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SOIL WATER EXTRACTION PATTERNS AND CROP, IRRIGATION, AND EVAPOTRANSPIRATION WATER USE EFFICIENCY OF MAIZE UNDER FULL AND LIMITED IRRIGATION AND RAINFED SETTINGS

K. Djaman, S. Irmak

ABSTRACT. The effects of full and limited irrigation and rainfed maize production practices on soil water extraction and water use efficiencies were investigated in 2009 and 2010 under center-pivot irrigation near Clay Center, Nebraska. Four irrigation regimes (fully irrigated treatment (FIT), 75% FIT, 60% FIT, and 50% FIT) and a rainfed treatment were implemented. The crop water use efficiency (CWUE, or crop water productivity), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE) were used to evaluate the water productivity performance of each treatment. The seasonal rainfall amounts in 2009 and 2010, respectively, were 426 mm (18% below normal) and 563 mm (9% above normal). Irrigation regime impacted soil water extraction pattern, which increased with irrigation amounts. In general, the soil water extraction decreased with soil depth, and the water extraction from the top soil (0-0.30 m) accounted for the largest portion of the seasonal total water extraction as 39%, 42%, 48%, 48%, and 51% of the total extraction under rainfed, 50% FIT, 60% FIT, 75% FIT, and FIT, respectively. The rainfed treatment extracted more water from the 0.60-0.90 m and 0.90-1.2 m layers (19% and 17% of the total, respectively) than all other treatments. In general, the deepest soil layer (1.5-1.8 m) contributed about 5% to 8% to the seasonal total water extraction. The efficiency values for the same treatments varied between the years due to their dependency on the seasonal water supply, water supply impact on water extraction, climatic conditions, and their impact on yield. The CWUE increased with irrigation from 1.89 kg m⁻³ for the rainfed treatment to 2.58 kg m⁻³ for the 60% FIT in 2009 and from 2.03 kg m⁻³ for the rainfed treatment to 2.44 kg m⁻³ for the FIT in 2010. The CWUE was strongly correlated to actual crop evapotranspiration (ET_a) ($R^2 = 0.99$ in both years), irrigation amounts ($R^2 \geq 0.97$ in both years), and grain yield ($R^2 = 0.95$ in 2009 and $R^2 = 0.99$ in 2010). The IWUE and ETWUE decreased with ET_a and the irrigation amounts in 2009, while they showed the opposite trend in 2010. The IWUE ranged between 3.63 kg m⁻³ for FIT and 5.9 kg m⁻³ for 50% FIT in 2009 and between 2.52 kg m⁻³ for 50% FIT and 3.24 kg m⁻³ for 75% FIT in 2010. On average, 60% FIT resulted in the largest IWUE of 4.33 kg m⁻³. The measured ETWUE varied from 4.65 kg m⁻³ for FIT to 6.09 kg m⁻³ for 50% FIT in 2009 and from 5.94 kg m⁻³ for 50% FIT to 6.73 kg m⁻³ for FIT in 2010. The 60% FIT and 75% FIT had similar or greater CWUE and ETWUE than the FIT in both years. The ETWUE was usually greatest when the ET_a was about 580 mm in 2009 and 634 mm in 2010, indicating that in these experimental, climate, and management conditions, the maximum ETWUE and crop water productivity can be obtained at ET_a values smaller than those for the fully irrigated treatment. The 60% and 75% FIT treatments were very comparable to the fully irrigated treatment in terms of productivity performance and are viable supplemental irrigation strategies for increasing crop water productivity of maize while using (withdrawal) 40% or 25% less irrigation water under these experimental, soil and crop management, and climatic conditions.

Keywords. Crop water productivity, Evapotranspiration water use efficiency, Full irrigation, Irrigation water use efficiency, Limited irrigation, Soil water extraction, Water use efficiency.

The growing world population under scarce water supplies imposes significant challenges in terms of development and evaluation of optimum agricultural water management strategies. That has

led to specific goals for conservation of water resources to aid in sustainability and/or enhancement of food and fiber production. To achieve these goals, sustainable methods to increase crop water use efficiency (CWUE, or crop water productivity, CWP) have been developed. In recent years, some of the focus has shifted to the limiting factors in agricultural production systems, notably the availability of either land or water. Within this context, deficit (limited) irrigation has been offered as a valuable strategy to increase CWUE, irrigation water use efficiency (IWUE), or evapotranspiration water use efficiency (ETWUE) in regions where water is the primary limiting factor in crop production. The CWUE, in general, is defined either as the yield or net income per unit of water used as transpiration or evapotranspiration (ET). The IWUE is defined as the addi-

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tional crop yield produced over rainfed production divided by the irrigation amount applied, while the ETWUE is the ratio of the mass of economic yield or biomass produced per unit of irrigation water used as actual crop evapotranspiration (ET_a). ETWUE can be regarded as the net evapotranspiration efficiency; it is based on the yield produced beyond the rainfed yield divided by net ET_a . It can be a more effective term than CWUE and IWUE because it accounts for the impact of crop yield produced (and its ET_a) under rainfed conditions in the crop water productivity. Thus, it might be a more realistic description of the impact of irrigation in increasing crop water productivity. At the crop production level, the IWUE can be used to differentiate and quantify the role that irrigation plays in improving CWUE relative to rainfed conditions. The IWUE can also be an important indicator in evaluating crop performance and an agricultural system's productivity under different irrigation management strategies (full irrigation vs. various levels of limited irrigation). The CWUE is a quantitative term used to define the relationship between the crop produced and the amount of water used in crop production (Tanner and Sinclair, 1983; Howell, 2001). Over the last few decades, the water use efficiency estimation procedures have not evolved substantially, but the techniques to quantify the variables used in these definitions, such as ET_a estimation and depth of applied irrigation water, have become more advanced.

In general, CWUE is usually computed as the ratio of grain yield to actual crop water use:

$$CWUE = Y / ET_a \quad (1)$$

where CWUE is expressed in kg m^{-3} on a unit water volume basis or in g kg^{-1} on a unit water mass basis, Y is grain yield (g m^{-2}), and ET_a (mm) is actual crop evapotranspiration. To distinguish the role that irrigation plays in the crop water productivity, the IWUE and ETWUE have been used (Viets, 1962; Bos, 1980, 1985; Howell, 2001; Irmak et al., 2011) as:

$$IWUE = (Y_i - Y_d) / I_i \quad (2)$$

$$ETWUE = (Y_i - Y_d) / (ET_i - ET_d) \quad (3)$$

where IWUE and ETWUE are in kg m^{-3} , Y is dry grain yield (g m^{-2}), I_i is applied irrigation water (mm), subscript i represents irrigation level, subscript d represents the treatment with no seasonal irrigation (rainfed or dryland), ET_i is the crop evapotranspiration for irrigation level i , and ET_d is the crop evapotranspiration for the equivalent rainfed treatment.

Water productivity varies not only from region to region but also from field to field depending on many factors, including cropping patterns and rotations, climate characteristics, irrigation method and water management practices, soil and crop management practices, recurrent selection and gene transference, and input parameters for farming practices, including labor, fertilizer, and machinery (Liu et al., 2010; Deng et al., 2006; Cai et al., 2003; Wang et al., 2002; Kang et al., 2002a). Furthermore, the same crop can have substantially different CWUE responses to full and limited irrigation and to rainfed conditions when applied to differ-

ent crop development stages in the same location. Irrigation regime vs. rainfed production systems can also have substantial impacts on crop root development and its functions at different soil layers, thus altering the crop water uptake rate, which in turn impacts crop water use, yield, and CWUE. For example, Sharp and Davies (1985) found that the deeper roots of rainfed maize plants exhibited very large rates of soil water depletion per unit root length as compared with well-watered plants. Some researchers indicated that deep rooting is a drought avoidance strategy in maize (Lorens et al., 1987; Wan et al., 2000; Vamerali et al., 2003; Hund et al., 2009). Garcia et al. (2009) observed regular soil water uptake from the entire soil profile by rainfed maize mainly during the stressed period corresponding to the tasselling and early ear growth stages of maize. Panda et al. (2004) and Farré and Faci (2006) reported that most of the maize water uptake was from the 0-0.50 m soil layer, whereas sorghum extracted water from deeper layers (0.50-1.0 m) and at smaller soil water contents. Lenka et al. (2009) reported that, with increasing water input, water extraction took place mostly from top layers, which is due to the fact that plant roots expand deeper in cases of water scarcity. Similar results were reported by Morgan and Condon (1986), Cabelguenne and Debaeke (1998), Kondo et al. (2000), Anwar et al. (2000), and Panda et al. (2004).

