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Maize response to irrigation and nitrogen under center pivot, subsurface drip and furrow irrigation: Water productivity, basal evapotranspiration and yield response factors

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Abstract

Information and data about quantification and comparison of crop water productivity indices for various irrigation levels and methods and nitrogen (N) application timings "simultaneously" under the same conditions do not exist. Unprecedented and extensive field experiments were conducted for maize (*Zea mays* L.) in 2016 and 2017 under center pivot (CP), subsurface drip irrigation (SDI) and furrow irrigation (FI) methods with full irrigation treatment (FIT), 80% FIT, 60% FIT and rainfed treatment (RFT) with three N application timings. N treatments were: (i) traditional (TN), (ii) non-traditional-1 (NT-1) and (iii) non-traditional-2 (NT-2). Irrigation yield production functions (IYPF); evapotranspiration-yield production functions (ETYPF), basal evapotranspiration (ETb), crop water productivity (CWP), irrigation water use efficiency (IWUE); evapotranspiration water use efficiency (ETWUE) and yield response factors (Ky) were quantified for each treatment and irrigation method. SDI method

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required the least seasonal irrigation amount in achieving maximum yield, followed by CP (>~30 mm more than SDI) and FI (>~55 mm more than SDI). Average crop water requirement for achieving maximum grain yield varied among the N treatments within and between the irrigation methods. Irrigation amounts for achieving maximum yields were about 160, 175 and 175 mm in TN, NT-1 and NT-2 nitrogen treatments, respectively, in the CP method; 130, 150 and 150 mm in TN, NT-1 and NT-2 nitrogen treatments, respectively, in the SDI method; and 184 mm in TN management in the FI method. The highest grain yield production per 25.4 mm of applied irrigation followed the order of CP-TN (2.07 Mg ha^{-1}) > SDI-NT-2 (1.91 Mg ha^{-1}) > FI-TN (1.22 Mg ha^{-1}). Across all treatments for the given irrigation method, the highest averaged CWP of 3.00 kg m^{-3} (slope = 0.067 kg m^{-3}) was observed in the SDI method ($p < 0.05$) followed by 2.84 kg m^{-3} (slope = 0.052 kg m^{-3}) in the CP method ($p < 0.05$) and 2.51 kg m^{-3} (slope = 0.046 kg m^{-3}) in the FI method. The lowest ETb was observed in FI-TN (169 mm), followed by CP-NT-2 (172 mm) and SDI-TN (255 mm). For two consecutive years, N treatments did not have significant ($p > 0.05$) influence on IWUE in the CP or SDI methods. The highest IWUE, CWP and ETWUE were always obtained with limited irrigation treatments (60% FIT and/or 80% FIT) whereas the lowest with FIT. Maize under limited irrigation management had $Ky < 1$ with CP, SDI and FI along with lower Ky values than the respective TN treatment in CP and SDI, suggesting that the yield reduction is impacted to a lesser degree from the magnitude of water stress. The overall conclusion disclosed that utilizing the combination of limited irrigation (80% FIT) with NT-1 fertigation under SDI and CP, while 80% FIT under FI can be viable management practices for achieving high grain yield and CWP in conditions similar to those presented in this research.

Keywords: Center pivot, Evapotranspiration water use efficiency, Furrow irrigation, Water productivity, Limited irrigation, Nitrogen management, Subsurface drip, Yield production function, Yield response factor

1. Introduction

The challenges in water resources availability vs. agricultural production have been becoming more widespread globally. In many areas, the surface and groundwater resources, which are critical for agricultural sustainability and have substantial positive influence on economy. In many cases, the level of these vital water resources is declining at a rate greater than recharge rate due to demand for irrigation water exceeding water supply/input and impacts of climate change. In addition, climate change is substantially influencing the magnitude of precipitation and variability in within-season distribution (Irmak et al., 2012), resulting in negative impact to the groundwater recharge and surface water resources as well as causing extreme flooding, run-off and drought conditions, further imposing stress on agricultural productivity and agricultural economy. In some areas, extreme declines in irrigation water supplies from the aquifer and increasing pumping costs impose further challenges to maintain high crop production potential while maintaining a reasonable economic net return. In such conditions, it is important to better understand crop yield and water productivity responses to irrigation, evapotranspiration, and nitrogen (N) management strategies under different irrigation levels and methods. Hence, the most effective, economical, relevant and efficient crop production strategies should be developed, and equally importantly, they should be implemented to enhance crop water productivity under these challenging conditions as well as to sustain water resources and agricultural productivity to meet increasing world population's food, feed and fiber demand.

Among other major grain crops, maize (*Zea mays* L.) is widely cultivated in the USA (37.1 million ha) and globally (197 million ha) and has substantial positive impacts on human and animal food and fiber demand and on agricultural economy. Maize is most produced grain crop globally and is believed to have originated in central Mexico ~7000 years ago from a wild grass, and Native Americans transformed maize into a source of human and animal food that is great sources of carbohydrates, protein, iron, vitamin B, and minerals. United States [378 million metric ton (MT)/yr], China (225 million MT/yr) and Brazil (83 million MT/yr) are the top three maize-producing countries in the world, producing approximately 454 million MT/yr (~40%) of the total 1140 million MT/year (Ranum et al., 2014; Erenstein et al., 2021). Given its critical role in world's food supply and security, researching, quantifying and implementing crop water productivity indices under different water and nitrogen management can enable producers and managers to enhance crop productivity per unit of input. In an effort to quantify and analyze maize water productivity response, several metrics are employed to investigate and communicate maximum or optimum grain yield production per unit of water under different (and globally dominant) irrigation methods (i.e., center pivot, CP; subsurface drip irrigation, SDI; furrow irrigation, FI). These metrics are crop water productivity (CWP), irrigation water use efficiency (IWUE), evapotranspiration water use efficiency (ETWUE), irrigation-yield production function (IYPF), evapotranspiration-yield production function (ETYPF), basal evapotranspiration (ETb), and yield response factors (Ky) (Irmak, 2015a; b).

CWP changes with location; irrigation amount, timing, frequency and method; hybrid characteristics; climate and crop and soil management practices (e.g., Kang et al., 2002; Irmak, 2015b) and N management (Ogola et al., 2002). Moreover, it has been reported that limited irrigation management enhances CWP (e.g., Payero et al., 2009; Ko and Piccinni, 2009; Djaman and Irmak, 2012; Irmak et al., 2019; Mohammed et al., 2019). Howell et al. (1998) reported a narrow CWP range of 1.65–1.70 kg m^{-3} for irrigated maize hybrids using a lateral-move sprinkler system. Djaman and Irmak (2012) reported higher CWP values, ranging from 1.89 kg m^{-3} in the rainfed to 2.58 kg m^{-3} in the 60% of full irrigation treatment for CP-irrigated maize. A 3-yr study (2005–2008) using SDI as a function of different irrigation management of 125% of full irrigation treatment (FIT), 75% FIT, 50% FIT, 25% FIT and rainfed treatment (RFT) coupled with three irrigation frequencies (low, medium and high) by Irmak et al. (2016) showed that maize CWP increased with seasonal ETc and ranged from 0.80 to 3.10 kg m^{-3}. Abd El-Wahed and Ali (2013) observed that maize CWP was significantly ($p < 0.05$) affected by irrigation method with CWP ranges of 1.40–1.42 kg m^{-3} for drip irrigation and 0.89–0.91 kg m^{-3} under sprinkler irrigation. Several researchers found that the N fertilizer under rainfed settings did not greatly impact CWP (e.g., Al-Kaisi and Yin, 2003; Halvorson et al., 2006).

Previous studies showed that maize IWUE under SDI, surface drip, sprinkler irrigation system and FI showed a wide range of values, ranging from 2.83 to 22.7 kg m^{-3}, 2.35–12.7 kg m^{-3}, 0.44–6.59 kg m^{-3}, and 0.86–5.6 kg m^{-3}, for those irrigation methods, respectively (Sammis, 1980;) while Howell (2001) found that the type of irrigation method did not significantly influence maize IWUE magnitudes in a semi-arid climate. Ogola et al. (2002) and Mansouri-Far et al. (2010) found that increased N supply increased IWUE for biomass and grain production. In addition to CWP and IWUE, ETWUE, IYPFs, ETYPFs and crop yield response factor (Ky) are effective performance indices that are used to quantify crop yield performance and CWP response to different management practices and environmental variables (Irmak, 2015a, 2015b). Only a few researchers quantified ETWUE, IYPFs, ETYPFs and Ky values to determine the influence of irrigation on potentially increasing CWP relative to rainfed production and differentiate CWP between limited irrigation and fully irrigation settings (Howell, 2000; Payero et al., 2008; Djaman and Irmak, 2012; Irmak, 2015b; Irmak et al., 2019; Mohammed et al., 2019) and these authors indicated that the ETWUE is maximized with less irrigation and can have substantial inter-annual variation for the same treatments and management conditions.

Aforementioned studies indicate significant variation in CWP indices between the regions and even in the same region between different crop management practices. While some researchers investigated limited irrigation under sprinkler and surface irrigation or sprinkler and SDI methods and their combination effects on CWP independently, to the best knowledge of the authors, no previous research has quantified and evaluated the impacts of irrigation rates and N timing management strategies on maize productivity indices (CWP, IWUE, ETWUE, IYPFs, ETYPFs and Ky) under FI, CP and SDI methods under the same environment, climate conditions and under the same soil and crop management practices simultaneously. The objectives of this research were to: (i) quantify, analyze and compare IYPFs and ETYPFs of maize under limited irrigation and full irrigation settings with three N application timings under CP, SDI and FI, (ii) measure and compare the CWP, IWUE and ETWUE; and (iii) quantify and compare basal evapotranspiration for all irrigation levels and N application timings; and (iv) quantify and compare seasonal maize Ky under all conditions to investigate how different irrigation levels and N management as well as irrigation method may potentially impact the aforementioned CWP indices.

2. Materials and methods

2.1. Site characteristics, irrigation and nitrogen management

Detailed experimental practices were reported by Irmak et al. (2022) and Mohammed and Irmak (2022) and only the field, crop and soil management practices that are closely related to the objectives of this research will be presented here. Field experiments were carried out in 2016 and 2017 growing seasons in the Irmak Research Laboratory (IRL) advanced field research facilities at the University of Nebraska-Lincoln (UNL), South Central Agricultural Laboratory (SCAL), located near Clay Center, Nebraska, USA (40° 43′ N and 98° 8′ W, with an elevation of 552 m above mean sea level). The dominant soil series in the research site is a Hastings silt loam; fine, montmorillonitic, mesic Udic Argiustoll with

0–1% slope. The field capacity, permanent wilting point and saturation point are 0.34, 0.14, and 0.53 $m^3 m^{-3}$, respectively (Irmak, 2010). Four irrigation levels of full irrigation treatment (FIT), 80% of FIT (20% deficit), 60% of FIT (40% deficit) and rainfed treatment (RFT) were imposed in each irrigation method (CP, SDI and FI). Three N application timing strategies/treatments were imposed in each irrigation level and method: (i) traditional nitrogen (TN) in which all the required seasonal N amounts were applied in spring as a pre-plant application, (ii) non-traditional-1 (NT-1) in which 30% of the seasonal total N requirements was applied in spring as a pre-plant, 40% and 30% as a side-dress at V8 (8-leaf collar) growth stage and VT/VR (tasseling/silking) stages, respectively, and (iii) non-traditional-2 (NT-2) in which 25% of the seasonal total N requirement was applied in spring as pre-plant, and the remaining 25%, 30% and 20% as a side-dress at V8, VT/VR and R3 (i.e., kernel milk) growth stages, respectively. The UNL N algorithm (Shapiro et al., 2008). was used to estimate the N requirement as urea ammonium nitrate (UAN; 32–0–0).

Two application methods were used to apply N in each field/irrigation method: (i) the BLU-JET (Model AT6020; Unverferth Manufacturing Co., Inc. Kalida, OH) fertilizer injector applicator was used to apply N for the traditional (TN) application treatments in the CP, SDI and FI fields, and (ii) a chemigation system was used to apply N to the non-traditional treatments of NT-1 and NT-2 at various growth stages in the CP and SDI methods/fields. The amount and timing of nitrogen applications for each treatment are presented in **Table 1**. Irrigations were triggered and managed based on full irrigation treatments of FIT, FIT-NT-1 and FIT-NT-2 in the CP, SDI and FI methods, respectively, with approximately 45% depletion of available water to avoid crop water stress. The volumetric soil water content (VSWC) that was used to manage irrigation and conduct soil-water balance analyses was measured with a 0.30 m increment down to 1.20 m in the soil profile on a weekly basis using a neutron attenuation moisture probe (Model 4300; Troxler Electronics Laboratories, Inc., NC, USA). The neutron gauge access tubes were installed at V2 or V3 (2 or 3 leaf collar) maize growth stages with two replications for each treatment in each irrigation method/field on the crop row between two healthy maize plants that represented average field conditions in terms of emergence, uniformity, slope, etc. During the installations, effort and care were taken not to damage any plant and that

Table 1 Nitrogen fertilization rate scheme for full irrigation treatment (FIT), 80% FIT, 60% FIT and rainfed treatments (RFT) for each nitrogen application timing treatment of traditional (TN) treatment, non-traditional-1 (NT-1) treatment and non-traditional-2 (NT-2) treatment under each irrigation method of center pivot (CP), subsurface drip irrigation (SDI) and furrow irrigation (FI) at various maize growth stages during the 2016 and 2017 growing seasons.

