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Optimizing preplant irrigation for maize under limited water in the High Plains

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ABSTRACT

Due to inadequate irrigation capacity, some farmers in the United States High Plains apply preplant irrigation to buffer the crop between irrigation events during the cropping season. The purpose of the study was to determine preplant irrigation amount and irrigation capacity combinations that optimize yield, water productivity, and precipitation use efficiency (PUE) and minimize soil water evaporation losses prior to planting. The CERES-Maize model embedded in the RZWQM2 model in combination with long-term climatic data from 1986 to 2014 for southwest Kansas were used for this research.

Experimental data from 2006 to 2009 was used to calibrate and validate the model. Model performance was satisfactory with high index of agreement (IA > 0.88). Relative root mean square error (RRMSE) ranged between 4.5% and 27%. Under very limited irrigation capacity (2.5 mm/day), applying 75–100 mm of preplant irrigation produced median yields that were 10–17% higher than not applying preplant irrigation. However, even at limited irrigation capacity the benefit of preplant irrigation were only realized if the seasonal yield potential was in the range of 6000 to 10,000 kg/ha corresponding to years with normal seasonal rainfall. Irrigation capacity had a stronger effect on maize grain yield compared to preplant irrigation amount. Preplant irrigation increased ET and transpiration under 2.5 mm/day irrigation capacity. Preplant irrigation amount did not have a substantial impact on water productivity at high and moderate irrigation capacity but had second order dominant effect under limited irrigation capacity. At low irrigation capacity (2.5 mm/day) increasing preplant irrigation increased median PUE up to 18% although the effect was second order dominant. Negligible water losses through deep percolation from 2.4 m soil profile were simulated. Increasing preplant irrigation resulted in significantly higher soil water evaporation losses prior to planting at all irrigation capacities. Overall preplant irrigation is beneficial under very limited irrigation capacity but is not necessary under sufficient irrigation capacity in most years. The decision to apply preplant irrigation should be evaluated and implemented carefully in combination with other agricultural water management technologies and strategies such as soil water monitoring, drip irrigation, and residue management.

1. Introduction

In the U. S. south and central High Plains, groundwater levels in the Ogallala aquifer are declining due to water withdrawals for irrigation exceeding average annual recharge (McGuire, 2004). This results in diminished well capacities that eventually became incapable of meeting full crop water needs during the summer growing season. For this reason, some irrigators on fine and medium textured soils apply preplant irrigation from groundwater to ensure that the soil profile has adequate water before planting to help their low irrigation capacity systems to better keep up with the crop water needs during the growing season. Preplant irrigation (also known as preseason, dormant season, off-season, or winter irrigation) is a water management strategy in which water is applied prior to or several months before planting. This practice is common to the U.S. South and Central High Plains (including areas in western Kansas, eastern Colorado and the panhandles of Texas and Oklahoma) as previously reported by Stone et al. (1994). Surveys conducted in western Kansas in the later part of the 20th

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Table 1
Preplant and growing season irrigation and growing season precipitation for a field study from 2006 to 2009 at Kansas State University Southwest Research-Extension Center near Tribune, Kansas (Schlegel et al., 2012).

Year	Preplant irrigation (mm)	Growing season irrigation (mm)			Growing season precipitation (mm)
		2.5[a] (mm/day)	3.8 (mm/day)	5 (mm/day)	
2006	76	243	320	483	176
2007	76	183	257	397	205
2008	76	209	278	375	238
2009	76	225	299	453	364

[a] Irrigation capacity.

century indicated over 60% of respondents used some form of preplant irrigation (Kromm and White, 1990). Recent droughts of 2011 and 2012 coupled with declining well capacities have stimulated interest again in preplant irrigation.

The major question for the producers is: when should preplant irrigation be used or when is it beneficial? Also, what is the best way to implement preplant irrigation in order to minimize nonproductive water losses that make this practice inefficient? Optimum preplant irrigation strategies target minimizing soil water evaporation, enhancing precipitation capture and storage and eliminating deep drainage. Preplant irrigation water is lost through two major processes; deep drainage and soil water evaporation. In wet years preplant irrigation might also use up storage that would have been used by spring rainfall which reduces rainfall storage efficiency. Stone et al. (2008) simulated efficiency of preplant irrigation and reported that available water in the soil at the time of the preplant irrigation application had the greatest effect on storage efficiency, which decreased dramatically when available water was greater than 60%. Stone et al. (2008) also reported that preplant irrigations made in the early spring were more efficient compared to irrigation made in the fall. Soil water during the off season is influenced by soil water at harvest which in turn is influenced by irrigation scheduling during the growing season. Given the significant effect of soil water on efficiency of preplant irrigation, a need exists for dynamic site specific decision support tools that can be used for predicting soil water over time and space and to assess need for and effect of preplant irrigation on soil water evaporation, transpiration, deep drainage, crop yield, and water productivity. Such a decision support tool can be developed from whole system agricultural models.

Whole system models integrate the physical, biological and chemical processes of an agricultural system and are very useful for extrapolating field research to different soils, climate and management, technology transfer and decision making (Ahuja et al., 2000). The need for such models and decision support tools will increase as farmers and other stakeholders demand quick transfer of research results in an integrated and usable form for site specific management. Calibrated and validated cropping systems models are an example of whole system agricultural decision support tools. Performance of these decision support tools can be enhanced by integrating them with field measurements such as soil water feedbacks. Examples of cropping systems models that can be used in assessing need and potential benefits of preplant irrigation include RZWQM2 (Ahuja et al., 2000), DSSAT-CSM (Hoogenboom et al., 2015), WOFOST (Van Diepen et al., 1989), APSIM (Keating et al., 2003), and AquaCrop (Raes et al., 2009) Agricultural systems models have been successfully applied in assessing irrigation management in the U.S. Great Plains (Saseendran et al., 2008; DeJonge et al., 2012; Ma et al., 2012; Kisekka et al., 2016a,b).

In this paper, the RZWQM2 (Root Zone Water Quality Model) was selected for the following reasons: 1) process oriented, dynamic, and simulates the impact of agricultural management practices such as tillage, residue management, irrigation, and fertility on soil water, crop production, and water quality (Ahuja et al., 2000), 2) DSSAT v4.0 has been embedded into RZWQM2 which provides a suite of detailed biophysical crop models for simulating crop growth and development (Ma et al., 2006), 3) RZWQM2 has advanced features for assessing limited irrigation strategies such as water allocation limits by period, irrigation scheduling based on ET or soil water deficit, and 4) an automatic optimization algorithm called PEST (Doherty, 2009) has also been embedded into RZWQM2 to facilitate parameter estimation which allows for reproducible and objective model calibrations.

