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Maize grain yield and crop water productivity functions in the arid Northwest U.S.

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ABSTRACT

Increased water demands and drought have resulted in the need to provide data to guide deficit water management decisions in irrigated maize (*Zea mays* L.) for grain production. The objective of this study was to develop relationships between maize grain yield and maize water use (ETc, crop evapotranspiration) under low and high nitrogen (N) input systems on a soil type (silt loam) common to maize production in the arid Northwest U.S. The treatments consisted of two N inputs (0 and 246 kg N ha^{-1} $year^{-1}$, -N and +N, respectively) and four water input treatments ranging from 100% to 25% of full irrigation. The full irrigation treatment was 20% less than evapotranspiration model calculated crop use (ETm), indicating that crop coefficient (Kc) values may need to be adjusted for maize in the arid Northwest U.S. There were no grain yield response differences between N input treatments in 2017 but during 2018 and 2019 (treatments on same plots), ETc versus grain yield relationships were different for the -N and +N treatments. Crop water production functions were developed using quadratic relationships between ETc and maize grain yield. The range of grain yield across all years and treatments were 15.03–7.23 Mg ha^{-1}. The range of crop water productivity (CWP) across all years and treatments were 1.6–2.6 kg m^{-3}. The ETc at maximum CWPs across all years and treatments had a range of 60–71% of ETm. These relationships are valuable to understanding maize response over a range of water availability and in developing tools to assess future production under water shortages.

1. Introduction

Changing climate conditions including variable regional and seasonal precipitation, increased water demands from agriculture and non-agricultural sectors, and increased irrigation costs have resulted in concerns about water supplies in many regions of the U.S. (McGuire, 2004; McGuire and Fischer, 1999; Lingle and Franti, 1998). In the Northwest U.S., because of water shortage concerns and shifting cropping systems, there are needs to provide research-based data to develop agricultural irrigation management practices that conserve irrigation water.

Developing crop water production functions (i.e. relationships between crop production factors and water use) is valuable to help evaluate and develop new irrigation management practices under water shortage scenarios. Several research studies have determined crop water production functions for maize (Trout and DeJonge, 2017; Steduto et al., 2007; Payero et al., 2006; Klocke et al., 2004; Zwart and Bastiaanssen, 2004; Stone, 2003; Schneekloth et al., 1991; Doorenbos and Kassam, 1986; Hanks, 1983; Sinclair et al., 1984; Tanner and Sinclair, 1983; Gilley et al., 1980; Barrett and Skogerboe, 1978; Stewart et al., 1977; Hanks et al., 1976; Hanks, 1974; de Wit, 1958; Robins and Domingo, 1953). Relationships between maize yield and ETc relationships can vary across management practices and weather conditions (Payero et al., 2006). There are no published water production functions for maize raised for grain in the arid regions of the Northwest U.S. This lack of data is partially due to maize historically not being a major crop in this region. More recently, maize production has increa-sed in areas of the Northwest U.S. due to increased dairy production. The average area of land in Idaho planted to maize from 2016 to 2020 (147,000 ha) is 2.6 times higher than two decades earlier. The number of dairy cows in Idaho has increased by approximately 118% in the past two decades (USDA-NASS, 2021).

Increasing CWP (producing more food per unit of water) is important in areas where water supplies are limited and in general across the world to match food production to a growing population, especially where water supplies are limited (Foley et. al, 2020). Crop water productivity

Abbreviations: ET, evapotranspiration; MAD, management allowable depletion; CWP, crop water productivity; WPF, water production functions; GY, grain yield.

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has units of kg of crop yield per m^3 of water used to achieve a given crop yield. Advancements in agricultural production from research (plant breeding, water management, other management factors) has resulted in increased CWP over time (Zwart and Bastiaanssen, 2004). In a review of published maize grain CWP, a large variation across the globe between 0.22 and 3.99 kg m^{-3} was found (Zwart and Bastiaanssen, 2004). In the central and eastern U.S., research studies have determined CWP values ranging from 0.65 to 3.23 kg m^{-3} (Foley et al., 2020). At 43 research locations across 13 countries and 4 continents, maize grain CWP ranged from 0.65 to 3.09 kg m^{-3} (Foley et al., 2020). The large variation in CWP is due to differences in any factor that affects the soil-plant-water relationships such as climate, soil, irrigation management, genetics, fertility, tillage, and other management practices. However, the goal is to increase CWP within a given system.

It is important to develop irrigation water management practices in the arid Northwest U.S. that consider water shortages and effects on maize production under a variety of production potentials. Regional specific research is needed to evaluate deficit irrigation management practices especially when water input from precipitation is low (Trout et al., 2020). The objective of this study was to develop relationships between maize grain production factors and crop water use (ETc, crop evapotranspiration) in the arid Northwest U.S. under low and optimum N input systems.).

2. Materials and methods

2.1. Site and soil description

The field study was conducted during 2017, 2018, and 2019 at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. The soil at the research site was a Portneuf silt loam (coarse-silty mixed mesic Durixerollic Calciorthid). The soil profile was well drained with a saturated hydraulic conductivity of 3.2 cm hr^{-1}. Available water holding capacity was 0.2 cm available water per cm soil depth (USDA, 2009). Plant available water was determined based on calculated water content at field capacity (approximately 0.32 m^3 m^{-3}) and water at permanent wilting point (approximately 0.14 m^3 m^{-3}).

2.2. Experimental design

The field study utilized a strip plot randomized complete block design (Fig. 1) with two annual N supply treatments (0 kg applied N ha^{-1} = -N, and 246 kg applied N ha^{-1} = +N) and four water supply treatments (Full irrigation treatment (FIT), 75FIT-approximately 75% of FIT, 50FIT-approximately 50% of FIT and 25FIT-approximately 25% of FIT). The FIT treatment aimed at supplying approximately 100% of crop water requirement based on model calculated crop ET (ETm). The +N treatment was based on recommendations from Brown et al. (2010). Each treatment combination was replicated four times. Each replicated block was separated by at least a 33 m wide strip of grass, the center of which was used to change sprinkler nozzles. Each experimental plot was 9.1 m wide (12 rows) × 41.1 m long. The length of the plot represented the distance between the linear move irrigation system towers. The harvest area within each plot was the 1.5 m (2 rows) × 22.9 m centered in the plot. The centered harvest areas allowed for 9.1 m borders at each end plot, eliminating experimental error associated with reduced water application uniformity caused by towers on the linear-move sprinkler irrigation system. The plot layout and locations did not change over the course of the study (i.e. plots were superimposed on previous year plots).