The water use efficiency data that exist in the literature for various crops, including maize, demonstrate that the variability in the efficiency values between different regions for the same crop justifies the locally measured data. For example, Cai et al. (2003) found that the water productivity of rice ranged from 0.15 to 0.60 kg m^{-3} while the water productivity of other cereals ranged from 0.2 to 2.4 kg m^{-3} in 1995; projecting that from 1995 to 2025, water productivity will increase with the global average water productivity of rice and other cereals, increasing from 0.39 to 0.52 kg m^{-3} and from 0.67 to 1.01 kg m^{-3} , respectively. In a large-scale field study conducted in 16 farmer fields (65 ha each field) in Nebraska (Irmak et al., 2012a), the CWUE values for 16 center-pivot irrigated maize hybrids ranged from 1.78 to 3.38 kg m^{-3} , and IWUE ranged from 8 to 29 kg m^{-3} . The IWUE in that study was calculated as the ratio of grain yield to irrigation amount, and the rainfed yields were not considered in the crop water productivity. A CWUE value of 1.6 kg m^{-3} was reported by Ko and Piccinni (2009) for a center-pivot irrigated field maize in southern Texas. Howell (2000) reported an increase in CWUE with increasing yield, while Howell et al. (1998) reported CWUE values that had a narrow range of 1.65 to 1.70 kg m^{-3} across maize hybrids. Stone et al. (2001) measured water use of 311 and 98 mm for fully irrigated and rainfed treatments, respectively, and observed that early droughts increased the CWUE when compared with late drought treatments. Ko and Piccinni (2009) reported that grain yield increased as irrigation increased, and there were significant differences between 100% and 50% ET treatments in volumetric water content, leaf relative water content, and canopy temperature, considering that irrigation management of maize at 75% ET is feasible with 10% reduction of grain yield and an increased CWUE. The greatest CWUE (1.6 kg

m⁻³) was achieved at 456 mm of water input, while grain yield plateaued at less than 600 mm. Mansouri-Far et al. (2010) obtained the largest IWUE when maize experienced water deficit at the vegetative stage, and an increased nitrogen supply improved the yield and IWUE when maize plants were exposed to at least one irrigation shortage at the vegetative stage. Howell et al. (1975) reported that deficit irrigation of maize reduced yields by affecting both seed mass and kernels per ear, which impacts CWUE.

While the aforementioned studies provide valuable data about crop efficiency response to water, most of these studies did not quantify the root water extraction pattern under various irrigation levels and did not quantify how the CWUE varies for different irrigation management practices relative to rainfed conditions. Because the water use efficiency for the same crop varies considerably between regions, developing local databases for CWUE, IWUE, and ETWUE is necessary. Such data and information can aid the water management community to better evaluate the response of crop yield to irrigation water applications under local farming conditions and to obtain more accurate crop productivity data for assessment and policy evaluations. The objectives of this study were to: (1) quantify fully irrigated and several levels of limited irrigation regimes and a rainfed production system on soil profile water extraction patterns, and (2) measure and compare the CWUE, IWUE, and ETWUE of maize under full and limited irrigation and rainfed conditions in the south central Nebraska climate with typical soil and crop management conditions.

MATERIALS AND METHODS

SITE DESCRIPTION

Field experiments were conducted in the 2009 and 2010 growing seasons at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (40° 43' N and 98°

8' W at an elevation of 552 m above mean sea level), near Clay Center, Nebraska. The long-term average annual rainfall in the area is 680 mm, with significant annual and growing season variability in both magnitude and timing. The 2009 and 2010 growing seasons' weather data at the site are presented in table 1. The soil at the site is a Hastings silt loam, which is a well-drained upland soil (fine, montmorillonitic, mesic Udic Argiustoll) with water holding characteristics of 0.34 m³ m⁻³ field capacity, 0.14 m³ m⁻³ permanent wilting point, and 0.53 m³ m⁻³ saturation point. The effective rooting depth for maize in the experimental site is 1.2 m. The total available water holding capacity of the top 1.2 m soil profile was approximately 240 mm. The available soil water in the top 1.2 m profile was kept between approximately 90% of the field capacity and the maximum allowable depletion, which was set to be approximately 45% of the total available water (TAW). The particle size distribution is 15% sand, 65% silt, and 20% clay, with 2.5% organic matter content in the top soil (Irmak et al., 2008; Irmak, 2010).

EXPERIMENTAL DESIGN AND GENERAL SOIL, CROP, AND IRRIGATION MANAGEMENT PRACTICES

Four irrigation treatments were evaluated: fully irrigated treatment (FIT), 75% FIT, 60% FIT, 50% FIT, and rainfed treatment. The fully irrigated treatment in this study represented the conditions in which the crop was irrigated when soil water depletion was about 40% to 45% of the total available water to avoid any potential water stress impact on crop yield. Irrigation timings were based on the soil water content of the fully irrigated treatment such that a total of 25 mm of irrigation water was applied to the FIT each time the soil water in the root zone in the FIT reference plot was depleted by about 40% to 45% of the TAW. Thus, at each irrigation event, about 25, 19, 15, and 13 mm of irrigation water was applied to the FIT, 75% FIT, 60% FIT,

Table 1. Average weather conditions during the 2009 and 2010 growing seasons and long-term (1983-2009) average values measured at the research site in south central Nebraska.

Year	Month	T_{max} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	Wind Speed (m s ⁻¹)	Total Rainfall (mm)	Incoming Shortwave Irradiance (W m ⁻²)
2009	April	15.7	2.7	91.2	43.1	5.4	84	208
	May	22.1	9.7	91.9	46.1	3.9	33	242
	June	25.8	15.5	95.4	57.4	2.8	137	209
	July	28.1	15.6	97.4	49.4	2.8	52	260
	August	28.0	15.3	93.0	47.5	3.5	100	243
	September	23.3	10.9	94.5	50.2	2.8	46	159
	October	12.1	2.0	96.9	61.2	4.3	87	98
2010	April	18.4	5.6	90.0	45.6	4.8	70	202
	May	19.5	9.2	93.1	57.8	4.2	126	224
	June	28.1	16.7	93.6	55.4	3.3	231	265
	July	30.1	19.1	94.7	54.1	3.1	57	245
	August	31.5	18.2	93.1	45.0	3.3	89	248
	September	25.9	11.6	93.8	47.2	3.6	57	174
	October	22.4	6.0	86.2	33.0	3.4	6	157
1983-2009 average	April	17.0	2.7	88.3	43.4	4.7	68	195
	May	22.8	9.6	90.4	49.3	4.2	111	226
	June	28.3	14.9	91.6	48.9	3.6	106	259
	July	30.5	17.5	93.3	53.4	2.9	88	259
	August	29.3	16.5	94.2	56.3	2.7	93	225
	September	25.3	10.7	92.3	46.3	3.1	71	183
	October	18.1	3.7	90.2	46.1	3.5	51	127

and 50% FIT treatments, respectively. A total of seven irrigations were applied in the 2009 growing season on the following dates: July 8, July 14, July 21, August 4, August 11, August 19, and August 27. In 2010, there were five irrigation applications on July 21, July 29, August 5, August 12, and August 19. The experimental design was a completely randomized design with three replications. Each replication plot was about 1 ha in size, and the sampling area in each replication was eight rows wide and 15.2 m long with 0.76 m row spacing. The experimental field was maintained as a ridge-till in both years.

Maize (*Zea mays* L.) hybrid Mycogen 2V732 was planted on April 23, 2009, emerged on May 4-6, and was harvested on October 15, 2009. In 2010, the same maize hybrid was planted on April 28, emerged on May 15, and was harvested on October 7, 2010. The planting population density was 73,000 plants ha⁻¹ in both years, and the planting depth was 0.05 m with a north-south planting direction. All treatments were fertilized equally, and the nitrogen amount applied to the entire field was based on soil samples taken from several locations in the field and the University of Nebraska-Lincoln nitrogen recommendation algorithms (Shapiro et al., 2003). Herbicide, insecticide, pesticide, and fungicide applications were applied to the entire field when needed. The experimental field (16 ha) was irrigated using a four-span hydraulic and continuous-move center-pivot irrigation system (T-L Irrigation Co., Hastings, Neb.). Early in the season, all treatments received the same depth of water from winter snowmelt and spring rainfall, bringing the soil water content to near field capacity for all treatments and providing adequate and uniform soil moisture for planting and crop germination.

MEASUREMENT OF SOIL WATER STATUS

Soil water status was monitored using two methods. Watermark Granular Matrix Sensors (GMS, Irrometer Co., Riverside, Cal.) were used to monitor soil matric potential (SMP) on an hourly basis. The GMS is an indirect method of measuring SMP, and the SMP readings were converted to soil water content in percent volume using predetermined soil-water retention curves for the study field (Irmak et al., 2010). The GMS devices were installed at 0.30 m increments down to 1.2 m in the soil profile. The sensors were installed in the plant row (each sensor was installed between two maize plants) in two replications of each treatment. The sensors were connected to a Watermark Monitor datalogger (Irrometer Co., Riverside, Cal.), and hourly readings were recorded throughout the growing season. In addition to the GMS devices, the soil water content was measured at 0.30, 0.60, 0.90, 1.2, 1.5, and 1.8 m soil depths twice a week throughout both growing seasons using a neutron probe soil moisture meter (model 4302, Troxler Electronics Laboratories, Inc., Research Triangle Park, N.C.). The soil profile water extraction was computed for each of the six soil layers (0-0.30, 0.30-0.60, 0.60-0.90, 0.90-1.2, 1.2-1.5, and 1.5-1.8 m) under each treatment for both seasons using the water balance method. The neutron probe-measured soil water content data were used in the water extraction analyses. The neutron probe access tubes

were installed between two maize plants in the plant row and about 4 m from the GMS devices. Irrigation timings were determined based on GMS and/or neutron probe soil moisture readings.