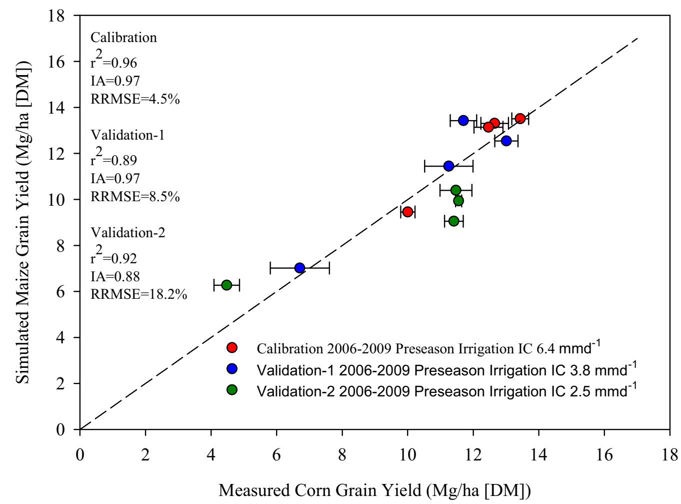

Fig. 1. Comparing simulated to measured maize grain yield in a preplant irrigation study that was conducted at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas, IC refers to irrigation capacity, IA is index of agreement and RRMSE is the relative root mean square.

The purpose of the study was to determine preplant irrigation amount and irrigation capacity combinations that optimize yield, water productivity, and precipitation use efficiency (PUE) and minimize soil water evaporation losses prior to planting. The research involved combining short term experimental data with long-term historic climatic data (1986–2014), and crop simulation modeling to determine optimum preplant irrigation water management in the United States High Plains.

2. Materials and methods

2.1. Experimental data

A field experiment was conducted at the Kansas State University Southwest Research-Extension Center near Tribune Kansas (38.5°N, 101.7°W, and 1086 m above sea level) from 2006 to 2009. The soil at the study site is a deep well drained Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustolls). The climate of the study site is semi-arid with mean annual precipitation of 440 mm and mean annual evapotranspiration of 1943 mm (1986–2014). The growing season precipitation from 2006 to 2009 is given in Table 1. The experimental design was a factorial with preplant irrigation (0 and 76 mm), irrigation capacity (2.5, 3.8 and 5.0 mm/day)

Table 2
Soil and plant parameters for simulating soil water flow and maize growth and development in RZWQM-DSSAT at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas.

Name	Description	Layer	Initial value	Lower bound	Upper bound	PEST[a] optimized value
		1	1.32	1	2	1.37
		2	1.32	1	2	1.32
		3	1.32	1	2	1.28
		4	1.32	1	2	1.28
	Bulk Density (g/cm3)	5	1.32	1	2	1.32
		6	1.32	1	2	1.32
		7	1.32	1	2	1.29
		8	1.32	1	2	1.32
Ks	Saturated Hydraulic Conductivity (cmh^{-1})	1	1.57	1	20	1.56
		2	3.24	1	20	3.23
		3	2.53	1	20	2.52
		4	1.00	1	20	1.00
		5	1.98	1	20	1.98
		6	3.51	1	20	3.49
		7	1.44	1	20	1.43
		8	1.82	1	20	1.82
$\theta_{1/3bar}$	Volumetric Soil Water Content at 1/3 bar ($cm^3\,cm^{-3}$)	1	0.33	0.28	0.38	0.34
		2	0.34	0.29	0.39	0.34
		3	0.30	0.26	0.35	0.29
		4	0.30	0.25	0.34	0.29
		5	0.33	0.28	0.38	0.32
		6	0.34	0.29	0.39	0.33
		7	0.24	0.20	0.28	0.24
		8	0.23	0.20	0.27	0.23
θ_{15bar}	Volumetric Soil Water Content at 1/3 bar ($cm^3\,cm^{-3}$)	1	0.16	0.13	0.18	0.16
		2	0.09	0.08	0.11	0.09
		3	0.15	0.13	0.18	0.16
		4	0.13	0.11	0.15	0.13
		5	0.14	0.12	0.16	0.14
		6	0.11	0.10	0.13	0.11
		7	0.14	0.12	0.16	0.14
		8	0.16	0.13	0.18	0.16
P1	Thermal time from seedling emergence to the end of Juvenile (degree days)		200.00	100.00	450.00	205.0
P2	Extent to which development is delayed due to increase in photoperiod		0.70	0.01	2.0	0.70
P5	Thermal time from silking to physiological maturity (Degree Days)		900.00	600	1000	867.0
G2	Maximum possible number of kernels per plant		516	440	1000	531.0
G3	Grain filling rate during the linear grain filling stage ($mgday^{-1}$)		12	5	16	12.5
PHINT	Phyllochron interval (degree days)		38.9	25	55	41.0

[a] Parameter Estimation algorithm.

and seeding rate (80,000 plants/ha) replicated four times. Experimental plots were 36 m long by 18 m wide with irrigation as the main plot factor and seeding rate as subplots (3 × 36 m) with maize row spacing of 76.2 cm. Standard practices for maize production in the region were followed including preplant application of 269 kg N ha^{-1} as urea-ammonium nitrate (the model developed based on this experimental data was not calibrated for nitrogen). The full season maize hybrids used were 33B53 in 2006, Pioneer 33B54 in 2007, Pioneer 34B99 in 2008, and Pioneer 34B94 in 2009. Maize was planted on 01/May/2006, 10/May/2007, 26/Apr/2008, and 06/May/2009. Two middle rows of each plot were mechanically harvested. For model calibration and validation only experimental data corresponding to the 80,000 plants/ha seeding rates was used. Total irrigation applications are summarized in Table 1. Details and results from the field study are reported in Schlegel et al. (2012). Irrigation was done using a linear move system modified to apply irrigation based on different treatment combinations. Preplant irrigation was applied in two events of 38 mm several days apart in early spring (April). In-season irrigations were initiated from late May to early September. In-season irrigation was scheduled as follows 35 mm weekly, 25 mm weekly and 35 mm bi-weekly for the 5.0, 3.8 and 2.5 mm/day irrigation capacities respectively. In case of sufficient rainfall, a scheduled irrigation was postponed. Soil water was measured using neutron attenuation with a field calibrated neutron probe. Seasonal crop water use (ETc) was esti-

