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Maize response to coupled irrigation and nitrogen fertilization under center pivot, subsurface drip and surface (furrow) irrigation: Growth, development and productivity

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Abstract

Water availability and water quality problems negatively impact agricultural productivity due to improper nitrogen (N) and irrigation management, which can also negatively affect environmental services. Coupled irrigation and N management practices must be developed and practiced for alleviating these challenges. Investigating crop growth and development and yield response to coupled irrigation and N management under different irrigation methods can aid in developing optimum agronomic management practices to enhance crop production efficiency. Field experiments were conducted in 2016 and

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2017 growing seasons to measure and compare maize (*Zea mays* L.) grain yield, leaf area index (LAI), plant height (and their relationships), and stem diameter under different N application timing treatments and traditional N application under different irrigation methods [center pivot (CP), subsurface drip irrigation (SDI), and furrow irrigation (FI)]. The irrigation levels were full irrigation treatment (FIT or 100%), 80% of FIT, 60% of FIT, and rainfed conditions (RFT) coupled with fertigation application timing treatments. The N treatments were: (i) traditional (TN) with spring pre-plant application, (ii) non-traditional-1 (NT-1) with three pre-season and in-season N applications, and (iii) nontraditional-2 (NT-2) with four pre- and in-season N applications. Grain yield, LAI, and plant height were significantly ($p < 0.05$) altered by increasing irrigation levels for the traditional N and non-traditional N treatments for the given irrigation method as well between the irrigation methods for the same treatment. The irrigation method had a substantial influence on LAI, and both CP and SDI had 24% higher averaged LAI than FI across traditional N treatments. The highest grain yields were observed under NT-1 and NT-2 at FIT across the irrigation methods. The highest grain yields of 17.3, 16.8 and 15.2 Mg ha^{-1} were observed in 100% NT-1-CP, 100%-NT-1-SDI, and 100% T-FI in the 2016 growing season, respectively; and 17.8, 16.7 and 14 Mg ha^{-1} were observed in 100% NT-1-CP, 100%-NT-2-SDI, and 100% T-FI in the 2017 growing season, respectively. The traditional N treatment showed significantly ($p < 0.05$) higher yield under CP than FI (8.1% and 25.5% higher under CP in 2016 and 2017, respectively). SDI had 8.1% and 23% higher yield than FI in 2016 and 2017 seasons, respectively. NT-1 and NT-2 treatments had significantly higher ($p < 0.05$) grain yields than traditional N treatment under CP and SDI; and NT-1 and NT-2 yields were significantly higher ($p < 0.05$) under CP than SDI. There was no significant difference ($p > 0.05$) in yield between NT-1 and NT-2. However, the TN-1 yielded 4.3% higher under CP than in SDI method. NT-1 can be an effective N management practice coupled with 80% of FIT irrigation level under CP and SDI. Results and analyses presented here can provide guidance to growers and their advisors to assess maize productivity under different irrigation and N management strategies under different irrigation methods in the soil, climatic and management practices similar to those presented in this research.

Keywords: Center pivot, Furrow irrigation, Grain yield, Irrigation levels, Leaf area index, Maize growth, Nitrogen application timings, Plant height, Subsurface drip irrigation

1. Introduction

Water and nitrogen (N) are essential inputs for crop production and are two of the most significant factors limiting maize grain yield potential. Increase in irrigation and N inputs maximizes maize yield up to an optimum level (Liu and Zhang, 2007; Irmak, 2015a, 2015b) and this level can vary substantially with region, climate and soil characteristics, management practices, hybrid and other factors. Limited N availability as well as water deficits in the crop root zone can impact critical plant traits such as leaf area index (LAI), photosynthesis rate, radiation/light interception and use efficiency, leaf area duration, net assimilation rate, chlorophyll content, Rubisco activity, shoot weight, plant N uptake, and hence biomass production and grain yield (Novoa and Loomis, 1981; Eck, 1984; Pandey et al., 1984, 2005; Muchow, 1988; McCullough et al., 1994). Moreover, water and N supply are critical not only for yield increase, but is also important for maintaining appropriate balance of these critical inputs in the plant root zone for grain quality (Mason and D'Croz-Mason, 2002).

Nitrogen fertilizer is typically applied either post-harvest in fall or spring before planting. Globally, farmers mostly tend to apply preplant N (Scharf and Lory, 2002), and this may lead to poor synchrony between N and crop demand. Furthermore, when excessive N is applied with the goal of creating a non-nitrogen stress conditions to increase yield productivity, this can cause significant environmental (including surface and groundwater resources), human, and animal health pollution risks. When overirrigation is practiced, this can cause anaerobic conditions in the plant root-zone that can negatively impact plant water and nutrient uptake, and can also increase leaching potential, both of which can result in reduced productivity. The last few decades have seen increased environmental issues in both water (Donner and Kucharik, 2008; Zhang et al., 2015; Zillén et al., 2008) and air (Aneja et al., 2009) due to suboptimal N fertilizer and irrigation management for maize production. Maize has the most considerable portion of N losses among all cereals (St. Luce et al., 2011). In the U.S., maize accounts for the most abundant fraction (37–51%) of the total annual N consumption (Snyder, 2012). In Nebraska, nitrates have been ranked as the most common source of Nebraska's groundwater contamination due to extensive irrigated maize production in approximately 1.82 million hectares (USDA, 2018). In addition to other forms of N loses, when N applications are made as a one-time application in fall after harvest or early spring before planting, precipitation, especially excessive precipitation, can accelerate N leaching. In-season or split/side-dressed N applications during critical crop growth stages has been suggested as a management option to potentially minimize N losses and increase N use efficiency (Welch et al., 1971; Stanley and Rhoads, 1977; Russelle et al., 1981; Fox et al., 1986; Tarkalson et al., 2009; Hammad et al., 2018). In-season N applications can utilize irrigation systems (i.e., center pivot, subsurface drip and other forms of pressurized irrigation systems) to deliver desired smaller N amounts to the crop at any stage with high efficiency and distribution uniformity.

A number of studies compared in-season N timing applications prior to V8 maize growth stage against pre-season or at planting N application (Jokela and Randall, 1989; Roth et al., 1995; Bundy et al., 1992; Reeves and Touchton, 1986; Stecker et al., 1993). The primary goals of these studies were to develop best management practices to maximize grain yields and N use efficiencies under different environmental conditions. Among very limited research, a comparison between pre-plant and in-season N applications on medium and fine-textured soils showed that in-season N applications are not likely to increase maize yields over the pre-plant application in most growing seasons (Bundy, 1986; Nelson and MacGregor, 1973; Stevenson and Baldwin, 1969). Polito and Voss (1991) reported from a 3-yr study in Iowa that maize yield did not increase when splitting N applications between pre-plant and in-season as compared with pre-plant N applications only. Randall et al., 1997 found similar observations across three ridge-tilled sites in Minnesota. Tarkalson et al. (2009) reported that there were no significant differences in maize grain yields between two N application rates that were made based on the University of Nebraska-Lincoln's (UNL) recommended algorithm rate minus 20% as split N applications at pre-plant, during planting, and at V14 growth stage on a silt loam soil. On the other hand, there are studies that found it is advantageous to carry out split N applications. Crop N demand is varied among the maize growing stages and splitting the total N amount for in-season applications may provide sufficient N supply at different crop growth stages that may effectively improve yields (Ciampitti and Vyn, 2011; Liu et al., 2014). Therefore, timing N with the exact required rate can be crucial to maximizing yield production (Vetsch and Randall, 2004; Raun et al., 2011; Mahama et al., 2016). This strategy may eliminate (or at least reduce) the duration of causing N to be susceptible to be lost by leaching, denitrification, ammonia volatilization, and denitrification, particularly during irrigation periods and/or excessive precipitation events. Maharjan et al. (2014) found that split urea application strategy increased yield and N uptake with lower nitrate leaching when compared to pre-plant-applied urea. They reported that the direct N_2O emissions were significantly lower under the split urea application. The impact of split applications has also been observed to be a function of the irrigation water amount. Maharjan et al. (2014) reported that full irrigation led to increase in NO_3 leaching, but did not impact N_2O emissions. Horváth et al. (2010) reported higher N losses under full irrigation treatments as well as increased direct N_2O emissions when compared with deficit irrigation treatments in sandy soil in a semi-arid condition.

Extensive N fertilizer is applied in irrigated maize production globally and in the midwestern US, including Nebraska. The total irrigated acreage in Nebraska is about 3.5 million ha (USDA, 2018) with center pivot irrigation (sprinkler irrigation) being the dominant irrigation method, which constitutes about 85% (2.9 million ha), followed by surface (furrow) irrigation (FI) as 14.5% (506,517 ha), and subsurface drip irrigation (micro irrigation) at 0.85% (30,000 ha). During 2008–2013, the proportion of irrigated land under sprinkler and micro irrigation have increased by about 9.5% and 763%, respectively, while there was a 25% decline in acreage under surface irrigation (USDA-NASS, 2014). This dramatic shift of irrigated acreage from surface to sprinkler and micro irrigation is directed towards enhancing water use efficiency using more efficient-irrigation technology in the light of increasing water scarcity and due to allocation/moratoriums in irrigation water withdrawal.

Irrigation and N dynamics have been shown to demonstrate interactions with each other, and hence should be managed in a coupled manner, especially when N is applied via irrigation system in sprinkler and microirrigation (including SDI) systems). Understanding these coupled effects of irrigation and N timing are becoming increasingly important due to: (a) increasing interest in split N application to reduce environmental pollution from N, (b) increasing interest in deficit or limited irrigation to maximize water use efficiency under limited water supply and irrigation capacities, and (c) the adoption of high-efficiency sprinkler and micro irrigation systems. However, to the best knowledge of the authors, research efforts that investigate these interactions, their impacts on crop growth and productivity, and how do these impacts vary across surface, sprinkler and microirrigation systems for maize grown under the same environment and management conditions simultaneously have not been investigated. The lack of experimentally-derived data, information and knowledge are likely due to the extreme challenges that does not make such research economically, labor-wise and time-wise feasible. This research is aimed at fulfilling these critical infrastructural and management requirements to accomplish the goal of quantifying and evaluating coupled impacts of irrigation rates and N timing management strategies on maize growth, development and yield productivity, and possible differences in these impacts under surface (furrow irrigation or FI), sprinkler (center pivot irrigation or CP) and micro irrigation (subsurface drip irrigation or SDI) methods in the same field with the same slope, soil properties, and environmental conditions. Specifically, these impacts were investigated via measuring and evaluating differences in maize growth and development (LAI, plant height and stem diameter) and grain yield, when managed under the above-mentioned irrigation rates, fertilization timings and irrigation methods.

2. Materials and methods

2.1. Experimental site characteristics

Field experiments were conducted during 2016 and 2017 growing seasons in the Irmak Research Laboratory (IRL) advanced irrigation engineering, plant physiology, evapotranspiration, climate science and their interactions research infrastructures/facilities at the UNL-South Central Agricultural Laboratory (SCAL), near Clay Center, Nebraska (44.6°N, 98.1°W; elevation: 552 m above mean sea level).