SEASONAL EVAPOTRANSPIRATION CALCULATIONS USING SOIL-WATER BALANCE APPROACH

Seasonal actual crop ET (ET_a, mm) was calculated using a general water balance equation:

$$P + I + U + Ron = Roff + D \pm \Delta W + ET_a \quad (4)$$

where P is rainfall (mm), I is irrigation water applied (mm), U is upward soil moisture flux (mm), Ron is surface runoff within the field (mm), $Roff$ is surface runoff from the field (mm), ΔW is the change in soil moisture storage in the soil profile (mm), and D is the deep percolation (mm) below the crop root zone. The deep percolation was estimated by daily soil water balance approach using a computer program that was written in Microsoft Visual Basic. The inputs to the program were daily weather data (including air temperature, incoming shortwave irradiance, relative humidity, wind speed, and rainfall), irrigation dates and amounts, initial water content in the soil profile at crop emergence, and crop- and site-specific information such as planting date, maturity date, soil parameters, maximum rooting depth, etc. (Payero et al., 2009; Bryant et al., 1992). The computer program calculated daily ET_a and the water balance in the crop root zone using the two-step approach ($ET_a = K_c \times ET_o$, where ET_o is evapotranspiration of a grass reference crop, and K_c is the crop coefficient). In the program, ET_o is calculated using the weather data as input to the Penman-Monteith equation (Monteith, 1965; Monteith and Unsworth, 1990; Irmak et al., 2012b), and K_c is used to adjust the estimated ET_o for the reference crop to that of maize crops at different growth stages and growing environments. The daily soil water balance equation for deep percolation is:

$$D_j = \max(P_j - R_j + I_j - ET_{aj} - CD_{j-1}, 0) \quad (5)$$

where D_j is deep percolation on day j , CD_{j-1} is root zone cumulative depletion depth at the end of day $j-1$, P_j is precipitation, R_j is precipitation and/or irrigation runoff from the soil surface on day j (mm), I_j is irrigation depth on day j (mm), and ET_{aj} is crop evapotranspiration on day j (mm), estimated by the two-step approach.

The surface runoff from individual treatment was estimated using the USDA Natural Resources Conservation Service (NRCS) curve number method (USDA-NRCS, 1985). According to the silt loam soil at the site and the known land use, slope, and the conservation tillage, $C = 75$ was used, which was obtained from USDA-NRCS (1985).

Assuming that the upward flux and runoff are negligible, the soil water balance equation is reduced to the following form for calculating maize seasonal evapotranspiration ET_a:

$$ET_a = P + I - R - D \pm \Delta W \quad (6)$$

DETERMINATION OF SOIL PROFILE WATER EXTRACTION

Profile distribution of the amount of rainfall and irrigation water to different soil depths was calculated based on a cascading method. First, water deficit was calculated for each layer as the difference in average soil moisture of the two neutron probe sampling dates and field capacity of the layer (Lenka et al., 2009). Whenever the rainfall and/or irrigation amount was more than the water deficit of the upper layer, the remaining water was considered to move to the next soil layer. This calculation was repeated for other layers up to 1.8 m so that the moisture distribution was calculated for the entire soil profile. The change in soil moisture and the contribution of rainfall and/or irrigation water for each layer were added to compute the water extraction from that particular soil layer for a weekly time step, and these values were summed throughout the growing season to obtain the seasonal total soil water extraction amount for each soil layer for each treatment.

WATER USE EFFICIENCY CALCULATIONS AND STATISTICAL ANALYSES

The CWUE, IWUE, and ETWUE were calculated to evaluate the efficiency and productivity response of maize under fully irrigated, limited irrigation, and rainfed settings (eqs. 1, 2, and 3). At maturity, two center rows over 15.25 m were hand-harvested to determine the grain yield of each replication of each treatment. The grain yield was determined from shelled ears and was adjusted to 15.5% moisture content and used in the efficiency calculations.

Analysis of variance (ANOVA) was performed using Proc Mixed in SAS (SAS, 2003). In addition, a regression procedure was used to perform stepwise multiple regression analysis, and means separation was done only for significant ANOVA results using Fisher's protected least significance difference (LSD) test at the 95% level of probability to identify significant differences in grain yield between treatments.

RESULTS AND DISCUSSION

WEATHER CONDITIONS DURING THE 2009 AND 2010 GROWING SEASONS

Monthly average climate variables for the 2009 and 2010 seasons as well long-term average values are summarized in table 1. On average, RH was similar in both years, and the seasonal average RH was 73% and 72% in 2009 and 2010, respectively. Wind speed was 8% higher in 2010 as compared with the 2009 season. The incoming shortwave irradiance was, on average, 30% and 24% less than the long-term average values in 2009 and 2010, respectively. The seasonal average solar irradiance in 2010 was 14% greater than the average in 2009. The seasonal total rainfall in 2009 and 2010, respectively, were 426 (18% below normal) and 563 mm (9% above normal). The long-term average growing season rainfall is 517 mm. There was more uniform distribution of rainfall in 2010. There were seven irrigation events in 2009 vs. five in 2010 for each irrigated treatment, resulting in water applications of 178 mm in 2009 and 127 mm in 2010 for the fully irrigated treatment.

EFFECT OF IRRIGATION ON SOIL WATER DEPLETION FROM EACH SOIL LAYER

Soil water depletion showed differences by soil layer and irrigation amount (figs. 1 and 2). Under rainfed conditions, water was taken up from all soil layers from the soil surface to the 1.8 m depth (figs. 1a and 2a). Plants concentrated water uptake in the 0.60-1.8 m depth from mid-July to late September, which corresponded to the maize tasseling to physiological maturity stages. The top soil layer (0-0.30 m) experienced the greatest soil water depletion, which was 90% of TAW in 2009 and 52% of TAW in 2010, as a combination of crop water uptake and soil water evaporation. Some researchers have indicated that deep rooting is a drought avoidance strategy used by plants, including maize (Lorens et al., 1987; Wan et al., 2000; Vamerali et al., 2003; Hund et al., 2009). Sharp and Davies (1985) found that the deeper roots of stressed maize plants exhibited very large rates of soil water depletion per unit root length as compared with well-watered plants. In this study, more water was depleted from the bottom soil layer in 2009 (23 mm or 39% of TAW) than in 2010, where the final depletion was 9 mm (14.5% of TAW) in the 1.5-1.8 m soil layer. This is due to less rainfall and less uniform distribution in 2009 as compared with 2010. In both growing seasons, the soil water depletion was above the threshold of 33 mm that corresponds to 55% of TAW mostly in the 0-0.30 m and 0.60-1.2 m soil layers. Crops were subject to water stress from early July 2009 and late July 2010, corresponding to the maize tasseling and maize silking stages, respectively; plant water uptake was mostly concentrated below 0.60 m, and soil water evaporation is mostly limited to the first 0.30 m of the top soil. Less water uptake occurred in the 0.30-0.60 m layer than in other layers due to the heavy clay in that zone. Considering the maize root zone of 1.8 m, only the rainfed maize experienced water stress in both growing seasons (fig. 3). This was also observed during both growing seasons (during tasseling stage in 2009 and silking stage in 2010) by a decrease in measured leaf area index (data not shown).

Under the 50% FIT (figs. 1b and 2b), the top soil layer was the most depleted during the growing season up to early September 2009 and August 24, 2010. The largest soil water depletion of the top soil was about 53 mm (81.5% of TAW) in 2009 and 40 mm (67% of TAW) in 2010 and was smaller than its value under the rainfed conditions. Maize water uptake was uniformly partitioned in the 0.60-1.5 m soil depth from the maize tasseling to maturity stages in 2009 and from the silking to maturity stages in 2010. Water uptake in the 50% FIT treatment from the bottom soil layer was observed only in 2009, starting in early July and corresponding to the maize tasseling and physiological maturity stages. Similar to the rainfed treatment, less water was depleted from the deeper layers by root uptake and evaporation.