Year	Irrigation method	Nitrogen treatment	Irrigation treatment	Nitrogen application time and rate (kg ha^{-1})				
				V0[a]	V8[a]	VT[a]	R3[a]	Total
2016	CP	TN	FIT	219.6	–	–	–	219.6
			80%FIT	220.2	–	–	–	220.2
			60%FIT	208.4	–	–	–	208.4
			RFT	216.8	–	–	–	216.8
		NT-1	FIT	66.8	89.1	66.8	–	222.7
			80%FIT	63.6	84.8	63.6	–	211.9
			60%FIT	66.6	88.7	66.6	–	222.0
		NT-2	FIT	57.9	57.9	69.5	46.3	231.8
			80%FIT	53.8	53.8	64.6	43.1	215.4
			60%FIT	55.8	55.8	66.9	44.6	223.3
	SDI	TN	FIT	218.2	–	–	–	218.2
			80%FIT	212.2	–	–	–	212.2
			60%FIT	210.0	–	–	–	210.0
			RFT	224.0	–	–	–	224.0
		NT-1	FIT	71.2	94.9	71.2	–	237.3
			80%FIT	68.8	91.7	68.8	–	229.3
			60%FIT	72.6	96.8	72.6	–	242.1
		NT-2	FIT	60.5	60.5	72.6	48.4	242.1
			80%FIT	57.2	57.2	68.7	45.8	229.1
			60%FIT	57.2	57.2	68.7	45.8	229.1
	FI	TN	FIT	199.5	–	–	–	199.5
			80%FIT	188.7	–	–	–	188.7
			60%FIT	221.9	–	–	–	221.9
			RFT	207.8	–	–	–	207.8
2017	CP	TN	FIT	198.7	–	–	–	198.7
			80%FIT	206.7	–	–	–	206.7
			60%FIT	235.1	–	–	–	235.1
			RFT	230.1	–	–	–	230.1
		NT-1	FIT	59.8	79.8	57.1	–	196.7
			80%FIT	52.9	70.6	52.9	–	176.4
			60%FIT	71.2	95.1	71.2	–	237.6
		NT-2	FIT	54.9	54.9	65.9	43.9	219.7
			80%FIT	56.5	56.5	67.8	45.2	225.9
			60%FIT	49.2	49.2	59.1	39.4	196.8

a. V0: seeding to emergence; V8: collar of 8 leaf is visible; VT: tasseling; R3: milk and kernels are full yellow milky.

there was a good contact between the soil and the access tubes down to 1.20 m soil depth and also any gap between the access tubes and the soil was avoided to prevent any irrigation and/ or precipitation water seeping through the space between the access tube and soil which can cause erroneous measurement. The neutron probe was calibrated for the experimental field to enhance the VSWC measurement accuracy. In each irrigation, the FIT received irrigation water to bring the soil profile to approximately 90% of the field capacity to reserve some soil-water holding capacity for any potential precipitation after irrigation. The 80% FIT and 60% FIT received 80% and 60% of the irrigation amount applied to the FIT. This irrigation management was practiced throughout each growing season.

In the CP method/field, plots were irrigated with a four-span hydraulic and continuous-move CP irrigation system (T-L Irrigation Co., Hastings, NE, USA). In the SDI method/field, plots were irrigated with a fully automated SDI system (Netafim-USA, Fresno, California). The FI plots were irrigated with a gated pipe FI system (Hastings Irrigation Pipe Co. NE, USA). The irrigation intervals were usually weekly, twice a week and weekly or bi-weekly for CP, SDI and FI, respectively. Filed experiments with each irrigation method were conducted using a different design and field layout as a function of each irrigation system's/ method's physical and operational characteristics and design. The experimental design in the CP field was a split-split plot design with N application timing as the main plots and the irrigation application levels as the subplots with four replications of each treatment, and each plot (replication) was about 1 ha in size. The experimental design in the SDI and FI fields/methods were randomized complete block design with three replications for each treatment. In the SDI field, each plot was 122 m long and 6.1 m wide. In the FI field, each plot was 68.5 m long and 6.1 m wide. All irrigation methods were established in one large field area by dividing the larger field into three parts to establish each irrigation system. Thus, the soil type, soil physical and chemical characteristics, slope and other terrain/ topographical characteristics are the same between the irrigation methods/fields and that it was assumed that the potential differences in ETc, IYPFs, ETYPFs, CWP, IWUE, ETWUE and Ky response to irrigation levels and N management are due to the irrigation method and not due to the differences in field characteristics.

2.2. Quantification of seasonal crop evapotranspiration

Seasonal maize evapotranspiration (ETc, mm) was calculated from emergence until physiological maturity using the general soil-water balance equation (Irmak, 2015a; b):

$$P + I + U = R + D \pm \Delta W + ETc \qquad (1)$$

where, P = precipitation (mm), I = irrigation water applied (mm), U = upward soil moisture flux (mm), R = surface run-off (mm), ΔW = change in soil moisture storage in the soil profile (mm) from the beginning to the end of the growing season, and D = deep percolation from the crop root zone (mm). The upward soil moisture flux was assumed negligible because the water table at the research fields is about 30 m below the soil surface (Irmak, 2015a). The run-off was estimated using the USDA Natural Resources Conservation Service (NRCS) curve number procedure (USDA-NRCS, 1985). The research site has a silt loam soil; therefore, C = 75 was used for the known land use, slope and tillage practice, which was obtained from USDA-NRCS (1985). Deep percolation was estimated using a daily water balance approach programmed in Microsoft Visual Basic (Payero et al., 2009; Djaman and Irmak, 2012). The equation for deep percolation is:

$$D_j = Max\,(P_j - R_j + I_j - ETc_j - CD_{j-1}, 0\,) \qquad (2)$$

where, D_j = deep percolation on a day j, P_j = precipitation, R_j = precipitation and/or irrigation run-off from the soil surface on a day j (mm), I_j = irrigation depth on a day j (mm), ETc_j is a crop evapotranspiration on a day j, and CD_{j-1} = root zone cumulative depletion at the end of day $j-1$. Deep percolation and surface run-off values were quantified for each treatment.

2.3. Quantification of water productivity indices

The water productivity indices (CWP, IWUE and ETWUE) were calculated for each treatment, for each irrigation method and for each year to quantify the crop production efficiency and productivity response to various irrigation levels (i.e., FIT, 80% FIT, 60% FIT and RFT) with three N application timings of each irrigation treatment. CWP was computed as the ratio of grain yield (Y) to ETc (Irmak, 2015b):

$$\text{CWP} = (\text{Y}/\text{ETc}) \times 100 \qquad (3)$$

where, CWP is expressed in kg m^{-3}, Y = grain yield (g m^{-2}) and ETc = crop evapotranspiration (mm). To determine various irrigation levels' potential influences on CWP with respect to rainfed treatment yield, IWUE and ETWUE (Howell, 2001; Djaman and Irmak, 2012; Irmak, 2015b) were also quantified for each treatment. This allows quantifying maize yield increase and/or yield obtained per unit of applied water in the case of IWUE and a per unit of water used (ETc) in the case of ETWUE:

$$\text{IWUE} = [(\text{Yi} - \text{Yr}) / \text{Ii}] \times 100 \qquad (4)$$

$$\text{ETWUE} = [(\text{Yi} - \text{Yr}) / (\text{ETci} - \text{ETcr}] \times 100 \qquad (5)$$

where, IWUE and ETWUE are expressed in kg m^{-3}, Y = grain yield (g m^{-2}), Ii = applied irrigation water (mm), while the subscript i and r represent irrigation level and rainfed treatment, ETci = crop evapotranspiration (mm) for a given irrigation level, and ETcr = crop evapotranspiration (mm) for the associated rainfed treatment.

2.4. Yield response factors (Ky)

Maize yield response to full and limited irrigation during the gowning season was determined using yield response factor (Ky) according to Doorenbos and Kassam (1979). This variable can provide invaluable information for aiding in the planning and management of irrigation systems in regions where water scarcity can substantially influence crop response to water application and the influence of limited irrigation on crop productivity relative to full irrigation. Ky correlates the amount of decrease in maize grain yield relative to per unit decrease in ETc (Irmak, 2015b) and is expressed as:

$$Ky = \frac{[\,1 - Ya/Ym\,]}{[\,1 - ETc/ETm\,]} \qquad (6)$$

where, Ky = yield response factor (dimensionless), Ya = actual grain yield obtained under limited irrigation (kg ha^{-1}), Ym = maximum yield under full irrigation (kg ha^{-1}), Ya/Ym = is relative grain yield (relative to the grain yield of FIT), ETc = crop evapotranspiration (mm) obtained under limited irrigation, ETm = maximum crop ET (mm) under full irrigation, ETc/ETm = is relative crop evapotranspiration (relative to fully irrigated ETc). When $Ky > 1$, this indicates that the decrease in grain yield is sensitive to water deficit and proportionally greater in yield reduction with lower ETc due to water stress, $Ky < 1$ indicates that the decrease in grain yield is less sensitive or more tolerant to water deficit and proportionally lower in yield reduction with reduced ETc, and $Ky = 1$ indicates that the crop grain yield loss is equal to the deficit ETc (Doorenbos and Kassam, 1979; Irmak, 2015b) as is the case of severe stress when irreversible plant damage can occur before any grain yield is produced (Irmak, 2015b). Ky values were calculated for each irrigation method and N management for each year.

2.5. Statistical analysis

Statistical analyses were carried out using GLIMMIX procedure in SAS (SAS Institute, Inc., Cary, N.C., USA, 2003) to identify and distinguish potential significant differences among the CWP, IWUE, and ETWUE and they were evaluated at the 95% confidence interval using a Fisher's protected least significant differences (LSD) procedure. In addition, linear regression analysis was used to evaluate slope response to irrigation levels and N application timings for each growing season and irrigation method.

3. Results and discussion

3.1. Weather characteristics

Daily and cumulative precipitation along with average magnitudes of monthly weather variables during 2016 and 2017 growing seasons (from May 1 to October 30) and long-term average (1983–2015) monthly weather variables at the research site were presented in Irmak et al. (2022) along with the detailed explanations of the weather characteristics and will not be repeated here.

3.2. Irrigation-yield production functions (IYPF) and yield production per unit of irrigation water applied

Maize grain yields across all treatments ranged from 9.1 to 17.3 Mg ha^{-1} in in 2016; and from 7.9 to 17.8 Mg ha^{-1} in 2017 (**Table 2**). There were considerable inter-annual variations in grain yields under RFT due to its strong relation to seasonal rainfall amounts and distributions throughout the growing season. Grain yields were markedly altered by irrigation levels for the TN and NT nitrogen treatments for the given irrigation method, and the overall trend was increasing in grain yield with increase in irrigation amount. Maize yields had quadratic/curvilinear relationship with seasonal irrigation amounts (**Fig. 1**) as was also described by Howell et al. (1997), Irmak et al. (2000), Payero et al. (2008), Irmak (2015a), Irmak et al. (2020). Overall maize yield response to seasonal irrigation (IYPF) showed maize yield increases with applied irrigation until a certain amount of irrigation before the curvilinear shape became plateaued (i.e., horizontal), which is indicative of excessive amount of applied irrigation when further increase in irrigation amount does not contribute to yield increase, which also indicates diminishing return (Irmak, 2015b). More likely, the number of factors contributed to the change of curve liner shape (i.e., becoming plateaued) such as applied amount of irrigation was exceeded or beyond the crop water requirement.

The average crop water requirement for achieving maximum grain yield varied among the N treatments within and between the irrigation methods (Fig. 1). Irrigation amounts for achieving maximum yields were 160, 175 and 175 mm in TN, NT-1 and NT-2 nitrogen treatments, respectively, in the CP method; 130, 150 and 150 mm in TN, NT-1 and NT-2 nitrogen treatments, respectively, in the SDI method; and 184 mm in TN management in the FI method. It is noticeable that the SDI required the least seasonal irrigation amount in achieving maximum yield, followed by CP (~ 30 mm more than SDI) and FI (~55 mm more than SDI) owing to the high irrigation efficiency in SDI (>95%) than CP (~75–80%) and FI (45–65%), which delivers the required amount of water and nutrients directly to the crop root zone with minimal losses as compared with CP and FI methods. Also, due to the negligible evaporation rate (from irrigation applications) from the soil surface in the SDI method results in the presence of adequate soil-water in the crop root zone that is potentially used for transpiration as compared with CP and FI method.

