainfall and irrigation). When data to derive actual ET_C are not available and the objective is to diagnose overall efficiency of the crop system with regard to total water inputs, WP expressed in terms of grain yield per unit of water supply is perhaps the most relevant parameter.

Boundary functions that define maximum attainable yield over a wide range of water supply have been used to benchmark on-farm WP and identify yield-limiting factors (e.g., French and Schultz, 1984; Grassini et al., 2009a). A major limitation of the boundary-function approach is not accounting for year-to-year variability in solar radiation, temperature, vapor pressure deficit, water supply distribution during the crop growing season, and water losses through soil evaporation, deep drainage, and unused water left in the ground at physiological maturity (Angus and van Herwaarden, 2001). Nevertheless, boundary-function benchmarks provide farmers and researchers a method to estimate realistic yield goals and water requirements, and to help identify management options to improve WP. Despite its potential, the benchmark approach has not yet been used to diagnose WP and irrigation management of irrigated maize.

In irrigated cropping systems, farmers tend to avoid risk by applying excessive amount of irrigation water in relation to crop water requirements to ensure maximum yield (Feres and Gonzalez-Dugo, 2009). The low irrigation efficiency, decreasing access to irrigation water, and resulting negative environmental effects that result have motivated calls for new approaches to irrigation management (Taylor et al., 1983; Loomis and Connor, 1992; Wallace et al., 1997). Flexible irrigation schedules based on meteorological data, crop phenology, and soil water-holding capacity, coupled with soil and crop water status monitoring and weather forecasts, allow decreased irrigation water amounts with little or no yield penalties (Stewart and Nielsen, 1990; Loomis and Connor, 1992). A further refinement of this approach, called limited or deficit irrigation, consists of application of water below 100% replacement of ET_C requirements during crop stages that are not critical for yield determination (Pereira et al., 2002; Feres and Soriano, 2007). Simulation models can serve to evaluate actual irrigation management and to identify new approaches to improve irrigation efficiency in a given location when soil and historical daily weather data are available (Stöckle and James, 1989; Villalobos and Feres, 1989).

This paper evaluates WP ($\text{kg grain ha}^{-1} \text{ mm}^{-1}$ water supply) and irrigation management of irrigated maize in the Western U.S. Corn Belt. Actual data from farmer's production fields and simulation analysis were combined to (i) establish a benchmark for maize WP in the Western U.S. Corn Belt, (ii) quantify WP in irrigated maize systems of central Nebraska, and (iii) identify opportunities to improve WP and irrigation management. This paper is complementary to a companion paper (Grassini et al., 2010b) that focuses on the agronomic practices and nitrogen fertilizer efficiency of these same irrigated maize systems.

2. Materials and methods

2.1. Development and validation of a water productivity benchmark for maize

A re-analysis of simulated grain yield and water supply data ($n=1019$) reported by Grassini et al. (2009b) was performed to establish a benchmark for on-farm WP. In this previous study, yield was simulated under rainfed and irrigated conditions at 18 locations across the Western U.S. Corn Belt using 20-y of weather data in combination with actual soil and crop management data. A boundary function was estimated for the relationship between

attainable grain yield and water supply [slope = $27.7 \text{ kg ha}^{-1} \text{ mm}^{-1}$; x-intercept (\approx seasonal soil evaporation) = 100 mm] over the range of water supply in which grain yield was responsive to increasing water availability. This boundary function defines the maximum attainable yield over a wide range of water supplies. A more relevant benchmark for crop producers is the mean attainable WP function, defined by the linear regression of simulated grain yield on water supply for all 1019 observations from the previous study. Outlier observations (<3% of all observations) were identified and removed from the regression analysis using the method of Schabenberger and Pierce (2001).

Actual yields from field experiments that provided 123 treatment-site-years of data, including crops grown under rainfed and irrigated conditions, were used to evaluate whether the boundary and mean attainable WP functions can serve as benchmarks for maize WP (Table 1). This database included a wide range of environments and irrigation treatments, and maize was managed to avoid limitations from nutrient deficiencies, diseases, insect pests, and weeds. Rainfall and irrigation were recorded at each site. Available soil water at sowing (ASW_S) was reported in 33% of the site-years; for the rest, ASW_S was estimated by an empirical algorithm shown to be robust for estimating this parameter in the Western Corn Belt (Grassini et al., 2010a, see Section 2.2 for more details).

Throughout this manuscript, grain yields are reported at a standard moisture content of $0.155 \text{ kg H}_2\text{O kg}^{-1}$ grain.

2.2. Quantification of water productivity in farmer's fields

A 3-y database (2005–2007) collected by staff in the Tri-Basin Natural Resources District (NRD) in central Nebraska was used to quantify maize WP and analyze irrigation management practices in farmer's fields ($n=777$). Maize production in the Tri-Basin NRD (≈ 1.7 million mg) is highly dependant on irrigated maize, which represents 94% of total production (USDA–NASS, 2001–2008). There are 6244 active registered groundwater wells for agricultural use in the area (Nebraska DNR, 2010). Average well and pumping depths are 58 and 34 m, respectively. There are three basins within the Tri-Basin NRD: Little Blue, Platte, and Republican. Flow meters are required on all wells in the Republican Basin portion of the district, which is the area included in our study. The database includes field-specific values for yield, previous crop, type of irrigation system, N fertilizer rate, and amount of applied irrigation. Each field included in the database was planted entirely with maize, and managed, and harvested as a unit. Irrigation systems represented in the database included center pivot sprinklers, surface gravity (mostly gated-pipe furrows), or a combination of both (49, 33, and 18% of the total fields, respectively). The latter category involves a center pivot that typically covers >85% of total field area coupled with surface irrigation in field corners. Because statistical analysis indicated that yield and amount of applied irrigation did not differ between fields with pivot or combined irrigation systems ($p>0.60$ and $p>0.15$, respectively), data from these two categories were pooled into a single "pivot" category. There were two kinds of center pivot sprinkler systems: (i) low-pressure sprinkler heads that hang near canopy level, and (ii) high-pressure sprinkler heads on the pivot beams well above the canopy. Average size of fields under pivot and surface systems was 53 and 32 ha, respectively. Main energy sources for irrigation pumping were natural gas, diesel, and electricity (49, 26, and 21% of total fields, respectively). Most farmers (≈ 70 –75%) rely on crop consultants to determine amount and timing of irrigation events. Irrigations are typically scheduled based on soil water content, water balance computations, and type of irrigation system. Detailed site and database description are provided by Grassini et al. (2010b).