Under the 60% FIT (figs. 1c and 2c), soil water content was relatively stable near field capacity in the 0.30-0.60 m soil layer in 2009 and in the 1.5-1.8 m layer in 2010. The top layer was depleted to 52.5% of TAW in 2009 and to 42.6% of TAW in 2010. In addition to the top layer, the wa-

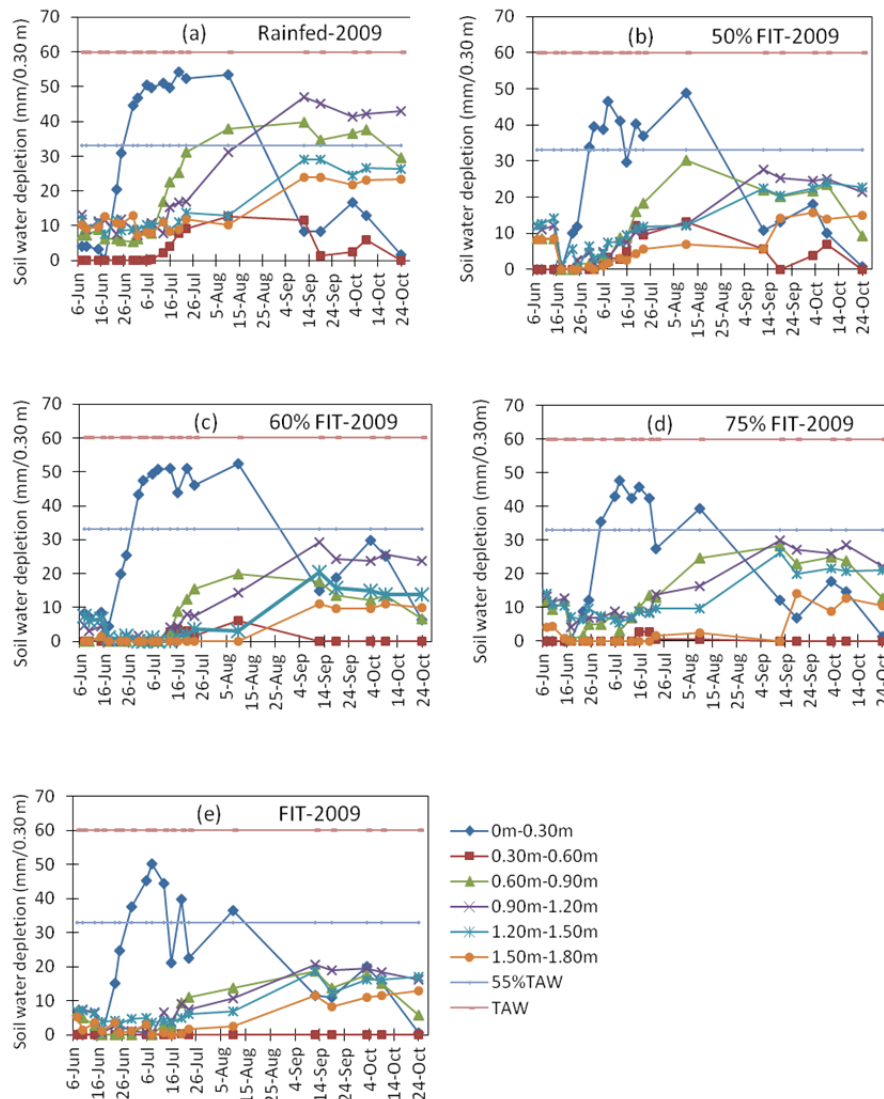


Figure 1. Seasonal soil water depletion from various soil depths and average maize root zone water depletion under different irrigation treatments in the 2009 growing season: (a) rainfed, (b) 50% FIT, (c) 60% FIT, (d) 75% FIT, and (e) FIT.

ter uptake was generally concentrated in the 0.60-1.5 m layer in both seasons later in the season; however, during the 2009 growing season, deep water uptake was observed in the bottom soil layer (1.5-1.8 m). Under the 75% FIT (figs. 1d and 2d), apart from the top soil layer, which was depleted above the threshold (79.5% of TAW in 2009 and 79.0% of TAW in 2010), the third and fourth soil layers were depleted to nearly 27 mm, which represents about 45% of TAW of each soil layer. In 2009, maize roots were able to extract soil water in layers down to the bottom layer mostly from mid-September to early October, which corresponded to the dent to maturity stages.

Overall, the soil water data in the root zone (fig. 3) indicate that the 75% FIT did not experience as much water depletion as the 50% FIT and 60% FIT in both seasons. The FIT treatment is the reference fully irrigated treatment, and the 0.30-0.60 m soil layer was always at or above its maximum water holding capacity (figs. 1e and 2e). There was soil water evaporation from the top soil up to near wilting point at mid-season (83.5% of TAW in 2009 and 72.5% of

TAW in 2010); this was replenished by late-season rainfall. As expected, the root zone soil water depletion at the end of the growing season (table 2) decreased linearly with seasonal irrigation amounts ($R^2 = 0.84$) for each of the two growing seasons (figs. 4a and 4b) and for the two years' pooled data (fig. 4c). In general, the greater amount of water uptake in the top layer (0-0.30 m) in most treatments was due to both soil evaporation and plant transpiration through roots.

EFFECT OF IRRIGATION ON SEASONAL SOIL WATER EXTRACTION PATTERNS FROM ENTIRE PROFILE

The proportional soil water extraction (i.e., of the total water uptake from the entire 1.8 m profile) for each soil layer under each irrigation regime is presented in table 3 and figure 5. In general, the soil water extraction decreased with soil depth. The greatest amount of extraction occurred under the fully irrigated treatment, and the rainfed maize extracted the least soil water in the root zone. Total soil wa-

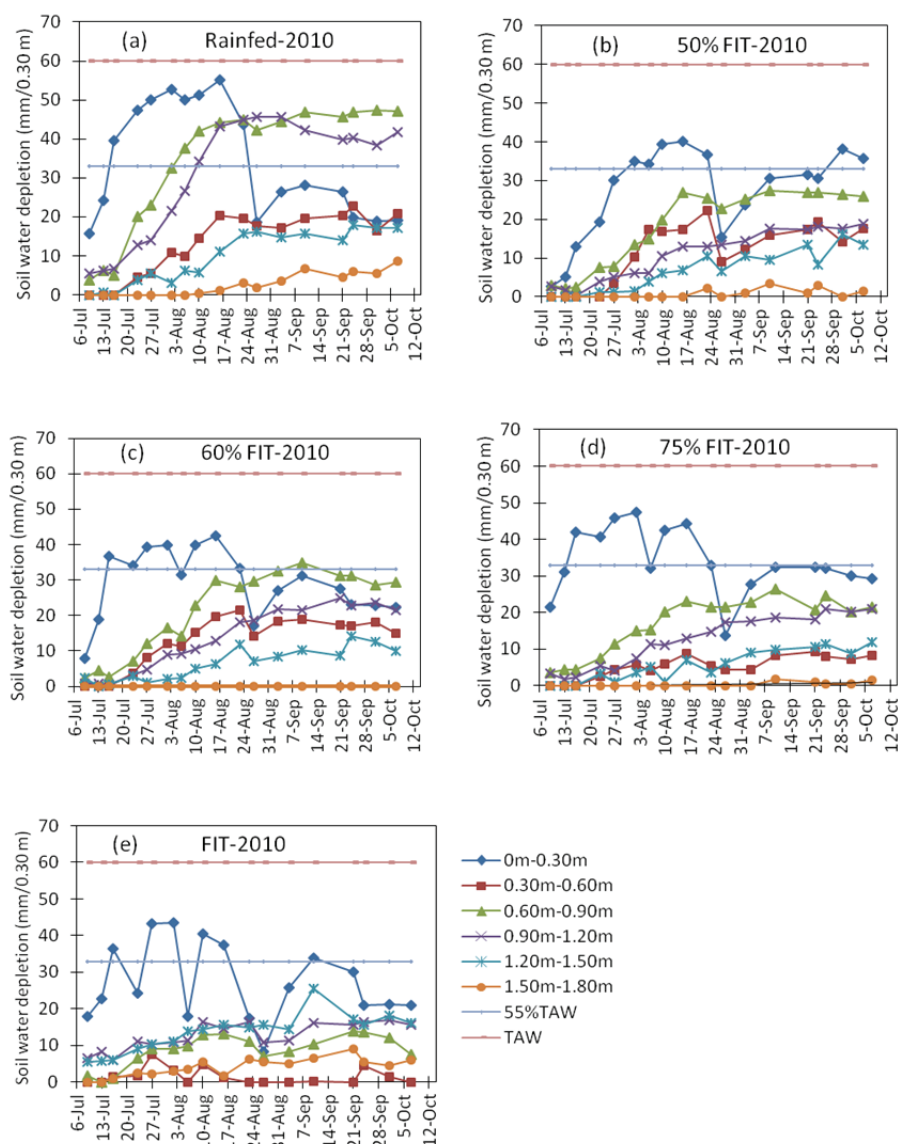


Figure 2. Seasonal soil water depletion from various soil depths and average maize root zone water depletion under different irrigation treatments in the 2010 growing season: (a) rainfed, (b) 50% FIT, (c) 60% FIT, (d) 75% FIT, and (e) FIT.

ter extraction under any treatment in 2010 was larger than the total extraction in 2009 for the same treatment, and it increased with seasonal irrigation amounts. Soil water extraction occurred though the whole soil profile of 0 to 1.8 m, and it varied substantially with irrigation regime. The extraction ranged from 559 mm to 659 mm in 2009 and from 668 mm to 710 mm in 2010, and extraction was comparable to crop evapotranspiration, which varied from 481 mm to 620 mm in 2009 and from 579 mm to 634 mm in 2010. Tolk et al. (1998) and Howell et al. (2002) reported water uptake by maize below 1.5 m. All treatments showed the largest water extraction values from the top layer (0 to 0.30 m) due to evaporation and perhaps increased root mass in this zone. The percentages of water extracted from the top soil were 38%, 42%, 48%, 48%, and 51% of the seasonal total extraction for the rainfed, 50% FIT, 60% FIT, 75% FIT, and FIT, respectively. On a two-year average basis, about 10% of soil water extraction for all treatments was measured in the 0.30-0.60 m soil layer,

with the 60% FIT showing the greatest extraction (13% of the total) from this layer. The decrease to minimum in soil water extraction from the 0.30-0.60 m layer could have been caused by larger bulk density, the heavy clay layer, larger soil water content observed in the 0.30-0.60 layer throughout the growing seasons, and consequently insufficient aeration. Similar observations were made by Bathke et al. (1992) and Bandyopadhyaya and Mallick (2003).