Production (large)-scale FI, CP and SDI research fields were used for these experiments. The research site is in a transition zone between sub-humid and semi-arid climates, with an average annual precipitation of approx. 680 mm. The frost-free dates are approximately between April 24 and October 19 (Irmak, 2010; Irmak, 2015a, 2015b; Irmak et al., 2019). The site is often impacted by cold, dry continental air masses from Canada in the winter and warm moist air from the Gulf of Mexico during summer and is subject to rapid weather fluctuations (Irmak, 2010). The highest wind speeds usually occur from January to late June, with March being the windiest month, with a long-term average daily wind speed fluctuation between 2 to over 8 m s^{-1} (Irmak et al., 2006). The soil at this research site in which three advanced irrigation methods were established is a Hastings silt loam; fine, montmorillonitic, mesic Udic Argiustoll with 0–1% slope. The particle size of distribution is 15% sand, 65% silt, and 20% clay with 2.5% organic matter content in the topsoil (Irmak, 2015a). The soil is homogenous across the three experimental fields (FI, CP, SDI) as a larger single field was divided into three sections to accommodate research to investigate different variables under the same soil and environmental conditions in the same field conditions. All three fields have a 0.34 m^3/m^3 field capacity, 0.14 m^3/m^3 permanent wilting point, and a 0.53 m^3/m^3 saturation point. Maximum effective maize rooting depth is 1.20 m when crop reaches full vegetative growth (i.e., near or at silking stage-R2). The total available water holding capacity for the top 1.20 m soil profile is about 240 mm (Irmak, 2015a).

The maize hybrid Golden Harvest G14H66–3010A with 114 days relative maturity (RM) was planted both in 2016 and 2017 growing seasons. The crop was planted at a seeding rate of approximately 78,505 seeds ha^{-1} on a 0.76 m row spacing and at 0.06 m planting depth. The planting dates and other management practices were carefully kept consistent across the three fields to allow fair comparisons of all variables of interest corresponding to each field. All fields were maintained as a ridge-till in both years. The detailed information on planting, emergence, harvest, and herbicides applications, amounts, methods, and dates, etc. are presented in **Table 1**.

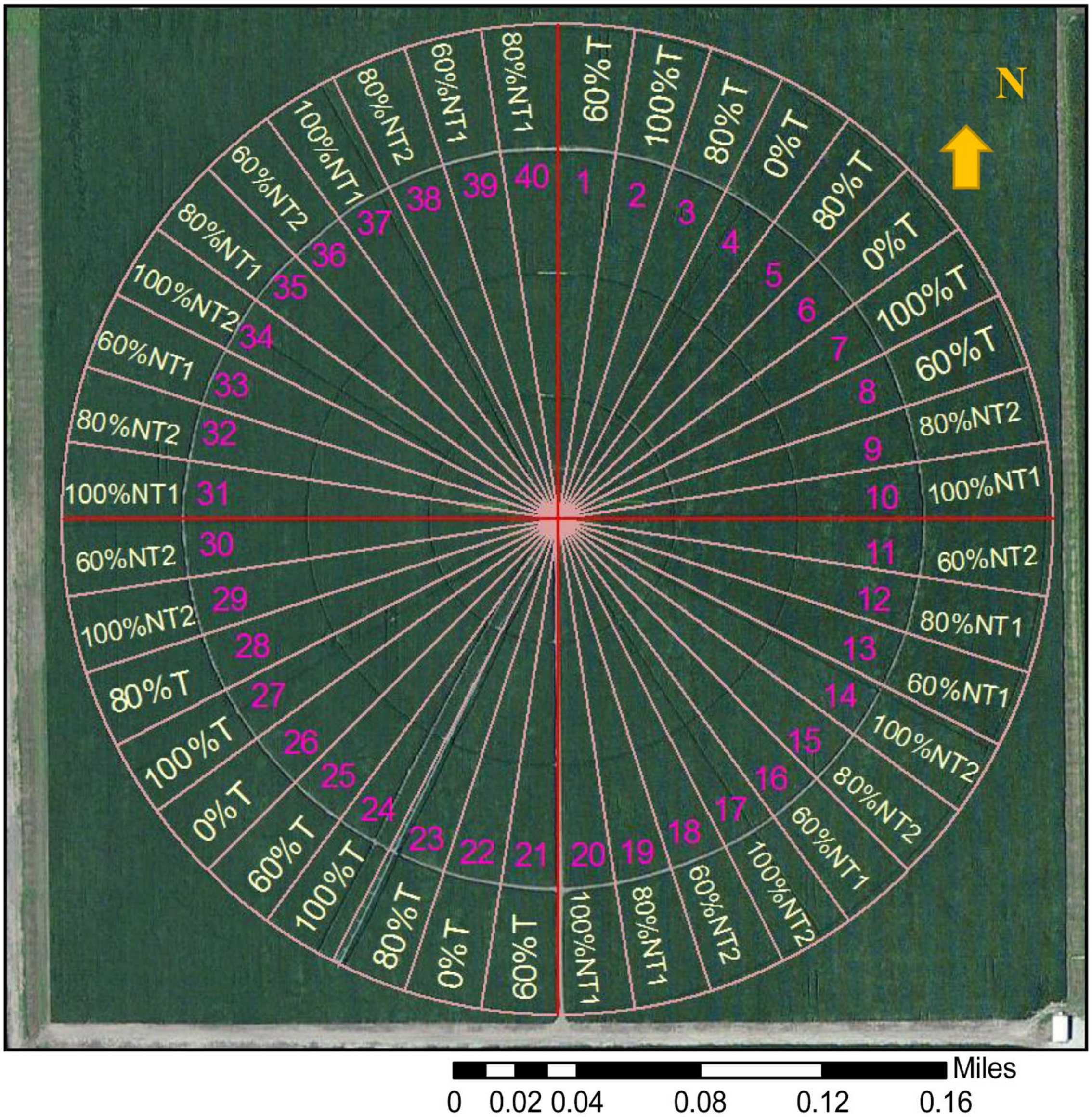
Table 1 General field management and cultural practices, including planting and emergence date, fertilizer and herbicide application amount and method, harvest, etc., in the center pivot, subsurface drip, and furrow irrigation methods at the research site in 2016 and 2017 growing seasons.

Field/Irrigation Method	*Year*	*Description*	*Date*	*Type*	*Amount per hectare*	*Method*
Center pivot	2016	Planting	06 May	–	–	Planter
		Emergence	16 May	–	–	–
		Harvest	01 Nov	–	–	8 rows-Combine
		Fertilizer	14 Mar	11–52–0	112 kg	Broadcast
		Fertilizer	05 May	32–0–0	Variable	In furrow-Traditional Treatments
		Herbicide	07 May	Acuron	5.8 L	Sprayer
		Herbicide	07 May	Roundup	2.3 L	Sprayer
		Herbicide	07 Jun	Roundup	2.3 L	Sprayer
		Herbicide	07 Jun	Status	0.36 L	Sprayer
		Herbicide	07 Jun	Aatrex	1.17 L	Sprayer
		Soil Practices	13 Jun	Cultivation	5-cm deep	Cultivator
Subsurface drip	2016	Planting	06 May	–	–	Planter
		Emergence	18 May	–	–	–
		Harvest	31 Oct	–	–	8 rows-Combine
		Fertilizer	14 Mar	11–52–0	123.3 kg	Broadcast
		Fertilizer	05 May	32–0–0	Variable	In furrow-Traditional Treatments
		Herbicide	07 May	Acuron	5.8 L	Sprayer
		Herbicide	07 May	Roundup	2.3 L	Sprayer
		Herbicide	07 Jun	Roundup	2.3 L	Sprayer
		Herbicide	07 Jun	Status	0.36 L	Sprayer
		Herbicide	07 Jun	Aatrex	1.17 L	Sprayer
		Soil Practices	13 Jun	Cultivation	5-cm deep	Cultivator
Furrow	2016	Planting	06 May	–	–	Planter
		Emergence	18 May	–	–	–
		Harvest	05 Oct	–	–	8 rows-Combine
		Fertilizer	14 Mar	11–52–0	123.3 kg	Broadcast
		Fertilizer	05 May	32–0–0	Variable	In furrow-Traditional Treatments
		Herbicide	07 May	Acuron	5.8 L	Sprayer
		Herbicide	07 May	Roundup	2.3 L	Sprayer
		Herbicide	07 Jun	Roundup	2.3 L	Sprayer
		Herbicide	07 Jun	Status	0.36 L	Sprayer
		Herbicide	07 Jun	Aatrex	1.17 L	Sprayer
		Soil Practices	13 Jun	Cultivation	5-cm deep	Cultivator

Field/Irrigation Method	*Year*	*Description*	*Date*	*Type*	*Amount per hectare*	*Method*
Center pivot	2017	Planting	12 May	–	–	Planter
		Emergence	27 May	–	–	–
		Harvest	06 Nov	–	–	8 rows-Combine
		Fertilizer	14 Mar	11–52–0	224 kg	Broadcast
		Fertilizer	05 May	32–0–0	Variable	In furrow-Traditional Treatments
		Herbicide	07 Apr	2–4-D	1.17 L	Sprayer
		Herbicide	07 Apr	Roundup	2.3 L	Sprayer
		Herbicide	24 May	Acuron	5.8 L	Aerial Spray
		Pesticide	04 Aug	Lorsban	1.17 L	Aerial Spray
		Pesticide	04 Aug	Brigade	0.46 L	Aerial Spray
		Fungicide	04 Aug	Headline Amp	1.17 L	Aerial Spray
		Pesticide	12 May	Force 3 G	6.00 kg	Sprayer
		Soil Practices	20 Jun	Row-Crop-Cultivation	5-cm deep	Cultivator
Subsurface drip	2017	Planting	12 May	–	–	Planter
		Emergence	27 May	–	–	–
		Harvest	06 Nov	–	–	8 rows-Combine
		Fertilizer	14 Mar	11–52–0	224 kg	Broadcast
		Fertilizer	05 May	32–0–0	Variable	In furrow-Traditional Treatments
		Herbicide	07 Apr	2–4-D	1.17 L	Sprayer
		Herbicide	07 Apr	Roundup	2.3 L	Sprayer
		Herbicide	24 May	Acuron	5.8 L	Aerial Spray
		Pesticide	04 Aug	Lorsban	1.17 L	Aerial Spray
		Pesticide	04 Aug	Brigade	0.46 L	Aerial Spray
		Fungicide	04 Aug	Headline Amp	1.17 L	Aerial Spray
		Pesticide	12 May	Force 3 G	6.00 kg	Sprayer
		Soil Practices	20 Jun	Row-Crop-Cultivation	5-cm deep	Cultivator
Furrow	2017	Planting	12 May	–	–	Planter
		Emergence	27 May	–	–	–
		Harvest	06 Nov	–	–	8 rows-Combine
		Fertilizer	14 Mar	11–52–0	224 kg	Broadcast
		Fertilizer	05 May	32–0–0	Variable	In furrow-Traditional Treatments
		Herbicide	07 Apr	2–4-D	1.17 L	Sprayer
		Herbicide	07 Apr	Roundup	2.3 L	Sprayer
		Herbicide	24 May	Acuron	5.8 L	Plane Sprayer
		Pesticide	04 Aug	Lorsban	1.17 L	Plane Sprayer
		Pesticide	04 Aug	Brigade	0.46 L	Plane Sprayer
		Fungicide	04 Aug	Headline Amp	1.17 L	Plane Sprayer
		Pesticide	12 May	Force 3 G	6.00 kg	Sprayer
		Soil Practices	20 Jun	Row-Crop-Cultivation	5-cm deep	Cultivator