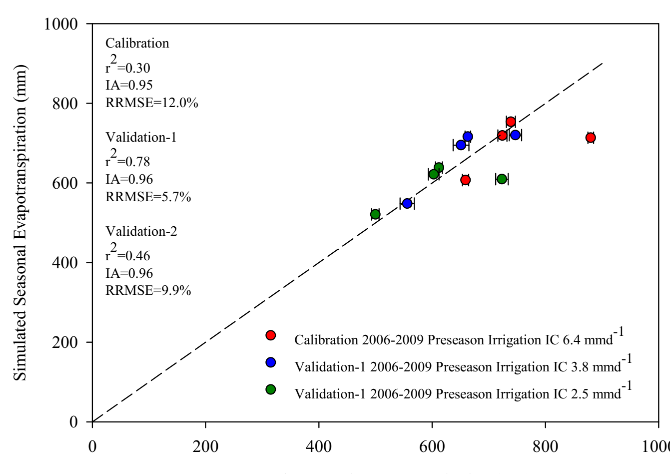

Fig. 2. Comparing simulated to measured seasonal evapotranspiration in a preplant irrigation study that was conducted at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas, IC refers to irrigation capacity, IA is index of agreement and RRMSE is the relative root mean square.

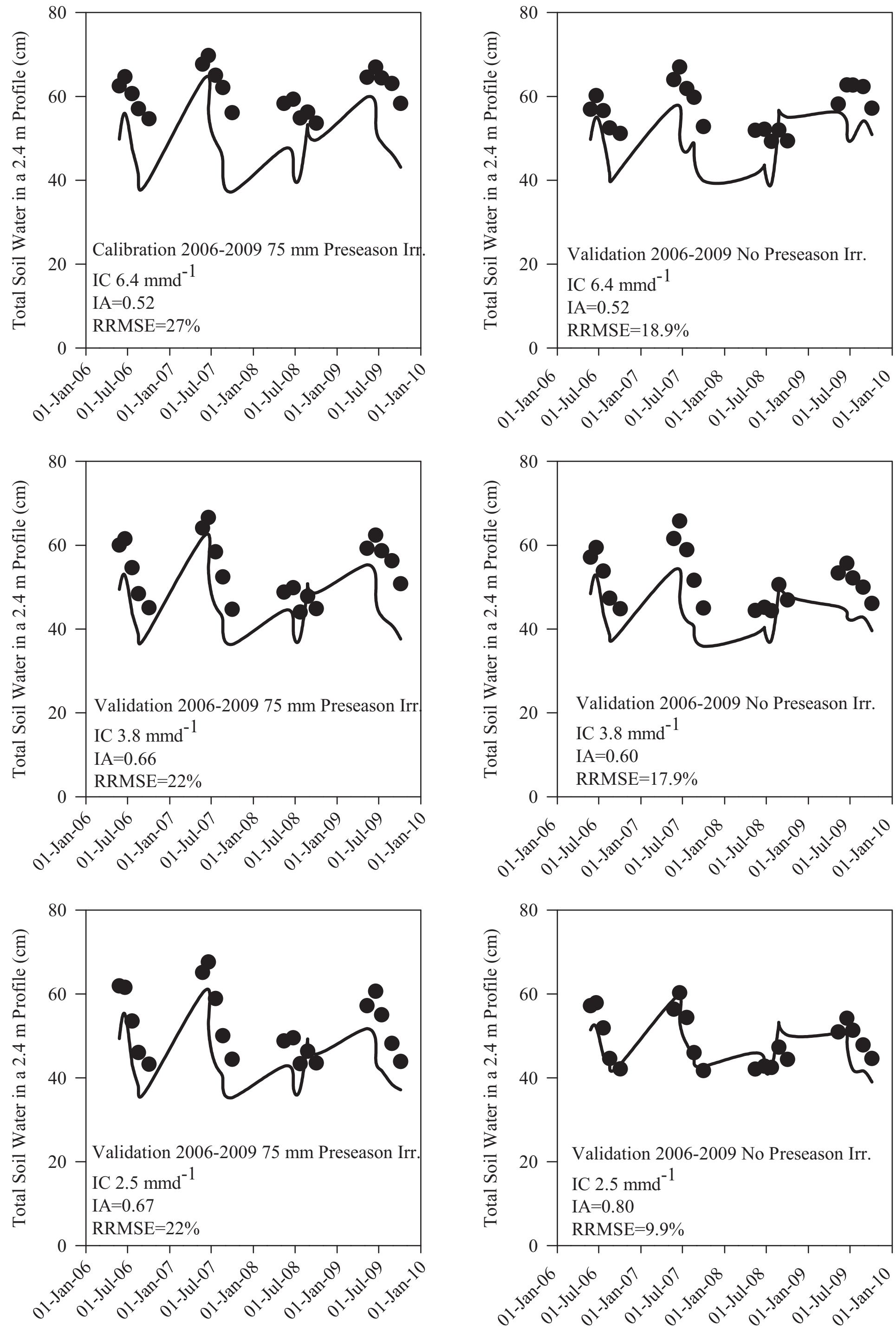

Fig. 3. Simulated and measured total soil profile soil water in a preplant irrigation study that was conducted at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas, IC refers to irrigation capacity.

mated from a soil water balance as reported in Schlegel et al. (2012).

2.2. Model description

The RZWQM2 model (version 3.0) with embedded DSSAT-CSM CERES-Maize 4.0 crop growth module was used in this study (Ma et al., 2012). In RZWQM2, unsaturated soil water flow and redistribution was modeled using a one dimensional Richards's equation. The potential evaporation and transpiration demand of the atmosphere were computed using the Shuttleworth–Wallace ET model (Ahuja et al., 2000). The Shuttleworth–Wallace ET model in RZWQM2 is an extension of the Penman-Monteith ET model but the former takes into account incomplete canopy cover and plant height in potential evaporation and transpiration estimations. Actual root water uptake described by the sink term in Richards's equation was calculated numerically using the Nimah and Hanks (1973) procedure. Actual root water uptake, potential evaporation and potential transpiration were used in computing water stress factors used in CERES-Maize to modulate plant growth process like leaf growth as soil water gets depleted. The CERES-Maize model embedded in RZWQM2 is a radiation-based mechanistic crop model that predicted maize growth and development based on weather (precipitation, solar radiation, maximum and minimum temperature, to a lesser extent photoperiod); 6 cultivar/genetic coefficients (P1, P2, P5, G2, G3, and PHINT [as defined in Table 2]); and management practices (plant population, row spacing, planting date, and irrigation management) as described in Jones et al. (2003). More details about the RZWQM can be found in Ahuja et al. (2000).