2.3. Cultural practices

To determine amounts of residual available N (NO_3-N + NH_4-N), and crop phosphorus and potassium needs, two soil cores (4.4 cm diameter) were taken in the spring of each year prior to planting across each replicated block to a depth of 0.6 m. The cores were split into two sampling depths of 0–0.3 m and 0.3–0.6 m. Soil samples were composited by depth increment. Soil samples were analyzed for nitrate-N (NO_3-N) and ammonium-N (NH_4-N) after extraction in 2 M KCl (Mulvaney, 1996) using a flow injection analyzer (Lachat Instruments, Loveland, CO). The 0–30 cm soil samples were tested for sodium bicarbonate extractable P and exchangeable K concentrations (Olson et al., 1954). Concentrations of P and K were adequate based on University of Idaho recommendations (Moore et al., 2009). The +N treatment had N applied as a side-dress at a rate of 246 kg ha^{-1} on June 7, 2017; June 12, 2018;

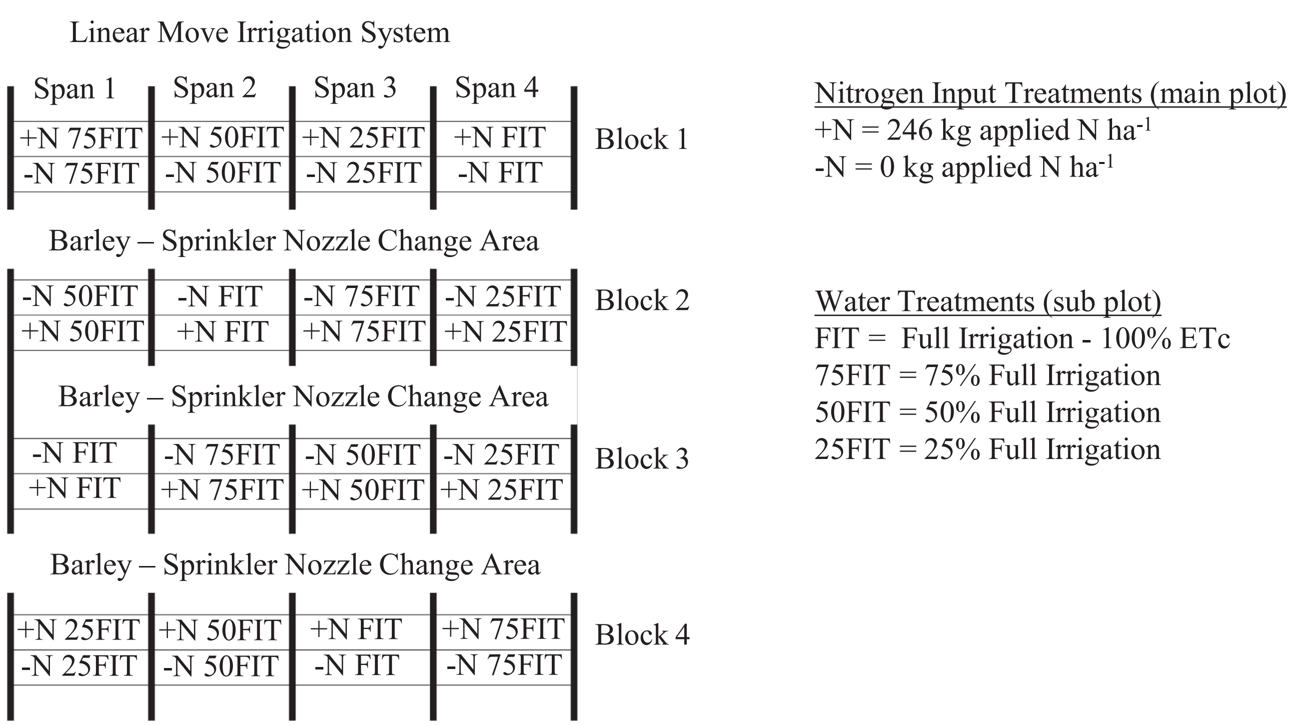

Fig. 1. Study design.

and June 24, 2019. Nitrogen was applied as urea (46% N) when maize was at growth stages between V4 and V6. Immediately following the applications, the urea was incorporated with approximately 14 mm of irrigation water applied uniformly across all plots.

Corn was planted on May 19, 2017; May 22, 2018; and May 23, 2019 at rate of 94,000 seeds ha^{-1}. The seed variety planted all three years of the study was Pioneer P9188R (Roundup Ready Corn 2). The seeds for all years were treated with the Raxil PPST 250 (combination of fungicides thiabendazole, fludioxonil, mefenoxam, and azoxystrobin, and the insecticide thiamethoxam). The crop was planted at 0.76 m row spacing at a seed spacing of 152.4 mm. Glyphosate and Dicamba were applied each year to all plots at maximum labeled rates to control weeds during a one-time application at the V3 to V4 growth stage.

2.4. Irrigation

Irrigation was used to supplement precipitation to meet water supply treatment requirements. Irrigation was applied using a linear-move irrigation system which traveled perpendicular to the N supply treatment strips (Fig. 1). Irrigation treatments were imposed by using a range of sprinkler nozzles with application rates of 24.71, 18.24, 12.71, and 6.58 L min^{-1} at a pressure of 138 kPa (for all irrigation treatments). The 24.71 L min^{-1} nozzle was used to apply the FIT (full irrigation treatment) treatment, applying water (offset by in-season precipitation) to match model calculated crop evapotranspiration (ETm). Model estimated crop evapotranspiration was based on the ASCE standardized reference evapotranspiration model (Allen et al., 2005) and daily crop coeffcients (Wright, 1982) using data from an Agrimet weather station (U.S. Bureau of Reclamation, Boise, ID) located 4.5 km from the plots. Estimated crop evapotranspiration rates were based on non-water stressed conditions. Daily crop coefficient (K_c) that varied through the season depending on the growth stage of the maize crop. The K_c values range from 0.3 at emergence, 1.0 at tasseling, and 0.8 at harvest (https://www.usbr.gov/pn/agrimet/cropcurves/CORNcc.html). The remaining nozzles applied irrigation water at approximately 75% (75FIT), 50% (50FIT), and 25% (25FIT) of ETm based on the manufacturer published values listed above. Across all treatments and years irrigation water and precipitation applied between 94% and 26% of ETm (Table 2 and Fig. 2).

Table 1
Average daily values of ASCE standardized reference evapotranspiration model alfalfa reference evapotranspiration (ETr), minimum air temperature (T_{min}), maximum air temperature (T_{max}), average air temperature (T_{avg}), solar radiation (Rs), relative humidity (RH), and wind speed at 2-m height (μ_2) during site-year growing seasons in Kimberly, ID.