2.2. Irrigation methods

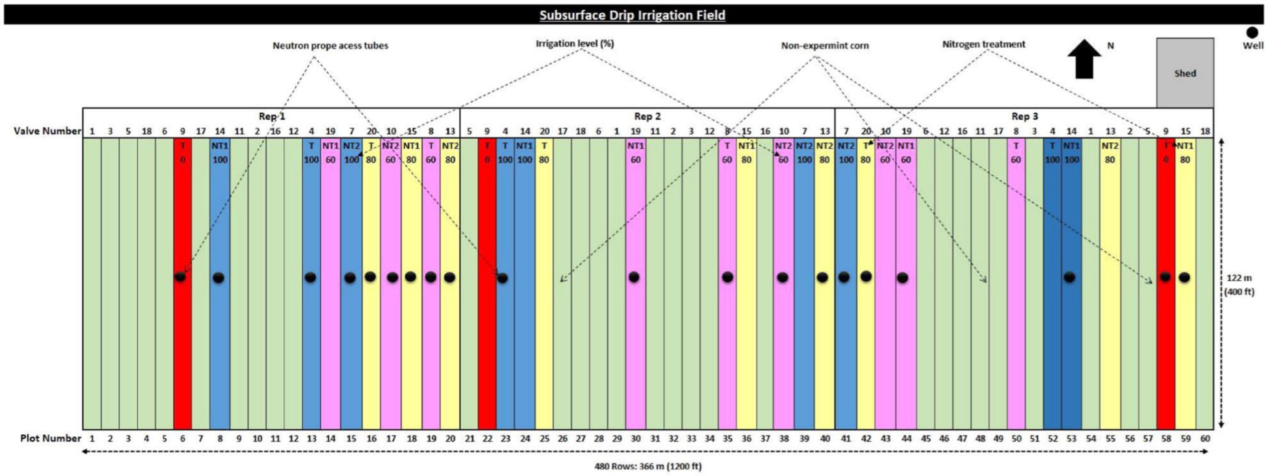
All experiments were conducted simultaneously and similarly on three fields, each of which was irrigated by one of three different irrigation methods (CP, SDI, and FI). It was critical to keep all the experimental variables same (soil, climate, management, hybrid, weed and disease management, etc.) so that any potential differences observed can be attributed to the impact of differences between the irrigation method. The CP irrigation engineering and evapotranspiration research field and system was established in 2005; the SDI field/system was established in 2005; and the FI field/system was established in 2015 all by the senior author (S. Irmak). All three fields were a part of a larger research field, and the larger field was divided into three sections to accommodate three irrigation systems. Thus, all three fields were one field with the same soil physical, chemical and hydraulic characteristics and topography. A four-span hydraulic and continuous-move center pivot irrigation system (T-L Irrigation Co., Hastings, NE, USA) with 16.2 ha field area coverage (**Fig. 1**) was used. The total length of the system is 195.8 m, with a total system flow of 90.8 L h^{-1}. Each treatment (i.e., plot) was approximately 0.40 ha (Fig. 1). The SDI system had a field area of ~5 ha (**Fig. 2**). The drip laterals were installed at 0.40 m below the soil surface with every other row in the middle of two crop rows with a 1.5 m spacing between the two laterals and 0.20 m spacing between the emitters. Irrigation was controlled by a controller and a set of valves that irrigates three replications for a given treatment. Each replication is 122 m long and 6.1 m wide. The system is equipped with pressure-compensating emitters that deliver a constant flow rate of 3.8 L h^{-1}. A Furrow irrigated field of ~1 ha field area (**Fig. 3**) was established and was irrigated using a gated pipe system (Hastings Irrigation Pipe Co., NE, USA). The main gated pipe was placed on the upper edge of the field with 73 m length and had controlled gates (outlet) that delivered water to every other crop row. Each plot was 6.1 m wide (8 crop rows) and 68.5 m long (Fig. 3) (Irmak, 2010, 2015a, 2015b; Irmak and Djaman, 2016a, 2016b).



Fertigation Managements
1. Traditional (TN).
2. Non-traditional 1 (NT-1).
3. Non-traditional 2 (NT-2).

Irrigation Levels
1. 0% (RFT)
2. 60% FIT
3. 80% FIT
4. FIT

Fig. 1. Center pivot (CP) irrigation method field treatments layout (with the actual CP field boundaries on the background) in the Irmak Research Laboratory.



Fertigation Management

1. Traditional nitrogen management (TN), in-furrow pre-plant N applied treatments.
2. Non-traditional nitrogen management (NT-1), split/timing -3 times (V0, V8, & VT), through system N applied treatments.
3. Non-traditional nitrogen management (NT-2), split/timing -4 times (V0, V8, VT, & R3) through system N applied treatments.

Fig. 2. Subsurface drip irrigation (SDI) method/field treatments layout in the Irmak Research Laboratory.

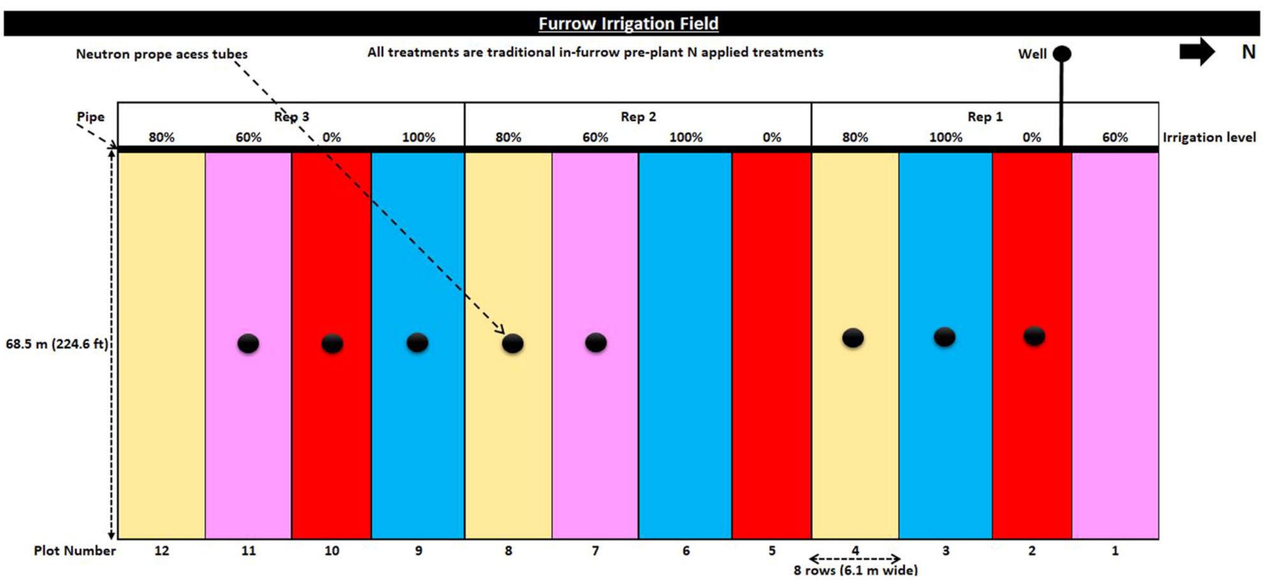


Fig. 3. Surface (furrow) irrigation (FI) method field treatments layout in the Irmak Research Laboratory.

2.3. Irrigation management and treatments imposed

In each of the three fields, four irrigation levels were imposed: full irrigation treatment (FIT or 100%), 80% of FIT (20% deficit), 60% of FIT (40% deficit), and rainfed (RFT) or non-irrigated control treatment. Irrigations in each field were triggered when the average of the top two layers of the soil profile, (i.e., soil depths of 0–0.30 and 0.30–0.60 m) of the FIT was at about 40–45% depletion (approximately at 21–22% vol soil moisture) before the tasseling stage (VT), following Irmak (2019a, 2019b). After VT, the average of the top three layers of the soil profile (i.e., depths of 0–0.30, 0.30–0.60 and 0.60–0.90 m) were used for irrigation timing (Irmak et al., 2010; Irmak, 2019a). The irrigation amounts were accordingly adjusted for the limited irrigation treatments. Thus, 60% FIT, 80% FIT and FIT received irrigation amounts of 19, 25 and 32 mm of irrigation water in each irrigation throughout the growing season in both years, respectively. A total of 6 irrigation events (184 mm) in 2016 and 5 irrigation events (158 mm) were applied to FIT in 2016 and 2017 growing seasons, respectively. The irrigation events occurred on June 28, July 14, July 25, August 4, August 11 and August 18 in 2016 growing season and on July 13, August 7, August 21, September 7 and September 14 in 2017 growing season. The irrigation amounts were controlled through a control panel [T-L Precision Point Control III System (T-L Irrigation Co., Hastings, NE, USA)] for the CP irrigation system and via a Galcon Galileo computerized irrigation control system (Galcon, Kfar Blum; https://www.galconc.com/) for the SDI system. In the FI system, the irrigation amounts/rates were controlled by adjusting the gated pipe outlets to deliver a certain water flow rate to furrows. In all irrigation systems, a variable frequency drive motor and controller were used to speed up or slow down the motor (U. S. Motors, Long Beach, CA, USA) to pump (Western Land Roller Irrigation Pump division, Hastings, NE, USA) a certain amount of water, depending on the need as measured by the pressure gauges (Irmak, 2015a, 2015b).

2.4. Nitrogen management and treatments imposed

Three N application timing treatments were evaluated with three replications in the SDI and FI fields and four replications in the CP field.

The N application timing treatments were practiced based on the crop growth stages as: (i) traditional (TN) with spring pre-plant application, (ii) non-traditional-1 (NT-1): 30% spring pre-plant, 40% and 30% side-dress at V8 (8-leaf collar-stage) and VT/VR (tasseling/silking) stages, respectively, and (iii) non-traditional-2 (NT-2): 25% spring pre-plant, 25%, 30%, and 20% side-dress at V8, VT/VR, and R3 (i.e., kernel milk) growth stages, respectively. Three N application timing treatments were supplied as liquid urea ammonium nitrate NH_4NO_3 (32—0—0) that was applied uniformly. The N was applied using two methods: (i) the BLU-JET fertilizer injector applicator (Model AT6020; Unverferth Manufacturing Co., Inc., Kalida, OH, USA) that injects the fertilizer into the soil in the center of the furrow for 8 rows at one pass. This process was utilized only for the TN application treatments, and (ii) the chemigation system that includes a fertilizer storage tank to inject the fertilizer through the irrigation system for the non-traditional treatments of NT-1 and NT-2 at various growth stages, starting from V0 growth stage, depending on the irrigation method/type. The NT-1 and NT-2 treatments were not included in the RFT. However, TN application timing treatment was included in the RFT.