2.3. Calibration and validation

Meteorological data was obtained from a weather station located near the study site and data accessed through the High Plains Regional Climate Center (http://www.hprcc.unl.edu/). The soil profile was set to 2.4 m comprising of eight layers 30 cm thick. Soil texture measured at the site was 12% sand, 63% silt, 25% clay within typical ranges of a Ulysses silt loam soil. Initial values and range of saturated hydraulic conductivity were obtained from the NRCS's Web Soil Survey for Ulysses silt loam soil. Initial values of cultivar coefficients were taken from one of the maize hybrids (7000 maize IB0031 PIO 3475) in the DSSAT-CSM database that produced close predictions to measured data during initial manual calibration. In this study, the treatment that received highest irrigation (75 mm preplant irrigation and 5 mm/day irrigation capacity) for each of the four years 2006–2009 was used for model calibration. The rest of the treatments (irrigation capacity of 3.8 and 2.5 mm/day with and without preplant irrigation) were used for model validation using data from 2006 to 2009 (Schlegel et al., 2012). One third of the data was used for calibration and the remaining two thirds were used for validation.

Following initial manual calibration of cultivar coefficients, all soil and plant parameters (P1, P2, P5, G2, G3, and PHINT), soil properties (bulk density, vertical *Ks*), and soil water capacity ($\theta_{1/3}$ and θ_{15}) were fitted using a gradient-based parameter optimization algorithm (PEST) embedded in the RZWQM2 model (Doherty, 2009). Default values for parameters related to carbon and nitrogen cycle processes were used. Parameter bounds in Table 2 were used to constrain automatic parameter estimation by PEST to ranges that were physically meaningfully for the study site based on expert knowledge. Parameters were log transformed to improve linearity to ensure the objective function was efficiently minimized. PEST Regularization was also used to minimize model overfitting. Following PEST optimization, the model was executed with uncertainty (with the best 26 parameter sets) to determine the parameter set that produced the least RMSE following similar procedures as reported in (Malone et al., 2010).

The model was executed continuously from January 1st, 2006 to December 31st, 2009 for each treatment. Observed grain yield, and seasonal crop water use (ET) were used to fit model parameters. Precise dates of critical growth stages were not recorded during the study but tasseling and physiological maturity are generally observed to occur in mid-July and late September respectively (Kisekka et al., 2016a,b). Initial soil water at planting was measured during the study. Model validation was done by comparing measured grain yield, seasonal ET and soil water to predicted values. The statistical goodness-of-fit indicators used in this study included Relative Root Mean Square Error (RRMSE), index of agreement (IA) and Relative Error.

2.4. Model application

The calibrated and validated model was applied to assess the effect of five preplant irrigation amounts (0, 25, 50, 75, 100%) applied in late spring between April 1st to 30th of each year on grain yield, ET, soil water evaporation, and precipitation use efficiency. This analysis was repeated for three irrigation capacities (2.5, 3.8, and 6.4 mm/day) over 29 years of historical weather data from January 1st, 1986 to December 31st, 2014. The model was continuously executed for the 29 years. Initial soil water on January 1st, 1986 was set to field capacity in the top 1.2 m of the soil profile and 60% of field capacity in the deeper profile up to 2.4 m. Planting was set to occur during the first week of May each year at a seeding rating of 80,000 seeds/ha. Nitrogen fertilizer was applied at a rate of 269 kg N ha^{-1} as urea-ammonium nitrate each year as pre-plant. Preplant and in-season irrigation were triggered whenever the soil water reached a defined threshold (60% of plant available water) and each irrigation application was limited to 25 mm. Frequency of irrigation was limited by irrigation capacity. Simulated maize yield was adjusted to 15.5% nominal moisture content to match nominal moisture content of measured yields.

2.5. Determining optimum preplant irrigation management strategies

The most efficient/optimum preplant irrigation management strategy was determined by evaluating two criteria including the mean-Gini dominance (MGD), and Stochastic Dominance Analysis (SD) (Tsuji et al., 1998; Kisekka et al., 2016a,b). The MGD decision criteria states that for example if two risky preplant irrigation management strategies A and B have the following characteristics, as shown in equation 1, then A is the more efficient of the two strategies:

$$E(A) \geq E(B) \\ \text{and} E(A) - G(A) \geq E(B) - G(B) \tag{1}$$

where E(.) is the expected value and G(.) is Gini-mean difference of distributions A and B.

The MGD decision criteria approach assumes that the decision maker is averse to risk and helps to avoid risky strategies. The Gini-mean difference in equation 1 is a function of Gini coefficient a measure of statistical dispersion. Gini coefficient is computed as half of the Gini-mean difference expressed as in equation 2 for unordered data following Dixon et al. (1987):

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}|x_i - x_j|}{2n^2\mu} \tag{2}$$

where |xi − xj| is the absolute difference of a randomly selected pair of values of a random variable, and μ is the arithmetic mean. For stochastic dominance analysis as an example, preplant irrigation management strategy A dominates strategy B if cumulative probability density function (CDF) of yield or water productivity gains from A lie to the right of the CDF of B over the entire probability interval 0–1.