Year	Month	ETr mm d^{-1}	T_{min} °C	T_{max} °C	T_{avg} °C	Rs MJ m^{-2} d^{-1}	RH %	μ_2 m s^{-1}
2017	May	5.9	5.3	20.9	13.3	23.3	57.3	3.0
	June	7.9	10.2	26.2	18.5	24.8	51.7	3.0
	July	8.5	13.8	33.3	23.8	24.3	46.7	2.1
	August	7.1	12.5	30.8	21.7	20.8	47.1	2.2
	September	4.8	7.8	23.5	15.6	16.1	54.9	2.4
	October	3.1	0.0	15.6	7.6	13.9	59.0	2.9
	Average	**6.2**	**8.3**	**25.1**	**16.7**	**20.6**	**52.8**	**2.6**
2018	May	5.5	7.8	22.0	14.7	21.5	64.7	2.6
	June	7.7	10.0	25.1	17.8	28.0	54.1	2.7
	July	9.3	13.5	32.5	23.1	28.3	43.1	2.3
	August	7.2	10.9	29.3	20.1	22.9	48.8	2.2
	September	5.8	7.0	25.0	16.0	19.7	40.2	2.4
	October	2.6	2.8	16.2	9.2	12.4	67.5	2.4
	Average	**6.4**	**8.7**	**25.0**	**16.8**	**22.1**	**53.0**	**2.4**
2019	May	4.8	5.7	19.1	12.2	20.3	66.8	2.7
	June	7.9	8.5	25.1	17.4	29.3	51.8	2.7
	July	7.7	12.7	30.0	21.3	24.9	55.8	2.2
	August	7.4	11.9	30.5	21.1	24.5	51.5	2.2
	September	4.9	7.8	23.4	15.5	18.0	62.4	2.5
	October	3.0	-2.3	13.3	5.3	13.3	56.8	3.0
	Average	**6.0**	**7.4**	**23.6**	**15.5**	**21.7**	**57.5**	**2.6**

Irrigation was applied twice a week early and late in the growing season and three times a week during peak water requirements. All irrigation treatments were irrigated on the same day. Each year, sufficient soil water was present in the soil surface for all maize plants to evenly emerge without supplemental irrigation. The first irrigation event after full maize emergence was determined based on soil water content, cumulative ETm, and precipitation. The first irrigations occurred on June 7, 2017; June 12, 2018; and June 24, 2019. Fig. 2 shows the cumulative irrigation and precipitation for each water treatment over time in relation to ETm. Seasonal ETc was estimated based on soil water balances as (Evett et al., 2012):

$$ETc = \Delta S + P + I – R - DP - U \quad (1)$$

where, ΔS is the decrease in soil water storage in the active root zone soil profile (1.2 m) between maize emergence and grain harvest, P is cumulative precipitation between emergence and grain harvest, I is cumulative irrigation between emergence and grain harvest, R is the difference between runoff and run on, DP is water percolating below the root depth. U is the upward soil water flux. All units are in mm. Precipitation was measured at the research site with rain gages in each replication. Past research from the plot area showed that negligible runoff (R) occurred at the irrigation rates used. Additionally, reservoir tillage was used on the plot area and there was no visual runoff during the season. Deep percolation (DP) was assumed to be zero based on soil water content being less than field capacity from emergence through grain harvest over the measured soil depth. Upward soil water flux was assumed to be zero as the ground water table was more than 5 m below the surface.

CWP was determined as:

$$CWP = \frac{GY}{ETc \times 10} \quad (2)$$

Where, GY is dry (0% water content) maize grain yield (kg ha^{-1}) and ETc (mm) × 10 is the crop water use of the maize plant on a hectare of land (m^3).

2.5. Soil water

For all years of the study, soil water content was measured using the neutron probe method (Evett and Steiner, 1995) on a periodic (weekly to every 2 weeks) basis following plant emergence from each plot at 0.30 m increments from the soil surface to a depth of 1.2 m. Volumetric soil water measurements were multiplied by soil depth to obtain soil water depth. For each neutron probe measurement date and time, soil water depths for each depth increment were summed over a depth of 1.2 m to determine total profile water content. Plant available water was determined based on estimated water content at field capacity (0.32 m^3 m^{-3}) and water at permanent wilting point (0.14 m^3 m^{-3}). Soil water measurements were compared to field capacity, 50% of available water, and permanent wilting point. A management allowable depletion (MAD) level of 50% was set as the depletion level above which the crop would be water-stressed (Jensen et al., 1990).

2.6. Harvest

Grain yield was determined from each plot by harvesting all grain from two 6.1-m row segments. Harvest dates were on October 5, 2019; October 18, 2018; and October 16, 2019. The killing frosts occurred before harvest each year on October 3, 2017; October 14, 2018; and October 9, 2019. For relationships with ETc, gain yields were adjusted to 155 mg kg^{-1} grain water content. When calculating CWP, dry grain yields were used (Eq. 2).

Table 2
Estimated model maize grain evapotranspiration (ETm) and growing season precipitation for the study site years.

Year	ETm[a]	Emergence to HarvestPrecipitation[b]	Emergence to harvestprecipitation % of average annual precipitation[c]	Emergence to harvestprecipitation % of ETm[d]
	mm			%
2017	661	39	15	5.9
2018	702	47	18	6.7
2019	638	27	11	4.2
Average	**667**	**38**	**15**	**5.7**

[a] ETm = ET estimated from the ASCE standardized reference evapotranspiration model (Allen et al., 2005) to supply 100% of maize water requirement.
[b] 2017 = May 27 – October 3, 2018 = June 1 – October 14, 2019 = June 1 – October 9.
[c] (Emergence to Harvest Precipitation/20-year annual average precipitation) × 100. 20-year annual precipitation = 256 mm.
[d] (Emergence to Harvest Precipitation/ ETm) × 100.