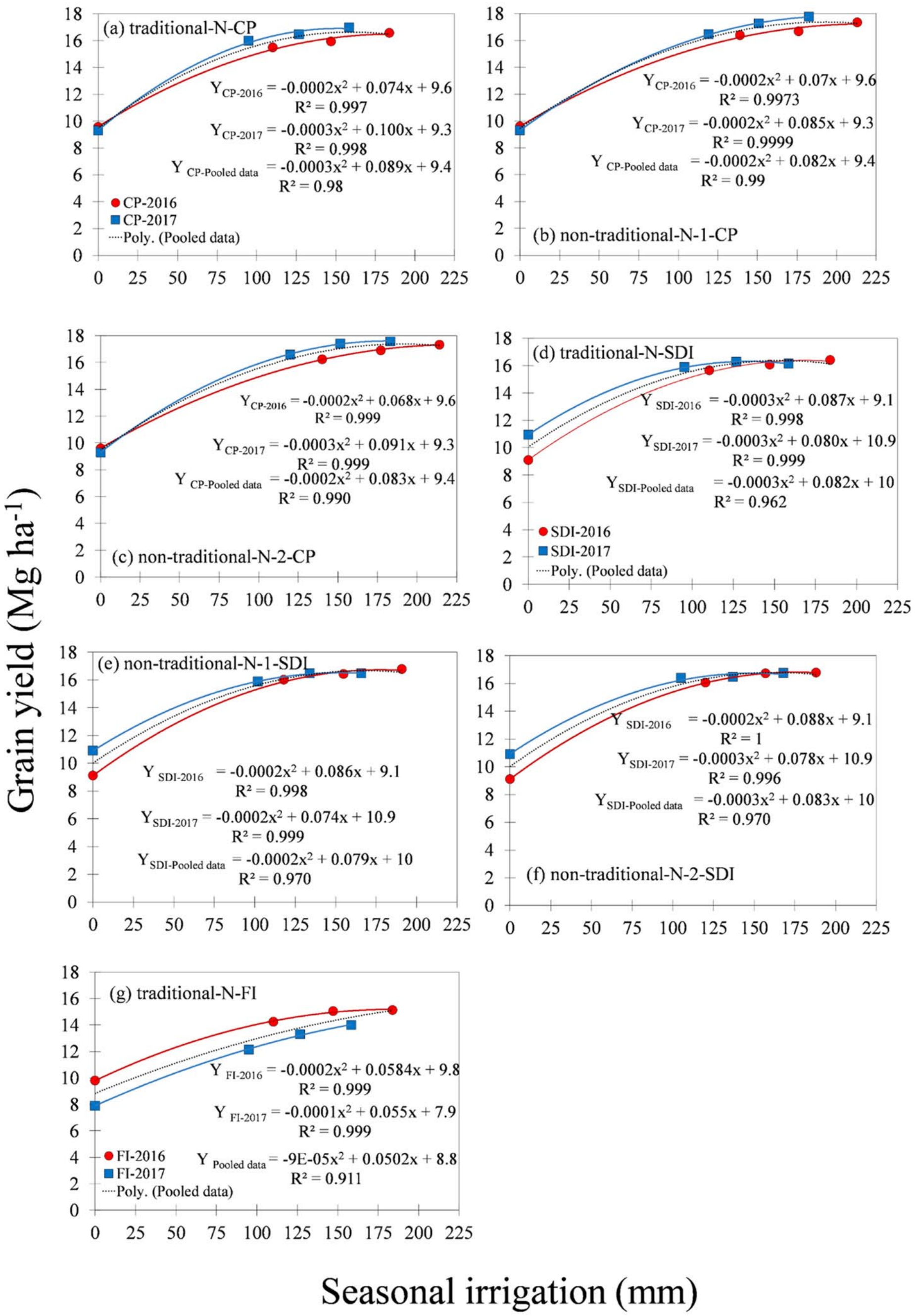

Fig. 1. Relationship between maize seasonal irrigation and grain yield (irrigation-yield production function, IYPF) for each irrigation method: (a) traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; (b) non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; (c) non-traditional nitrogen-2 (NT-2) treatment under CP irrigation method; (d) traditional nitrogen under subsurface drip irrigation (SDI) method; (e) non-traditional nitrogen-1 under SDI method; (f) non-traditional nitrogen-2 under SDI method; (g) traditional nitrogen (N) under furrow irrigation (FI) method, for the 2016 and 2017 growing seasons.

Table 2 Seasonal irrigation, rainfall, seasonal maize evapotranspiration (ETc), grain yield, crop water productivity (CWP), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE) of maize at fully irrigation treatment (FIT), and various limited irrigation levels (i.e., 80% FIT and 60% FIT) including rainfed setting treatments (RFT) under center pivot (CP), subsurface drip irrigation (SDI), and furrow irrigation (FI) methods/fields in 2016 and 2017 growing seasons.

Year	Irrigation Method	Nitrogen treatment	Irrigation treatment	Irrigation (mm)	Rainfall (mm)	Seasonal ETc^b (mm)	CV^a Seasonal ETc (%)	Grain yield^b (Mg ha^{-1})	CV^a Grain yield (%)	CWP^b (kg m^{-3})	IWUE^b (kg m^{-3})	ETWUE^b (kg m^{-3})
2016	CP	Traditional	FIT	184	374	612 b	1.05	16.6 abc	1.4	2.71 ab	3.81 de	4.97 ab
			80% FIT	147	374	573 d	0.49	16.0 dc	3.0	2.78 ab	4.33 bcd	6.22 ab
			60% FIT	110	374	550 e	0.64	15.5 d	5.6	2.82 a	5.37 a	7.50 a
			Rainfed	0	374	471 f	0.15	9.6 e	4.0	2.04 c	–	–
		Nontraditional-1	FIT	213	374	660 a	2.68	17.3 a	1.5	2.63 b	3.64 e	4.11 b
			80% FIT	176	374	609 b	1.97	16.7 abc	6.0	2.74 ab	4.04 de	5.14 ab
			60% FIT	139	374	596 BCE	1.66	16.4 BCE	2.8	2.75 ab	4.91 ab	5.46 ab
		Nontraditional-2	FIT	214	374	661 a	0.21	17.3 a	1.6	2.62 b	3.61 e	4.06 b
			80% FIT	177	374	596 BCE	0.23	16.9 ab	1.1	2.84 ab	4.14cde	5.83 ab
			60% FIT	140	374	588 cd	3.25	16.2 bcd	5.2	2.76 ab	4.73 abc	5.66 ab
2017	CP	Traditional	FIT	159	463	567 b	0.49	17.0 abc	3.5	3.00 BCE	4.84 egf	5.22 b
			80% FIT	127	463	514 e	0.00	16.5 bdc	4.7	3.21 a	5.66 bcd	7.64 b
			60% FIT	95	463	484 f	3.80	16.0 d	4.9	3.31 a	7.04 a	10.46 a
			Rainfed	0	463	420 g	3.02	9.3 e	6.6	2.22d	–	–
		Nontraditional-1	FIT	182	463	614 a	2.88	17.8 a	1.3	2.88c	4.65 gf	4.30 b
			80% FIT	151	463	556 BCE	1.40	17.3 ab	1.3	3.11ab	5.28 def	5.88 b
			60% FIT	119	463	524 ed	1.35	16.5 dc	4.3	3.14 ab	6.00 BCE	6.88 b
		Nontraditional-2	FIT	183	463	617 a	0.57	17.6 a	2.6	2.85c	4.52 g	4.21 b
			80% FIT	151	463	541 cd	0.52	17.4 a	0.7	3.22 a	5.36 cde	6.70 b
			60% FIT	119	463	513 e	2.07	16.6 bdc	4.0	3.24 a	6.09 b	7.89 ab
2016	SDI	Traditional	FIT	184	374	569 b	1.04	16.4 ab	1.1	2.88 abc	3.99 b	7.60 b
			80% FIT	147	374	539 d	1.00	16.1 ab	1.1	2.98 abc	4.74 ab	10.49 b
			60% FIT	110	374	501 e	1.42	15.7 b	1.8	3.12 a	5.96 a	23.08 a
			Rainfed	0	374	473 f	1.35	9.1c	27.6	1.92 d	–	–
		Nontraditional-1	FIT	191	374	602 a	0.47	16.8 a	0.4	2.79c	4.03 b	5.96 b
			80% FIT	155	374	558 BCE	1.27	16.4 ab	3.3	2.94 abc	4.73 ab	8.62 b
			60% FIT	118	374	544 cd	3.25	16.0 ab	6.0	2.94 ab	5.85 ab	9.72 b
		Nontraditional-2	FIT	188	374	596 a	1.07	16.8 a	2.4	2.82 BCE	4.09 b	6.25 b
			80% FIT	157	374	556 BCE	1.28	16.7 a	2.3	3.00 abc	4.86 ab	9.14 b
			60% FIT	120	374	530 d	1.34	16.0 ab	1.8	3.03 ab	5.80 ab	12.20 b

Table 2 (continued)

Year	Irrigation Method	Nitrogen treatment	Irrigation treatment	Irrigation (mm)	Rainfall (mm)	Seasonal ETc[b] (mm)	CV[a] Seasonal ETc (%)	Grain yield[b] (Mg ha^{-1})	CV[a] Grain yield (%)	CWP[b] (kg m^{-3})	IWUE[b] (kg m^{-3})	ETWUE[b] (kg m^{-3})
2017	SDI	Traditional	FIT	159	463	531 b	0.13	16.1 a	2.6	3.04 cd	3.28 b	4.49 b
			80% FIT	127	463	488c	2.17	16.3 a	1.3	3.34 ab	4.20 ab	7.30 b
			60% FIT	95	463	446 e	1.10	15.9 a	3.4	3.56 a	5.19 a	15.94 a
			Rainfed	0	463	415 f	2.22	10.9 b	6.9	2.64 e	–	–
		Nontraditional-1	FIT	166	463	573 a	0.73	16.5 a	3.4	2.87 d	3.33 b	3.49 b
			80% FIT	134	463	527 b	2.54	16.5 a	1.3	3.13 BCE	4.13 ab	4.92 b
			60% FIT	102	463	474 cd	1.94	15.9 a	5.3	3.35 a	4.84 ab	8.30 b
		Nontraditional-2	FIT	168	463	575 a	0.24	16.7 a	1.5	2.91 de	3.45 b	3.61 b
			80% FIT	137	463	523 b	1.89	16.5 a	1.3	3.15 BCE	4.03 ab	5.08 b
			60% FIT	105	463	468 d	0.90	16.4 a	1.7	3.50 a	5.18 a	10.26 b
2016	FI	Traditional	FIT	184	374	579 a	0.02	15.2 a	0.6	2.62 a	2.91 a	5.12 b
			80% FIT	147	374	553 b	0.09	15.1 a	3.3	2.72 a	3.57 a	6.69 b
			60% FIT	110	374	507c	0.08	14.3 a	3.0	2.81 a	4.04 a	13.92 a
			Rainfed	0	374	475 d	0.15	9.8 b	7.0	2.07 b	–	–
2017	FI	Traditional	FIT	159	463	552 a	0.34	14.0 a	13.7	2.54 a	3.85 a	3.95 b
			80% FIT	127	463	494 b	0.26	13.3 a	9.6	2.69 a	4.26 a	5.59 ab
			60% FIT	95	463	456 c	0.35	12.2 a	13.4	2.66 a	4.47 a	7.26 a
			Rainfed	0	463	398 d	0.30	7.9 b	15.3	1.99 b	–	–

a. CV = coefficient of variation.

b. Grain yield, crop water productivity (CWP), irrigation water use efficiency (IWUE), evapotranspiration water use efficiency (ETWUE) means followed by the same letter within a same irrigation method and year are not significantly different at the 5% significance level.

Moreover, the SDI's high degree of uniformity combined with dry soil surface resulted in less weed germination/pressure as compared with FI and CP (visual observation). Whereas the FI has a high degree of non-uniformity that coupled with high flow rate that could be led to soil erosion and potential cause of soil surface sealing and hence relatively high magnitude of run-off.

Both NT-1 and NT-2 within the same irrigation method revealed highest seasonal irrigation requirements in achieving maximum yield than the TN treatment [15 and 20 mm more irrigation requirements in the CP and SDI, respectively (Fig. 1a, b, c, d, e and f)]. This is more likely because of two major reasons: (i) applying N (i.e., fertigation) three (i.e., NT-1) or four (i.e., NT-2) times at critical maize growth stages (i.e., VE, V8, VT and R3) throughout the growing seasons promoted more vigorous maize root development plus increased healthy leaf area per plant, which resulted in high transpiration rate, hence more seasonal irrigation requirements to satisfy crop water requirements, (ii) the amount of required irrigation water to apply fertilizer through fertigation (i.e., combination of fertilization and irrigation) was higher in the CP than SDI method and differed by as much as 14% as a function of differences in the way the water is delivered to the plants between the irrigation methods (Table 2).