3. Results and discussion

3.1. Model calibration and validation

Calibrated parameters for soil physical and hydraulic properties and maize cultivar coefficients are shown in Table 2. These values are within range of those reported by Stone et al. (2011) for Ulysses silt loam soils near Tribune Kansas. Bulk density values in Table 2 are within range of 1.24–1.46 g/cm^3 reported by USDA NRCS in western Kansas (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). Optimized saturated hydraulic conductivity values in Table 2 were also within range of 0.4–5 cm/h that was measured in the USDA NRCS soil surveys. Other studies that

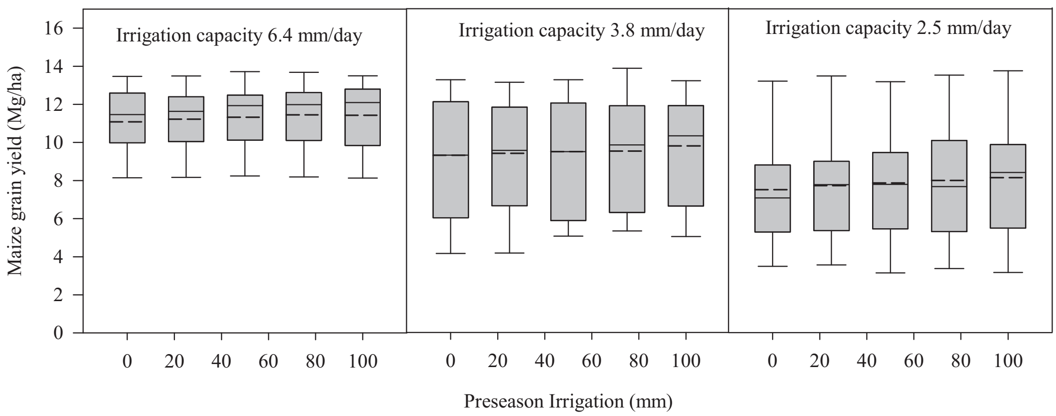

Fig. 4. Simulated maize grain yield under five preplant irrigation amounts and three irrigation capacities using historical weather data from 1986 to 2014 for Tribune, Kansas in a deep silt loam soil (solid line is median and dashed line is mean).

have used inverse modeling and measured soil water to characterize soil physical properties include (Šimůnek and Nimmo, 2005; Muñoz-Carpena et al., 2008; Kisekka et al., 2015).

Maize cultivar coefficients are within range of those reported by Kisekka et al. (2016a,b) for maize hybrids grown in the US Central High Plains. Simulated grain yield from 2006 to 2009 for the treatment with preplant irrigation of 75 mm and irrigation capacity of 6.4 mm/day (well-watered treatment) were in agreement with measured yield (Fig. 1). Although phenology data was not recorded, it was observed that anthesis occurred in mid-July (personal communication) which was in agreement with simulated phenology, which indicated that silking occurred on 07/10/2006, 07/19/2007, 07/12/2008 and 07/13/2009 respectively. Physiological maturity was generally observed to occur in late September although exact dates were not recorded, the corresponding model simulations were September 01, 2006, September 07, 2007, September 10, 2008 and September 12, 2009.

Seasonal ET was well simulated for all treatments with predicted values within 4–8% of the measured seasonal ET as shown by the goodness-fit-indicators in Fig. 2 and Table 3 with the exception of the 75 mm preplant irrigation and 6.4 irrigation capacity treatment in 2009. The ability of the model to predict grain yield and seasonal ET of maize with acceptable accuracy implies that this model could be applied for various assessments including generation of production functions, optimization of preplant irrigation management and strategic irrigation scheduling under deficit irrigation.

Total soil water storage was also well simulated for both the calibration and validation treatments as shown in Fig. 3. However, the model had a tendency to under predict measured total profile soil water. Possible reasons for the discrepancy include uncertainty in conceptualization of unsaturated flow, measurement uncertainty due to heterogeneity in soil conditions e.g., the sensing volume of the neutron attenuation technique decreases as soil water content increases. Ma et al. (2016) also noted the challenge of spatial soil heterogeneity of soil properties in agricultural systems modeling and reported that best results were obtained when crop parameters and soil field capacity were fit simultaneously.

3.2. *Optimizing preplant irrigation amount and irrigation capacity combinations*

In order to determine preplant irrigation amount and irrigation capacity combinations that optimize maize grain yields, water productivity, and precipitation use efficiency (PUE) and minimize soil water evaporation losses the mean-Gini dominance (MGD), and Stochastic Dominance Analysis (SD) analysis techniques were used.

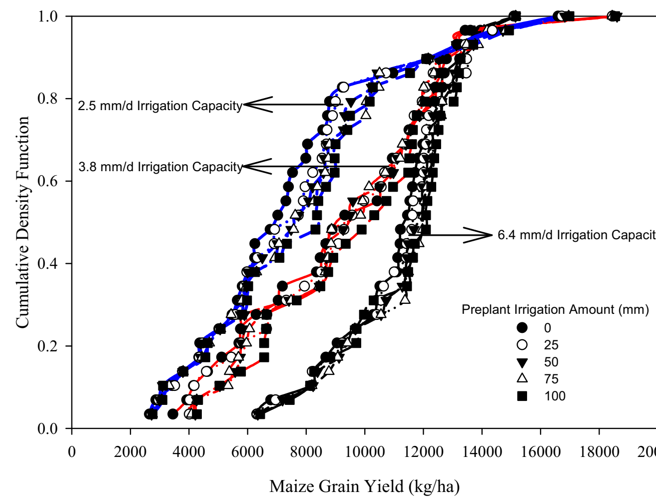

Fig. 5. Cumulative probability density function of maize grain yield for different amounts of preplant irrigation and irrigation capacity simulated using CERES-Maize in RZWQM for climatic data from 1986 to 2014 for Tribune, Kansas.

3.2.1. *Maize grain yield*

At very limited irrigation capacity of 2.5 mm/day, applying 50–100 mm of preplant irrigation produced median yields that were 10–17% higher than not applying preplant irrigation. Increases in yield were small under 3.8 and 6.4 irrigation capacity. It can be seen in Fig. 4 that the upper whiskers of the boxplots were larger under 2.5 mm/day compared to higher irrigation capacities, implying increased variability in high yields as irrigation capacity decreases. At very low irrigation capacity, the crop relies heavily on plant available water at planting that is made available to the crop to between rainfall and irrigation events during the growing season. Under limited irrigation capacity, irrigation might be triggered based on soil water status but the actual irrigation events may not occur. This is particularly common with center pivot systems in the High Plains that take several days to complete one revolution due to diminished well capacity from the Ogallala aquifer.

At low (2.5 mm/day) to moderate (3.8 mm/day) irrigation capacity, applying 100 mm of preplant irrigation was the optimum strategy (Table 5). At high irrigation capacity of 6.4 mm/day, applying 75 mm of preplant irrigation produced the highest expected mean grain yield and highest difference between expected grain yield and Gini mean difference as shown in Table 5.