The N algorithm developed by Shapiro et al. (2008) was used to determine the amount of N required for three N treatments (TN, NT-1 and NT-2). The algorithm is based on expected crop yield (i.e., 1.05 times of a 5-year average yield) and incorporates N credit for soil organic matter, residual soil nitrate (determined from plot-specific soil sampling that was conducted in this research in the spring before planting each year), and other credits, including N from legumes, manure, other organic materials, and from irrigation water, maize and N price adjustment, and timing adjustment:

$$N\ need\ (lb/ac) = \left[35 + (1.2 \times EY) - (8 \times NO_3 - N_{ppm}) - (0.14 \times EY \times OMC) - other\ N\ credits\right] \times Price_{adj} \times Timing_{adj} \quad (1)$$

where,

EY = expected grain yield (bu/ac).

Nitrate-N ppm = average nitrate-N concentration in the root zone (0.60–1.20 m soil depth) in parts per. million (ppm).

OM = percent organic matter.

Other N credits include N from legumes, manure, other organic materials, and from irrigation water.

$Price_{adj}$ = adjustment factor for prices of maize and N.

$Timing_{adj}$ = adjustment factor for fall, spring and split N applications.

2.5. Field measurements

2.5.1. Measurements of soil water status and soil sampling

Soil-water status was measured using neutron attenuation soil moisture gauge (Model 4300; Troxler Electronics Laboratories, Inc., NC, USA) in both growing seasons and was used for irrigation management decisions. The soil-water content was measured at 0–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50 m soil layers on a weekly basis. The neutron probe access tubes were installed using a Giddings soil sampling probe (Giddings Machine Co., Fort Collins, CO, USA). Neutron gauge access tubes were installed in all three fields and treatments and replications. The access tubes were installed in a representative location (i.e., uniform emergence, slope, etc.) in the plots between the healthy maize plants without destruction them to obtain representative soil-water status data. Prior to planting and immediately following the harvest each year, soil samples were collected from two replications of each treatment from all three fields, resulting in a total of 48 soil samples (20 cores from CP field, 20 cores from SDI field and 8 cores from FI field). The samples were collected using a Giddings soil sampling probe from all 5 soil layers (0–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50 m). The soil samples were placed in labeled and water/weather-proof plastic bags and were sent for analyses for nitrate-N and ammonium-N (KCl NO_3-N + NH_4-N) in the laboratory. In addition to the soil samples, plant and grain samples were taken at harvest from 10 plants of each treatment from each field for plant N content analyses.

2.5.2. Canopy growth and development and growing degree days

Leaf area index (LAI) was measured on a weekly to bi-weekly basis from V3 (3-leaf collar) through R6 (physiological maturity) stages using the model LAI-2200 C Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, NE, USA). Plant height was measured from V3 through R1 (silking-stage) on a weekly to bi-weekly basis. Plant height was measured as the distance between the soil surface (near the stem) to the tip of the longest leaf before tasseling and/or to the tip of the tassel after tasseling stage. Both LAI and plant height were sampled roughly in the same area in the plot interior. Leaf collar method (leaf collar visible) was used to determine the physiological growth stages. Ten plants from the middle of the plots (two replications per treatment) that represented at least ≥ 50% of the population were used to stage vegetative/reproductive growth stages on a weekly to bi-weekly basis throughout both growing seasons. Stem diameter (cm) was measured from 10 plants from the interior row that randomly sampled, by using a Vernier caliper at R3 (i.e., kernel milk) stage at the base of the stem above the soil surface. Growing Degree Days (GDD) was used as the base scale to represent the progression of in-season maize growth and development. GDD (°C) is a quantitative indicator to denote the heat accumulation throughout the growing season, which is considered as one of the significant factors that control the rate of plant development in addition to other factors such as soil-water status, fertilizers, light/daylight length, etc. The cumulative GDD was calculated using the most widely accepted method (McMaster and Wilhelm, 1997) (Eq. 1). The air temperature data used for computation of GDD was measured at an Agricultural Weather Data Network (AWDN) automated weather station managed by the High Plains Regional Climate Center (HPRCC).

$$Cumulative\ GDD = \sum_{i=1}^{n} \left(\frac{T_{max} + T_{min}}{2} - T_{base} \right) \qquad (2)$$

where, T_{max} and T_{min} are daily maximum and minimum air temperatures, and T_{base} is the crop-specific base temperature (taken as 10°C). For days when the average of T_{max} and T_{min} was lower than T_{base}, it was replaced by the T_{base}, and hence GDD for that day was computed as 0. No upper limit for temperature (e.g., ≥30℃ for maize) was imposed, because there exists strong evidence to show that transpiration and hence assimilation processes are not hindered at such temperatures (≥30℃) under the environmental conditions at the experimental site (Irmak and Mutiibwa, 2010).

2.6. Experimental design and statistical analysis

While the treatments were the same between the irrigation methods, each experimental field had a different experimental design/layout, which was a function of irrigation system design. The CP field had a split-split plot design, with N application timing in the main plots and the irrigation application levels in the subplots with four replications for each treatment. The SDI and FI fields had a randomized complete block design with three replications for each treatment. To distinguish potential significant differences in LAI, plant height, stem diameter and grain yield, as a result of treatments imposed, GLIMMIX procedure in SAS (SAS Institute, Inc., 2003; Cary, NC, USA) was used for statistical analyses. A Fisher's protected least significant differences (LSD) test was conducted at the 95% confidence level to determine if there were significant differences between the treatments and identify which ones are different from each other).

3. Results and discussion

3.1. Weather conditions

Monthly summaries of meteorological variables at the experimental site during 2016 and 2017 growing seasons, along with long-term (1983–2015; 30-year climatology) means, are presented in **Table 2**. The 2017 growing season was wetter than 2016 growing season and most of the high precipitation events occurred during May and late September through October. Nevertheless, both growing seasons were drier than the long-term mean growing season precipitation (**Fig. 4**) (by 24% in 2016 and 5% in 2017). During 2017 growing season, the site received about 58 mm of precipitation after planting, which along with low air temperatures caused delay in maize emergence by about a week (Table 2). The maximum (T_{max}), minimum (T_{min}), and average (T_{avg}) air temperatures were slightly warmer (0.4, 1.0 and 0.7 °C) in the 2016 growing season than in 2017. The warmer temperatures in 2016 contributed to the increase in the accumulated growing degree days from planting to harvest. From emergence to harvest, cumulated GDD values were 1752 and 1589 °C in 2016 and 2017

Table 2 Monthly weather variables during 2016 and 2017 growing seasons and long-term average values at the research site.

Year	Month	T_{max}[a] (°C)	T_{min} (°C)	T_{avg} (°C)	RH[b] (%)	Soil Temp. (°C) at 10 cm	u_2[c] (m s^{-1})	R_s[d] (MJ m^2 d^{-1})	Total rainfall (mm)
2016	May	22.0	8.7	15.4	70.4	15.7	3.9	19.4	172.5
	Jun	31.3	17.0	24.2	60.4	26.3	3.7	26.3	5.1
	Jul	30.1	18.0	24.0	76.7	26.6	3.0	21.5	63.5
	Aug	28.3	16.6	22.4	78.9	25.9	2.8	19.4	63.0
	Sep	25.4	13.0	19.2	77.0	20.2	3.2	14.8	66.8
	Oct	21.5	5.6	13.6	71.8	15.1	3.4	11.6	5.6
	Average	**26.4**	**13.2**	**19.8**	**72.5**	**21.6**	**3.3**	**18.8**	**376**[e]
2017	May	22.5	8.7	15.6	64.6	16.4	4.0	21.7	153.9
	Jun	30.1	15.4	22.8	61.0	25.2	3.0	25.1	22.6
	Jul	31.2	18.5	24.8	72.5	27.2	2.0	22.7	50.8
	Aug	27.2	14.3	20.7	77.8	23.8	1.8	19.8	89.6
	Sep	26.8	12.3	19.6	69.0	20.9	2.3	15.0	52.7
	Oct	18.4	4.2	11.3	66.4	13.0	3.6	10.3	102.2
	Average	**26.0**	**12.2**	**19.1**	**68.6**	**21.1**	**2.8**	**19.1**	**471**[e]
Long-term average (1983–2015)	May	22.8	9.3	16.0	67.7	17.5	4.2	19.8	110.9
	Jun	28.3	15.0	21.7	69.0	23.5	3.7	22.6	102.6
	Jul	30.5	17.4	23.9	72.0	26.7	3.0	22.5	88.3
	Aug	29.2	16.4	22.8	75.0	25.7	2.8	19.7	84.8
	Sep	25.4	10.6	18.0	68.4	20.8	3.2	15.9	55.3
	Oct	18.4	3.6	11.0	66.1	13.3	3.6	11.3	53.8
	Average	**25.8**	**12.0**	**18.9**	**69.7**	**21.3**	**3.4**	**18.6**	**495**[e]

a. T_{max}, T_{min}, and T_{avg} = Maximum, minimum and average air temperature, respectively.
b. u_2 = Wind speed at 2 m height.
c. R_s = Incoming shortwave radiation.
d. RH = Relative humidity.
e. Seasonal total rainfall.

growing seasons, respectively. Maize was harvested at 179 days after planting (DAP; November 01) in 2016 (except FI field which was harvested 152 DAP; October 05) and at 178 DAP (November 06) in 2017. Relative humidity (RH) and wind speed (u_2) were higher (by 5.6% and 18%, respectively) in the 2016 growing season than 2017. The substantial u_2 variability across the two seasons did not proportionally translate into RH variability. Incoming solar radiation (R_s) during 2016 growing season was 1.6% lower than in 2017, but was similar to long-term mean R_s.

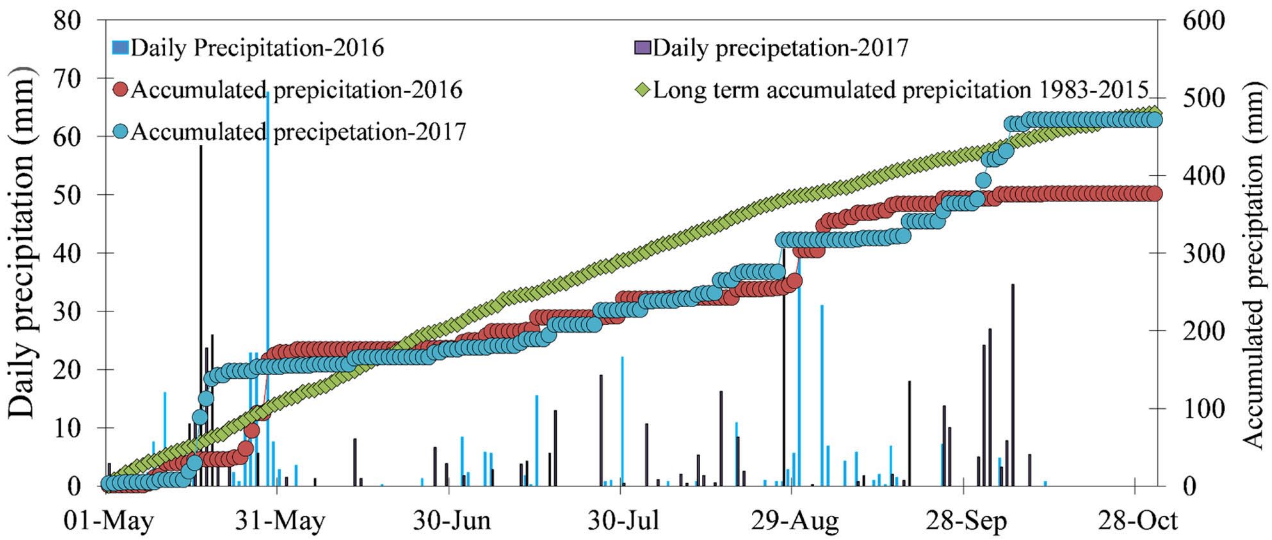


Fig. 4. Daily and cumulative precipitation in 2016 and 2017 growing seasons along with the long-term average accumulated precipitation (1983–2015) measured at the experimental site.