Table 1

Sources of grain yield and water supply data used to validate the water productivity benchmark shown in Fig. 1. All of these field studies were located in the Western U.S. Corn Belt and used optimal management practices.

Source	Locations ^a	Years	Water regime	Irrigation system	Field description
Burgert (2009)	Edgar, Geneva, Hordville, Mead, Wahoo, West Point, York	2007–2008	Irrigated ($n = 30$) ^b	Center pivot	Farmers' fields (50–60 ha)
Hergert et al. (1993)	North Platte	1983–1991	Irrigated ($n = 16$) and rainfed ($n = 9$)	Solid-set sprinkler	Experimental plots (0.06 ha)
Irmak and Yang (unpublished data)	Clay Center, North Platte	2005–2006	Irrigated ($n = 14$) and rainfed ($n = 4$)	Subsurface drip irrigation	Experimental plots (0.1 ha)
Payero et al. (2006a)	North Platte	1992–1996	Rainfed ($n = 5$)	–	Experimental plots (0.1 ha)
Payero et al. (2006b)	North Platte	2003–2004	Irrigated ($n = 15$) and rainfed ($n = 2$)	Solid-set sprinkler	Experimental plots (0.02 ha)
Payero et al. (2008)	North Platte	2005–2006	Irrigated ($n = 16$)	Subsurface drip irrigation	Experimental plots (0.1 ha)
Suyker and Verma (2009)	Mead	2001–2006	Irrigated ($n = 8$) and rainfed ($n = 3$)	Center pivot	Experimental plots under progressive management (50–65 ha)
Yang et al. (2004)	Manchester	2002	Rainfed ($n = 1$)	–	Farmer field, winner of National Corn Growers yield contest (≈ 30 ha)

^a All sites are located within Nebraska, except for Manchester (Iowa).

^b For each site-year, separate fields were either irrigated by the farmer's standard irrigation practices or by a limited-irrigation approach.

Seasonal water supply for each field-year observation was estimated as the sum of ASW_5 in the rooting zone (0–1.5 m) plus sowing-to-maturity rainfall and applied irrigation. An empirical model that accounts for variations in non-growing season precipitation, residual soil water left by previous summer crop, and available water-holding capacity (AWHC) was used to estimate ASW_5 (Grassini et al., 2010a). Non-growing season precipitation was calculated as total precipitation in the period from October 1st (approximate date by which crop canopy is completely senescent) and average actual sowing date in the following year. Residual water left in the soil profile by previous crop was assumed to be 60% of AWHC based on 20-y simulations of soil water dynamics performed for irrigated maize crops in Tri-Basin NRD area (Grassini et al., 2009b). Based on field geographic coordinates and satellite images, AWHC was estimated from the SSURGO soil database (USDA–NRCS) for a zone (~ 380 m radius) centered on each field. Most fields were spatially homogeneous for soil type and AWHC; a weighted average was used to estimate AWHC in those fields that included soil types with different AWHC, but these were <5% of total fields. Sowing-to-maturity rainfall was calculated as total rainfall between average actual sowing date and simulated date of physiological maturity for each site-year. Because rainfall exhibited very high spatial variability across the Tri-Basin NRD area, three weather station networks were used to ensure appropriate density and distribution of rain gauges (Automated Weather Station Network [AWDN, $n = 8$], National Weather Service Cooperative Station Network [NWS, $n = 8$], and Nebraska Rainfall Assessment and Information Network [NeRAIN, $n = 17$]; see Fig. 1 in Grassini et al. (2010b)). A modified inverse distance weight method proposed by Franke and Nielson (1980) was used to interpolate daily rainfall values for each field during the 2004–2007 seasons.

For each field-year observation contained in the Tri-Basin NRD database, water productivity (WP) was calculated as the quotient of yield and seasonal water supply. Additionally, an estimate of WP for rainfed maize crops was calculated based on Tri-Basin NRD (3-county average) rainfed yields (USDA–NASS, 2005–2007) and estimated water supply without irrigation. For each year, irriga-

tion water-use efficiency (IWUE) was calculated as the quotient of (i) yield and applied irrigation [IWUE(Y, I)] and (ii) the difference between irrigated yield minus Tri-Basin NRD average rainfed yield and applied irrigation [IWUE($\Delta Y, I$)]. Calculation of ΔY seeks to minimize the effect of variability in rainfall and/or ASW_5 on irrigation water-use efficiency across years (Howell, 2001). Variation in applied irrigation and IWUE($\Delta Y, I$) were investigated using detailed data on crop management collected from a subset of 123 fields that include information on sowing date, seeding rate, hybrid relative maturity, and tillage system. Tillage systems included conventional disk tillage (CT) or conservation tillage under strip-, ridge-, or no-till practices. These three types of conservation tillage were combined into a single no-till category (NT) because yield and applied irrigation did not differ among them ($p > 0.10$ for all t -test comparisons).

Regression analysis was performed to investigate relationships between applied irrigation amount, sowing-to-maturity rainfall, and ASW_5 . Two approaches were used to assess causes of variation in applied irrigation due to management practices: (i) regression analysis and (ii) two-tailed t -test or Wilcoxon test when distribution of observed values deviated from normality. Management practices included in this analysis were: type of irrigation and tillage system, previous crop, rate of N fertilizer, seeding rate, sowing date, and hybrid relative maturity. Since the amount of applied irrigation differed among years ($p < 0.001$), the statistical analysis was performed separately for each year.

2.3. Simulation analysis of water productivity and irrigation management

Hybrid-Maize model (Yang et al., 2004, 2006) was used to simulate yield and irrigation requirements for each of the 123 fields in the Tri-Basin NRD database subset using actual weather records, soil properties, and detailed crop management data. Details on crop growth simulation and model inputs are provided elsewhere (Grassini et al., 2010b). The purpose of these simulations was to compare WP, applied irrigation, and IWUE achieved by farmers with the values predicted by the simulation model with optimal irrigation. Hybrid-Maize simulates soil water dynamics as

the balance between inputs from precipitation and/or irrigation and water losses through soil evaporation, crop transpiration, and percolation below the root zone. Under optimal irrigation mode, Hybrid-Maize estimates minimum water application requirement to achieve water stress-free growth. Crop water uptake is based on: (i) rooting depth and soil water potential, which in turn is based on water release characteristics as determined by soil texture and (ii) maximum crop transpiration as estimated from reference evapotranspiration (ET_0) and leaf area index. An irrigation event is triggered whenever crop water uptake does not meet maximum transpiration. Although the amount of water applied per irrigation event can be altered in the Hybrid-Maize model to adjust for different types of irrigation systems (Yang et al., 2006), in the present study we used the default value of 32 mm per irrigation event. Interception of incoming irrigation water by the crop at full canopy is set at 1.5 mm per irrigation event. Hybrid-Maize model was set to stop irrigation when soil water content of the top 30 cm reaches 95% of field capacity. Maximum root depth was set at 1.5 m based on soil water extraction patterns reported for irrigated maize (Payero et al., 2006a).