The grain yield production per 25.4 mm of irrigation, which is the most common amount of water that maize producers apply per irrigation with CP method (Irmak, 2015b), exhibited intra-annual and inter-annual variations between N application timing treatments within and between the irrigation methods. Grain yield production per 25.4 mm of irrigation ranged from 1.60 (NT-2) to 1.75 Mg ha^{-1} (TN); from 2.02 (TN) to 2.11 Mg ha^{-1} (NT-2) and 1.35 Mg ha^{-1} in the CP, SDI and FI methods, respectively, in 2016; and from 2.03 (NT-1) to 2.35 Mg ha^{-1} (TN); from 1.79 (NT-2) to 1.84 Mg ha^{-1} (TN); and 1.33 Mg ha^{-1} in the CP, SDI and FI methods, respectively, in 2017 (**Fig. 2**a and b). The highest grain yield production per 25.4 mm of irrigation amount for pooled data (representing the two growing seasons) followed the order of CP-TN (2.07 Mg ha^{-1}) > SDI-NT-2 (1.91 Mg ha^{-1}) > FI-TN (1.22 Mg ha^{-1}) (Fig. 2c). The TN had about 6% and 4.5% higher yield production per 25.4 mm of irrigation than NT-1 and NT-2 in the CP method, respectively, owing to the amount of water that was applied with N fertigation being unbeneficial and might be lost as soil-water evaporation from the canopy (intercepted

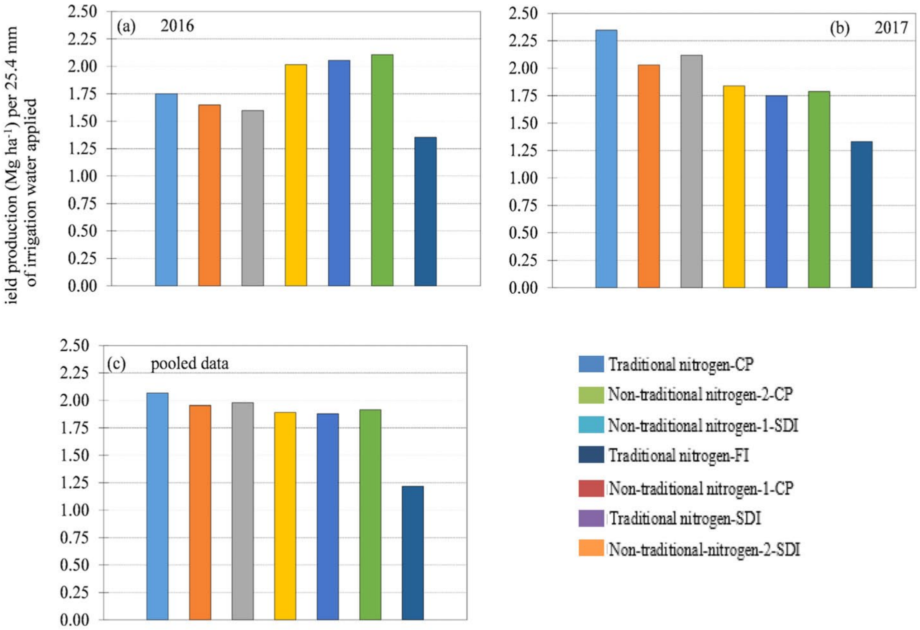

Fig. 2. Grain yield production per 25.4 mm of irrigation water for the: (a) 2016; (b) 2017 growing seasons, and (c) pooled of 2016 and 2017 data for each irrigation method: traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; nontraditional nitrogen-2 (NT-2) treatment under CP irrigation method; traditional nitrogen under subsurface drip irrigation (SDI) method; non-traditional nitrogen-1 under SDI method; non-traditional nitrogen-2 under SDI method; traditional nitrogen under furrow irrigation (FI) method.

water by the canopy) and soil surface. As a result, a quadratic shape and associated slope magnitudes did not respond (increase) with irrigation water beyond the required/optimum amount of applied application. On the other hand, the highest yield production per 25.4 mm was obtained in SDI-NT-2 (1.91 Mg ha^{-1}) and was higher by 1% and 1.6% than the TN and NT-1, respectively. For all irrigation methods, there were strong relationships between maize grain yields and seasonal irrigation amounts ($R^2 \geq 0.99$) for individual treatments as well as for the pooled data where the R^2 values ranged from 0.91 in the FI-TN to 0.99 in the CP-NT-1 and NT-2. One of the primary factors that forms strong grain yield relation to applied irrigation (i.e., forming curvilinear shape) is the quantity of yield under rainfed conditions in a given year. Lower yield during below normal precipitation year under rainfed condition exhibits a curvilinear relationship and results in increase in grain yield production per unit of water applied. Therefore, maize grain yield response to applied irrigation varies substantially between locations and years as well as in the same location between the years (Irmak, 2015a; b). Inter-annual variations in yield response to per unit of irrigation were observed by several researchers. For example, for FI-irrigated maize in a semi-arid region, Kipkorir et al. (2002) reported that crop water requirement was about 1100 mm for achieving maximum grain yield during dry years. Irmak (2015a) observed an average of 1.45 Mg ha^{-1} maize grain yield production per 25.4 mm in long-term research (six years) under CP. Moreover, Irmak et al. (2020) reported various range of yield production per 25.4 mm for maize in four different locations and climates under SDI and sprinkler irrigation methods for three years of research. However, none of these field research accounted for N timing impact on yield productivity per unit of irrigation amount applied. The ranges of average observed values of yield increase per 25.4 mm of irrigation were 0.80–1.40 Mg ha^{-1} (SDI), 0.87–1.40 Mg ha^{-1} (SDI), 1.20–1.40 Mg ha^{-1} (sprinkler) and 1.40 Mg ha^{-1} (SDI).

3.3. Evapotranspiration-yield production functions (ETYPF) and basal evapotranspiration (ETb)

Maize seasonal ETc exhibited substantial variations between the treatments in a given growing season and for the same treatments between the years and ranged from 471 mm (CP-RFT-TN) to 661 mm (CPFIT-NT-2) in 2016; and from 398 mm (FI-RFT-TN) to 617 mm (CP-FITNT- 2) in 2017 (Table 2). In almost all cases, FIT had the highest ETc and RFT had the lowest ETc in both years. Maize ETYPFs had a strong and linear increase with increasing ETc and also exhibited intra-annual variation between the irrigation methods within the same year and inter-annual variation within and between the irrigation method (**Fig. 3**). However, the ETYPFs exhibited less intra-annual variation between the N application timing treatments within the same irrigation method for the given year, except between TN and NT-1 and NT-2 in the CP method in 2016 (Fig. 3a, b and c). Grimes et al. (1969) reported that the quadratic relationship between yield and ETc could be result of a potential decrease in water utilization efficiency by the plant and probable deep percolation occurrence with the highest irrigation level. This could be the case in the

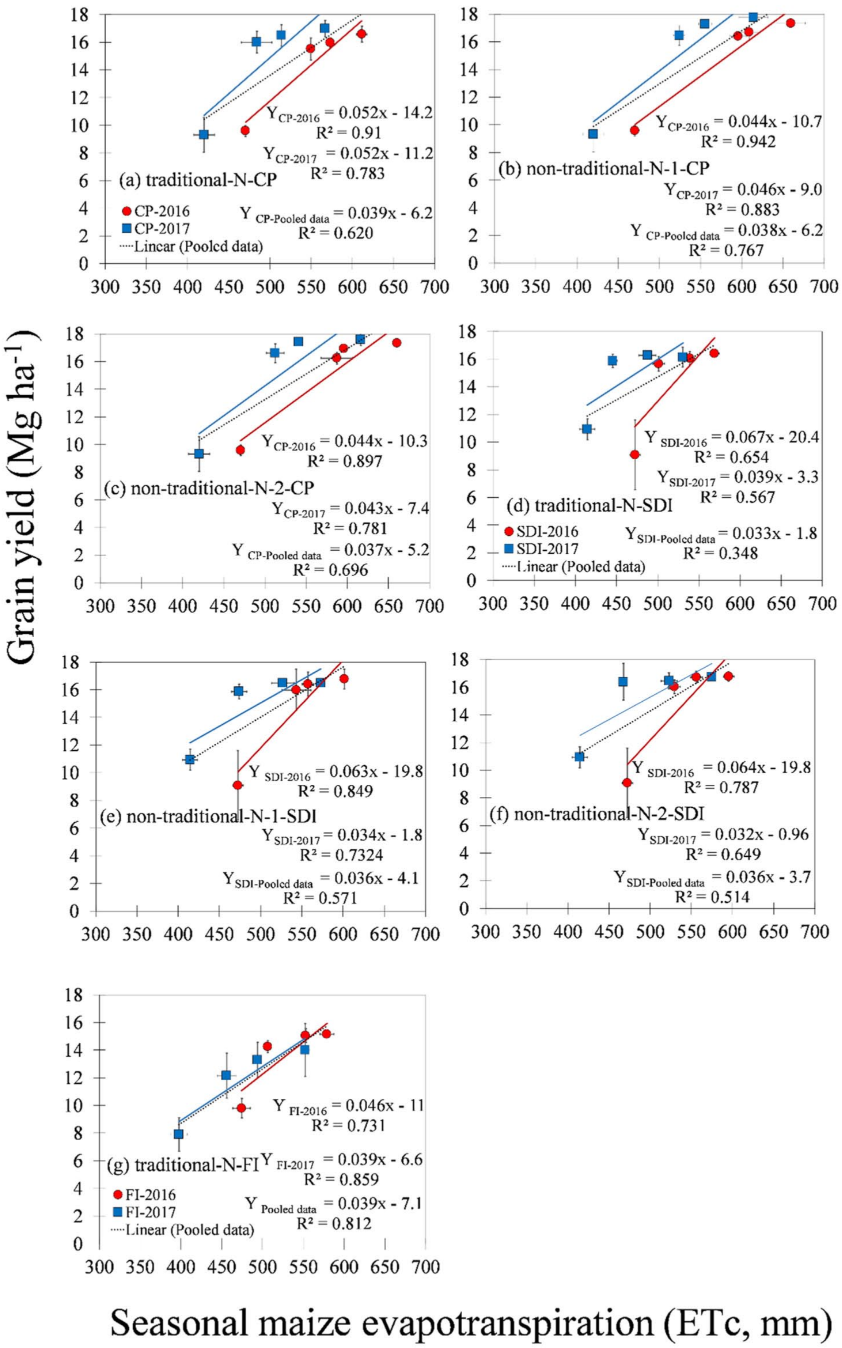

Fig. 3. Relationship between maize grain yield and seasonal maize evapotranspiration (evapotranspiration-yield production function, ETYPF) for each irrigation method: (a) traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; (b) non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; (c) non-traditional nitrogen-2 (NT-2) treatment under CP irrigation method; (d) traditional nitrogen under subsurface drip irrigation (SDI) method; (e) nontraditional nitrogen-1 under SDI method; (f) non-traditional nitrogen-2 under SDI method; (g) traditional nitrogen (TN) under furrow irrigation (FI) method, for the 2016 and 2017 growing seasons. Vertical bars represent grain yield standard deviation and horizontal bars represent seasonal maize evapotranspiration standard deviation.

SDI-FIT in the current research. While Irmak et al. (2016) stated that the quadratic relationship between maize grain yield and ETc might occur under SDI when ETc increases when irrigation applications exceed irrigation requirement in which crop yield would not respond to increased irrigation amount. Others reported linear relationships between ETc and yield (e.g., Hanks, 1974; Doorenbos and Kassam, 1979; Howell et al., 1995; Payero et al., 2006, 2008; Irmak et al., 2019; Mohammed et al., 2019). Across all treatments, the 2016 growing season showed higher ETYPF slopes than 2017 growing season. This might be attributed to the relatively higher (~100 mm) total precipitation coupled with cooler average air temperatures in 2017 than in 2016. This outcome reveals that the year (i.e., weather variables; precipitation amount and distribution; day and night air temperatures, wind speed, relative humidity, solar radiation and vapor pressure deficit), irrigation management (timing and amount), planting and emergence date, fertilizer management (including timing of N applications), and irrigation method can all have impact on maize grain yield response to seasonal ETc. Sinclair et al. (1984) demonstrated that the highest slope of maize grain yield response to ETc represents the seasonal transpiration efficiency, which is an effective variable to evaluate any irrigation and/or N management strategy as well as irrigation method's impact on crop performance. Across two growing seasons and N treatments, the ETYPF slopes followed the order of 0.067 kg m^{-3} (SDI) > 0.052 kg m^{-3} (CP) > 0.046 kg m^{-3} (FI). The highest ETYPF slope with SDI is related to its high irrigation efficiency than other methods. When the pooled ETYPFs data for all irrigation and N management treatments for both years for a given irrigation method are considered, the pooled ETYPF data had same/similar slope values for all three irrigation methods (0.039 for CP and FI, and 0.036 for SDI). Another important finding in Fig. 3a, b, c, d and e is that the irrigation levels had more pronounced impacts on grain yield response to ETc than the N application timings. While this research was not specifically designed to investigate which variable (water or N) would have a greater impact on grain yield productivity and ETc, the results of this research points toward more importance of water than nitrogen in terms of maximizing grain yield per unit of ETc under these experimental conditions.