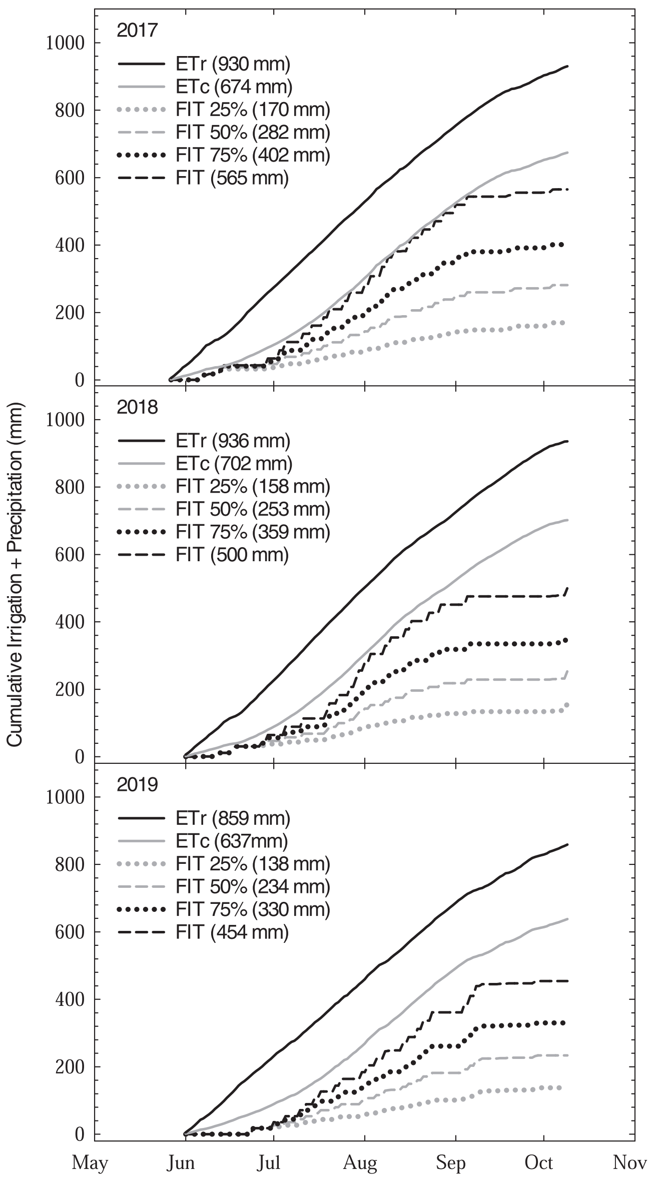

Fig. 2. Cumulative water (irrigation and precipitation) input depth over the growing season for water treatments and calculated crop evapotranspiration (ETm) based on the ASCE standardized reference evapotranspiration model.

2.7. *Water production functions*

Water production functions (WPF) were developed from the yield and crop water use data:

GY-ETc WPF = grain yield vs·ETc (3)

CWP-ETc WPF = crop water productivity vs·ETc (4)

GY-IP WPF = grain yield vs·water input (irrigation + precipitation) (5)

CWP -IP WPF = crop water productivity vs·water input (irrigation + precipitation) (6)

The WPFs were normalized relative to treatment mean maximum grain yield, ETc, and CWP to remove experimental error associated with year-to-year variability in yield potential (Trout and DeJonge, 2017; Doorenbos and Kassam, 1986). The normalized WPFs are labeled in this paper as follows:

Rel GY-Rel ETc WPF = relative grain yield vs·relative ETc (7)

Rel CWP- Rel ETc WPF = relative crop water productivity vs·relative ETc(8)

2.8. *Statistical analyses*

Statistical analysis was conducted separately for each year due to temporal variability, and compounded effects of the irrigation treatments. Analysis of variance was conducted for irrigation supply and nitrogen supply treatment main effects and the interaction for grain yield and CWP using a strip plot design model in Statistix 8.2 (Analytical Software, Tallahassee, FL). Irrigation supply was the main plot and nitrogen supply was the sub-plot. Significance was determined at the 0.05 level. For significant main effects or interactions, quadratic regression equations were developed in Sigma Plot 13.0 (Systat Software Inc.) to describe the response of the dependent variable (grain yield, CWP) to independent variables (ETc).

3. Results and discussion

3.1. *Crop, climate, water input, ET, and soil water content*

The management practices in the study led to production conditions that were similar to the conditions across the growing area. Emergence dates were May 27, 2017; June 1, 2018; and June 1, 2019. The 5-year average yield for corn in Idaho is 13.0 Mg ha^{-1}. The maximum grain yields (+N, FIT treatment) in the study were 15.4, 13.2, and 10.2 Mg ha^{-1} in 2017, 2018 and 2019, respectively. The plant populations in the study across all treatments were 90,000, 89,500, and 87,600 plants ha^{-1}.

The climate at Kimberly is arid, with 20-year (2000–2019) average annual precipitation of approximately 256 mm (Bureau of Reclamation AgriMet System). The maize growing season (May 15 to October 15) 20-year average precipitation and alfalfa-reference evapotranspiration was 69 and 1029 mm, respectively. On average, 27% of the annual precipitation occurs during the maize growing season. The 2017, 2018, and 2019 growing season (May 15 to October 15) precipitation was 67, 79, and 88 mm. The maize growing season precipitation in 2017 was 2 mm lower than the 20-year average. The maize growing season precipitation in 2018 and 2019 was 10 and 19 mm higher than the 20-year average, respectively. Table 1 contains additional climatic data for each year of the study. Table 2 contains the precipitation and ET data for the maize from emergence to harvest for the research sites.

At the start of this study, water treatments were based on applying water at set amounts relative to ETm (approximately 100%, 75%, 50% and 25%). However, during the 2017 growing season, soil water content (0–1.2 m depth) indicated that water input less than ETm was sufficient to maintain soil water between field capacity and 50% of available water (Fig. 3). Therefore, water input to the FIT treatment in 2018 and 2019 was adjusted to maintain soil water content between field capacity and 40% of available water. Corn can extract down to 50% of available water (50% maximum allowable depletion) without causing water stress (Jensen et al., 1990; James, 1988). The 75FIT, 50FIT, and 25FIT water inputs were based on applying water (irrigation and precipitation) relative to the FIT treatment water input (approximately 75%, 50% and 25% of the FIT treatments). In 2018 and 2019, the FIT cumulative ETc was 28.8% lower than cumulative ETm (Fig. 2, Table 3). Even though FIT ETc was lower than ETm, soil water data showed that the FIT treatment ETc was adequate to meet crop demand with no water stress each year (Fig. 3). In 2018 and 2019, precipitation outside of the growing season was adequate to increase soil water (0–1.2 mm soil depth) to between field capacity and 40% of available water for all treatments except the 25FIT treatment in 2018 (Fig. 3). This data indicates that maize crop coefficients (Kc) may be too high at this location and research needs to be conducted to evaluate Kc adjustments. Crop coefficients adjust reference ET to estimate model calculated crop use ET (ETm):

$$\text{ETm} = \text{Kc} \times \text{ET(reference)} \tag{9}$$

Crop coefficients are primarily used for irrigation management.