Hybrid-Maize was also used to mimic effects of limited-irrigation management on yield and applied irrigation. The amount of water applied in each irrigation event under optimal irrigated mode was reduced by 25% throughout the crop cycle except for a -14 to $+7$ d window around silking in which crops were kept fully irrigated. This approach was motivated by two observations: (1) the silking-pollen shed window is highly sensitive to water deficit (Otegui et al., 1995) and (2) recent on-farm studies using this approach in eastern and central Nebraska reported substantial water savings with negligible impact on yield compared with fully-irrigated fields (Burgert, 2009). Daily values of incident solar radiation, temperature, relative humidity, FAO-Penman-Monteith ET_0 , and rainfall, as well as specification of soil properties (AWHC and soil texture) and soil water content at sowing are required to simulate soil water dynamics and irrigation requirements with Hybrid-Maize model. Relative humidity and ET_0 for each field were interpolated from nearest meteorological stations as was done for incident radiation and temperature in Grassini et al. (Grassini et al., 2010b). Methodology to obtain daily values for rainfall, soil properties, and ASW_5 in each of the 123 fields is described in Section 2.2.

Estimated field-level water savings, calculated as the difference between actual and optimal- or limited-irrigation management, were scaled up to the 3-county Tri-Basin NRD area to quantify the potential reduction in the annual water volume allocated to irrigated maize. Total irrigated maize land area in the Tri-Basin NRD was derived from USDA-NASS statistics (1999–2008) while the frequency and average size of the fields under different irrigation systems were retrieved from the Tri-Basin NRD database.

3. Results

3.1. Benchmark for maize water productivity and evaluation versus observed data

The estimated mean WP function from the simulated data of Grassini et al. (2009b) had a slope of 19.3 ± 0.4 kg grain ha^{-1} mm^{-1} ($p < 0.001$, $r^2 = 0.75$) (Fig. 1a). Variation around the mean WP regression line results from normal variation in temperature, solar radiation, and water supply distribution among locations and years. The x -intercept, which is presumably an estimate of seasonal soil evaporation, was indistinguishable from the value derived from the boundary function (100 mm). Actual grain yield and water supply reported for rainfed and irrigated maize field experiments grown under near-optimal management practices in the Western

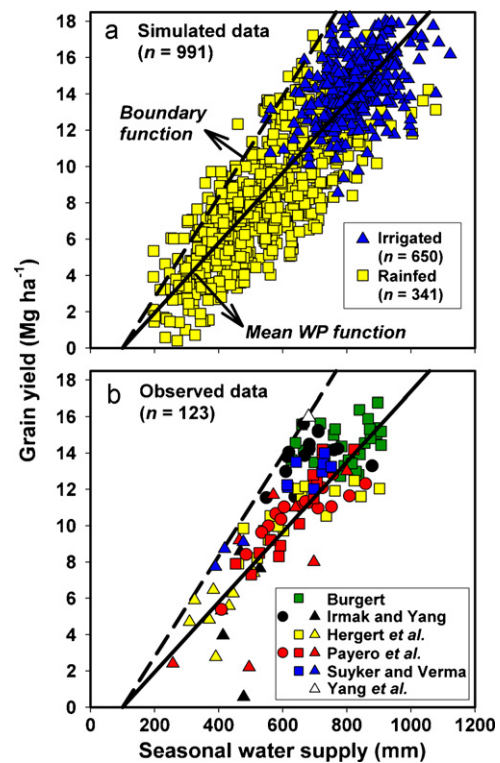


Fig. 1. (a) Relationship between simulated maize grain yield and seasonal water supply (available soil water at sowing to 1.5 m depth, plus sowing-to-maturity rainfall and applied irrigation), modified from Grassini et al. (2009b). Dashed and solid lines are the boundary- and mean water productivity (WP) functions, respectively (slopes = 27.7 ± 1.8 and 19.3 ± 0.4 kg ha^{-1} mm^{-1} , respectively; x -intercept = 100 mm). Outlier observations are not shown. (b) Actual grain yield and water supply data from field studies in the Western U.S. Corn Belt managed to produce yields without limitation from nutrients or pests under rainfed (\blacktriangle), irrigated-sprinkler or pivot (\blacksquare) or subsurface drip irrigation (\bullet). Data source description and citations are provided in Table 1.

U.S. Corn Belt were in reasonable agreement with the boundary- and mean WP benchmarks derived from simulated data (Fig. 1b). Irrigated crops grown in fields under subsurface drip irrigation, limited irrigation, and rainfed conditions with progressive management practices approached the boundary function. Most of the observations in Fig. 1b, however, were distributed around the mean WP function except for a few rainfed crop observations that were exposed to very severe water deficit during the critical silking-pollen shed window. Coefficients of the linear regression between actual yields and water supply were not different from those of the mean WP function ($p > 0.70$; data not shown).

3.2. Total water supply and seasonal patterns of rainfall and maximum ET_C

Rainfall patterns during maize growing season in the Tri-Basin NRD varied greatly across years (Fig. 2a). Rainfall was below the 20-y average around silking in 2005, early in the growing season and around silking in 2006, and at end of grain filling in 2007. Simulated ET_C patterns were relatively stable across years except for some variation in the critical period around silking (Fig. 2b). Total seasonal water supply ranged from 898 to 971 mm across years (Fig. 2c). ASW_5 (range: 210–290 mm) and sowing-to-maturity rainfall (range: 388–467 mm) accounted for ~ 25 and 45% of seasonal water supply, respectively. Higher ASW_5 in 2007 was explained by above average rainfall during the non-growing season (data not shown). Average applied irrigation decreased from 347 in 2005 to 213 mm in 2007 due to higher rainfall and lower ET_C around and