Stochastic dominance analysis results are shown in Fig. 5 and they confirm results from the MGD analysis. It is shown in Fig. 5 that applying 100 mm of preplant irrigation was dominant at the

Table 3
Maize grain yield and seasonal evapotranspiration validation goodness-of-fit indicators for treatments that did not receive 75 mm of preplant irrigation during a field study conducted at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas and simulations were from CERES-maize in RZWQM2.

Irrigation capacity (mm/day) with no-preplant irrigation	Grain yield			Seasonal evapotranspiration		
	[a]r^2	[b]IA	[c]RRMSE (%)	r^2	IA	RRMSE (%)
6.4	0.64	0.96	9.0	0.32	0.95	10.4
3.8	0.67	0.84	19.9	0.36	0.93	13.0
2.5	0.44	0.60	32.0	0.48	0.94	12.0

[a] Coefficient of determination.
[b] Willmont Index of Agreement.
[c] Relative root mean square error.

Table 4
Mean seasonal transpiration and average number of seasonal irrigation events at different amounts of preplant irrigation simulated using 29 years of historical weather data (1986–2014) and the DSSAT-CSM embedded in the RZWQM2 at Kansas State University Southwest Research-Extension Center near Tribune.

Preplant irrigation amount (mm)	Seasonal Transpiration (mm) Irrigation capacity (mm/day)			Average number of seasonal irrigation events[1] Irrigation capacity (mm/day)		
	6.4	3.8	2.5	6.4	3.8	2.5
0	497 a	497 a	401 a	19	16	12
25	492 a	492 a	408 b	19	15	12
50	492 a	492 a	418 b	18	15	11
75	486 a	486 a	421 c	18	15	11
100	495 a	495 a	430 c	17	14	11

[1] Each irrigation event was 25 mm.

lowest irrigation capacity. However, the dominance of the 100 mm preplant irrigation scenario was second order since its cumulative density function (CDF) was not to the right of all the other CDFs over the entire range of possible yields. Under limited irrigation capacity (2.5 mm/day), preplant irrigation produced higher yields if the yield potential in a given cropping season was in the range of 6000 to 10,000 kg/ha. This corresponded to years with normal growing season (May to October) rainfall of 336 mm. In very wet years and very dry years there was no substantial differences in yields between different preplant irrigation amounts and irrigation capacity combinations. For irrigation capacity of 3.8 and 6.4 mm/day, the benefit from preplant irrigation were not consistent meaning preplant irrigation might not be necessary in most years. It can also be seen from Fig. 5 that there is a 90% chance that increasing irrigation capacity would increase yields since the CDFs of the highest irrigation capacity were to the right of those with lower irrigation capacity. If a producer has a constrained water supply, reducing the total number of irrigated land also termed as concentrating water (Howell et al., 2012) to increase irrigation capacity would increase median yield and also reduce year to year variability in grain yield (Klocke et al., 2015). However, as noted by Howell et al. (2012) concentrating water could reduce income potential in wet years.

3.2.2. Evapotranspiration and water productivity

Fig. 6 also shows that the median ET for all levels of preplant irrigation was higher than the 625 mm on average required to meet full maize water requirements in western Kansas under irrigation capacities of 6.4 and 3.8 mm/day (Stone and Schlegel, 2006). For limited irrigation capacity of 2.5 mm/day, at least 75 mm to 100 mm of preplant irrigation was required to attain median seasonal ET of 625 mm/day or higher. The goal in water limited cropping systems is to maximize ET since it is directly related to biomass production and grain yield (Stewart and Peterson, 2014). Under very limited water scenarios, late spring preplant irrigation can increase seasonal ET but the goal should be to partition more water to transpiration while reducing soil water evaporation to improve water productivity. Fig. 6 also shows that reducing irrigation capacity reduced seasonal ET due to reduced root uptake and transpiration.

Transpiration did not vary substantially at different amounts of preplant irrigation for irrigation capacities of 6.4 and 3.8 mm/day. This implies that extra water could have been lost to soil water evaporation or deep drainage. But results from this study indicated that deep drainage from the 2.4 m soil profile was negligible therefore most of the water was lost to soil water evaporation. However, for very limited irrigation capacity of 2.5 mm/day, median transpiration increased with increase in preplant irrigation amount (Table 4). The results suggest that preplant irrigation is beneficial under very limited irrigation capacities but is not necessary under sufficient irrigation capacity (≥3.8 mm/day).

Optimum preplant irrigation amounts were also analyzed based on water productivity as an indicator of how well water applied before planting was used for grain production. Table 6 shows that preplant irrigation amount did not have a substantial impact on water productivity at high and moderate irrigation capacity of 6.4 and 3.8 mm/day respectively. Stochastic dominance analysis revealed that similar to yield, there is a narrow range (11–15 kg/ha-mm) of water productivity where applying 100 mm preplant irrigation improved water productivity under the 2.5 mm/day irrigation capacity. Results in Fig. 7 also indicate that irrigation capacity has a more dominant effect on water productivity compared to preplant irrigation amounts.

3.2.3. Precipitation use efficiency

Optimum combinations of preplant irrigation amounts and irrigation capacity were also evaluated based on their ability to enhance precipitation capture and storage expressed in form of precipitation use efficiency (PUE). PUE was calculated as a ratio of grain yield to precipitation. The precipitation was summed from harvest of previous year's crop to physical maturity of the crop in the current year (i.e., from October to September). Fig. 8 shows that preplant irrigation had strong effect on PUE at the lowest irrigation capacity. At low irrigation capacity (2.5 mm/day) increasing preplant irrigation increased median PUE up to 18%. This is due to the fact that applying 75–100 mm of preplant irrigation resulted in increased yield compared to the scenario with 0 mm of preplant irrigation at 2.5 mm/day irrigation capacity. A concern with preplant irrigation is to ensure that it does not reduce storage for