For the top layer, water extraction increased with irrigation regimes due to probable increase in root mass in this zone and the availability of water for evaporation. This agrees with the results reported by Lenka et al. (2009), who reported that the percent extraction by maize from the 0-0.60 m layer varied from 70% to 79% according to irrigation treatments, and the bottom layer of 0.90-1.2 m contributed only 3% to 14% to the seasonal total water extraction. Less water (10% on average) was extracted from the second (0.30 to 0.60 m) layer. The rainfed treatment extracted more water from the 0.60-0.90 m and 0.90-1.2 m layers

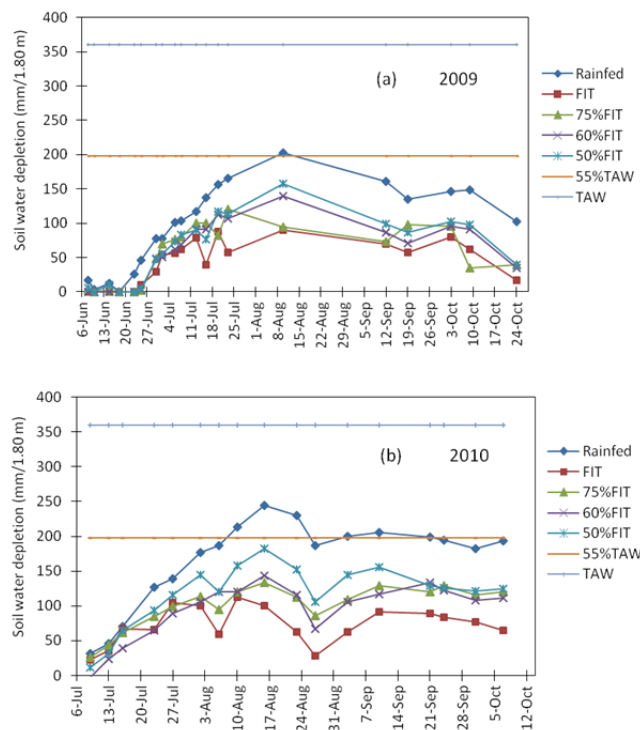


Figure 3. Average maize root zone water depletion under rainfed, 50% FIT, 60% FIT, 75% FIT, and FIT during the (a) 2009 and (b) 2010 growing seasons.

(19% and 17% of the total, respectively) than all other irrigated treatments, which had moderate extraction throughout the soil profile below the top layer, ranging from 8% to 16%. Joffre et al. (2001) observed that when heavier soil layers reduce plant water, the water lost by transpiration reduces the water potential, and the extraction moves toward deeper layers. In contrast to the results reported by Joffre et al. (2001), Farré and Faci (2006) and Gordon et al. (1995) found little water depletion below 0.90 m for rainfed maize. Brown et al. (2009) also reported the influence of water supply on water extraction patterns in the overlying layers for the perennial Lucerne. Soil water uptake varied widely with location, crop management practices, etc.

CROP WATER USE EFFICIENCY (CWUE)

The maize yield, CWUE, IWUE, and ETWUE values are presented in table 4. The relationship between CWUE and seasonal ET_a , seasonal irrigation amount, grain yield for individual years, as well as the pooled data for ET_a , irrigation, and grain yield are presented in figure 6. Overall,

the CWUE ranged from 1.89 to 2.58 kg m^{-3} in 2009 and from 2.03 to 2.44 kg m^{-3} in 2010 (table 4). In 2009, the CWUE increased with irrigation, reached the largest value with the 60% FIT, and thereafter decreased slightly with increasing irrigation. In 2010, the CWUE increased with increasing seasonal ET_a and the amounts of applied irrigation water (fig. 6). The 60% FIT had the largest CWUE of 2.58 kg m^{-3} in 2009, and the FIT resulted in the largest CWUE of 2.44 kg m^{-3} in 2010. The rainfed maize had the smallest CWUE of 1.89 and 2.03 kg m^{-3} in 2009 and 2010, respectively. The CWUE values for the same treatments varied between the years due their dependency on the seasonal water supply, water supply impact on water extraction, climatic conditions, and their impact on yield (table 1). These results are in agreement with Guohua et al. (2010), who reported CWUE values between 1.9 and 2.3 kg m^{-3} for the fully irrigated maize that had the largest CWUE. Farré and Faci (2006) reported that CWUE for maize decreased with decreasing irrigation and ranged from 1.89 to 2.05 kg m^{-3} . Similar results were reported by Howell et al. (1995) and Payero et al. (2008), who found that CWUE increased nonlinearly with seasonal ET_a , and the CWUE increased with irrigation up to the point where additional irrigation did not produce additional economical yield. In contrast, Li et al. (2010) reported greater CWUE values above 2.5 kg m^{-3} . Fang et al. (2010) reported that CWUE increased with the amount of irrigation applied during the dry growing seasons in 2001-2002 (1.65 to 1.87 kg m^{-3}) and wet seasons in 2002-2003 (1.78 to 2.2 kg m^{-3}). Katerji et al. (2010) observed that CWUE varied with years and locations and ranged from 1.34 to 1.81 kg m^{-3} , which was similar to the results reported by Zhang et al. (2004) of CWUE ranging between 1.01 and 1.72 kg m^{-3} . In contrast, Zhang et al. (2008) reported negative correlation between CWUE and ET_a for maize.

Regression analysis in figure 6 indicated a quadratic relationship between CWUE and ET_a ($R^2 = 0.99$ in 2009 and 2010, fig. 6a) and between CWUE and irrigation amounts ($R^2 \geq 0.97$ in both years, fig. 6b), and a linear relationship between CWUE and grain yield ($R^2 = 0.95$ in 2009 and $R^2 = 0.99$ in 2010, fig. 6c). The pooled data for CWUE vs. ET_a had a smaller R^2 value than the individual years due to differences in ET_a and yield under the same treatments during both years, mostly under rainfed conditions (fig. 6d). When evapotranspiration or irrigation are relatively small, water availability is the limiting factor for grain yield, and an increase in evapotranspiration or irrigation results in

Table 2. Soil profile water depletion per depth and total soil profile water depletion at the end of the growing season under full and various levels of limited irrigation settings and rainfed conditions in 2009 and 2010.

Soil Depth (m)	End-of-Season Total Soil Water Depletion (mm)									
	Rainfed		50% FIT		60% FIT		75% FIT		FIT	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
0-0.30	0	19	0	36	6	22	0	29	0	21
0.30-0.60	0	21	0	18	0	15	0	8	0	0
0.60-0.90	30	47	9	26	7	29	13	22	6	8
0.90-1.2	43	42	21	19	24	22	22	21	16	16
1.2-1.5	26	17	23	14	14	10	21	12	17	16
1.5-1.8	23	9	15	0	10	0	11	0	13	6
0-1.8	124	155	69	114	61	98	68	94	53	66
Average (0-1.8)	139		91		79		81		59	

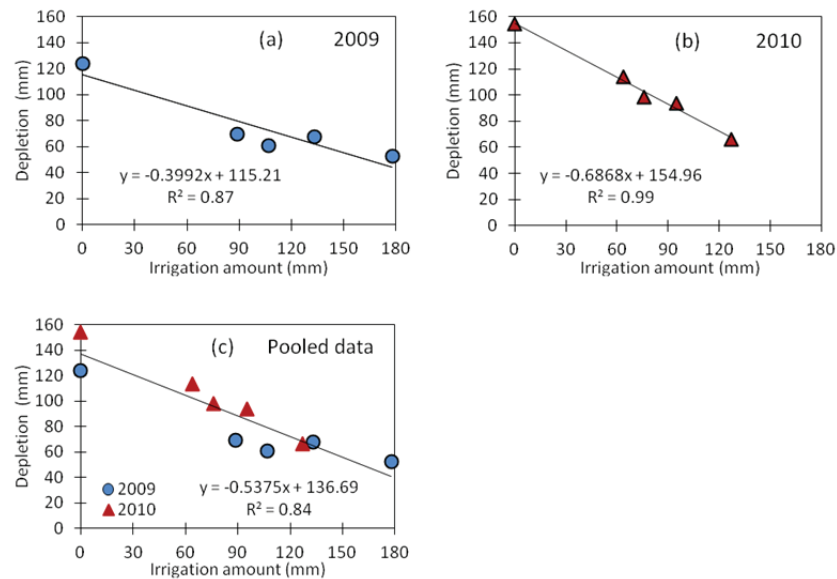


Figure 4. Seasonal total soil water depletion in the 1.8 m profile at the end of the maize growing season in (a) 2009 and (b) 2010 as a function of total seasonal irrigation amounts, and (c) the two-year pooled data.