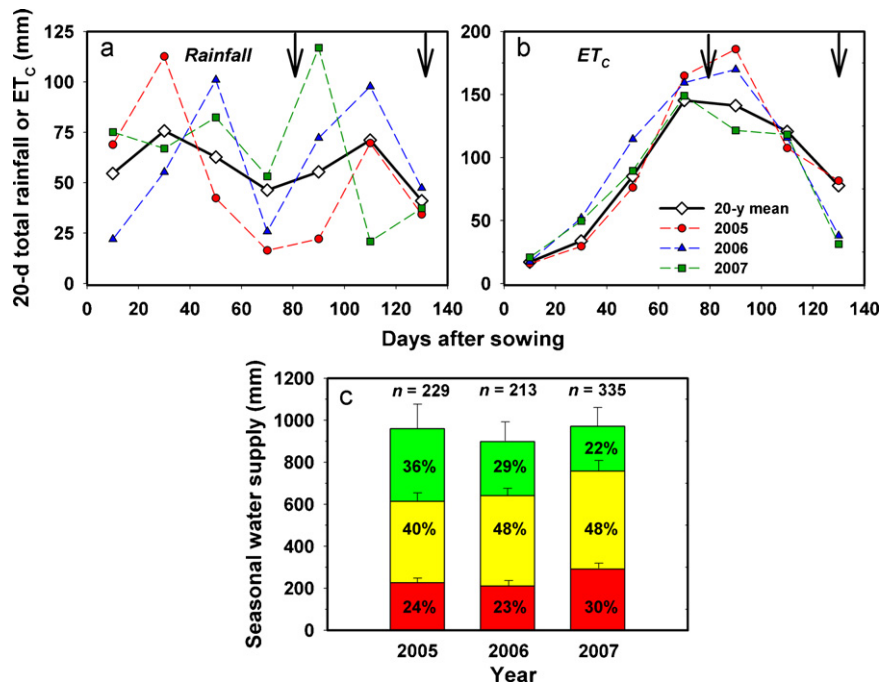


Fig. 2. (a and b) Patterns of 20-d total rainfall and simulated crop evapotranspiration under non-limiting water supply (ET_c) using the Hybrid-Maize model for maize crops with average management practices (sowing date: DOY 114, 115, and 123, respectively; relative maturity: 113 d; 7.2 plants m^{-2}) used in the Tri-Basin NRD in 2005–2007 seasons. Each observation is the average of four locations inside or near the Tri-Basin Natural Resources District (NRD). Vertical arrows indicate dates of silking and physiological maturity (left and right arrow, respectively). (c) Total water supply during maize growing seasons, disaggregated by available soil water at sowing, sowing-to-maturity rainfall, and applied irrigation (bottom, mid, and top bars, respectively), shown as mean values from irrigated maize fields in the Tri-Basin NRD. Values inside bars are percentage of total water supply in each year. Error bars indicate the standard deviation of each water supply component.

after silking in 2007. Separate regression analyses performed for each year indicated that variation in water supply was explained by applied irrigation (r^2 range: 0.86–0.96) but not ASW_s or sowing-to-maturity rainfall (r^2 range: 0.02–0.09) and this pattern was consistent across irrigation systems.

3.3. Actual and simulated water productivity in irrigated maize fields in central Nebraska

Yields from farmer’s fields in the Tri-Basin NRD fell below the mean WP function although *ca.* 4% of the cases approached or even exceeded this benchmark (Fig. 3a and b). Average yield for these irrigated fields was 20% below the yield predicted from the mean WP function. In contrast, mean rainfed yield in the Tri-Basin counties (USDA–NASS, 2005–2007) was 53% of the yield predicted from mean WP benchmark for the same amounts of water supply. Grassini et al. (2010b) estimated a mean yield potential (Y_p) of 15.4 Mg ha^{-1} for the Tri-Basin NRD, which corresponds to a water supply value of 900 mm derived from mean WP function. This value represents the water supply required to achieve Y_p . Although grain yield rarely exceeded Y_p (only 13 out of the 777 field-years), 55% of total fields exceeded this water requirement threshold. Relatively fewer fields exceeded this 900 mm water supply threshold with pivot than with surface irrigation (45 versus 73% of fields).

The apparent water excess, calculated as the difference in seasonal water supply between observed values and the water supply for an equivalent yield from the mean WP function, was strongly related to applied irrigation ($p < 0.001$; r^2 range: 0.75–0.85) and weakly associated with ASW_s or sowing-to-maturity rainfall ($r^2 < 0.05$ across years). Across all field-year observations, irrigated maize WP ranged from 8.2 to 19.4 with a mean of 14 kg ha^{-1} mm^{-1} , which represents 73% of the attainable WP derived from the slope of the mean WP function (Fig. 4). Fields under pivot had 13% greater WP than counterparts under surface irrigation. WP was relatively

stable across years as indicated by the small inter-annual coefficient of variation (4%). Interestingly, mean WP of irrigated fields was ~60% larger than estimated WP for rainfed maize fields. This difference may reflect the importance of water supply distribution during the growing season of rainfed crops and/or differences in agronomic management between irrigated and rainfed crops such as plant population and N fertilizer rate (see also Section 3.5).

Grain yield with optimal irrigation was simulated for a subset of 123 fields using Hybrid-Maize model in combination with actual weather records and site-specific soil and management data (Fig. 3c). About 75% of simulated yields were within $\pm 10\%$ of predicted yields from the mean WP benchmark. Seasonal water supply values of simulated crops, calculated as the sum of actual ASW_s, sowing-to-maturity rainfall, and optimal irrigation water requirement as predicted by Hybrid Maize, were ≤ 900 mm in 88% of the simulated site-years. Whereas on average actual yields were 89% of simulated yields, Fig. 3c indicates that 25% of field-years, especially those with surface irrigation, had water supply values that exceeded simulated crop water requirements by >33%.

3.4. Impact of agronomic management practices on water productivity and irrigation efficiency

Statistical analyses of the detailed data on crop management collected from 123 of the 777 field-years indicated significant effects of irrigation system, previous crop, and tillage (all $p < 0.01$) on grain yield, applied irrigation amount, and/or IWUE ($\Delta Y, I$) (Fig. 5). While no difference in grain yield was observed between irrigation systems ($p > 0.20$), applied irrigation under pivot was 41% lower than under surface irrigation ($p < 0.001$). Within years, higher variation in applied irrigation amounts was observed with surface irrigation than under pivot (CVs = 44 versus 31%). Also, applied irrigation under NT was 20% lower than under CT. Crop residues left in the field may reduce irrigation requirements by increasing precipi-