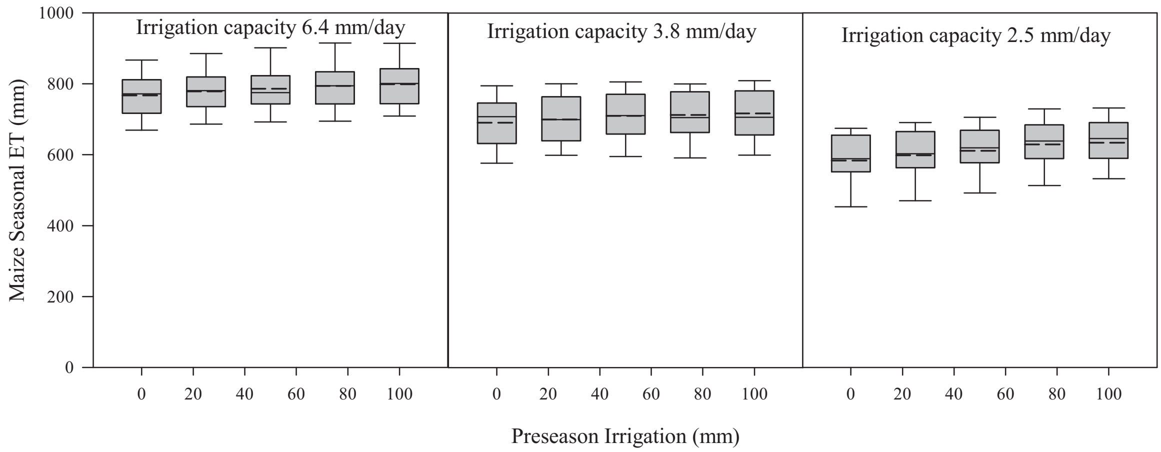

Fig. 6. Simulated seasonal maize evapotranspiration (solid line in boxplot is median and dashed line in mean) under five preplant irrigation amounts and three irrigation capacities using historical weather data from 1986 to 2014 for Tribune, Kansas in a deep silt loam soil.

Table 5
Maize grain yield (kg/ha) for different preplant irrigation amounts and irrigation capacities averaged over 29 years (1986–2014) of weather data at Kansas State University Southwest Research-Extension Center near Tribune, Kansas.

Preplant irrigation (mm)	Irrigation capacity					
	2.5 mm d^{-1}		3.8 mm d^{-1}		5.0 mm d^{-1}	
	$E(x)$	$E(x)$-$G(x)$	$E(x)$	$E(x)$-$G(x)$	$E(x)$	$E(x)$-$G(x)$
	Grain Yield (kg/ha)					
0	7464	3851	9306	5353	11083	8842
25	7675	4020	9407	5659	11225	8950
50	7814	4056	9491	5787	11321	9141
75	7948	4123	9526	5836	11450	9293
100	8098	4229	9798	6228	11424	9174

Table 6
Maize water productivity (kg/ha-mm) for different preplant irrigation amounts and irrigation capacities averaged over 29 years (1986–2014) of weather data at Kansas State University Southwest Research-Extension Center near Tribune, Kansas.

Preplant irrigation (mm)	Irrigation capacity					
	2.5 mm d^{-1}		3.8 mm d^{-1}		5.0 mm d^{-1}	
	$E(x)$	$E(x)$-$G(x)$	$E(x)$	$E(x)$-$G(x)$	$E(x)$	$E(x)$-$G(x)$
	Grain Yield (kg/ha-mm)					
0	12.48	7.45	13.22	8.54	14.45	11.69
25	12.52	7.59	13.25	8.58	14.44	11.38
50	12.49	7.39	13.19	8.77	14.44	11.59
75	12.34	7.20	13.20	8.70	14.47	11.64
100	12.47	7.36	13.52	9.24	14.35	11.28

precipitation, this study shows that if preplant irrigation is applied in late spring in combination with soil water monitoring (irrigation was triggered at 60% plant available in this study) it did not reduce PUE in fact it enhanced PUE at very limited irrigation capacity. It is worth noting from Fig. 8 that at moderate irrigation capacity of 3.8 mm/day preplant irrigation amounts of 100 mm improved PUE at lower levels. No effect of preplant irrigation on PUE at high irrigation capacity of 6.4 mm/day. It can also be seen in Fig. 8 that reducing irrigation capacity by irrigating larger land area compared to available water supply reduced PUE. We recommend that producers match size of irrigated land to available water resources in order to guarantee sufficient irrigation capacity that enhances PUE.

3.2.4. Soil water evaporation losses prior to planting

Water losses due to soil water evaporation prior to planting increased with preplant irrigation amount at all irrigation capacities as shown in Fig. 9. Scenario with 0 mm preplant irrigation had the least soil water evaporation loss prior to planting. Increase in soil water evaporation with preplant irrigation is expected as there would be more water available for the evaporation process. Under sufficient irrigation capacity (≥3.8 mm/day), we recommend no preplant irrigation to minimize soil water evaporation losses. Under limited well capacity we recommend applying at least 75 mm of preplant irrigation in late spring (April) prior to planting. Also, this analysis indicated negligible losses through deep percolation from 2.4 m soil profile indicating the biggest potential water loss from preplant irrigation would be soil water evaporation.

Different irrigation application methods might influence storage efficiency of preplant irrigation. For example, subsurface drip irrigation (SDI) would reduce soil water evaporation losses compared to preplant irrigation done with a sprinkler irrigation system. Mobile Drip Irrigation (MDI) might also reduce soil water evaporation due to reduced surface wetting (Kisekka et al., 2016a,b). Lamm (2002) noted that SDI could be beneficial for applying preplant irrigation to increase seasonal capacity by allowing irrigation to be applied under near freezing temperatures which would not be possible with center pivot irrigation systems. Residue management might also improve the efficiency of preplant irrigation. Irrigators

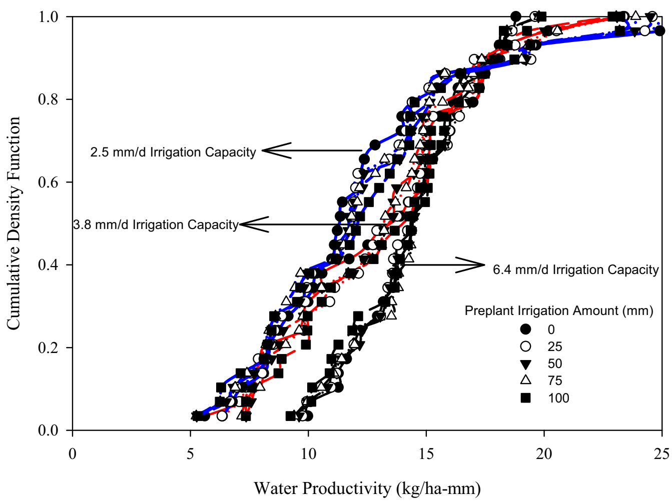

Fig. 7. Cumulative probability density function of maize water productivity for different amounts of preplant irrigation and irrigation capacity simulated using CERES-Maize in RZWQM for climatic data from 1986 to 2014 for Tribune, Kansas.