3.2. Irrigation level and method and N management impacts on plant height

Plant height is an important plant growth and development variable that influences numerous plant physiological and biophysical properties such as light interception, aerodynamic resistance, radiation absorption, leaf area, etc. Also, plant height has strong correlation to LAI (Djaman et al., 2013), which can provide a practical approach for estimating this variable. Averaged maize plant height by N and irrigation method as well as plant height distribution as a function of cumulative GDD for different N and irrigation level treatments in the CP, SDI, and FI methods in 2016 and 2017 growing seasons are shown in **Figs. 5c,d, 6, 7, 8** and **Table 3**. Overall, there was a significant difference ($p < 0.05$) in plant height in the FI between the given irrigation level within the growing season. For example, plant height values were significantly higher at FIT, 80% FIT, 60% FIT irrigation levels in 2016 than for the respective treatments in 2017 growing seasons. Also, in terms of method differences including all treatments, the plant height values were significantly ($p < 0.05$) higher in order of FI > CP > SDI in 2016 growing season; and they were significantly ($p < 0.05$) higher in order of CP > SDI > FI in 2017 growing.

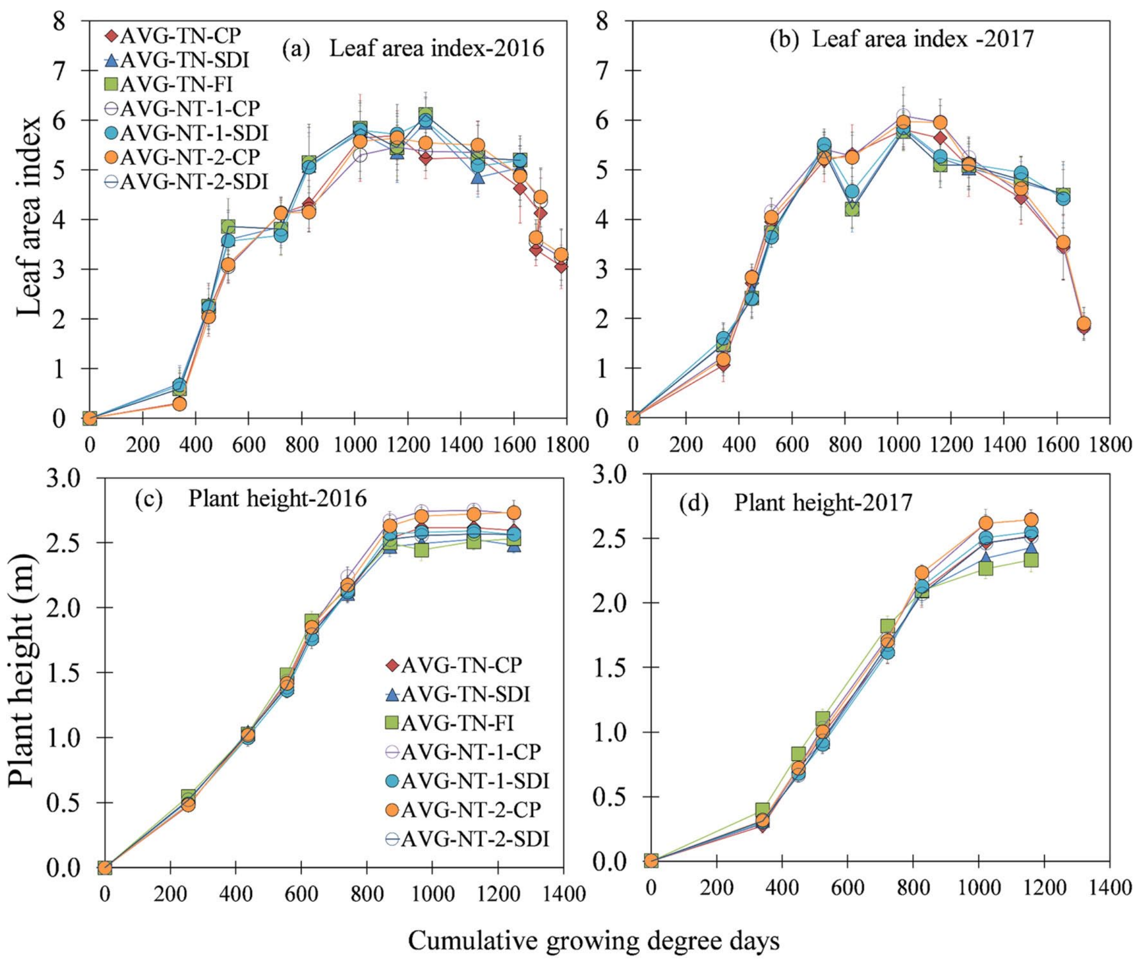


Fig. 5. Average treatment distribution of maize leaf area index (LAI) by irrigation method of center pivot (CP), subsurface drip irrigation (SDI) and furrow irrigation (FI) in 2016 (a) and 2017 (b). Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

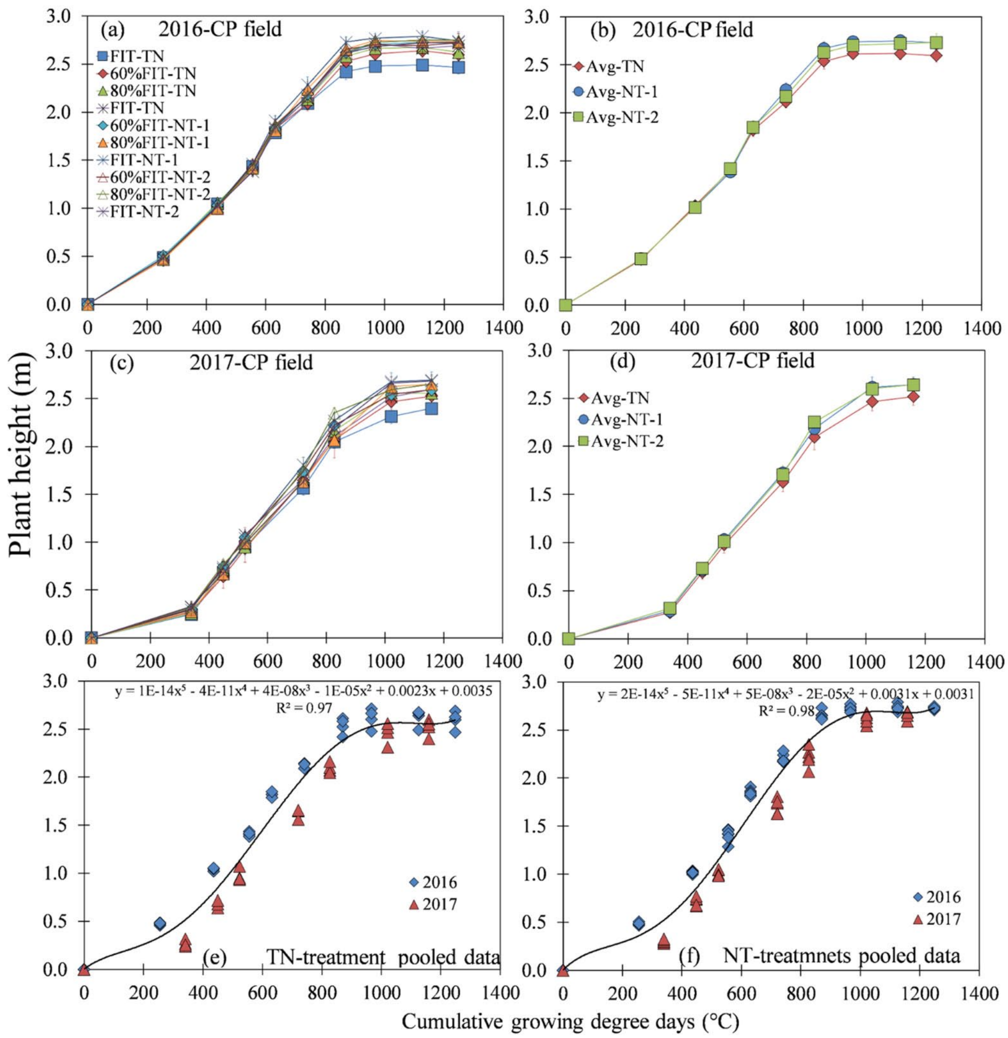


Fig. 6. Distribution of plant height at center pivot (CP) field, (a) all treatments in 2016, (b) average of all irrigation levels, including rainfed conditions by nitrogen treatment; traditional (TN), non-traditional-1 (NT-1), and nontraditional-2 (NT-2) in 2016, (c) all treatments in 2017, (d) average of all irrigation levels including rainfed conditions by nitrogen treatment; traditional (TN), non-traditional-1 (NT- 1), and non-traditional-2 (NT-2) in 2017, (e) pooled data for traditional nitrogen treatment, (f) pooled data for non-traditional nitrogen treatments. Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