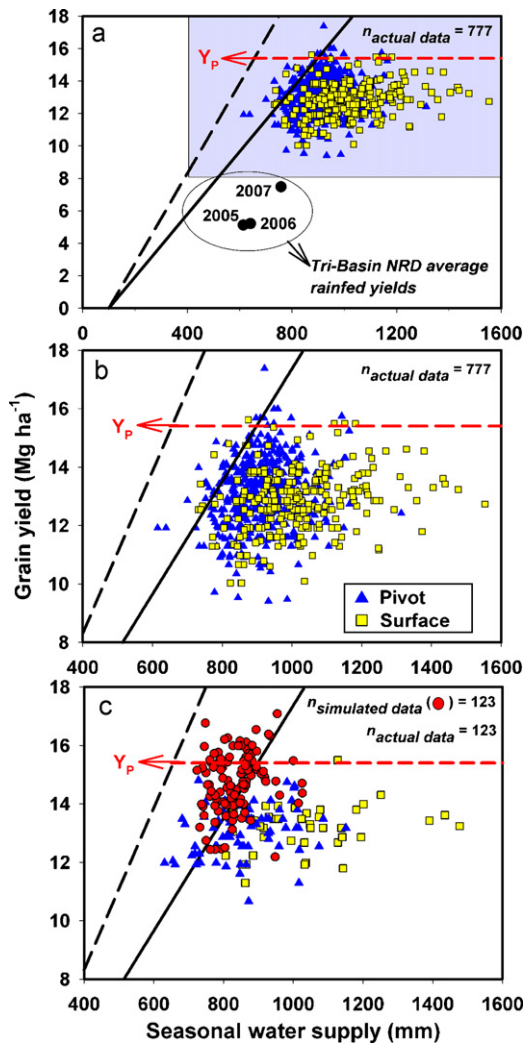


Fig. 3. (a) Relationship between farm grain yields and seasonal water supply (available soil water at sowing plus sowing-to-maturity rainfall and applied irrigation) from 777 field-years in the Tri-Basin Natural Resources District. Average rainfed yields for the three Tri-Basin counties were obtained from USDA-NASS (2005–2007) and are shown for comparison. Data within shaded area are shown (b) disaggregated by irrigation system type, or (c) as actual yield and simulated yield (●) with optimal irrigation based on output from the Hybrid-Maize model in combination with actual weather records and crop management data collected from a subset of 123 fields. The dashed and solid lines are the boundary- and mean water productivity functions, respectively, as shown in Fig. 1. Note scale differences for axes in (a) versus (b) and (c). Horizontal dashed lines indicate average simulated yield potential (Y_p) in the Tri-Basin NRD (15.4 Mg ha^{-1}) reported by Grassini et al. (2010b).

tation storage efficiency during the non-growing season and by reducing direct soil evaporation and runoff as found by Nielsen et al. (2005) and Klocke et al. (2009). Hence, fields under pivot or NT exhibited higher IWUE ($\Delta Y, I$) than their counterparts with surface irrigation and CT. Impact of the tillage \times previous crop interaction on grain yield was also notable: while no difference between tillage systems was observed when maize followed soybean, fields under continuous maize had higher yields with CT. Highest average IWUE ($\Delta Y, I$) ($35 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and yield (13.5 Mg ha^{-1}) were obtained from fields under pivot irrigation, NT, and soybean–maize rotation.

There was no detectable effect of N fertilizer rate, sowing date, or seeding rate on irrigation amount ($p > 0.15$) across years or irrigation systems. Although short-season hybrids (RM 106–112 d) received 25 mm less irrigation water than full-season hybrids (RM 113–118 d), this difference was sta-

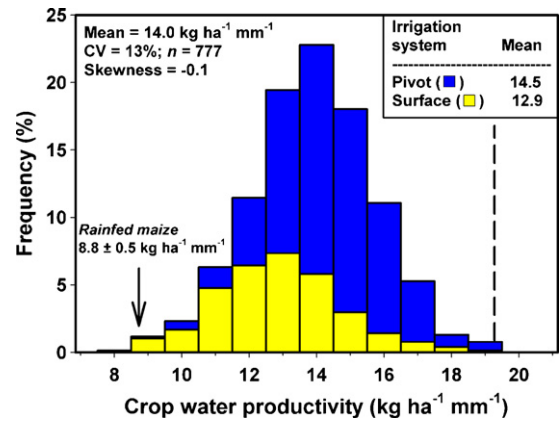


Fig. 4. Frequency distribution of crop water productivity (WP) for irrigated maize fields in the Tri-Basin Natural Resources District. WP was calculated as the ratio of grain yield-to-seasonal water supply; frequencies are disaggregated by irrigation system. Statistical distribution parameters are shown in upper left. Vertical dashed line indicates the attainable WP derived from the slope of the mean WP function as shown in Fig. 1. Vertical arrow indicates mean WP for rainfed crops.

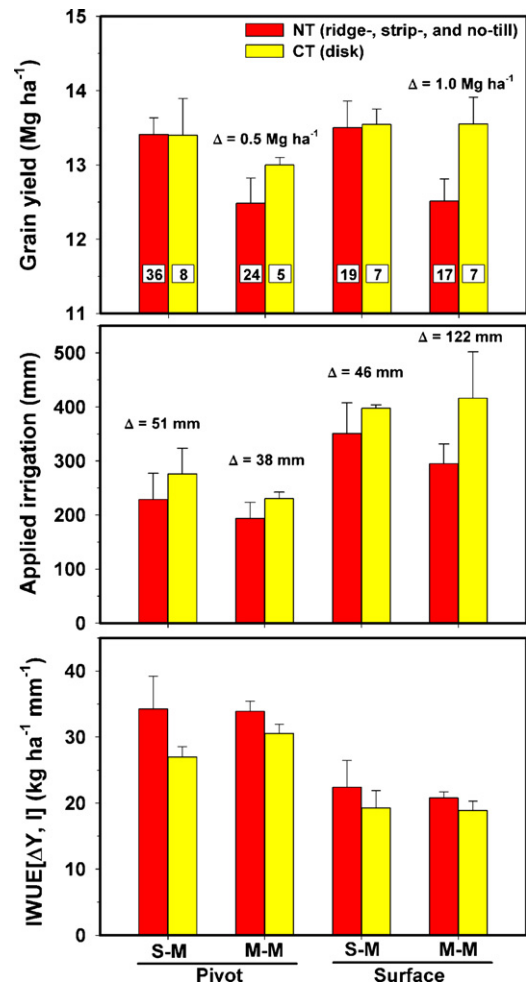


Fig. 5. Mean (\pm SE) grain yield, applied irrigation, and irrigation water-use efficiency [IWUE($\Delta Y, I$)] under different combinations of irrigation system (pivot or surface), rotation (soybean–maize [S–M]; maize–maize [M–M]), and tillage (no-till [NT]; conventional [CT]) in irrigated maize fields in the Tri-Basin Natural Resources District. All values are 3-y means (2005–2007). IWUE($\Delta Y, I$) was calculated as the ratio of (irrigated yield minus average rainfed yield) to applied irrigation. Values inside bars in the top panel indicate number of observations for each irrigation system \times rotation \times tillage combination. Differences (Δ) for selected comparisons between tillage systems are shown.