Basal evapotranspiration (ETb) is defined as the amount of evaporative losses that occur for crop establishment and development before the crop starts the first increment of grain yield formation (Irmak, 2015a, 2015b; Irmak et al., 2019). This variable is important for water availability vs. crop water requirements assessments, especially in areas where water limitations can influence water resources allocation. Implementation of any conservation practices [e.g., reduced or no-tillage practices, SDI (due to its effectiveness in reducing surface evaporation losses), drought-tolerant hybrid selection, planting spacing adjustments to achieve early canopy closure to reduce evaporation, etc.] that can reduce evaporative losses (ETb) from crop emergence to the period when plants start producing grain yield can aid in mitigating water-limiting conditions. These practices can provide additional amount of water to be used later in the growing season during later and more water stress-sensitive part of the vegetative and reproductive growth stages (Irmak, 2015b). ETb exhibited intra-annual variation between the irrigation methods within the same year and also inter-annual variation for the same treatments and irrigation methods (**Fig. 4**). However, there was less intra-annual variation between N timing treatments within the same

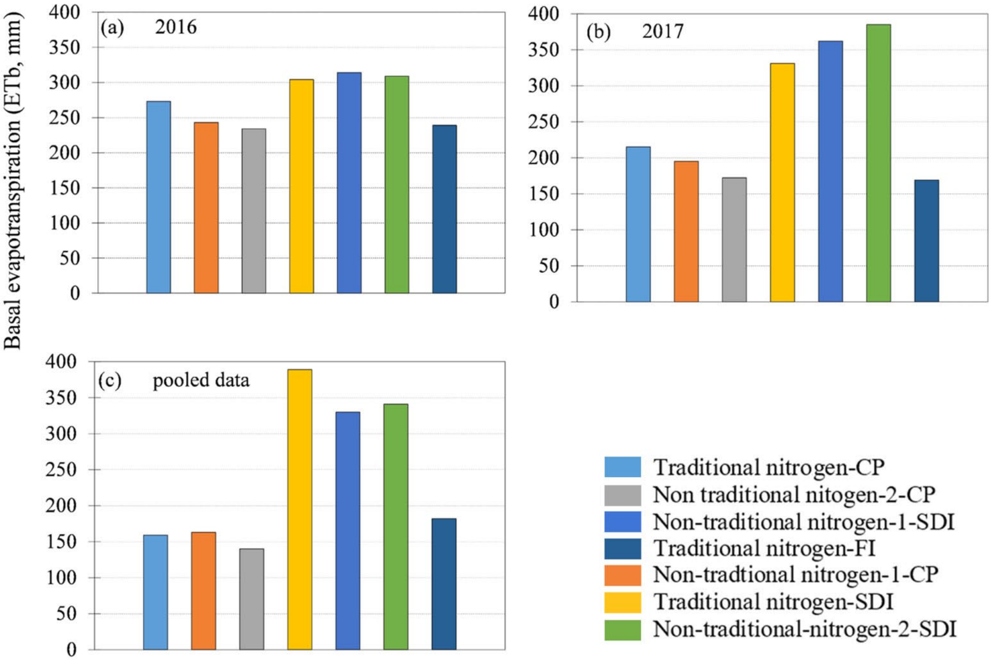

Fig. 4. Basal maize evapotranspiration (ETb) for the: (a) 2016; (b) 2017 growing seasons, and (c) pooled of 2016 and 2017 data for each irrigation method: traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; nontraditional nitrogen-2 (NT-2) treatment under CP irrigation method; traditional nitrogen under subsurface drip irrigation (SDI) method; non-traditional nitrogen- 1 under SDI method; non-traditional nitrogen-2 under SDI method; traditional nitrogen under furrow irrigation (FI) method.

irrigation method and year, except in 2017. Fig. 4b reveals that there was a substantial intra-annual variation between N treatments within the same irrigation method. Overall, the highest ETb values were followed the order of CP > FI > SDI in 2016; and FI > CP > SDI in 2017.

ETb values across all treatments ranged from 234 mm (CP-NT-1) to 314 mm (SDI-NT-1) in 2016; and from 169 (FI-TN) to 385 mm (SDI-NT-2) in 2017. Inconsistency in ETb between the two years can be attributed to the weather variables coupled with irrigation practices (timing and amount) impact on ETb. Other researchers (Musick and Dusek, 1980; Howell et al., 1995; Irmak, 2015a; Mohammed et al., 2019; Irmak et al., 2019) reported ETb range of 129–418 mm, depending on numerous factors such as climate, location, soil characteristics, irrigation timing and frequency, type of irrigation method, crop and field management practices and maize hybrid characteristics. While very limited research quantified ETb values previously, to the best of the knowledge of the authors, this current research is the first that accounted for the impact of N management on ETb and quantified ETb values for different irrigation and N management under three major irrigation methods simultaneously under the same environmental conditions, soil characteristics, crop management practices under the same climatic conditions.

3.4. Water Productivity Indicators

3.4.1. Crop water productivity (CWP)

Across all treatments and irrigation methods, CWP ranged from 1.92 kg m^{-3} (SDI-RFT-TN) to 3.12 kg m^{-3} (SDI-60% FIT-TN) in 2016; and from 1.99 kg m^{-3} (FI-RFT-TN) to 3.56 kg m^{-3} (SDI-60% FIT-TN) in 2017 (Table 2 and **Fig. 5** and **Fig. 6**). The season of the year significantly ($p < 0.05$) influenced the CWP across all treatment and irrigation methods. The CWP values were 13.1% and 11% higher in CP and SDI, respectively, in 2016 than the corresponding values in 2017. The FI method had 3.6% lower average CWP values 2016 than in 2017 because of the higher yield production per unit of water and low water use. Both irrigation method and irrigation levels had significant role on the magnitude of the CWP values. The CWP values were, in most cases, greater for the limited irrigation levels (60% FIT and 80% FIT) and lowest for FIT across the irrigation methods regardless the N treatments. Other researchers (Kang et al., 2000; Kang and Zhang, 2004) observed CWP values between 2.7

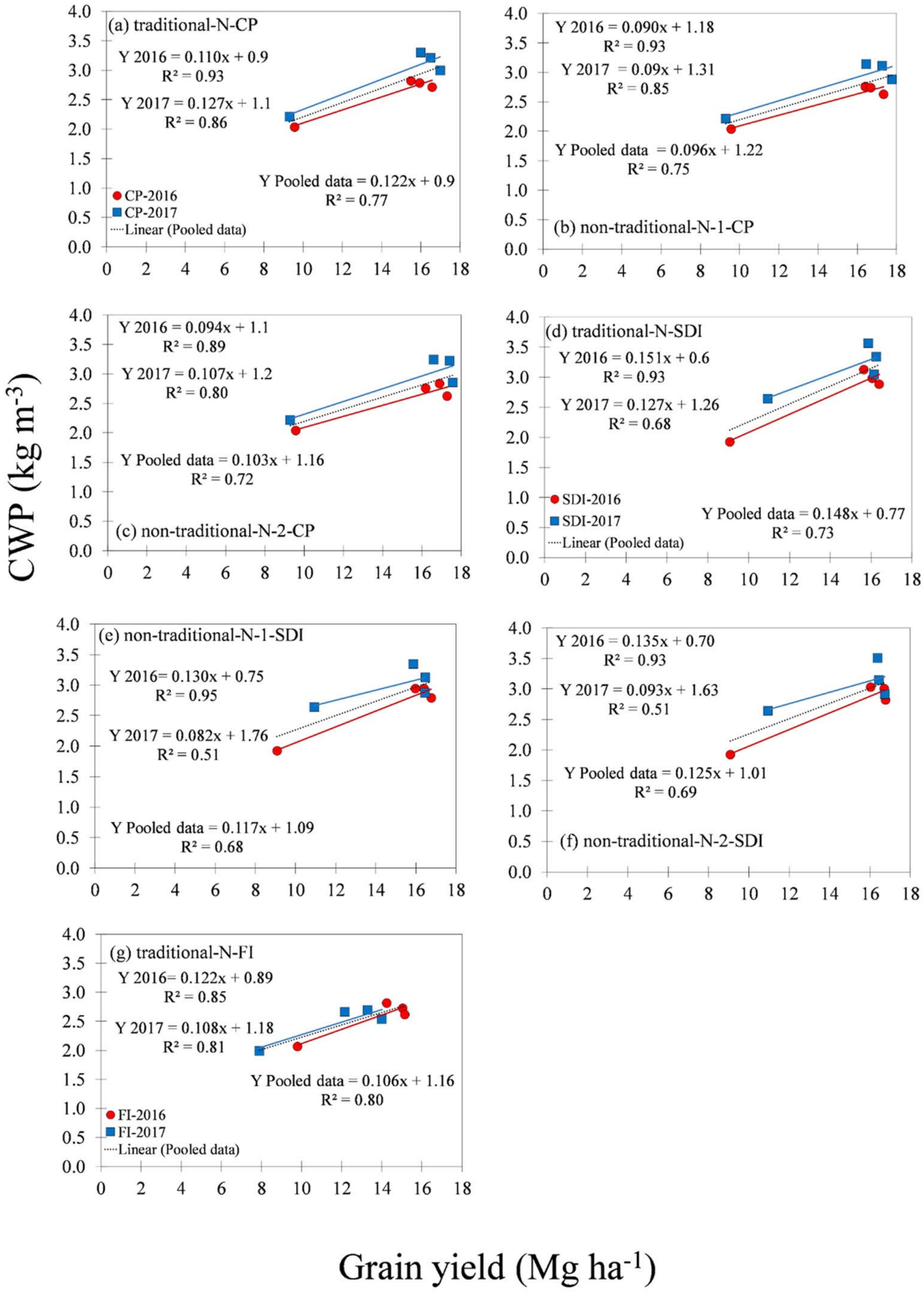

Fig. 5. Relationship between crop water productivity (CWP, kg m^{-3}) and maize grain yield (Mg ha^{-1}) for each irrigation method: (a) traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; (b) non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; (c) non-traditional nitrogen-2 (NT- 2) treatment under CP irrigation method; (d) traditional nitrogen under subsurface drip irrigation (SDI) method; (e) non-traditional nitrogen-1 under SDI method; (f) non-traditional nitrogen-2 under SDI method; (g) traditional nitrogen (TN) under furrow irrigation (FI) method for the 2016 and 2017 growing seasons.

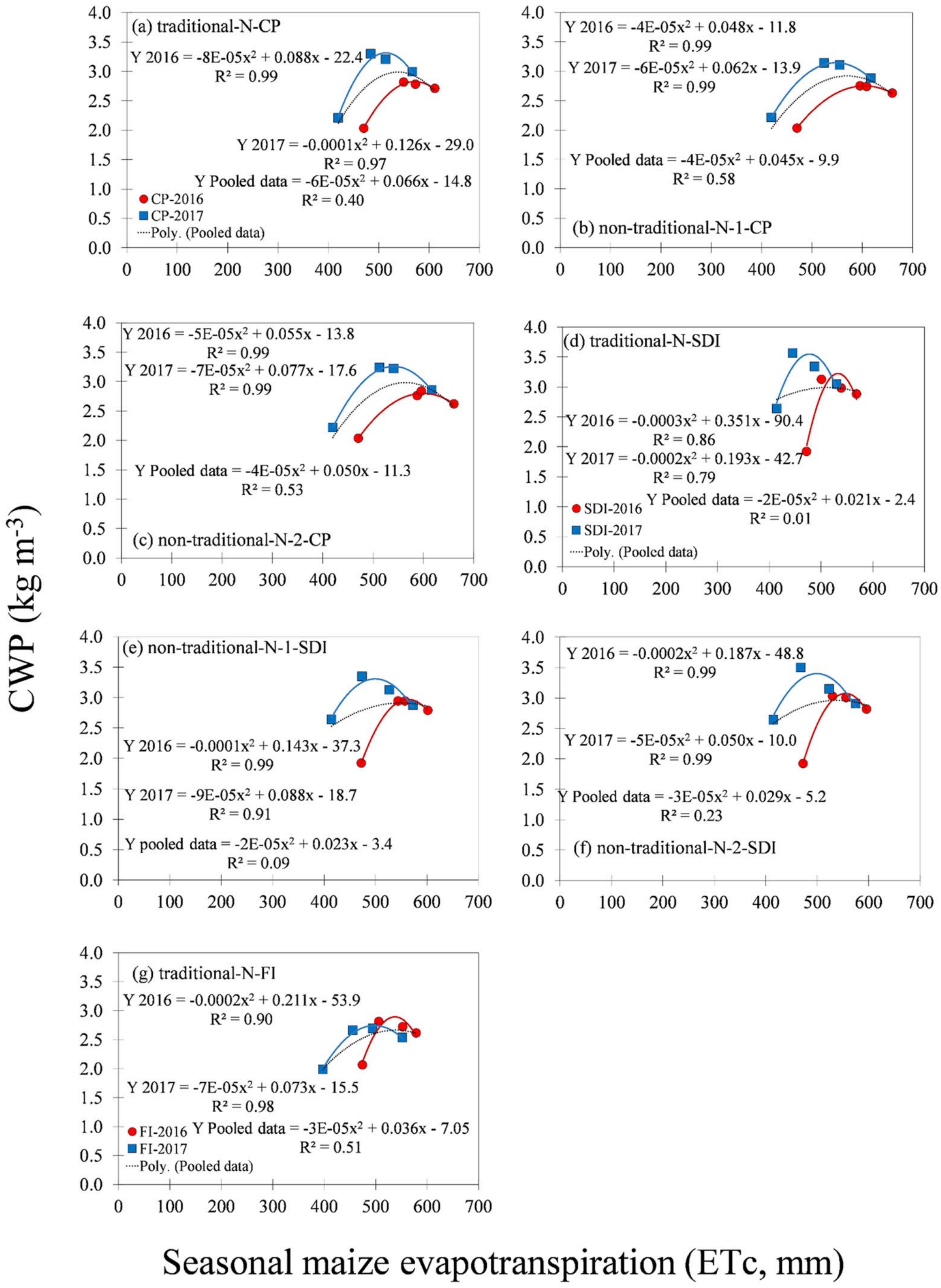

Fig. 6. Relationship between crop water productivity (CWP, kg m^{-3}) and seasonal maize evapotranspiration (ETc, mm) for each irrigation method: (a) traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; (b) non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; (c) non-traditional nitrogen-2 (NT-2) treatment under CP irrigation method; (d) traditional nitrogen under subsurface drip irrigation (SDI) method; (e) non-traditional nitrogen-1 under SDI method; (f) non-traditional nitrogen-2 under SDI method; (g) traditional nitrogen under furrow irrigation (FI) method in 2016 and 2017.