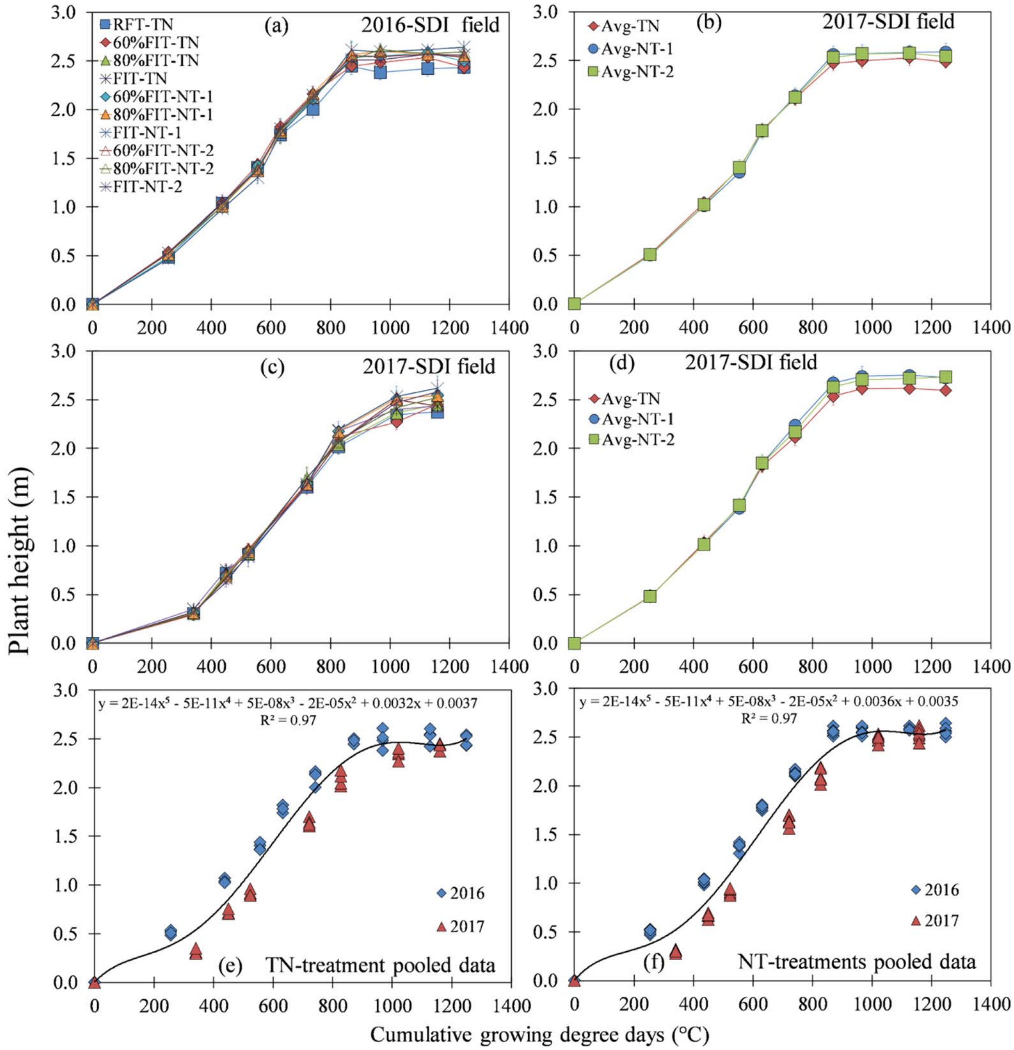


Fig. 7. Distribution of plant height at subsurface drip irrigation (SDI), (a) all treatments in 2016, (b average of all irrigation levels including rainfed conditions by nitrogen treatment; traditional (TN), non-traditional-1 (NT-1), and non-traditional-2 (NT-2) in 2016, (c) all treatments in 2017, (d) average of all irrigation levels including rainfed conditions by nitrogen treatment; traditional (T), non-traditional-1 (NT-1), and non-traditional-2 (NT-2) in 2017, (e) pooled data for traditional nitrogen treatment, (f) pooled data for non-traditional nitrogen treatments. Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

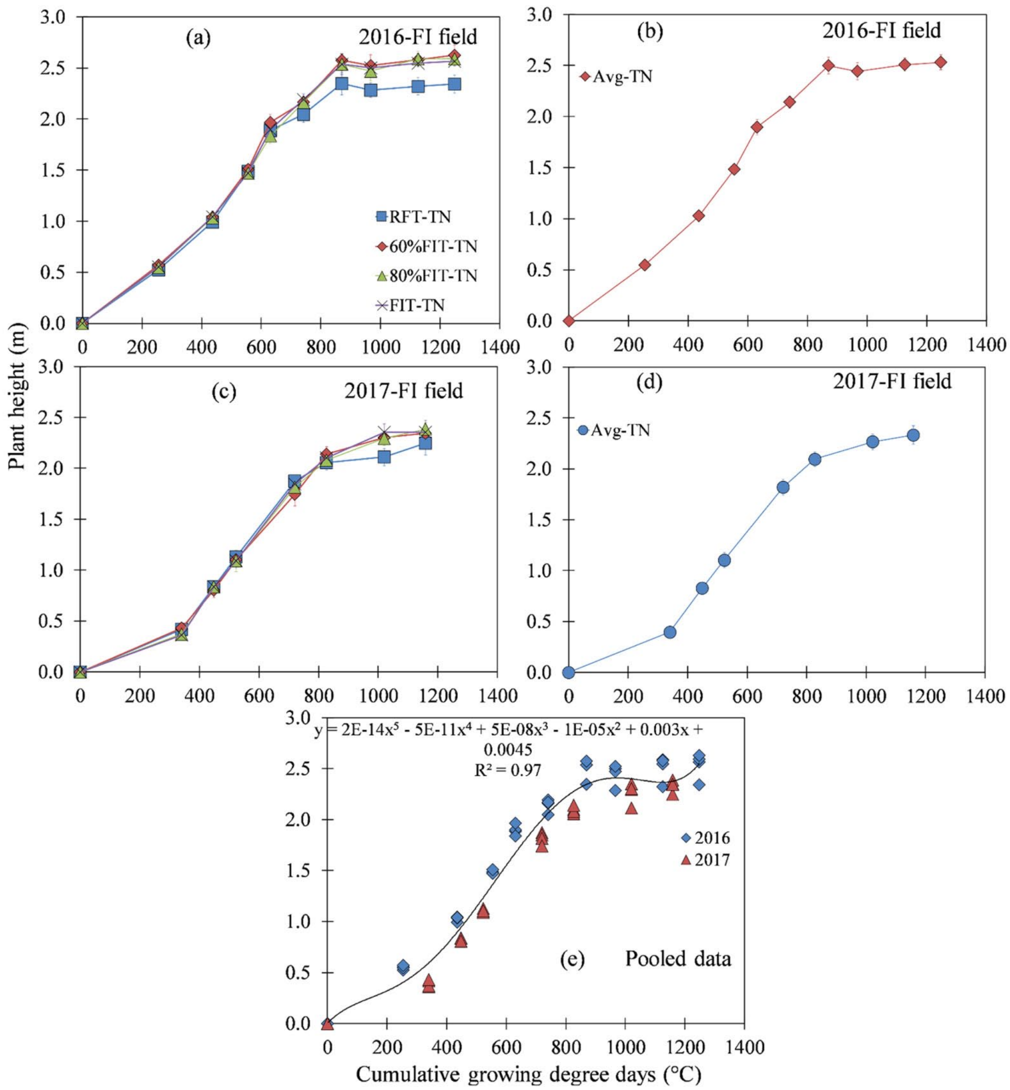


Fig. 8. Distribution of plant height at furrow irrigation (FI), (a) all treatments in 2016, (b) average of all irrigation levels traditional nitrogen treatment (TN) in 2016, (c) all treatments at in 2017, (d) average of all irrigation levels traditional nitrogen treatment (T) in 2017, (e) pooled data for traditional nitrogen treatment. Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

Table 3 Seasonal irrigation, grain yield (adjusted to 15.5 grain moisture content), peak leaf area index (LAI), seasonal average LAI, maximum plant height, and stem diameter for maize in the center pivot, subsurface drip, and furrow irrigation methods/fields in 2016 and 2017 growing seasons.

Year	Irrigation method	Nitrogen treatment	Irrigation level/ treatment	Irrigation amount (mm)	Grain yield (Mg ha^{-1})	*CV Yield (%)	Peak LAI	Seasonal average LAI	Maximum plant height (m)	Stem diameter (cm)	Standard deviation
2016	Center pivot	Traditional	FIT	184	16.6 abc	1.4	6.65 a	4.14 ab	2.7 a	2.20 a	2.54
			80% FIT	147	16.0 dc	3.0	6.23 ab	4.23 ab	2.6 ab	2.13 a	1.94
			60% FIT	110	15.5 d	5.6	5.90 ab	3.92 b	2.6 ab	2.27 a	2.60
			Rainfed	0	9.6 e	4.0	5.39 b	3.43 c	2.45 b	2.27 a	1.20
		Nontraditional-1	FIT	188	17.3 a	1.5	6.12 ab	4.22 ab	2.75 a	2.39 a	2.06
			80% FIT	156	16.7 abc	6.0	5.95 ab	4.05 ab	2.7 a	2.29 a	1.49
			60% FIT	124	16.4 BCE	2.8	5.98 ab	4.08 ab	2.7 a	2.25 a	1.48
		Nontraditional-2	FIT	189	15.8 a	1.6	6.24 ab	4.26 a	2.7 a	2.16 a	1.77
			80% FIT	157	15.6 ab	1.1	6.25 ab	4.28 a	2.75 a	2.25 a	1.32
			60% FIT	126	15.5 bcd	5.2	6.09 ab	4.22 ab	2.75 a	2.33 a	1.17
2017	Center pivot	Traditional	FIT	159	17.0 abc	3.5	6.15 ab	4.30 ab	2.6 a	2.60 abcd	0.09
			80% FIT	127	16.5 bdc	4.7	6.18 ab	4.01 BCE	2.55 ab	2.61 abc	0.11
			60% FIT	95	16.0 d	4.9	5.64 b	3.98 BCE	2.5 ab	2.40 cd	0.08
			Rainfed	0	9.3 e	6.6	5.53 b	3.85c	2.4 b	2.35 d	0.15
		Nontraditional-1	FIT	183	17.8 a	1.3	6.03 ab	4.35 a	2.65 a	2.53	0.08
			80% FIT	151	17.3 ab	1.3	6.53 a	4.26 ab	2.65 a	2.70 ab	0.10
			60% FIT	119	16.5 dc	4.3	6.56 a	4.28 ab	2.6 a	2.59 abcd	0.07
		Nontraditional-2	FIT	183	17.6 a	2.6	6.22 ab	4.19 ab	2.65 a	2.58	0.10
			80% FIT	151	17.4 a	0.7	6.37 ab	4.25 ab	2.65 a	2.48 bcd	0.04
			60% FIT	120	16.6 bdc	4.0	6.60 a	4.31 ab	2.6 a	2.84 a	0.22

Year	Irrigation method	Nitrogen treatment	Irrigation level/ treatment	Irrigation amount (mm)	Grain yield (Mg ha^{-1})	*CV Yield (%)	Peak LAI	Seasonal average LAI	Maximum plant height (m)	Stem diameter (cm)	Standard deviation
2016	Subsurface drip	Traditional	FIT	184	16.4 ab	1.1	6.35 a	4.44 ab	2.55 abc	2.31 ab	1.48
			80% FIT	147	16.1 ab	1.1	6.14 a	4.27 ab	2.55 abc	2.20 b	1.62
			60% FIT	110	15.7 b	1.8	6.01 a	4.26 ab	2.45 BCE	2.30 ab	2.12
			Rainfed	0	9.1 c	27.6	6.01 a	4.07 b	2.4c	2.42 ab	1.63
		Nontraditional-1	FIT	166	16.8 a	0.4	6.36 a	4.35 ab	2.65 a	2.27 ab	1.48
			80% FIT	134	16.4 ab	3.3	6.24 a	4.36 ab	2.55 abc	2.25 ab	2.47
			60% FIT	103	16.0 ab	6.0	6.08 a	4.38 ab	2.5 abc	2.44 a	1.70
		Nontraditional-2	FIT	169	16.8 a	2.4	6.40 a	4.35 ab	2.6 ab	2.28 ab	1.69
			80% FIT	137	16.7 a	2.3	6.28 a	4.48 a	2.6 ab	2.21 b	2.05
			60% FIT	105	16.0 ab	1.8	6.25 a	4.48 a	2.5 abc	2.27 ab	1.75
2017	Subsurface drip	Traditional	FIT	159	16.1 a	2.6	5.87 a	4.28 a	2.45 abc	2.57	0.05
			80% FIT	127	16.3 a	1.3	6.00 a	4.40 a	2.45 abc	2.79 a	0.08
			60% FIT	95	15.9 a	3.4	5.56 a	4.26 a	2.45 abc	2.68 ab	0.04
			Rainfed	0	10.9 b	6.9	6.03 a	4.19 a	2.35c	2.43 c	0.07
		Nontraditional-1	FIT	192	16.5 a	3.4	6.09 a	4.42 a	2.6 a	2.65 ab	0.03
			80% FIT	155	16.5 a	1.3	5.79 a	4.32 a	2.5 abc	2.73 ab	0.08
			60% FIT	118	15.9 a	5.3	5.91 a	4.39 a	2.55 ab	2.62 abc	0.05
		Nontraditional-2	FIT	194	16.7 a	1.5	5.86 a	4.30 a	2.6 a	2.74 ab	0.07
			80% FIT	157	16.5 a	1.3	5.57 a	4.26 a	2.5 abc	2.64 abc	0.07
			60% FIT	121	16.4 a	1.7	5.61 a	4.24 a	2.4 BCE	2.57 BCE	0.10
2016	Furrow	Traditional	FIT	184	15.2 a	0.6	4.81 b	3.90 a	2.6 a	2.26 a	1.93
			80% FIT	147	15.1 a	3.3	5.66 a	3.90 a	2.6 a	2.18 a	1.69
			60% FIT	110	14.3 a	3.0	5.60 a	4.05 a	2.65 a	2.22 a	1.18
			Rainfed	0	9.8 b	7.0	4.67 b	3.47 b	2.35 a	2.18 a	2.24
2017			FIT	159	14.0 a	13.7	5.30 ab	4.25 ab	2.35 a	2.34 a	0.06
			80% FIT	127	13.3 a	9.6	5.60 ab	4.38 a	2.4 a	2.46 a	0.09
			60% FIT	95	12.2 a	13.4	5.84 a	4.44 a	2.3 a	2.36 a	0.10
			Rainfed	0	7.9 b	15.3	5.16 b	3.99 b	2.2 b	2.36 a	0.06