significant increases in both grain yield and CWUE. However, the rate of increase in both grain yield and CWUE starts to decrease as evapotranspiration or irrigation further increase. Once CWUE reaches its maximum value, an increase in total crop water use could still lead to a marginal increase in grain yield, and thus CWUE would decrease (Kang et al., 2002b). In general, the CWUE increased with ET_a ; however, in 2009, the 60% FIT had the largest CWUE, indicating a diminishing return in which the CWUE did not respond or increase with ET_a beyond a certain threshold value of ET_a . This threshold value is approximately 580 mm (figs. 6a and 6d). The 580 mm value corresponds to the 60% FIT. The 75% FIT and FIT had similar ET_a and CWUE, but 25% less irrigation water was applied to the 75% FIT. Between the 75% FIT and FIT, there were 14 and 6 mm increases in ET_a in 2009 and 2010, respectively, and the FIT resulted in only 0.02 and 0.08 kg m^{-3} increases in CWUE in 2009 and 2010, respectively. Between

2009 and 2010, the rainfed treatment had similar CWUE (1.89 kg m^{-3} in 2009 and 2.03 kg m^{-3} in 2010) with different ET_a (481 mm in 2009 vs. 579 mm in 2010) (table 4). In 2009, peak CWUE was approximately 2.5 kg m^{-3} and occurred at about 580 mm of ET_a , about 110 mm of irrigation, and approximately 1500 g m^{-2} of grain yield (fig. 6). The peak 2010 results were similar, in that peak CWUE was almost as large as the 2009 peak CWUE but occurred at larger ET_a , irrigation applied, and grain yield. The 2010 peak CWUE occurred at about 630 mm ET_a , about 125 mm irrigation, and approximately 1550 g m^{-2} grain yield. The CWUE was relatively insensitive to ET_a , irrigation applied, and grain yield as compared with IWUE, and interannual differences in CWUE were less as compared with IWUE. This could be interpreted as the crop being relatively insensitive to the source of water, whether irrigation, precipitation, or soil water storage.

Table 3. Soil profile water extraction patterns under full and various levels of limited irrigation settings and rainfed conditions in 2009 and 2010.

Treatment	Total Soil Water Extraction in 2009 (mm)							ET_a (mm)
	0-0.30	0.30-0.60	0.60-0.90	0.90-1.2	1.2-1.5	1.5-1.8	0-1.8	
Rainfed	238	16	117	107	43	38	559	481
50% FIT	250	42	87	90	76	33	578	567
60% FIT	310	87	58	74	39	16	584	578
75% FIT	328	40	54	83	86	49	641	606
FIT	374	77	53	62	42	50	659	620
Treatment	Total Soil Water Extraction in 2010 (mm)							ET_a (mm)
	0-0.30	0.30-0.60	0.60-0.90	0.90-1.2	1.2-1.5	1.5-1.8	0-1.8	
Rainfed	230	93	108	102	73	61	668	579
50% FIT	271	84	113	76	71	51	667	606
60% FIT	295	81	113	81	71	52	692	616
75% FIT	315	61	104	95	71	55	700	628
FIT	322	53	83	95	95	62	710	634
Treatment	Average of Both Years Total Soil Water Extraction (mm)							Avg. ET_a (mm)
	0-0.30	0.30-0.60	0.60-0.90	0.90-1.2	1.2-1.5	1.5-1.8	0-1.8	
Rainfed	234	54	113	105	58	49	613	530
50% FIT	260	63	100	83	74	42	622	587
60% FIT	302	84	86	77	55	34	638	597
75% FIT	322	50	79	89	79	52	671	617
FIT	348	65	68	79	69	56	685	627

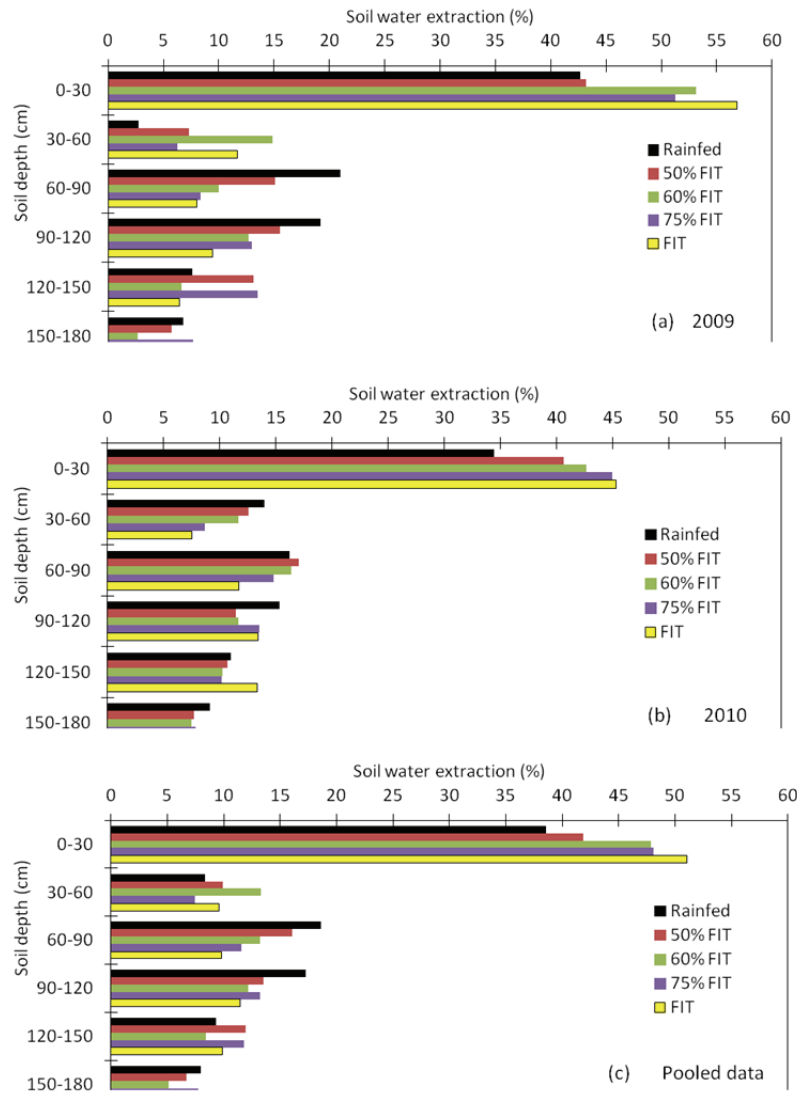


Figure 5. Soil water extraction (% of seasonal total) for maize under different irrigation regimes and rainfed conditions in (a) 2009, (b) in 2010, and (c) average of the two growing seasons (pooled data).

Table 4. Irrigation, actual evapotranspiration (ET_a), grain yield, crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE) of maize under full irrigation, various levels of limited irrigation, and rainfed conditions in 2009 and 2010.

Year	Treatment	Irrigation (mm)	ET_a (mm)	Grain Yield ^[a] (Mg ha ⁻¹)	CWUE (kg m ⁻³)	IWUE (kg m ⁻³)	ETWUE (kg m ⁻³)
2009	Rainfed	0.00	481	9.1 c	1.89	-	-
	50% FIT	89	567	14.3 b	2.52	5.90	6.09
	60% FIT	107	578	14.9 b	2.58	5.47	6.01
	75% FIT	133	606	15.0 ab	2.48	4.50	4.79
	100% FIT	178	620	15.5 a	2.50	3.63	4.65
2010	Rainfed	0.0	579	11.8 c	2.03	-	-
	50% FIT	64	606	13.4 b	2.20	2.52	5.94
	60% FIT	76	616	14.2 b	2.30	3.18	6.55
	75% FIT	95	628	14.8 a	2.36	3.24	6.31
	100% FIT	127	634	15.5 a	2.44	2.92	6.73

^[a] Grain yield means followed by the same letter within a year are not significantly different at the 5% significance level.