Table 2

Grain yield (GY; Mg ha⁻¹), irrigation (I; mm), and irrigation water-use efficiency (IWUE; kg ha⁻¹ mm⁻¹) for a subset of 123 field-years in the Tri-Basin Natural Resources District (NRD) under actual irrigation management (disaggregated by irrigation system) and simulated optimal or limited irrigation.

	Actual irrigation ^a						Simulated optimal irrigation ^b			Simulated limited irrigation ^b		
	Surface			Pivot			GY	I	IWUE	GY	I	IWUE
	GY	I	IWUE ^c	GY	I	IWUE						
2005 (n=33)	13.7	493	28 [18]	13.6	313	44 [27]	15.3	265	58	14.4	225	64
2006 (n=33)	12.9	359	36 [21]	12.8	208	62 [37]	15.1	241	63	14.8	207	72
2007 (n=57)	13.1	313	42 [18]	12.9	166	77 [32]	14.2	124	114	13.9	106	131
Mean	13.3	388	35 [19]	13.1	229	61 [32]	14.9	210	78	14.3	179	89
Tri-Basin total ^d	582	114		1167	238		1975	279		1909	238	

^a Data based on actual yield and applied irrigation.

^b Grain yield and optimal irrigation amounts were simulated using Hybrid-Maize model in combination with actual weather records and field-specific soil and crop management data; assumes all fields were irrigated by center pivot.

^c IWUE calculated as the ratio of grain yield to applied irrigation [IWUE(Y, I)] or irrigated yield minus 3-county average rainfed yield to applied irrigation [IWUE(ΔY, I), shown between brackets]. IWUE(ΔY, I) was not calculated under simulated optimal or limited irrigation due to lack of model inputs for simulating rainfed yields.

^d Assuming 78 and 22% of the irrigated maize cropland area in the Tri-Basin NRD (133,000 ha) to be under pivot and surface categories, respectively, based on frequency and average size of the fields under surface and pivot included in the database analyzed in this study. Total production and irrigation volume are expressed in Mg × 10³ and m³ × 10⁶, respectively.

tistically significant only for fields under pivot in one year ($p=0.03$).

3.5. Opportunities for increasing irrigation water efficiency through irrigation management

Large variation in IWUE(Y, I) was found as a result of differences in applied irrigation across years (Table 2). Mean IWUE(Y, I) was 35 and 61 kg ha⁻¹ mm⁻¹ for fields under surface irrigation and pivot systems, respectively (Table 2). Three-year pooled CVs were 20 and 28%, respectively for surface and pivot systems. When IWUE values were adjusted by subtracting average rainfed yield from irrigated yields in each year, resulting IWUE(ΔY, I) mean values were 19 (surface irrigation) and 32 kg ha⁻¹ mm⁻¹ (pivot), and year-to-year variation was reduced substantially (3-y pooled CVs = 11 and 14%). Average IWUE(ΔY, I) in the present study (26 kg ha⁻¹ mm⁻¹) is similar to largest values of IWUE(ΔY, I) reported by Howell (2001) for maize grown under near-optimal conditions in Texas, U.S. (range: 17–25 kg ha⁻¹ mm⁻¹) and well above Nebraska state-level IWUE(ΔY, I) average (16 kg ha⁻¹ mm⁻¹) estimated from USDA-NASS data (FRIS, 2003–2008). Average IWUE(ΔY, I) in the present study is greater than the mean attainable WP derived from the slope of mean WP function as shown in Fig. 1 (26.0 versus 19.3 kg ha⁻¹ mm⁻¹). This discrepancy reflects the fact that IWUE(ΔY, I) accounts for the response of grain yield to both applied irrigation and the generally better management practices under irrigated than rainfed conditions as pointed in Section 3.3. For example, average N fertilizer rate used by Tri-Basin farmers included in this study was 49% greater than recommended rainfed N rate in Nebraska (Klein and Wilson, 2010), and irrigated fields have higher plant density than rainfed fields (7.5 versus 4.9 m⁻²) in the same region (Grassini et al., 2009b).

Grain yield, irrigation requirements, and IWUE(Y, I) were also simulated under two irrigation management scenarios (optimal and limited irrigation) using Hybrid-Maize model in combination with actual weather records and field-specific soil and crop management data for 123 maize field-year subset (Table 2). On average, mean actual applied irrigation under pivot and surface systems exceeded simulated optimal water requirements by 8% and 46%, respectively. Relative difference between simulated optimal and actual irrigation was greatest in the wettest year (2007). Elimination of applied irrigation excess and also the gap between actual and simulated Y_p would increase IWUE(Y, I) by 29 and 122% in pivot and surface systems, respectively. Finally, simulated IWUE(Y, I) under a limited-irrigation regime was 14% higher than with optimal irrigation due to a reduction in applied irrigation by 15% and

only a 4% decrease in yield. Examination of the simulated water balances indicated that grain yield reduction was not proportional to the reduction in applied irrigation but rather to the decrease in ET_c with the limited-irrigation regime (data not shown). Simulated soil water dynamics revealed that greater water depletion from deep soil layers under limited irrigation, compared with optimal irrigation, ameliorated the impact of reducing irrigation water inputs on ET_c. These results are in agreement with (i) data reported by Stöckle and James (1989) for maize crops simulated under limited irrigation in soils with high AWHC and ASW₅ similar to those in the Tri-Basin NRD, and (ii) on-farm studies of center-pivot maize fields in Nebraska where a limited-irrigation regime reduced applied irrigation by 34% without significant yield penalty compared with farmer's irrigation management (Burgert, 2009).

Scaling-up of previous estimated field-level water savings to the entire 3-county Tri-Basin NRD area gave an estimated irrigation water-use reduction of 47 million m³ y⁻¹ from converting current maize fields under surface irrigation to pivot systems (Table 2). An additional reduction of 25 million m³ would occur from more precise timing and amount of irrigation through greater congruence with actual crop water requirements (i.e., optimal irrigation). Finally, additional water saving of 41 million m³ was estimated if all farmers used pivot irrigation and utilized the limited-irrigation approach as simulated in this study although there would likely be a small yield penalty of about 4%.