and 5 kg m^{-3}. In both years, irrigation method significantly ($p < 0.05$) influenced CWP. Across all treatments for the given irrigation method, the highest averaged CWP of 3.00 kg m^{-3} was observed in the SDI method ($p < 0.05$) followed by 2.84 kg m^{-3} in the CP method ($p < 0.05$) and 2.51 kg m^{-3} in the FI method. One reason for the lower CWP values in the FI method is mainly because of the rapid downward water movement (deep percolation) of water as well as higher surface run-off than SDI and CP. Overall, the N treatments also significantly ($p < 0.05$) influenced CWP. The averaged CWP was higher in traditional N treatment (i.e., averaged FIT, 80% FIT, and 60% FIT, excluding RFT) than NT-1 and NT-2. The CWP in the TN treatment was 2.2% and 1.1% higher ($p > 0.05$) in the CP method than the values in the NT-1 and NT-2, respectively. Similarly, the CWP values in the TN treatment were 4.3% and 2.3% higher ($p > 0.05$) than the NT-1 and NT-2, respectively in the CP method; and 6.1% and 3.8% higher ($p > 0.05$) than the respective treatment values, respectively, in the SDI method in 2017. These results are most likely due to the additional water which was utilized for fertigation purpose (in-season fertigation) relatively decreased CWP due to large amount of total season irrigation water application.

The two-year average CWP was 7.3% and 2.6% higher ($p < 0.05$) in the NT-1 and NT-2 treatments in the SDI method than respective values in the CP method. Across all treatments, in most cases, CWP reached its maximum value in the 60% FIT and/or 80% FIT in the SDI method and this can be interpreted as a result of decreased soil surface evaporation in the SDI method that might partitioned more water for crop productivity through transpiration as suggested by Howell (2001), which could indicate that crop transpiration is inhibited under drought conditions (i. e., dry and/or partial dry root-zone) (Fig. 5) if soil-water availability is suboptimal. In general, there was a significant difference ($p < 0.05$) in maize CWP among the coupling effect of irrigation levels and N application timings treatments (Table 2). Maize in RFT had significantly ($p < 0.05$) lower CWP values than irrigated treatments across irrigation methods in both years (Table 2). This is due to irrigated treatments having greater ETc than RFT, which resulted in more grain yield production. Djaman and Irmak (2012) reported maize CWP ranging from 1.89 to 2.58 kg m^{-3} in two-year research (2009–2010) under CP irrigation with the lowest CWP value occurring in the RFT. Similar results were observed by Irmak (2015b) from a six-years research who reported maize CWP ranging from 1.21 to 2.51 kg m^{-3} also under CP irrigation. In a three-year drought-tolerant and conventional maize hybrids performance response to water and planting population density research, Irmak et al. (2019) reported CWP values ranging from 1.47 and 3.46 kg m^{-3}; and from near zero to 3.05 kg m^{-3} under linear-move sprinkler irrigation system and SDI methods, respectively, with drought-tolerant maize hybrids having higher CWP than the conventional hybrids. Mohammed et al. (2019) reported CWP values between near zero and 2.69 kg m^{-3} in a semi-arid climate, and from 0.32 and 2.47 kg m^{-3} in another semi-arid climate, under the SDI method. The lower CWP values observed in these two studies were due to the historically driest year (i.e., 2012), which influenced the rainfed treatments' yields negatively (and substantially). Rafiee and Shakarami (2010) reported higher maize CWP values, ranging from 3.6 to 4.5 kg m^{-3}, under FI and fixed every other furrow irrigation, respectively, and 4.2 kg m^{-3} of highest CWP under every other row furrow irrigation. Zhou et al. (2019) found a range of 2.3–2.9 kg m^{-3} and 1.5–1.8 kg m^{-3} of maize CWP under surface drip irrigation and border irrigation systems, respectively. The current research results are also comparable (but notably higher) than those observed in other studies such as Hanks et al. (1978), Musick and Dusek (1980), Payero et al. (2008), Irmak and Djaman (2016) and Irmak et al. (2016). There was a strong linear relationship between CWP and grain yield, whereas non-linear (2nd order polynomial quadratic) relationships between CWP and ETc were observed (Figs. 5 and 6). The quadratic relationship between CWP and ETc had much higher R^2 values ($R^2 \geq 0.79$; Fig. 6) for the individual years than respective values obtained from CWP vs. grain yield linear relationships. However, the pooled R^2 values were much lower than the respective treatments' CWP values obtained from the CWP vs. grain yield linear relationships (Fig. 6). Other researchers (Howell, and Payero et al., 1995, 2008) found that CWP increased non-linearly with increased seasonal ETc. In other words, after certain threshold, economical grain yield did not respond to additional amount of irrigation water applied (inefficiency in irrigation management). However, Li et al. (2010), Fang et al. (2010), Katerji et al. (2010), Irmak (2015b) and Irmak et al. (2016) reported linear relationships between CWP and ETc.

3.4.2. Irrigation water use efficiency (IWUE)

In all cases, across all treatments, the highest IWUE was always obtained with 60% FIT and lowest with the FIT. IWUE ranged from 2.91 (CP-FIT-TN) to 5.96 kg m^{-3} (SDI-60% FIT-TN) in 2016; and from 3.28 (SDI-FIT-TN) to 7.04 kg m^{-3} (CP-60% FIT-TN) in 2017 (Table 2, **Fig. 7**). Across all treatments, the highest averaged IWUE values of 4.89, 4.29 and 3.51 kg m^{-3} were found in the SDI, CP and FI methods, respectively, in 2016; whereas the highest averaged IWUE values of 5.49, 4.19 and 4.19 kg m^{-3} were found in the CP, FI and SDI methods, respectively, in 2017. The lower averaged IWUE value for SDI in 2017 could be due to the fact that plants in the FIT did not utilize all the applied irrigation water and that while FIT is an adequate full irrigation strategy, it could be an over-irrigation in the case of SDI method. This was confirmed with the neutron probe-measured soil-water content data (data not shown). Thus, the grain yield did not reach its expected potential peak value, resulting in lower IWUE under FIT across N treatments. This may support the concept that when the SDI system is properly designed, installed and managed, crops grown in the SDI method can have less irrigation water requirements, due to reduced surface evaporation and other water losses, than CP and FI to produce comparable or greater, yields when all irrigation methods are practiced/operated under the same conditions with the same soil and crop management practices and climate. There was a sharp increase in IWUE under limited irrigation treatments as compared with FITs (Table 2 and Fig. 7). Similar to the findings with CWP, most of the maximum IWUE values were observed with the 60% FIT followed by 80% FIT and FIT across all treatments, irrigation methods and growing seasons. This is more likely due to the plants in the limited irrigation treatments having the tendency to fully utilize the applied water and promoting deeper soil-water extraction and utilizing the stored soil-water more effectively than the plants in the FITs. Hence, depending on other factors, where irrigation water is limited, employing SDI method could be a viable option for optimizing maize grain yield production while reducing total applied irrigation amounts and increasing IWUE.

In most cases, the IWUE values were significantly ($p < 0.05$) higher in 60% FIT than FIT in all irrigation methods and N management treatments, except IWUE in the FI method did not have any significant differences between irrigation levels in either growing season (Table 2). When

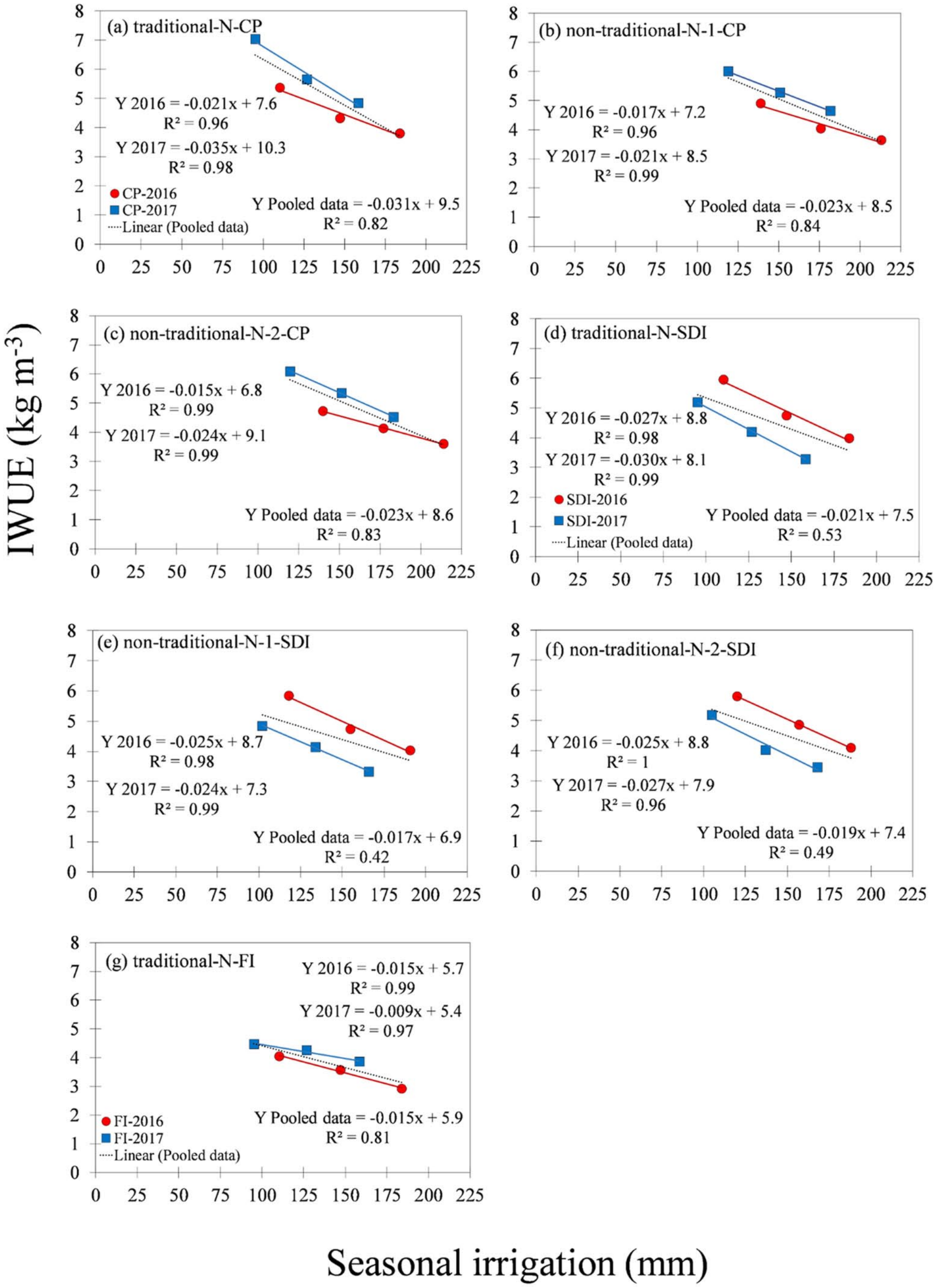

Fig. 7. Relationship between irrigation water use efficiency (IWUE, kg m^{-3}) and seasonal irrigation (mm) for each irrigation method: (a) traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; (b) non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; (c) non-traditional nitrogen-2 (NT- 2) treatment under CP irrigation method; (d) traditional nitrogen under subsurface drip irrigation (SDI) method; (e) non-traditional nitrogen-1 under SDI method; (f) non-traditional nitrogen-2 under SDI method; (g) traditional nitrogen under furrow irrigation (FI) method in 2016 and 2017 growing seasons.

comparing the traditional N across all irrigation methods, irrigation levels and years, there was a significant ($p < 0.05$) interaction between irrigation method and year as well as significant ($p < 0.05$) impact of irrigation levels on IWUE response (i.e., FIT, 80% FIT and 60% FIT). For example, in 2016, across irrigation levels, CP method had significantly ($p < 0.05$) higher (28%) IWUE values than FI method; and SDI method had significantly ($p < 0.05$) higher (40%) IWUE than FI method. The IWUE values between the CP and SDI methods were not significantly different ($p > 0.05$). In 2017, CP method had significantly ($p < 0.05$) higher (40%) IWUE than FI method; CP had significantly ($p < 0.05$) higher IWUE (39%) than SDI; and IWUE values between the SDI and FI methods were not significantly different ($p > 0.05$). The 2017 growing had the highest averaged IWUE values in CP and FI methods, whereas highest averaged IWUE values in SDI were observed in 2016.