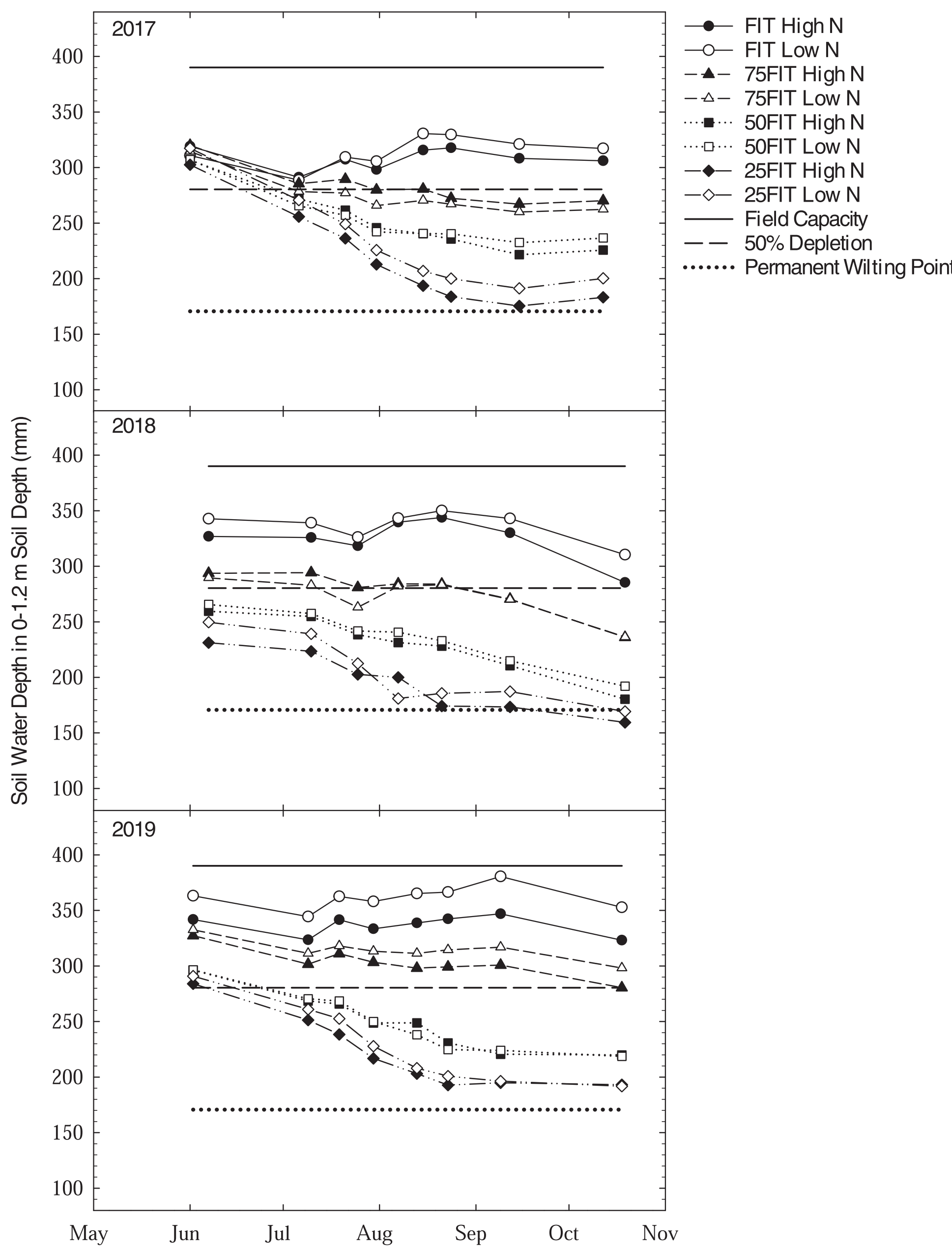

Fig. 3. Soil water depth of irrigation treatments (volumetric soil water $m^3\ m^{-3} \times$ soil depth) in the 0–1.2 m active root zone soil profile over the growing season. Each point is the average of all four treatment replications. Horizontal lines represent field capacity (solid), permanent wilting point (dotted), and 50% depletion of available water (dashed).

Table 3
Growing season soil (0–1.2 m depth) water decrease (ΔS, emergence-harvest), precipitation (P), irrigation (I), and maize grain water use (ETc) in 2017, 2018, and 2019.

Year	N Input Treatment	Water Input Treatment	ΔS	P	I	ETc	(P + I)/ETm[a]	ETc/ETm
			mm				%	
2017	-N	FIT	-6.4	30.7	526	550	84	83
		75%FIT	52.2	30.7	363	446	60	67
		50%FIT	70.5	30.7	243	344	41	52
		25%FIT	117.0	30.7	131	279	24	42
2017	+N	FIT	13.0	30.7	526	570	84	86
		75%FIT	49.8	30.7	363	444	60	67
		50%FIT	80.9	30.7	243	355	41	54
		25%FIT	119.4	30.7	131	281	24	43
2018	-N	FIT	32.2	47.2	455	534	72	76
		75%FIT	53.3	47.2	315	416	52	59
		50%FIT	73.8	47.2	209	330	37	47
		25%FIT	80.5	47.2	114	242	23	34
2018	+N	FIT	41.5	47.2	455	544	72	77
		75%FIT	57.9	47.2	315	420	52	60
		50%FIT	79.3	47.2	209	336	37	48
		25%FIT	71.7	47.2	114	233	23	33
2019	-N	FIT	10.5	27.2	427	465	71	73
		75%FIT	27.7	27.2	303	358	52	56
		50%FIT	77.8	27.2	207	312	37	49
		25%FIT	99.2	27.2	111	237	22	37
2019	+N	FIT	18.7	27.2	427	473	71	74
		75%FIT	44.8	27.2	303	375	52	59
		50%FIT	76.5	27.2	207	311	37	49
		25%FIT	90.8	27.2	111	229	22	36

[a] ETm = estimated crop water use from the Kimberly-Penman ET model (Wright, 1982).

Therefore, they should be calibrated to address both maintaining non-water stress soil water conditions and prevention of over irrigation. The Kc values used in this study were developed from lysimeter plots at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly Idaho (Wright, 1982) (same location as this study). For field maize and sweet maize, the Kc values are 0.3, 0.4–0.9, 1.0, and 0.8 for initial, developmental, mid-season, and late season crop growth, respectively. These Kc values on average across the growing season are lower than published FAO values (Brouwer and Heibloem, 1986). Using the FAO Kc values to calculate season maize ETm for this study would have been 16%, 12%, and 12% greater than the ETm derived from the USDA-ARS Kc values (Wright, 1982) in 2017, 2018, and 2019, respectively (Fig. 3). The USDA-ARS daily crop coefficients (Wright, 1982) were used in this study because they are locally calibrated.

The FIT treatment ETc ranged from 75% to 88% of ETm across years and N input treatments. The 75FIT treatment ETc had a range of 60–73% of ETm (Table 3). Both the FIT and 75FIT treatments had soil water content in the 0–1.2 m soil depth between field capacity and the maximum allowable soil water depletion level of50% of available soil water across all years, N input treatments, and measurement dates except the 75FIT treatment at grain harvest in 2018 (Fig. 3). Across all years and N input treatments, the 75FIT treatment removed 49 mm more cumulative water annually from the soil profile than the FIT (Table 3). The 50FIT and 25FIT treatments resulted in soil water content in the 0–1.2 m soil depth being below the maximum allowable soil water depletion level of 50% of available soil water during the mid and late season each year.