4. Discussion

Useful benchmarks are those based on understanding of biophysical processes that determine crop productivity in response to environment × management interactions. The challenge is translating these complex processes into practical decision-support tools of use to farmers and policy-makers. The WP benchmark established in the present study offer a robust and relatively straightforward framework to quantify and improve WP of irrigated maize systems, and this framework could be used on other irrigated crops as well. Evaluating yield for a specific field relative to the attainable yield with the same water supply on the mean WP benchmark regression estimates the yield gap. In the Tri-Basin NRD, for example, the average size of this grain yield gap was 2.3 Mg ha⁻¹. The larger the magnitude of this gap, the lower the WP. Likewise, difference in water supply on the mean WP benchmark regression line at current yield levels and water supply for a given field (or district) indicates the potential water excess above crop water requirements for the same yield level. On average, the apparent water excess for irrigated

maize in the Tri-Basin NRD was 170 mm (median: 145 mm). Thus, benchmark comparisons can be made to quantify WP of individual fields or for entire irrigation districts, regions, and states. Depending on the particular objective, farmers can improve WP by (i) reducing the yield gap at the same level of water supply (e.g., better crop, nutrient, and pests management), (ii) maintaining yield with a reduced level of water supply (e.g., better irrigation management), or (iii) combining the previous two approaches.

Analysis of farm yields and water supply of a large number of individual fields over several years helps identify maximum attainable yield levels with current management practices in a given region. In the Tri-Basin NRD, maximum field yields rarely exceeded the mean yield potential estimated by simulation (15.4 Mg ha^{-1}), which required a total water supply of about 900 mm based on the WP regression line. Fields that received more than this amount were over-watered. Likewise, to increase relevance of the mean WP function as a benchmark in the Tri-Basin NRD, it is useful to consider water supply values $>900 \text{ mm}$ as equal to 900 mm for calculation of yield gaps or the potential water savings. Such an approach was used in the above calculations for mean yield gap and water saving potential in the Tri-Basin NRD.

The present study shows that on-farm data can be used to identify specific technologies and crop management options that increase irrigation water-use efficiency and to quantify the potential impact of these technologies on irrigation water use and crop production at field to regional levels. Resulting information can be then used to support policies and incentives that help farmers adopt practices that reduce water and energy used for irrigation. For example, available field-scale options in the Tri-Basin NRD to reduce applied irrigation amounts without yield loss include converting current surface irrigation systems to pivot, fine-tuning of irrigation scheduling, and implementation of conservation tillage in fields under soybean–maize rotation. Total annual water saving from adoption of the first two of these practices (i.e., converting existing surface systems to pivot, fine-tuning of current irrigation schedule) represents $\sim 32\%$ of the total annual water volume allocated to irrigated maize in the Tri-Basin NRD.

Increasing scarcity and greater competition for use of freshwater resources will force irrigated agriculture to be more efficient in use of available supplies. Quantification of water use and WP in actual irrigated cropping systems provides critical information to guide policies and regulations about water use and allocation with the goal of maintaining or increasing productivity while protecting natural resources. A concern is whether the WP benchmark developed in this study can be used to perform assessments of maize WP, identify constraints, and predict impact of management options in other regions with different climates. While the biophysical link between crop production and water supply will hold across environments, the three parameters that define the WP benchmark (x -intercept, slope, and Y_p) may change as a result of climatic and/or management differences. Hence, with appropriate calibration of these parameters, the maize WP benchmark approach can be used beyond the Western U.S. Corn Belt. For example, the value of the slope of the WP function can be related to site-specific seasonal daytime vapor pressure deficit or ET_0 (Sadras and Angus, 2006). Preliminary results for a major maize-producing region in China (Yellow-Huai River Valley) indicate that slope of the mean WP function for maize is 25% greater than the slope derived for the Western U.S. Corn Belt due to a more humid climate. Likewise, average maize Y_p in Yellow-Huai River Valley is 33% lower than average Y_p in Tri-Basin NRD as estimated by Bai et al. (2010) using a crop simulation model in combination with long-term weather data and actual management practices.

Acknowledgments

We are grateful to the Tri-Basin NRD board and staff, especially to Tammy Fahrenbruch for providing access to the crop and water use reports and helping with the survey and the many farmers who collaborated in this study. We also thank Drs Albert Weiss, James Specht, and Shashi Verma for useful comments on an earlier version of the paper. Support for this project comes from the Water, Energy and Agriculture Initiative, made possible with funding from the Nebraska Corn Board, the Nebraska Soybean Board, the Agricultural Research Division (ARD) at the University of Nebraska–Lincoln (UNL) and Nebraska Public Power District through the Nebraska Center for Energy Sciences Research at UNL. The senior author wishes also to acknowledge financial support from the Fulbright Program, UNL, and the ARD for his graduate assistantship.