Similar findings were observed when comparing N treatments across CP and SDI and between their irrigation levels. There was a significant interaction between irrigation method and year ($p < 0.05$) as well as significant ($p < 0.05$) impact of irrigation levels on IWUE. However, the N treatments did not have significant ($p > 0.05$) influence on IWUE in the CP or SDI methods. Across irrigation methods (i.e., CP and SDI) and years, there was no significant ($p > 0.05$) difference in IWUE between any of the N treatments. The highest averaged IWUE values of 4.76, 4.63 and 4.58 kg m^{-3} were observed under TN, NT-1 and NT-2, respectively. In 2016, across irrigation levels and N treatments, SDI method had significantly ($p < 0.05$) higher (14%) IWUE than CP method. In 2017, the CP method had significantly ($p < 0.05$) higher (31%) IWUE than SDI method. When comparing the combination of NT-1 and NT-2 vs. TN, again, there was a significant interaction between irrigation methods and years ($p < 0.05$) as well as significant ($p < 0.05$) impact of irrigation levels, irrigation method and the combination of NT-1 and NT-2 vs. TN on IWUE. Across the years, the highest averaged IWUE values of 5.12, 4.75, 4.46 and 4.39 kg m^{-3} were observed in CP-TN, the combination of CP-NT-1 and CP-NT-2 and SDI-TN, respectively. In the CP method, NT had significantly ($p < 0.05$) higher IWUE than the combination of NT-1 and NT-2 treatments, whereas no significant ($p > 0.05$) difference was observed between NT and the combination of NT-1 and NT-2. The IWUE of the combination of NT-1 and NT-2 was significantly ($p < 0.05$) higher in the CP than in the SDI method.

Across all treatments, irrigation methods and years, IWUE decreased linearly with increased seasonal irrigation amounts (Fig. 7). The correlation between IWUEs and seasonal irrigation amounts were strong ($R^2 \geq 0.96$). The pooled data R^2 values were smaller in the SDI and varied substantially among irrigation methods with the respective treatment values in the individual years. IWUE ranged from 0.82 (TN) to 0.84 (NT-1), from 0.42 (NT-1) to 0.53 (TN) and from 0.81 (TN) in the CP, SDI and FI methods, respectively. In both years, the IWUE reached its maximum values at different range of the total seasonal amount of irrigation water applied and the ranges for the same irrigation level and N treatments varied substantially between the irrigation methods (i.e., 95–110, 119–140 and 120–140 mm for TN, NT-1 and NT-2, respectively, under the CP method; 95–110, 102–118 and 105–120 mm for TN, NT-1 and NT-2, respectively, under SDI; and 95–110 for TN under FI method). Howell et al. (1995) reported IWUE range of 1.51–2.48 kg m^{-3} for irrigated maize under low energy precision application (LEPA) in a semi-arid climate and they observed that the trend for IWUE decreased with increasing seasonal irrigation amount. Djaman and Irmak (2012) reported IWUE range between 2.52 and 5.90 kg m^{-3} for irrigated maize under CP. Irmak et al. (2016) reported higher IWUE range of 1.10–9.40 kg m^{-3} for SDI-irrigated maize under different irrigation frequencies (low, medium and high). Hassanli et al. (2009) reported maize IWUE ranging from 1.43 to 1.5 kg m^{-3} and 1.91–2.12 kg m^{-3} under furrow with hydro flume and SDI method, respectively, in an arid climate. Howell (2001) concluded that the IWUE does not differ much with changing irrigation methods and reported IWUE range of 1.98–2.53 kg m^{-3}, 1.73–2.36 kg m^{-3} and 1.79–2.35 kg m^{-3} for maize under surface irrigation (level basins), LEPA and SDI methods, respectively, which is in contrast with the results observed in the current research, which presents strong evidence otherwise.

3.4.3. Evapotranspiration water use efficiency (ETWUE)

The ETWUE is another effective assessment of cropping system's performance to irrigation level and methods and N management. In many (but not all) cases, the highest ETWUE values were usually found with 60% FIT and lowest with FIT. ETWUE ranged from 4.06 (CP-FITNT- 2) to 23.08 kg m^{-3} (SDI-60% FIT-TN) in 2016, respectively; and from 4.21 (FIT-TN-2) to 10.46 kg m^{-3} (60% FIT-TN), 3.49 (SDI-FIT-NT-1) to, and 3.95 (FI-FIT-TN) to 15.94 kg m^{-3} (SDI-60% FIT-TN) in 2017 (Table 2).

Across all treatments, the highest averaged ETWUE values of 10.34, 8.58 and 5.44 kg m^{-3} were found in the SDI, FI and CP methods, respectively, in 2016, whereas the highest averaged ETWUE values of 7.04, 6.58 and 5.60 kg m^{-3} were found in the SDI, CP and FI methods, respectively, in 2017. Across all treatments, irrigation methods and years, the ETWUE decreased linearly with increased seasonal ETc (**Fig. 8**). The correlation between ETWUEs and seasonal ETc were strong (Fig. 8) ($R^2 \geq 0.92$). The pooled data R^2 values were higher (≥ 0.86) in the CP and comparable to the individual years, whereas much lower (≥ 0.14) pooled R^2 values were observed in the SDI and FI methods. This is because ETWUE magnitudes are mainly controlled by weather variables and, as a result, influenced by the amounts of seasonal ETc and grain yield of the rainfed treatment. Therefore, the large variations of these two variables were more profound in the SDI and FI than in the CP method. This is probably because of increased variability in rainfed grain yields between the treatments (less variability in the grain yield in the CP method). Higher yields in RFT in the SDI method and lower yields in the FI which were associated with relatively lower ETc in 2017, causing the intra-annual variation in ETWUE among the irrigation treatments and inter-annual variation between the years for the same treatments under the given irrigation method. Irmak (2015b) reported week correlation ($R^2 = 0.31$) between CWP and ETc in a wet season and similar observations were also made by Payero et al. (2008) ($R^2 = 0.16$) who associated the cause of weak correlation to minimal crop water stress during the growing season. However, Irmak (2015b) showed a stronger correlation ($R^2 = 0.64$) from a long-term (six years) field research.

The peak ETWUEs occurred when the ETc values were approximately 550 (60% FIT-TN), 595 (60% FIT-NT-1) and 587 mm (60% FITNT- 2) in the CP method; 501 (60% FIT-TN), 543 (60% FIT- NT-1) and 530 mm (60% FIT-NT-2) in the SDI method; and 507 mm (60% FIT-TN) in the FI method in 2016 (Fig. 8). In 2017, the values were 484 (60% FIT-TN), 524 (60% FIT-NT-1) and 513 mm (60% FIT-NT-2) in the CP method; 446 (60% FIT-TN), 474 (60% FIT-NT-1) and 467 mm (60% FIT-NT-2) in the SDI method; and 456 mm (60% FIT-TN) in the FI method (Fig. 8). In all cases, across all treatments, irrigation methods and years, the ETWUE at 60% FIT was significantly higher ($p < 0.05$) than ETWUE in FIT (Table 2). When comparing the traditional N across all irrigation methods, there were not any significant interactions between the variables, except

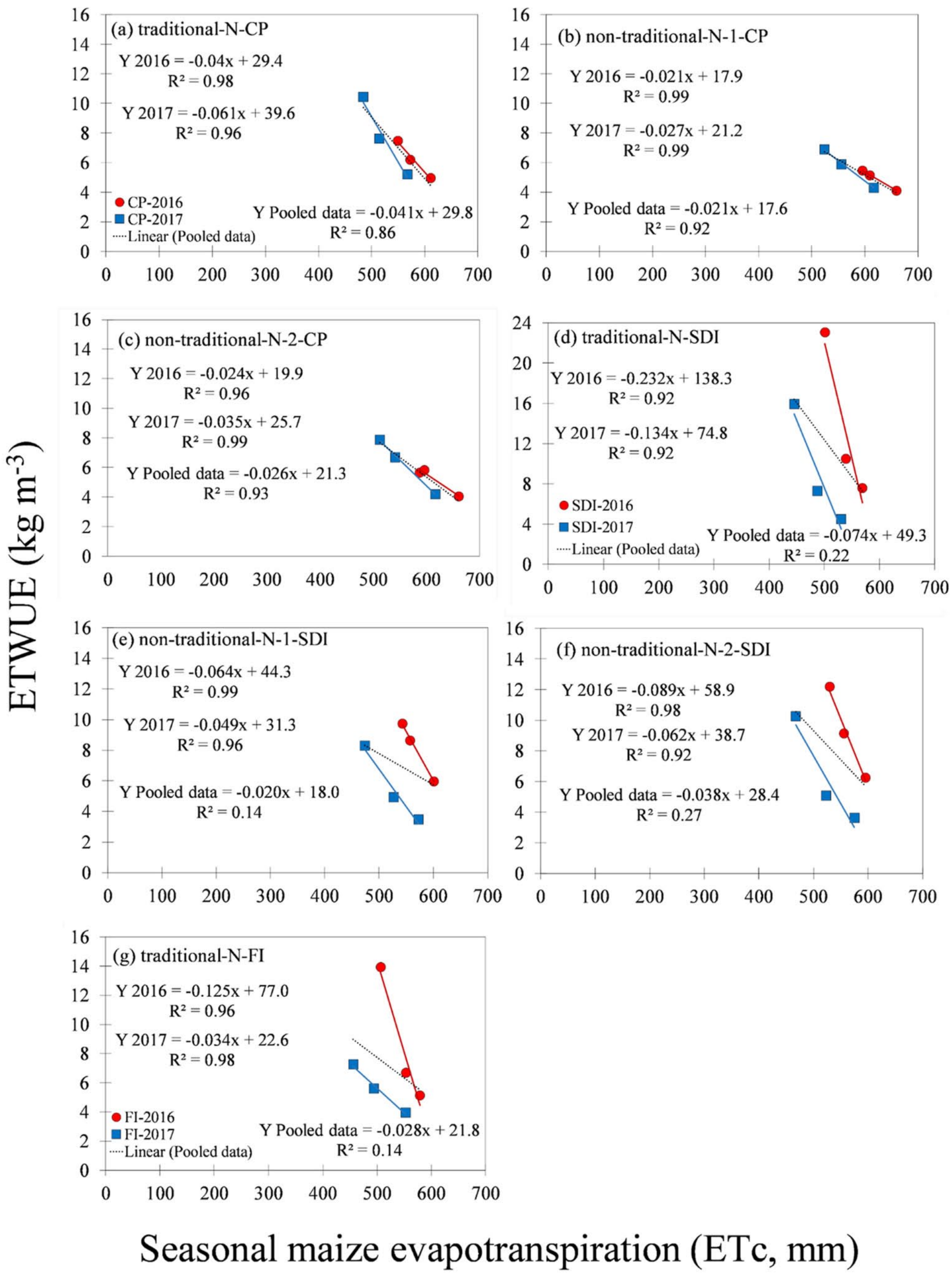

Fig. 8. Relationship between crop evapotranspiration water use efficiency (ETWUE, kg m^{-3}) and seasonal maize evapotranspiration (ETc, mm) and for each irrigation method: (a) traditional nitrogen (TN) treatment under center pivot (CP) irrigation method; (b) non-traditional nitrogen-1 (NT-1) treatment under CP irrigation method; (c) non-traditional nitrogen-2 (NT-2) treatment under CP irrigation method; (d) traditional nitrogen under subsurface drip irrigation (SDI) method; (e) nontraditional nitrogen-1 under SDI method; (f) non-traditional nitrogen-2 under SDI method; (g) traditional nitrogen under furrow irrigation (FI) method, for the 2016 and 2017 growing seasons.