3.2. Nitrogen input

In 2017, there were no differences in maize grain yields between the -N and +N treatments across water input amounts. Research conducted at the general location of this study and on similar soil types have shown that there are high N mineralization rates that can often lead to crops not responding to N inputs (Tarkalson et al., 2016; Westermann and Carter, 1975; Carter et al., 1976; Stanford and Smith, 1972). For example, in N rate studies in sugar beet in southern Idaho, 8 of 14 research sites showed no sucrose yield response to N inputs (Tarkalson et al., 2016). All 8 non responsive sites had N inputs based on both published University of Idaho and Amalgamated Sugar Company recommendations. An unpublished data set from research conducted from 2010 to 2017 in southern Idaho assessing maize grain yield response to N supplies showed that only 7 out of 15 sites had significant maize grain yield responses to added N (Tarkalson, personal communication). The 7 non-responsive sites had an average N input requirement of 62 kg N ha^{-1} based on published recommendations (Brown et al., 2010). All these past sugar beet and maize N input studies were conducted on sites where no differences in N input occurred in the several years leading up to the study. However, in this study, N input differences were seen in 2018 and 2019 (significant water input by N input interactions) likely due to cumulative effects of the N inputs treatments (plots were in same locations all three-years) (Table 4). The cause of the water input by N input interactions were due to greater maize grain yield for the +N treatment than the -N treatment at the FIT water input treatment. There were no differences in maize grain yield between N input treatments at the other water input treatments.

3.3. Water input and water production functions

In 2017, there were significant grain yield differences among water input treatments across the two N input treatments, and in 2018 and 2019 there were significant interactions between water input and N input treatments. Because of the arid conditions of the region, responses to irrigation water input are very common. The average growing season rainfall across the three-year study period was 38 mm, while the average ETm for field maize was 667 mm (Table 2). Precipitation during the growing season represented an average of 5.6% of maize ETm, highlighting the importance of irrigation in this arid production system.

Water production functions (WPF) for all site-years are shown in Figs. 4 and 5. All WPFs were fit to quadratic regression models (Eqs. 4–9). In 2017, the quadratic model was fit to the combination of both N input treatments due to the significant ANOVA water input treatment main effect, non-significant N input main effects, and non-significant N input and water input treatment interactions (Fig. 3). In 2018 and 2019, the quadratic model was fit separately for each N input treatment due to the significant ANOVA interaction between N input and water input.

Table 4
Probability values (P > F) from analysis of variance for the effects of water input treatments and production level treatments on maize grain yield and crop water productivity (CWP) during the three years of the study. Significance was determined at the 0.05 probability level.

	Source	df[a]	2017	2018	2019
			P > F		
Grain Yield	Nitrogen Input (NI)	1	0.798	0.263	0.083
	Water Input (WI)	3	**< 0.001**	**< 0.001**	**< 0.001**
	NI × WI	3	0.180	**0.001**	**< 0.001**
CWP	Nitrogen Input (NI)	1	0.181	0.625	0.239
	Water Input (WI)	3	**0.018**	**< 0.001**	**< 0.001**
	NI × WI	3	0.265	**0.002**	**0.006**

[a] Degree of Freedom

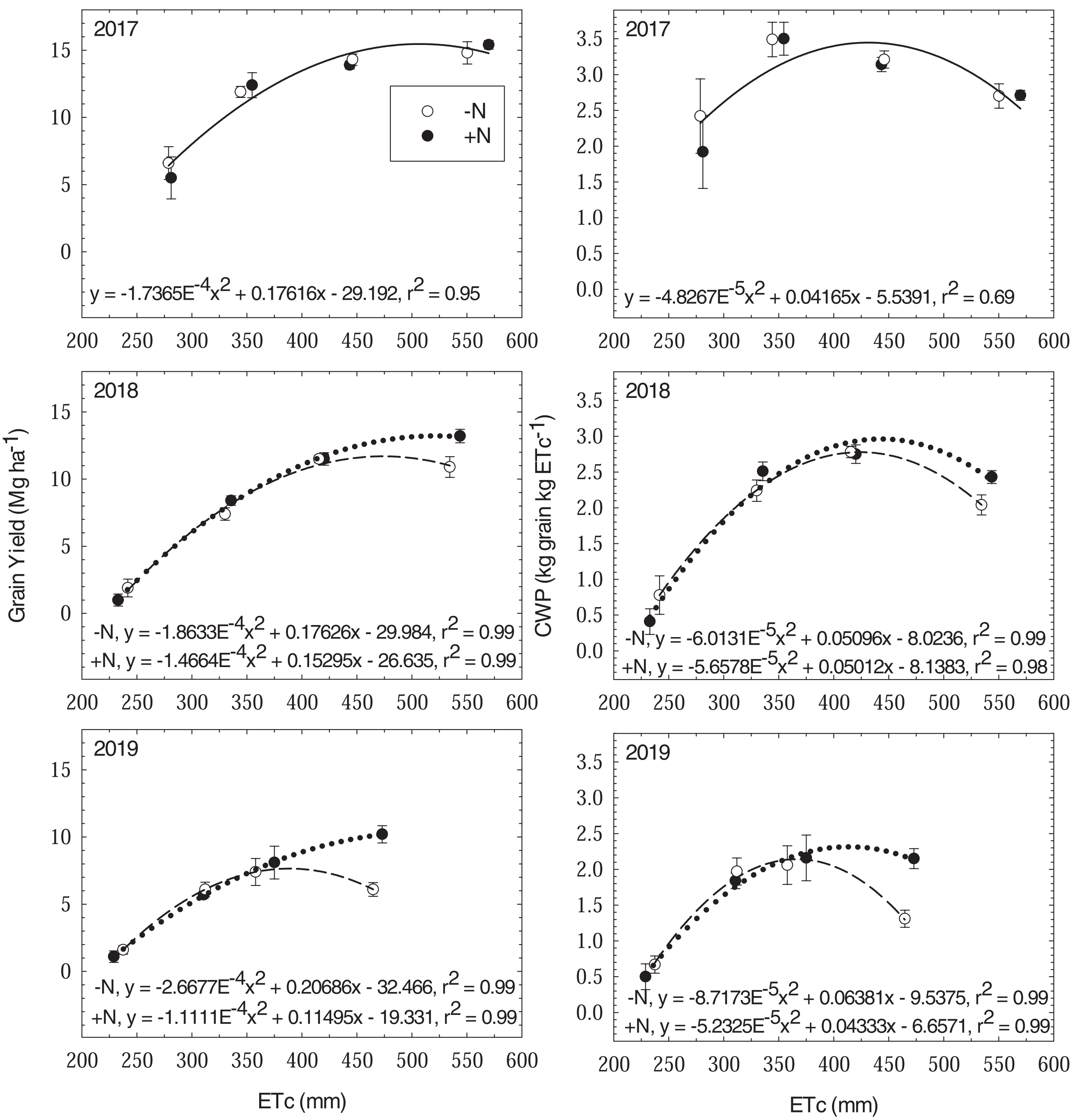

Fig. 4. Relationships between grain maize yield (measured at 15.5% water content) and crop water use (ETc), and crop water productivity (CWP) and ETc in 2017, 2018, and 2019. Each data point represents treatment means. Error bars are the standard error to the treatment mean. Quadratic regression lines were presented for relationships with significant ANOVA probability levels (Table 4). Solid regression lines represent combined -N and +N data, dashed regression lines represent -N data, and dotted regression lines represent +N data.