References

- Angus, J.F., van Herwaarden, A.F., 2001. Increasing water use and water use efficiency in dryland wheat. *Agron. J.* 93, 290–298.
- Bai, J., Chen, X., Dobermann, A., Yang, H., Cassman, K.G., Zhang, F., 2010. Evaluation of NASA satellite- and model-derived weather data for simulation of maize yield potential in China. *Agron. J.* 102, 9–16.
- Bouman, B.A.M., Peng, S., Castañeda, A.R., Visperas, R.M., 2005. Yield and water use of irrigated tropical aerobic rice systems. *Agric. Water Manage.* 74, 87–105.
- Burgert, M.J., 2009. Large scale implementation of research-based irrigation management tools/strategies for maize. PhD Dissertation, University of Nebraska–Lincoln.
- Falkenmark, M., Lundqvist, J., Klohn, W., Postel, S., Wallace, J., Shuval, H., Seckler, D., Rockström, J., 1998. Water scarcity as a key factor behind global food insecurity: round table discussion. *Ambio* 27, 148–154.
- Fereres, E., Connor, D.J., 2004. Sustainable water management in agriculture. In: Cabrera, E., Cobacho, R. (Eds.), *Challenges of the New Water Policies for the XXI Century*. A. A. Balkema, Lisse, The Netherlands, pp. 157–170.
- Fereres, E., Gonzalez-Dugo, V., 2009. Improving productivity to face water scarcity in irrigated agriculture. In: Sadras, V.O., Calderini, D.F. (Eds.), *Crop Physiology: Applications for Genetic Improvement and Agronomy*. Elsevier, Amsterdam, The Netherlands, pp. 123–143.
- Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* 58, 147–159.
- Franke, R., Nielson, G., 1980. Smooth interpolation of large sets of scattered data. *Int. J. Numer. Methods Eng.* 15, 1691–1704.
- French, R.J., Schultz, J.E., 1984. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Aust. J. Agric. Res.* 35, 743–764.
- Grassini, P., Hall, A.J., Mercau, J.L., 2009a. Benchmarking sunflower water productivity in semiarid environments. *Field Crops Res.* 110, 251–262.
- Grassini, P., Yang, H., Cassman, K.G., 2009b. Limits to maize productivity in Western Corn-Belt: a simulation analysis for fully-irrigated and rainfed conditions. *Agric. For. Meteorol.* 149, 1254–1265.
- Grassini, P., You, J., Hubbard, K.G., Cassman, K.G., 2010a. Soil water recharge in a semi-arid template climate of the central U.S. Great Plains. *Agric. Water Manage.* 97, 1063–1069.
- Grassini, P., Thorburn, J., Burr, C., Cassman, K.G., 2010b. High-yield irrigated maize in the Western U.S. Corn Belt. I. On-farm yield, yield-potential, and impact of agronomic practices. *Field Crops Res.*, doi:10.1016/j.fcr.2010.09.012.
- Hergert, G.W., Klocke, N.L., Petersen, J.L., Nordquist, P.T., Clark, R.T., Wick, G.A., 1993. Cropping systems for stretching limited irrigation supplies. *J. Prod. Agric.* 6, 520–529.
- Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* 93, 281–289.
- Klein, R.N., Wilson, R.K., 2010. Nebraska crop production budgets. Nebguide EC872. Univ. of Nebraska Coop. Ext. Service, Lincoln (online WWW). Available from <http://cropwatch.unl.edu/web/economics/budgets> (accessed 01.09.10).
- Klocke, N.L., Currie, R.S., Aiken, R.M., 2009. Soil water evaporation and crop residues. *Trans. ASABE* 52, 103–110.
- Loomis, R.S., Connor, D.J., 1992. *Crop Ecology. Productivity and Management in Agricultural Systems*. Cambridge University Press, Cambridge.
- Nebraska Department of Natural Resources (DNR), 2010. Registered groundwater wells by Natural Resources District, (online WWW). Available from <http://dnrdata.dnr.ne.gov/wellssql/Summary.asp?type=nrd> (accessed 01.03.10).
- Nielsen, D.C., Unger, P.W., Miller, P.R., 2005. Efficient water use in dryland cropping systems in the Great Plains. *Agron. J.* 97, 364–372.
- Otegui, M.E., Andrade, F.H., Suero, E.E., 1995. Growth, water use, and kernel abortion of maize subjected to drought at silking. *Field Crops Res.* 40, 87–94.
- Passioura, J., 2006. Increasing crop productivity when water is scarce—from breeding to field management. *Agric. Water Manage.* 80, 176–196.

- Payero, J.O., Klocke, N.L., Schneekloth, J.P., Davison, D.R., 2006a. Comparison of irrigation strategies for surface-irrigated corn in West Central Nebraska. *Irrig. Sci.* 24, 257–265.
- Payero, J.O., Melvin, S.R., Irmak, S., Tarkalson, D., 2006b. Yield response of corn to deficit irrigation in semiarid climate. *Agric. Water Manage.* 84, 101–112.
- Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D., Petersen, J.L., 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. *Agric. Water Manage.* 95, 895–908.
- Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. *Agric. Water Manage.* 57, 175–206.
- Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. *Agric. Water Manage.* 96, 1517–1524.
- Postel, S.L., 1998. Water for food production: will there be enough in 2025? *BioSci* 48, 629–637.
- Rosegrant, M.W., Ringler, C., Zhu, T., 2009. Water for agriculture: maintaining food security under growing scarcity. *Annu. Rev. Environ. Resour.* 34, 205–222.
- Sadras, V.O., Angus, J.F., 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. *Aust. J. Agric. Res.* 57, 847–856.
- Schabenberger, O., Pierce, F.J., 2001. *Contemporary Statistical Models for the Plant and Soil Sciences*. CRC Press.
- Stewart, B.A., Nielsen, D.R. (Eds.), 1990. *Irrigation of Agricultural Crops*. ASA, CSSA, SSSA, Madison, WI.
- Stöckle, C.O., James, L.G., 1989. Analysis of deficit irrigation strategies for corn using crop growth simulation. *Irrig. Sci.* 10, 85–98.
- Suyker, A.E., Verma, S.B., 2009. Evapotranspiration of irrigated and rainfed maize–soybean cropping systems. *Agric. For. Meteorol.* 149, 443–452.
- Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), 1983. *Limitations to Efficient Water Use in Crop Production*. ASA, CSSA, SSSA, Madison, WI.
- USDA–National Agricultural Statistics Service (NASS), 1999–2008. *Crops U.S. state and county databases*, Washington, DC [online WWW]. Available from <http://www.nass.usda.gov/index.asp> (accessed 01.10.09).
- USDA–National Agricultural Statistics Service (NASS), 2003 and 2008. *Farm and Ranch Irrigation Survey (FRIS)*, Washington, DC [online WWW]. Available from <http://www.agcensus.usda.gov/> (accessed 15.12.09).
- USDA–Natural Resources Conservation Service (NRCS), 2009. *Soil survey geographic (SSURGO) database for Gosper, Kearney, and Phelps counties, Nebraska* [online WWW]. Available from <http://soildatamart.nrcs.usda.gov> (accessed 01.10.09).
- Villalobos, F.J., Fereres, E., 1989. A simulation model for irrigation scheduling under variable rainfall. *Trans. ASAE* 32, 181–188.
- Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. *Agric. Ecosyst. Environ.* 82, 105–119.
- Wallace, J.S., Batchelor, C.H., Gregory, P., Sinclair, F.L., Valentin, C., Lal, R., Kijne, J., Sivakumar, M.V.K., Riley, R., Billing, D.W., 1997. Managing water resources for crop production [and discussion]. *Philos. Trans. R. Soc. Lond. B* 352, 937–947.
- Yang, H.S., Dobermann, A., Cassman, K.G., Lindquist, J.L., Walters, D.T., Arkebauer, T.J., Cassman, K.G., 2004. Hybrid-Maize: a maize simulation model that combines two crop modelling approaches. *Field Crops Res.* 87, 131–154.
- Yang H.S., Dobermann, A., Cassman, K.G., Walters, D.T., 2006. Hybrid-Maize (ver. 2006). A simulation model for corn growth and yield. Nebraska Cooperative Extension CD 9, University of Nebraska-Lincoln, Lincoln, NE [online WWW]. Available from <http://www.hybridmaize.unl.edu/UserGuide.htm>.