irrigation methods ($p < 0.05$) and irrigation levels ($p < 0.05$), but not growing season ($p > 0.05$). In both years, the highest averaged ETWUE value of 8.69 kg m^{-3} observed in the SDI method, which was significantly higher ($p < 0.05$) than 7.09 kg m^{-3} observed in the FI method, and it was also significantly higher ($p < 0.05$) than the ETWUE value (6.01 kg m^{-3}) in the CP method. No significant difference ($p > 0.05$) in ETWUE values was observed between FI and CP methods when comparing N treatments across CP and SDI methods and the irrigation levels. There were two-way interactions between irrigation method and irrigation levels ($p < 0.05$), and between irrigation levels with N treatments ($p < 0.05$). In 2016, the ETWUE was significantly ($p < 0.05$) higher in the SDI than CP methods, whereas no significant differences ($p > 0.05$) were observed between SDI and CP methods in 2017. When comparing the combination of NT-1 and NT-2 vs. TN, there were two-way interactions between irrigation method and irrigation levels ($p < 0.05$), irrigation method with year ($p < 0.05$), irrigation method with N treatments ($p < 0.05$) as well as irrigation levels with N treatments ($p < 0.05$). Moreover, in both years, the combination of NT-1 and NT-2 had significantly ($p < 0.05$) higher ETWUE in SDI than CP method. Similarly, TN treatment had significantly ($p < 0.05$) higher ETWUE in SDI than CP. These results indicate that the SDI method is more beneficial than CP and FI methods in terms of enhancing ETWUE (SDI method's ability to convert more of ETc to yield/productivity than other irrigation methods), especially when coupled with TN-1 management. In other words, a unit of ETc could produce more grain yield in SDI than in CP method. Overall, the ETWUE values of this research are higher than those reported by Djaman and Irmak (2012) who observed ETWUE range between 4.65 and 6.73 kg m^{-3} for CP-irrigated maize. Also, Irmak (2015b) reported CP-irrigated maize ETWUE range of 1.18–7.16 kg m^{-3}. Irmak et al. (2016) reported much higher ETWUE values for SDI-irrigated maize, ranging from 1.4 to 11.3 kg m^{-3}. Howell (2001) found ETWUE range of 1.96–2.66 kg m^{-3}, 2.13–3.85 kg m^{-3} and 1.98–2.43 kg m^{-3} for surface (level basin)-, LEPA- and SDI-irrigated maize, respectively.

3.5. Yield response factor (Ky)

Maize yield response factor (Ky, dimensionless) is an important index that reveals the complex and variable relationships between ETc and crop production. Overall, across all irrigation methods, relative yield decreased linearly with increasing relative ETc (**Fig. 9**). Ky values varied with irrigation levels within irrigation method and between irrigation methods between the years. Across all treatments, irrigation methods and years, all RFTs showed water stress (Ky > 1). Plants in the RFT also exhibited early leaf senescence before the physiological maturity

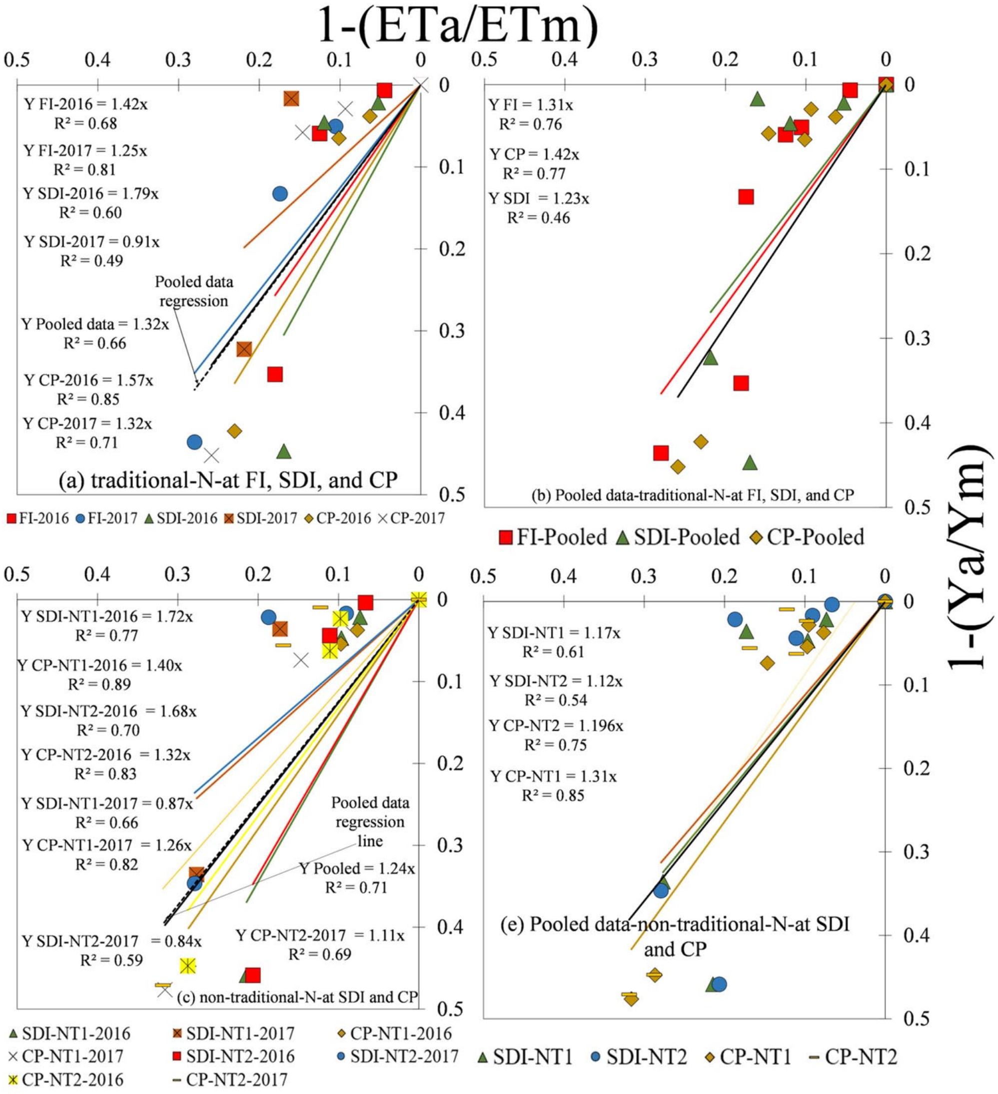

Fig. 9. Relationship between relative evapotranspiration deficit and relative yield deficit (aka yield response factor, Ky) in 2016 and 2017 growing seasons for: (a) traditional nitrogen (TN) treatment under furrow irrigation (FI), subsurface drip irrigation (SDI), and center pivot (CP); (b) traditional nitrogen treatment under FI, SDI and CP method for the pooled data; (c) non-traditional nitrogen treatments 1 (NT-1) and 2 (NT-2) under SDI and CP methods; and (e) non-traditional nitrogen treatments 1 (NT-1) and 2 (NT-2) under SDI and CP for the pooled data.

was fully completed (visual observations in the field in both growing seasons), resulting in grain yield reduction as compared with other treatments. However, maize under limited irrigation managements of 80% FIT and 60% FIT showed Ky < 1, which indicates that the yield reduction is impacted to a lesser degree from the magnitude of water stress under these limited irrigation strategies and plants can tolerate to the magnitude of water deficit they underwent under these treatments, which resulted in higher yield than those observed in the RFT. Thus, plants in the limited irrigation treatments had proportionally lower yield reduction with reduced ETc. These lower Ky values also imply that the limited irrigation of 80% FIT and 60% FIT could be feasible strategies in terms of reducing amount of irrigation water withdrawals by 20% and 40% relative to FIT with low potential of yield reduction. On a two growing season average basis, across all treatments seasonal Ky values were 0.82, 0.75 and 0.90 in the CP, SDI and FI methods/fields, respectively. Moreover, the NT-1 and NT-2 treatments' Ky values were lower than the respective TN treatment in CP and SDI, owing to the crops' exposure in the non-traditional N treatments to water stress was less (in terms of duration) than plants in the TN treatment, which demonstrates the substantial effect of N timing strategy on maize yield. These results confirm that the grain yield reduction is lower for maize under non-TN treatments than NT. This could be attributed to sufficient N in the root-zone enhanced biomass production hence, increased ETc and their ratio relatively decreased as compared with TN. Under non-TN treatments, maize can extend its roots and extract adequate water and nutrient throughout the growing season, subsequently, shoots are extended and ETc can increase. These results indicate that under semi-arid climates and regions with similar environmental conditions and agronomic management practices, coupled limited irrigation management and non-traditional N treatments for maize, could be a viable management strategy for increasing CWP without yield reduction.

Averaged across all treatments, seasonal Ky values were less than 1 in the limited irrigation treatments. With the SDI method having the lowest averaged Ky value of 0.75 among all irrigation methods indicates that the SDI would provide more tolerance to water deficit or water stress than CP and followed by FI methods and can be a feasible method under water-limiting environments. The most likely factors that may influence Ky values substantially are water stress timing (e.g., at which growth stage) during the growing season and the period length/duration, type of irrigation system, irrigation frequency, weather variables and crop management practices, including irrigation management, irrigation method as well as N management (Irmak, 2015a; b). Thus, Ky values can vary substantially between the regions/locations, implying the importance of developing local Ky values (Irmak, 2015b). The Ky values of the current research are lower than those reported by others. For example, for CP-irrigated maize Irmak (2015a) reported average Ky values of 1.89, 1.89, 1.39, 1.80 and 2.64 in 2006, 2007, 2008, 2009 and 2010, respectively. Ky values reported by Irmak et al. (2016) for SDI-irrigated maize were much lower (1.65, 0.91, 0.91 and 0.83 in 2005, 2006, 2007 and 2008, respectively). Retta and Hanks (1980) reported Ky values between 1.12 and 1.39 for maize under sprinkler irrigation. To the best of the authors' knowledge, none of these studies; however, accounted for N management impact on Ky values, making this current research unique and contributing key finding, information and data to the scientific community and agricultural water and crop management professionals.

4. Summary and conclusion

This research quantified CWP, IWUE, ETWUE, IYPFs, ETYPFs, ETb and Ky values under different irrigation levels, different N application timing strategies under three different major irrigation methods in the same environmental and climatic conditions, soil characteristics and crop management conditions simultaneously. While the research resulted in a large amount of important data, insight and information, the key findings and conclusions can be summarized as:

1. Maize yield had strong quadratic relationship ($R^2 \geq 0.99$) with seasonal irrigation amounts (IYPF) across all N treatments and irrigation methods in both growing seasons. Combined treatments of CP-TN (2.07 Mg ha^{-1}) proved to be the best combination to obtain highest grain yield production per 25.4 mm of irrigation application followed by SDI-NT-2 treatment (1.91 Mg ha^{-1}) and FI-TN treatment (1.22 Mg ha^{-1}). TN treatment had about 6% and 4.5% higher yield production per 25.4 mm of irrigation water than CP-NT-1 and CPNT- 2, respectively. The highest yield production per 25.4 mm of

irrigation water was found in the SDI-NT-2 (1.91 Mg ha^{-1}) and was 1% and 1.6% higher than the TN and NT-1 treatments, respectively.

2. Under limited irrigation, the highest slopes of ETYPFs were observed in the SDI method (0.067), followed by CP (0.052), and FI (0.046). In both years, the highest averaged ETWUE value of 8.69 kg m^{-3} was observed in the SDI-TN, which was significantly higher ($p < 0.05$) than 7.09 kg m^{-3} in the FI-TN and it was also significantly higher than the ETWUE (6.01 kg m^{-3}) observed in the CP-TN. The SDI method performed the best in terms of increasing maize grain yield with less water than other methods.
    - i. Across two years and N treatments, the ETb values of 169, 172 and 215 mm were observed in the FI-TN, CP-NT-2 and SDI-TN, respectively.
    - ii. Across all treatments, CWP reached its peaked value in the 60% FIT and/or 80% FIT. Across all treatments for the given irrigation method, the highest averaged CWP of 3.00 kg m^{-3} was in the SDI method ($p < 0.05$) followed by 2.84 kg m^{-3} in the CP method ($p < 0.05$) and 2.51 kg m^{-3} in the FI method. The N treatments significantly ($p < 0.05$) influenced CWP with the averaged CWP being higher in the TN nitrogen treatment than both NT-1 and NT-2 treatments under both CP and SDI.
    - iii. Ky values were lower under limited irrigation levels of 80% FIT and 60% FIT, which can be feasible strategies in terms of reducing amount of irrigation water withdrawals by 20% and 40% relative to FIT with low potential of yield reduction. SDI-NT had the lowest averaged Ky values followed by CP-TN and FI-TN.

Results demonstrated that the improved CWP with less N input can be achieved, and this can vary substantially with different combinations of irrigation levels, N management strategies and with irrigation methods and this research quantified the dynamics involved with these variations. These extensive and unprecedented results can aid maize producers and managers to maximize grain yield and water productivity by utilizing the effective and efficient irrigation levels and N management combinations based on their specific irrigation method in conditions similar to those presented in this research. Results presented here can also be used for modeling maize response to irrigation and nitrogen management under different irrigation methods and can be used for forecasting maize response to water and nitrogen by accounting for irrigation methods' impact on productivity.

* * * * *

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

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