*CV = coefficient of variation

In comparison of the combination of non-traditional (NT) methods of NT-1 and NT-2 vs. TN with respect to irrigation method (i.e., CP and SDI) differences by holding levels of irrigation, nitrogen and year constant, showed that there were significantly higher ($p < 0.05$) plant height values in CP method than in SDI (60% FIT-NT), CP > SDI (60% FIT-TN), CP > SDI (80% FIT-NT), and CP > SDI (FIT-TN) in 2016 growing season; and in CP > SDI (60% FIT -NT), CP > SDI (80% FIT-NT), and CP > SDI (FIT-TN) in 2017 growing season. The plant height was significantly lower in the RFT than 60% FIT, 80% FIT, and FIT-TN irrigation level in the FI method in 2016 season; and in the RFT than 80% FIT and FIT irrigation levels in 2017 growing season. On the other hand, there was no significant difference ($p > 0.05$) between RFT and other irrigation levels in the SDI in both years. The RFT plant height was significantly lower than those in the FIT-TN in both years (Table 3).

Plant height was influenced by irrigation treatments across all irrigation methods more in 2016 than in 2017. As expected, the lower and higher plant heights were observed at RFT and FIT, respectively, across the N treatments, irrigation methods, and years. However, in most cases, plant height had similar magnitudes between the irrigation treatments of 60% FIT, 80% FIT, and FIT across the irrigation methods, N treatments, and years. The lowest plant height of 2.3 (FI- RFT), 2.4 (SDI-RFT) and 2.5 m (CP-RFT) was observed in the 2016 growing season, and 2.2 (FI-RFT), 2.4 (SDI-RFT) and 2.4 m (CP-RFT) was observed in 2017. This result was similar to the findings of Chilundo et al. (2016) that Similarly findings was reported by O. Robles et al. (2017) that differences in maize height were observed between the two growing seasons of 2015 (1.96 m) and 2016 (2.15 m) seasons and the irrigation treatment had significantly affect maize height in 2016 under low-pressure solid-set sprinkler irrigation system. In contrast, in the work of Chilundo et al. (2016) reported that irrigation methods of furrow and drip irrigation methods had not influenced maize height and irrigation 75% of the crop water requirement level yielded higher plant than 100% level. Researchers (e.g., Birch et al., 2002; Bennouna et al., 2004) reported that maize, when exposed to water stress during vegetative and tasseling stages, reduce plant height. Soler et al. (2007) reported that maize under rainfed conditions had < 5% reduction in height as compared with maize under irrigated conditions (2.17 m). The measured maximum maize height of 2.7 (CP-FIT-TN), 2.5 (SDI-FIT-TN), 2.6 (FI-FIT-TN), 2.8 (CP-FIT-NT-1), 2.6 (SDI-FIT-NT-1), 2.7 (CP-FIT-NT-2) and, 2.6 m (SDI-FIT-NT-2) was observed in 2016 growing season; and 2.6 (CP-FIT-TN), 2.4 (SDI-FIT-TN), 2.4 (FI-FIT-TN), 2.7 (CP-FIT-NT-1), 2.6 (SDI-FIT-NT-12.7 (CP-FIT-NT-2) and, 2.6 m (SDI-FIT-NT-2) in 2017 growing season. Across years and treatments, plant height reached peaked measures around 104 DAP (August 17) and 95 DAP (August 14) in 2016 and 2017, respectively.

3.3. Irrigation level and method and N management impacts on leaf area index

The seasonal (2016, 2017) patterns of LAI as a function of cumulative growing degree days (CGDD) for all N and irrigation treatments for CP, SDI, and FI methods are presented in **Figs. 9, 10, and 11**, respectively. The impact of N timing and irrigation levels across three irrigation methods were studied using two LAI features: (a) mean LAI during the growing season; and (b) peak LAI during the growing season. No significant difference was detected for the seasonal mean LAI between 2016 and 2017 for CP and SDI methods, but FI had significantly higher ($p = 0.0001$) LAI in 2017 than in 2016. However, within each growing season, LAI showed significant differences among the irrigation methods (Table 3). In 2016, LAI was significantly ($p < 0.05$) higher in SDI by 5.8% than CP and by 9.6% than FI, while there were no significant differences ($p = 0.0681$) between CP and FI, but CP had 3.8% higher magnitudes than FI. In 2017, LAI in FI was significantly ($p < 0.0031$) higher by 6.1% than CP, but there were no significant differences ($p = 0.5734$) between FI and SDI. Moreover, SDI was significantly ($p = 0.0107$) higher by 5.1% than CP. Mean LAI was found to be significantly different among irrigation methods, but only for specific irrigation-levels. For example, in the 60% FIT, LAI was significantly ($p = 0.0051$) higher in FI than CP, and in CP than SDI ($p = 0.0036$), and also in SDI than FI ($p = 0.044$) and CP than SDI ($p = 0.0321$) for the 80% FIT), and higher in SDI than FI for FIT). Mean LAI was significantly different between CP and SDI methods when averaged over N timing, year, and irrigation levels. Moreover, mean LAI showed significant differences ($p < 0.05$) between the RF and all irrigation levels, across all the irrigation methods.

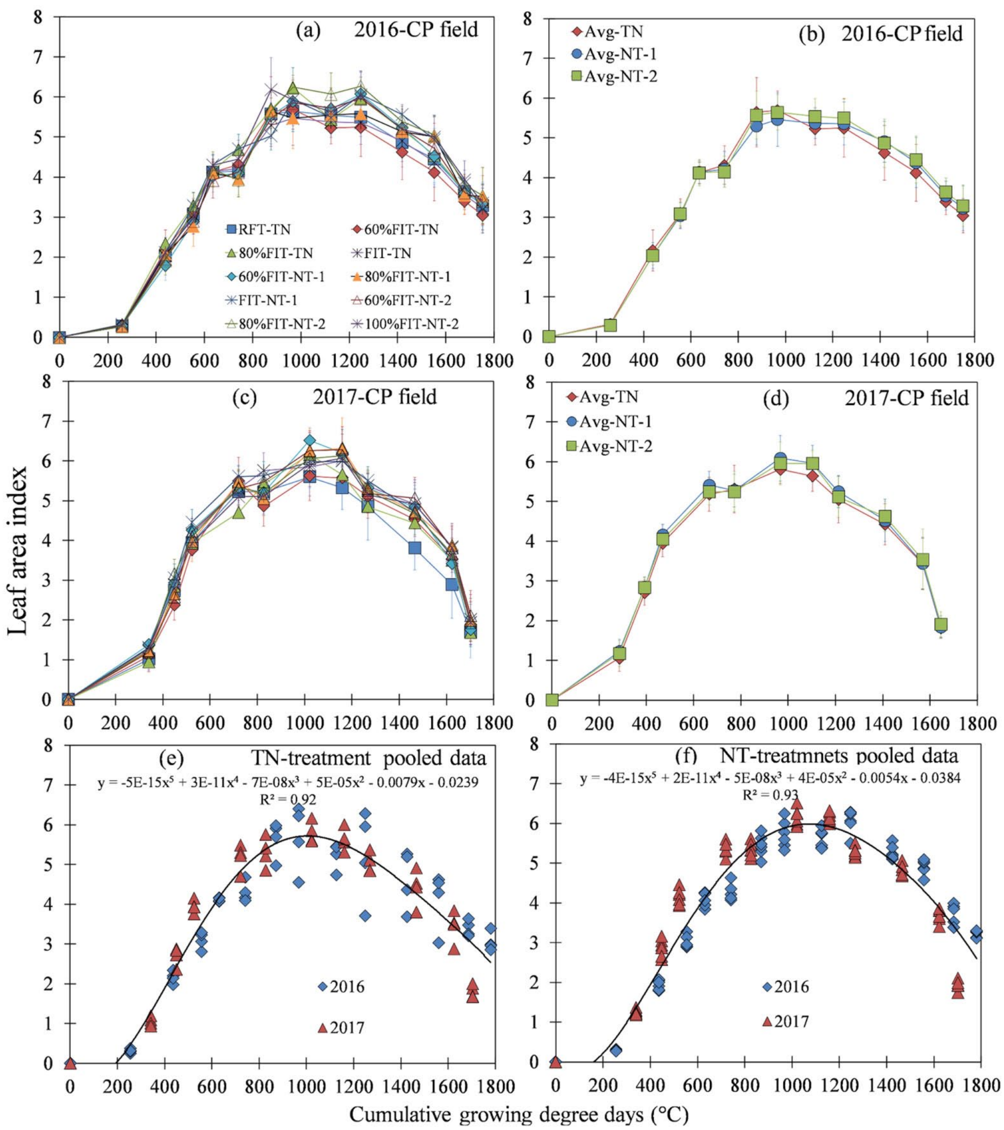


Fig. 9. Distribution of maize leaf area index (LAI) in the center pivot field (CP): (a) all treatments in 2016, (b) average of all irrigation levels, including rainfed conditions by nitrogen treatment; traditional (TN), non-traditional-1 (NT-1), and non-traditional-2 (NT-2) in 2016, (c) all treatments in 2017, (d) average of all irrigation levels, including rainfed conditions by nitrogen treatment; traditional (TN), nontraditional-1 (NT-1), and non-traditional-2 (NT-2) in 2017, (e) pooled data for traditional nitrogen treatments, (f) pooled data for nontraditional nitrogen treatments. Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