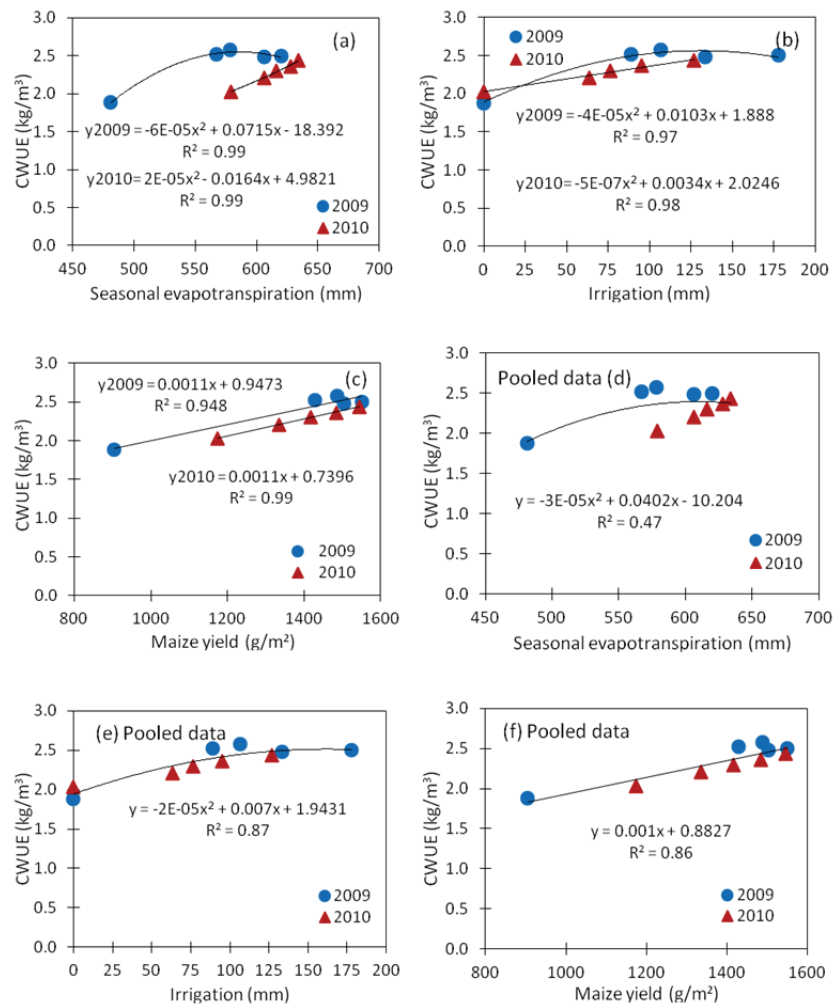


Figure 6. Relationship between crop water use efficiency (CWUE) vs. (a) seasonal ET_a , (b) seasonal irrigation amount, (c) grain yield, (d) pooled data for ET_a , (e) pooled data for irrigation, and (f) pooled data for grain yield.

IRRIGATION WATER USE EFFICIENCY (IWUE)

IWUE ranged from 3.63 to 5.9 kg m⁻³ with an average of 4.87 kg m⁻³ in 2009, and from 2.52 to 3.24 kg m⁻³ averaging 2.97 kg m⁻³ in 2010 (table 4). The IWUE was larger in 2009 than in 2010 due to less rainfall in 2009, as the crop yield response to irrigation is always larger in drier years than in wet conditions. IWUE clearly had much larger interannual variability as compared with CWUE, with much larger IWUE values occurring over the entire range in 2009 as compared with 2010 (fig. 7). Hence, the greater positive impact of irrigation in 2009 (a drier year) as compared with 2010 (both quantity and distribution of rainfall were more favorable) is clearly visible in figure 7. The peak IWUE occurred at about 570 and 630 mm ET_a in 2009 and 2010, respectively (about the same ET_a as for CWUE), at about 85 and 100 mm irrigation in 2009 and 2010, respectively (at somewhat less irrigation as compared with CWUE), and at approximately 1425 and 1450 g m⁻² grain yield in 2009 and 2010, respectively (also less grain yield as compared with CWUE). The IWUE decreased quadratically with seasonal ET_a ($R^2 = 0.99$) (fig. 7a), irrigation amounts ($R^2 = 0.99$) (fig. 7b), and grain yield ($R^2 = 0.83$) (fig. 7c) in 2009. Overall, there was a gradual increase in IWUE with decreasing irrigation and ET_a in 2009. The increase in IWUE

with ET_a , applied irrigation, and grain yield up to a certain threshold in 2010 (fig. 7) implies a full use of the applied water and perhaps a tendency to promote deeper soil water extraction to make better use of both the stored soil water and growing season rainfall (Howell, 2001). Our results are similar to the results of other studies, but caution needs to be taken when results of different studies are compared because of the various expressions of IWUE used by different researchers. In some cases, IWUE is calculated as the ratio of grain yield to seasonal irrigation amount, and this procedure incorporates the productivity of rainfed yields from the rainfall and stored soil water. This may be useful in environments where the rainfed yield is expected to be zero (i.e., semi-arid and arid) and where the potential for deep percolation and/or surface runoff is minimal. Based on the irrigation water productivity equation used in the calculations, the results of this study are somewhat large in 2009 as compared with the results reported by Yazar et al. (1999), but the values obtained in 2010 are in close agreement with their results (2.13 to 3.69 kg m⁻³), as were the results of Howell et al. (1995), who showed decreasing IWUE with increasing seasonal irrigation. Zhang et al. (2004) reported reduced IWUE under full irrigation and concluded that it is feasible to reduce irrigation amount in a

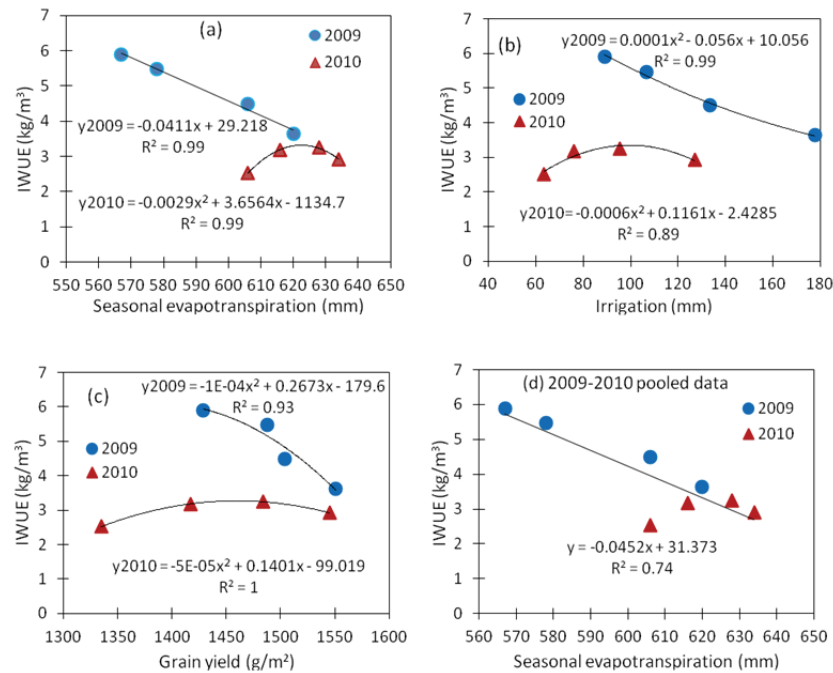


Figure 7. Relationship between irrigation water use efficiency (IWUE) vs. (a) seasonal evapotranspiration, (b) seasonal irrigation, (c) grain yield, and (d) pooled data for seasonal evapotranspiration.

certain growing stage of maize to maximize the irrigation water productivity. Zhang et al. (2004) reported IWUE of 3.44 kg m^{-3} , and Howell (2001) reported that the IWUE is consistent with irrigation methods, i.e., surface (level basins), low-energy precision application (LEPA), subsurface drip, and surface drip, and its values ranged from 1.73 to 2.58 kg m^{-3} . Evett et al. (2006) reported a quadratic increase of IWUE with declining irrigation amounts, and their IWUE values ranged from 2.0 to 4.5 kg m^{-3} .

The IWUE is strongly related to climatic variability (i.e., the severity of the hot and dry weather), which causes interannual variability of rainfed yields. Therefore, a larger IWUE value may indicate drier years, when irrigation has a larger impact on maize yield than in wet years. While the IWUE term is more commonly used because of its simplicity and because it does not involve the challenging task of determining ET_a , it may not reflect a complete assessment of water productivity. This is because: (1) not all irrigation water applied to the field is used for ET_a , as some water may be lost to deep percolation and/or runoff, and (2) stored soil water at planting and rainfall from planting to maturity also contribute to ET_a (Irmak et al., 2011). Therefore, the IWUE varies more substantially between years than the CWUE as a function of rainfall and irrigation management practices. Thus, the CWUE, and especially the ETWUE, are additional terms that can be used when quantifying the efficiency of a crop production system because they directly reflect the amount of grain yield produced per amount of water used, rather than per depth of water applied. In the use of IWUE, especially in subhumid, humid, and semiarid areas, the rainfed amounts should be accounted for to more accurately reflect the impact of irrigation on crop water productivity.