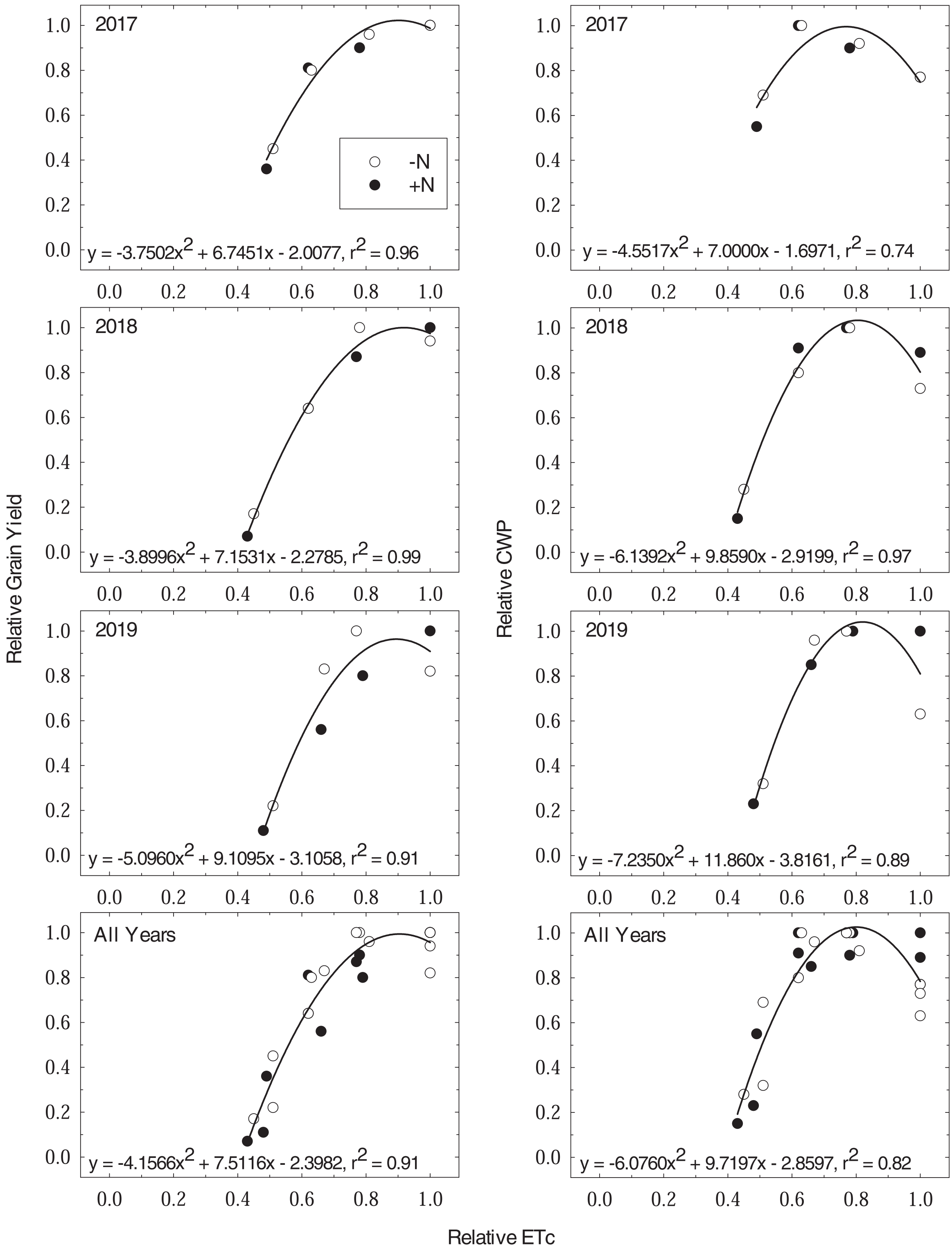

Fig. 5. Relative maize grain yield and maize crop water production functions. Water production functions are derived from the relationships between relative maize grain yield and relative crop water use (ETa), and relative crop water productivity (CWP) and relative ETc in 2017, 2018, 2019, and combined years. maize.

These quadratic models of the WPFs show that less grain is produced as more water is used or applied up to maximum yield. Curvilinear water response functions for maize grain and ETc were seen in other studies (Comas et al., 2019; Trout and DeJonge, 2017; Hernandez et al., 2015). Trout and DeJonge (2017) stated that it is possible that in other studies that produced linear WPFs, the data may be scattered enough not to discern a curvilinear relationship. One reason some studies can have high data variability is due to highly variable growing season precipitation. However, in areas with less in-season precipitation it is easier to control water input with scheduled irrigation. As stated earlier, southern Idaho and many areas of the arid northwest western U.S. have limited in-season precipitation (5.6% of maize grain ETm during this study). Other research highlighted the development of WPFs in maize where deficit water allocation varies depending on growth stage. It has been shown grain production is the greatest when a greater proportion of allocated deficit irrigation occurs during the reproductive and grain fill stages, and a lesser proportion during vegetative growth stages (Trout et al., 2020; Stewart and Hagen, 1973; Hexen and Heady, 1978; Berck and Hefland, 1990). In our study, water allocation was applied as a fraction of ETm over the entire season and did not take into account growth stage.