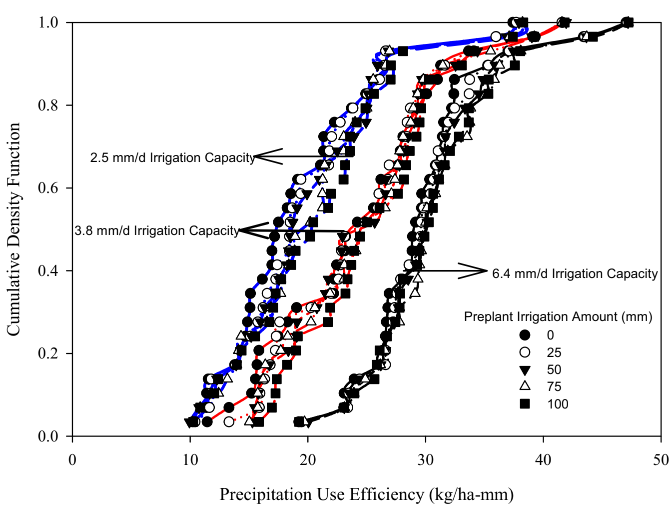

Fig. 8. Cumulative probability density function of precipitation use efficiency (PUE) for different amounts of preplant irrigation and irrigation capacity simulated using CERES-maize in RZWQM for climatic data from 1986 to 2014 for Tribune, Kansas.

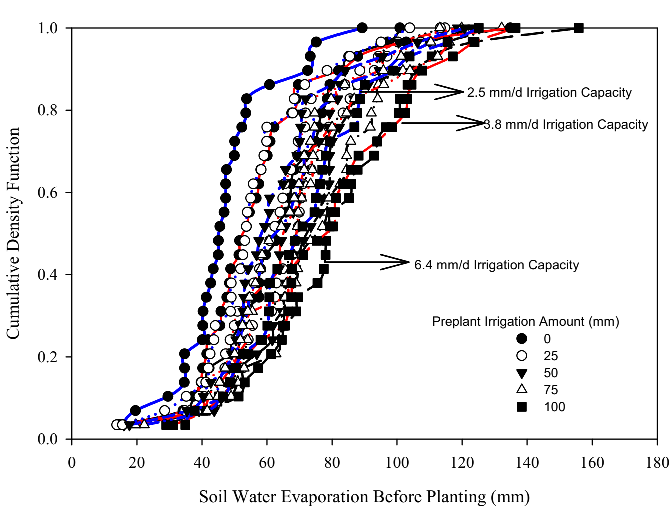

Fig. 9. Cumulative probability density function of soil water evaporation prior to planting in late spring for different amounts of preplant irrigation and irrigation capacity simulated using CERES-maize in RZWQM for climatic data from 1986 to 2014 for Tribune, Kansas.

need to integrate technologies (e.g., soil water sensors) in implementation of preplant irrigation that help reduce water losses due to soil water evaporation and deep drainage but enhances precipitation capture and storage.

Although most of the earlier experimental research (Musick et al., 1971; Stone et al., 1983; Stone et al., 1987; Stone et al., 1994; Stone et al., 2008) showed that preplant irrigation was an inefficient use of water in most years, recent findings by Schlegel et al. (2012) have showed that under very limited well capacity (2.5 mm/day) preplant irrigation increased yield and was profitable. In addition, Ma et al. (2012) noted that preplant irrigation was necessary to ensure good germination in dry years. Musick and Lamm (1990) in their review of preplant irrigation in the South and Central High Plains listed conditions where preplant irrigation would have the best and least benefit, in general these conditions underscored the need to make preplant irrigation decisions based on knowledge of soil water and local rainfall patterns. The approach used in this study helps to build on earlier work by extrapolating short term experimental results to long term climatic conditions to understand effect of preplant irrigation on water limited maize production in the high plains under a wide range of growing conditions.

The decision to apply preplant irrigation should be evaluated carefully since it depends on irrigation capacity and cropping season yield potential. Optimum preplant irrigation for systems with 2.5 mm/day irrigation capacity is 100 mm. No preplant irrigation for systems with 3.8 and 6.4 irrigation capacity is required in most years. Overall, a producer would obtain higher yields, water productivity and PUE by increasing their irrigation capacity by reducing irrigated areas to match limited water supply.

4. Conclusions

A simulation study was conducted to assess the effect of preplant irrigation amounts and irrigation capacities on maize production in western Kansas region of the United States High Plains. The calibrated and validated CERES-maize model embedded in the RZWQM2 adequately predicted yield, ET, and soil water. The calibrated and validated model was applied to assess effect of five preplant irrigation amounts (0, 25, 50, 75 and 100 mm) and three irrigation capacities (2.5, 3.8 and 6.4 mm/day) on maize yield. Under very limited irrigation capacity of 2.5 mm/day, applying 75–100 mm of preplant irrigation produced median yields that were 10–17% higher than not applying preplant irrigation. However, even at limited irrigation capacity the benefit of preplant irrigation were only realized if the seasonal yield potential was in the range of 6000 to 10,000 kg/ha corresponding to years with normal seasonal rainfall. Irrigation capacity had a stronger effect on maize grain yield compared to preplant irrigation amount. Preplant irrigation increased ET and transpiration under 2.5 mm/day irrigation capacity. Preplant irrigation amount did not have a substantial impact on water productivity at high and moderate irrigation capacities but had second order dominant effect under limited irrigation capacity. At low irrigation capacity (2.5 mm/day) increasing preplant irrigation increased median PUE up to 18% although the effect was second order dominant. No effect on PUE at high irrigation capacity. Water losses due to soil water evaporation prior to planting increased with preplant irrigation amount at all irrigation capacities. Under very limited irrigation capacity (≤2.5 mm/day) we recommend applying 75–100 mm of preplant irrigation in late spring (April). No preplant irrigation is recommended at high irrigation capacity to minimize soil water evaporation losses. Deep percolation losses from 2.4 m soil profile were negligible. The decision to apply preplant irrigation should be evaluated and implemented carefully in combination with other agricultural water management technologies and strategies such as soil water monitoring, drip irrigation, and residue management to mitigate negative effects of soil water evaporation and deep drainage.

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