EVAPOTRANSPIRATION WATER USE EFFICIENCY (ETWUE)

While the ETWUE requires the difficult task of measuring yield and ET_a for both irrigated and rainfed settings, it accounts for the management components that IWUE and CWUE do not account for, and it can be a better performance indicator of crop water productivity. As previously mentioned, the primary difference between the CWUE and ETWUE is that the ETWUE is a measure of the impact of irrigation in potentially increasing the crop water productivity relative to the rainfed production. Maize ETWUE values for the two growing seasons are presented in table 4 and figure 8. The ETWUE ranged from 4.65 kg m^{-3} for the FIT to 6.09 kg m^{-3} for the 50% FIT in 2009. In 2009, the ETWUE averaged 5.4 kg m^{-3} across all treatments, while the average of CWUE across all treatments was 4.9 kg m^{-3} . Peak ETWUE occurred at or nearly at the same ET_a , irrigation, and grain yield values as for CWUE in both 2009 and 2010 (fig. 8). The only exception might be that in 2009, peak ETWUE occurred at a grain yield of 1425 g m^{-2} (instead of 1500 g m^{-2} for CWUE). The 2009 ETWUE was inversely related to ET_a , irrigation, and grain yield, which would have also been the case for CWUE in figure 6 if the rainfed data were excluded from the regressions. Similarly, the 2009 IWUE was also inversely related to each respective variable. The ETWUE and CWUE were both directly related to each respective variable in 2010. The interannual variability of ETWUE was reversed, as compared with CWUE and IWUE, in that the 2010 ETWUE values were larger than the 2009 values. The average values of ETWUE and CWUE across all treatments in 2010 were 6.4 and 3.9 kg m^{-3} , respectively. The ETWUE was larger than the CWUE for all treatments in both years due to smaller ET_a differences between the rainfed and irrigated treatments, resulting in a smaller denominator in equation 3

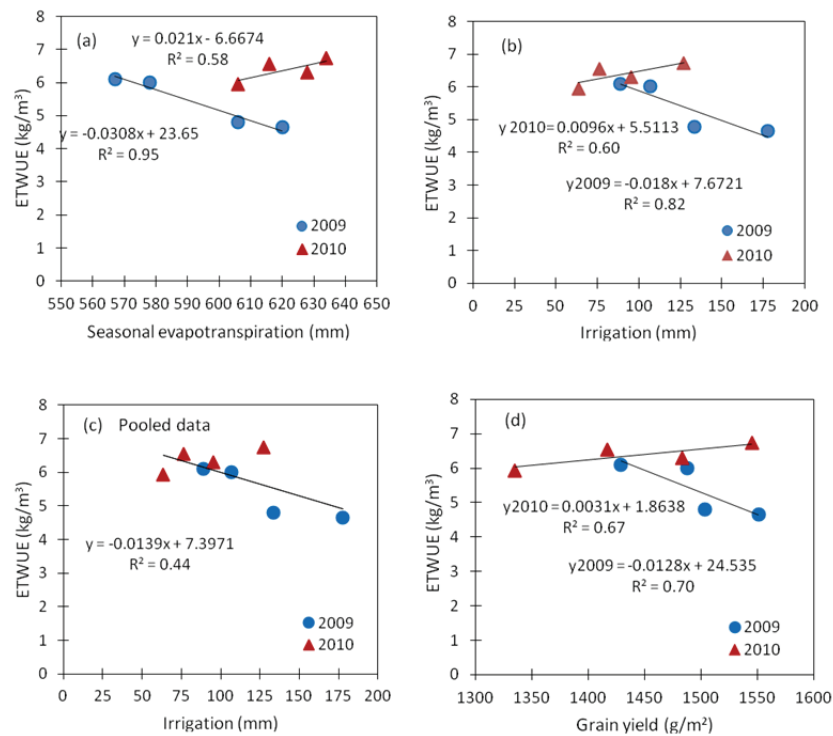


Figure 8. Relationship between maize evapotranspiration water use efficiency (ETWUE) vs. (a) seasonal evapotranspiration, (b) seasonal irrigation, (c) pooled data for seasonal irrigation, and (d) grain yield.

(i.e., 139 mm ET_a difference between the rainfed and FIT in 2009, and 55 mm ET_a difference in 2010), and ranged from 5.94 kg m⁻³ for the 50% FIT to 6.73 kg m⁻³ for the FIT. Figure 8 indicates a linear decrease of ETWUE with ET_a ($R^2 = 0.95$), irrigation amount ($R^2 = 0.82$), and grain yield ($R^2 = 0.70$) in 2009, while the ETWUE increased linearly with ET_a ($R^2 = 0.58$), irrigation ($R^2 = 0.60$), and grain yield ($R^2 = 0.67$) in 2010. On a two-year average, ETWUE decreased with increasing irrigation amount. The relationships between ETWUE and seasonal evapotranspiration, irrigation, and grain yield were mainly controlled by the rainfed treatment's seasonal evapotranspiration and yield. The ETWUE was largest when the ET_a was about 570 mm in 2009 and about 634 mm in 2010, indicating that in these experimental, climate, and management conditions, the maximum ETWUE can be obtained at ET_a values smaller than those for the fully irrigated treatment during a dry year such as 2009, making the 60% FIT and 75% FIT viable limited irrigation practices under these experimental conditions.

The results of this study are in agreement, generally, with those reported by Howell (2001), who stated that generally ETWUE was largest with less irrigation. However, they are much larger than results of Pejić et al. (2011), who reported maize ETWUE values that varied from 0.67 to 2.34 kg m⁻³, and Howell et al. (1997), who reported ETWUE values ranging from 1.79 to 2.38 kg m⁻³. Mishra et al. (2001) reported maize ETWUE of 1.58 kg m⁻³ in India, where the largest grain yield during their experimentation was 5.14 Mg ha⁻¹. The ETWUE mostly depends on precipitation amount and distribution and establishes whether or not the growing period is favorable for plant production

(Pejić et al., 2012). Howell (2001) indicated that ETWUE generally is largest with less irrigation, implying full use of the applied water and perhaps a tendency to promote deeper soil water extraction to make better use of both stored soil water and growing season rainfall. Irrigating at 50% and 65% depletion before anthesis (averaged over post-anthesis irrigation frequencies) resulted in the largest ETWUE for sweet sorghum [*Sorghum bicolor* (L.) Moench] biomass yield over the 35% depletion (Miller and Ottman, 2010). Mukherjee et al. (2012) reported the largest ETWUE for the least irrigated tomato. However, the largest ETWUE values were reported for fully irrigated onion (*Allium cepa* L.) (Sarkar et al., 2008), rajmash (*Phaseolus vulgaris* L.) (Kundu et al., 2008), and winter wheat (*Triticum* spp.) (Sun et al., 2006) as compared with the deficit-irrigated respective treatments because deficit irrigation allowed greater use of soil water and rainfall, thereby increasing the ETWUE and the IWUE.

SUMMARY AND CONCLUSIONS

The soil water depletion for each layer and seasonal total soil water extraction patterns from the entire root zone (0–1.8 m) for fully irrigated, limited-irrigation, and rainfed maize production were quantified. The relationships between maize crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE) vs. crop evapotranspiration (ET_a), irrigation amount, and grain yields were developed under south central Nebraska soil, climate, and management conditions through extensive field campaigns conducted in 2009 and 2010. Four irrigation regimes (fully irrigated

treatment (FIT), 75% FIT, 60% FIT, and 50% FIT) and a rainfed treatment were studied. The seasonal rainfall was 426 mm (18% below normal) in 2009 and 563 mm (9% above normal) in 2010. Irrigation regime impacted soil water extraction pattern, which increased with applied irrigation. In general, the soil water depletion decreased with soil depth. Under all water supply conditions, water extraction from the top soil (0-0.30 m) accounted for the largest portion of the total water extraction as 39%, 42%, 48%, 48%, and 51% of the seasonal total extraction under the rainfed, 50% FIT, 60% FIT, 75% FIT, and FIT treatments, respectively, due to a combination of soil evaporation and the presence of more root density in the top layer. The top layer water extraction was usually followed by extraction from the 0.60-1.2 m soil layer, where the rainfed treatment extracted more water than the irrigated treatments. The deepest soil layer (1.5-1.8 m) contributed about 5% to 8% to the seasonal total water extraction.

The CWUE had a quadratic relationship with irrigation amounts. The IWUE and ETWUE decreased with the irrigation amount during the 2009 growing season, and both were less sensitive to irrigation in 2010 as a result of greater amounts and better distribution of rainfall. On average, the 60% FIT resulted in the largest IWUE of 4.33 kg m^{-3} . In 2009, all the irrigated treatments had very similar CWUE values, which averaged 2.52 kg m^{-3} with different ET_a , indicating a diminishing return in which the CWUE did not respond or increase beyond a certain threshold value of ET_a . This threshold value was found to be approximately 580 mm, and it corresponds to the 60% FIT. The rainfed treatment had similar CWUE values in 2009 (1.89 kg m^{-3}) and 2010 (2.03 kg m^{-3}) with substantially different ET_a (481 mm in 2009 and 579 mm in 2010). The ETWUE values were 6.09, 6.01, 4.79, and 4.65 kg m^{-3} in 2009 and 5.94, 6.55, 6.31, and 6.73 kg m^{-3} in 2010 for the 50%, 60%, 75%, and FIT, respectively. The 60% FIT had greater CWUE and ETWUE than the FIT in 2009. The difference in ET_a corresponding to the greatest ETWUE during the two growing seasons indicates that in these experimental, climate, and management conditions, the maximum ETWUE and crop water productivity can be obtained at the ET_a values smaller than its maximum value measured with the FIT. The rainfed ET_a and its yield drastically influenced ETWUE and IWUE, which were more reduced as the in-season drought increased. The 60% and 75% FIT treatments had yields that were comparable to the fully irrigated treatment and were found to be viable supplemental irrigation strategies for increasing crop water productivity of maize while using 40% or 25% less irrigation water under these experimental, soil and crop management, and climatic conditions. Maximizing either CWUE, IWUE, or ETWUE may be the primary goal for maximizing the crop water productivity for irrigated maize in locations that have conditions of climate, soil, and crop management similar to south central Nebraska.

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