Water production functions (linear or curvilinear) are important for irrigation management (Trout and DeJonge, 2017; Trout et al., 2020). Water production functions serve as the basis for making deficit irrigation management decisions (Trout et al., 2020). Maximizing net income is a major goal of all agricultural production, and water input costs and WPF's need to be accounted for to maximize net income (Trout et al., 2020). Due to the complexity of the irrigation systems (water sources, irrigation costs, irrigation type, and other factors) in the arid northwest U.S., determining how to use the WPF's to maximize net incomes needs to be evaluated on a site/scenario specific basis. The curvilinear GY-ETc WPFs in our study indicates that the marginal productivity (unit of grain yield per unit water consumed or applied) decreases as water use increases up to a point of an economic optimum yield (based on crop price and all input costs). At this point, additional available irrigation water should be applied at the same rate across the cropping area (Trout and DeJonge, 2017). Under linear WPFs in limited irrigation scenarios, the marginal productivity is constant and there are no negative effects of applying full ETc to as much land as the water supply allows. An example of a negative effect from spreading water across the cropping area under a linear WPF scenario would be increased production costs (e.g. seed, fuel, fertilizer) without increased total yield. These interpretations of WPFs are generalized. Site-specific evaluation of water costs and benefits need to be considered when interpreting how to use WPFs to allocate limited water (Trout and DeJonge, 2017).

Based on the GY-ETc WPFs (Fig. 4), treatment mean maximum grain yield in 2017 was 15.03 Mg ha^{-1} produced at an ETc of 560 mm (99% of FIT ETc, 85% of ETm). In 2018 for the -N and +N treatments, maximum grain yields and associated required ETc were 11.6 Mg ha^{-1} at an ETc of 495 mm (90% of FIT ETc, 71% of ETm) and 13.19 Mg ha^{-1} at an ETc of 555 mm (99% of FIT ETc, 79% of ETm), respectively. In 2019 for the -N and +N treatments, maximum grain yields and associated required ETc were 7.23 Mg ha^{-1} at an ETc of 410 mm (86% of FIT ETc, 64% of ETm) and 9.83 Mg ha^{-1} at an ETc of 486 mm (100% of FIT ETc, 76% of ETm), respectively. Across both N input treatments, maximum yields decreased with successive years. This is likely due to several variables including yield lag associated with a continuous maize system over the course of the study and seasonal climatic factors. Maize grain yield declines in continuous maize systems have been observed in many growing areas. However, the reasons have not been fully determined. A comparison of continuous maize versus a maize-soybean rotation in Illinois showed that continuous maize had a grain yield decline of 1.5 Mg ha^{-1} compared to a maize-soybean rotation over a 5-year period (Gentry et al., 2013). Gentry et al. (2013) concluded that differences in N availability, maize residue accumulation, and weather likely had a role in the decline. In our study from 2017 to 2019, maximum yields declined 7.8 and 5.2 Mg ha^{-1} for the -N and +N treatments. However, the yield decline may not be fully due to the yield penalty associated with the continuous maize rotation, year to year differences in yield are often significant due to various factors such as climate. The amount and accumulation pattern of growing degree days over the season can significantly affect maize biomass accumulation and grain yields (Dobermann et al., 2003).

Based on the CWP-ETc WPFs (Fig. 5), across all years and N input treatments, the range of maximum CWP was 1.6–2.6 kg m^{-3}. There are limited studies determining CWP in the arid northwest U.S., therefore the closest geographical comparisons are from 11 studies conducted in the Midwest U.S. (TX, NE, KS, and CO). The CWP from these 11 studies under optimum ETc ranged from 1.4 to 2.4 kg mm^{-3} (Trout and DeJonge, 2017; Schlegel et al., 2016; Irmak, 2015; Djaman et al., 2013; Spurgeon and Yonts, 2013; Klocke et al., 2011; Lamm et al., 2009; Payero et al., 2008; Schneider and Howell, 1998; Schneekloth et al., 1991; Howell et al., 1989). The range of CWP in our study (1.6–2.6 kg mm^{-3}) had a similar range as in the 11 Midwest U.S. studies (1.4–2.4 kg mm^{-3}). The range of CWPs in our study was within the range of published studies from 43 research locations across 13 countries and 4 continents of 0.65–3.09 kg m^{-3} (Foley et al., 2020).

The data in our study shows that CWP can be maximized at an ETc lower than maximum ETc and ETm (Fig. 5). Across years and N input treatments, the ETc to achieve maximum CWP was on average 84% of the FIT ETc treatment and 66% of ETm. In our study, yearly maximum CWP and associated ETc values from the WPF models are: 2017: 2.6 kg mm^{-3} and 470 mm (85% of FIT ETc, 71% of ETm), 2018: 2.2 kg mm^{-3} and 445 mm (81% of FIT ETc, 63% of ETm) for -N and 2.4 kg mm^{-3} and 460 mm (82% of FIT ETc, 66% of ETm) for +N, 2019: 1.6 kg mm^{-3} and 380 mm (80% of FIT ETc, 60% of ETm) for -N, and 1.8 kg mm^{-3} and 440 mm (91% of FIT ETc, 69% of ETm) for +N.

The quadratic models defining the GY-ETc WPF were extrapolated to determine the minimum ETc at which maize grain yield production starts (Fig. 4) (pre-production ETc). In 2017 (combined -N and +N), 231 mm of ETc was needed to start producing grain yield. In 2018, 237 and 227 mm of ETc were needed to start producing grain yield for the -N and +N treatments, respectively. In 2019, 223 and 229 mm of ETc were needed to start producing grain yield for the -N and +N treatments, respectively. Across all years and N input treatments, the average pre-production ETc was 229 mm. The range of pre-production ETc was minimal (14 mm). The average pre-production ETc across all treatments and years was 44% of FIT ETc. This pre-production ETc/FIT ETc was in the upper range of other published values of 20–50% (Stewart et al., 1977, 2017). Regarding the amount of water input (irrigation and precipitation) needed to start producing maize grain, in 2017 (combined -N and +N), 72 mm of water input was needed during the growing season to start producing grain yield. In 2018, 138 and 146 mm of water input were needed to start producing grain yield for the -N and +N treatments, respectively. In 2019, 111 and 115 mm of water input were needed to start producing grain yield for the -N and +N treatments, respectively. These values are less than minimum ETc values, because stored soil water provided the additional water input needed to meet minimum ETc to produce grain.

The normalized WPFs (Rel GY-Rel ETc WPF and Rel CWP- Rel ETc WPF) are presented in Fig. 5. Normalization of data allows for compensation across years and locations (Trout and DeJonge, 2017). In Fig. 5, the normalization of the data allowed for plotting of data across N input treatment for each year and across years.

4. Conclusions

The maize WPFs developed maize in this study can serve as the basis for maximizing net income in maize production under deficit irrigation in the arid Northwest U.S. The WPFs were different for N limited and sufficient systems. The locally calibrated Kc values used in the Kimberly-Penman Reference Evapotranspiration Model may result in overestimating ETc and may need to be adjusted. Additional research is needed to make any adjustment to the Kc values. This data supports the need to monitor both soil water status and ETc during the season to understand maize water stress levels, and to assist in irrigation scheduling. These results were based on maize growth in a deep silt loam soil. Results could be different in soils with lower water holding capacity and shallow soils. Future research objectives could assess similar objectives from this study on other soil types and soil depths.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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