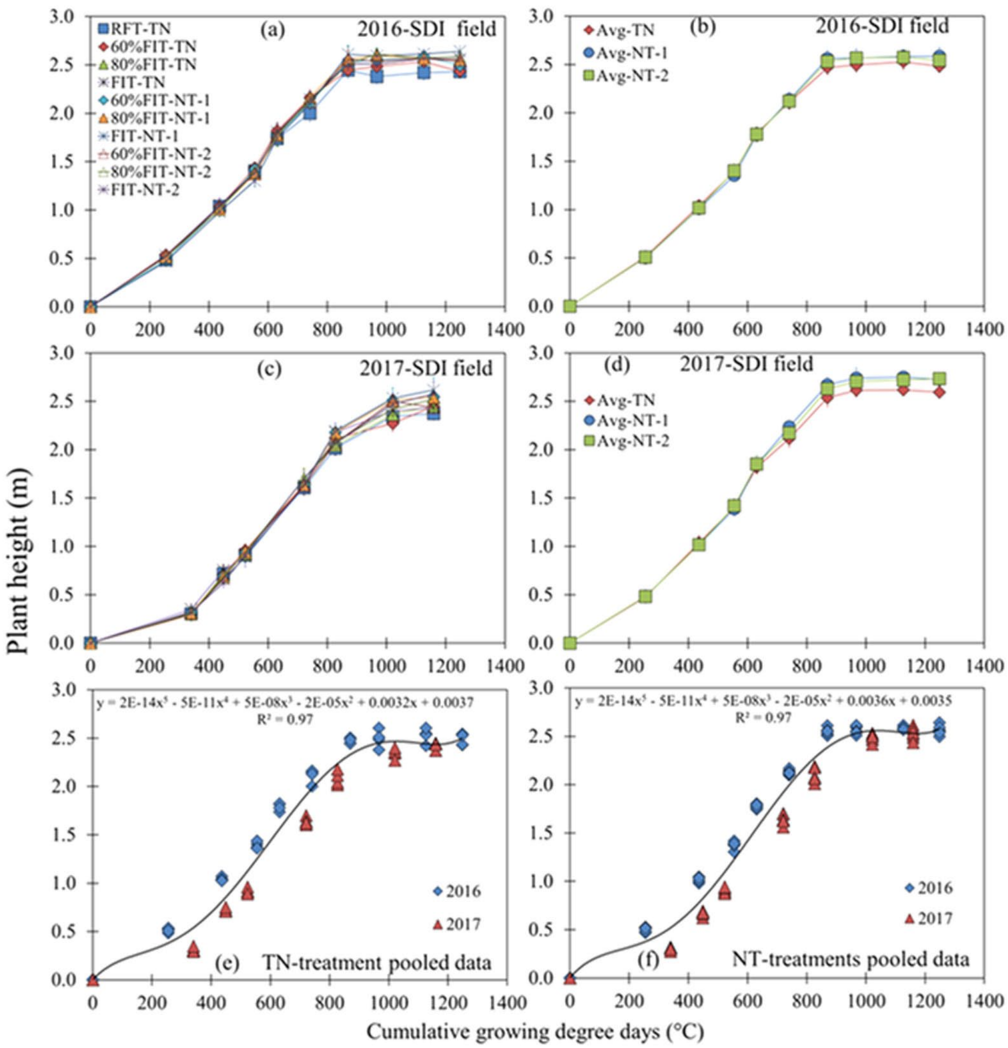


Fig. 10. Distribution of maize leaf area index (LAI) at subsurface drip irrigation (SDI) field, (a) all treatments in 2016, (b) average of all irrigation levels including rainfed conditions by nitrogen treatment; traditional (TN), nontraditional-1 (NT-1), and non-traditional-2 (NT-2) in 2016, (c) all treatments at in 2017, (d) average of all irrigation levels including rainfed conditions by nitrogen treatment; traditional (TN), non-traditional-1 (NT-1), and non-traditional-2 (NT-2) in 2017, (e) pooled data for traditional nitrogen treatment, (f) pooled data for non-traditional nitrogen treatments. Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

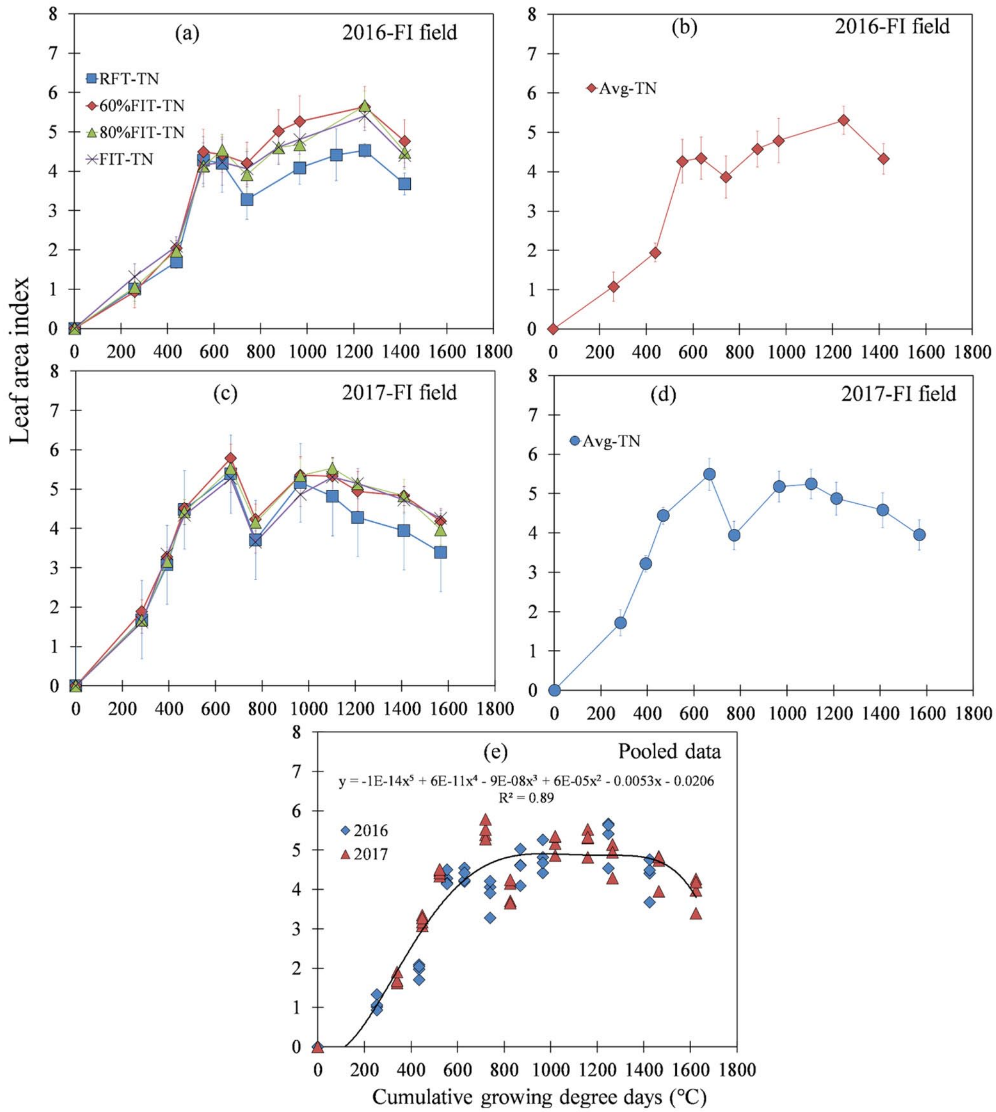


Fig. 11. Distribution of maize leaf area index (LAI) at furrow irrigation (FI) field, (a) all treatments in 2016, (b) average of all irrigation levels traditional nitrogen treatment (TN) in 2016, (c) all treatments at in 2017, (d) average of all irrigation levels traditional nitrogen treatment (TN) in 2017, (e) pooled data for traditional nitrogen treatment. Each data point represents an average of 10 measurements. Vertical bars represent standard deviation.

Generally, there was no significant difference ($p > 0.05$) between mean and peak LAI any of the irrigation (except RFT) and nitrogen treatments in both years at both seasonally averaged LAI and peaked LAI (Table 3). The peak LAI of 5.0, 5.7 and 4.2 $m^2 m^{-2}$ occurred at 77, 95, and 61 DAP (July 21, August 8, and July 5) in 2016, while peak LAI of 5.6, 6.0, and 5.4 $m^2 m^{-2}$ occurred at 81, 81, and 61 DAP (July 31, July 31, and July 11) in 2017, in the CP, SDI, and FI, respectively. The peak LAI of 6.4, 6.3, and 5.6 $m^2 m^{-2}$ were observed in FIT-TN, FIT-NT-1%, and 60% FIT-TN for CP, SDI, and FI during 2016, respectively. During 2017, the peak LAI of 6.5, 6.1, and 5.8 was observed in 60% FIT-NT-1, FIT-NT-1%, and 60% FIT-TN for CP, SDI, and FI, respectively. The mean LAI was not impacted by any limited irrigation treatment, because the initial soil water content was similarly sufficient between the treatments and there was no water stress impact on plant growth and development, and thus LAI was similar in most of the treatments. The differences in soil water availability in various treatments, and thus LAI, only began to appear later in the season as a function of irrigation treatment, but differences were not large enough to be statistically significant or affect foliage growth. The lowest mean LAI was found in RFT across all irrigation methods during both growing seasons. Also, RFT reached its peak LAI earlier than other treatments since the imposition of water stress causes a tendency for plants to senesce/mature early.

The peak LAI values varied among irrigation methods and growing seasons as well as in their time of occurrence. In 2017 (as well as 2016) growing season, the mean of peak LAI in TN treatment across all irrigation levels was similar between CP (5.9) and SDI (5.8) but was 7.3% higher than the average of irrigation treatments in FI (5.5). The mean of peak LAI of NT-1 and NT-2 across all irrigation levels was 7% higher in CP (6.2) than SDI (5.8), 13% higher in CP (6.2) than FI, and 5.5% higher in SDI than FI. There were no substantial differences between peak and mean LAI in NT-1 and NT-2 across the irrigation treatments within a given irrigation method and between CP and SDI. In 2016, the mean of peak LAI across the irrigation all treatments (FIT, 80% FIT and 60% FIT) for the TN treatment was identical for CP (6.2) and SDI (6.2), which were 24% greater than that in FI (5.0). The irrigation method had a substantial influence on LAI, and this could be attributed to the differences in irrigation efficiency achieved in these irrigation methods (irrigation efficiency of SDI > CP > FI). Higher irrigation efficiency may allow greater quantity of water retention in the soil profile/root zone per unit of water pumped in SDI and CP methods than in FI. Moreover, the potential for nutrient leaching can be highest in FI method, followed by CP and SDI. However, we observe from our findings that LAI was not impacted by TN or NT application of nitrogen in and across CP and SDI methods. The mean LAI values in NT-1 and NT-2 across all irrigation levels were similar to that of TN treatment, within SDI and CP, as well as across them. This means crop obtained adequate N from the root zone in either N application treatment (i.e., TN and NT-1 and NT-2).

There were no substantial differences in LAI across the N and irrigation treatments in SDI. As mentioned previously, the two N treatments only differed in application timing, and not amount. This implies that while NT nitrogen application, at least theoretically, is intended to improve N uptake, we did not observe this in our experiments, at least when LAI differences are considered. This might be due to lower opportunity for N leaching or loss at the site or during the growing seasons. Moreover, the N amounts that were applied were conservatively sufficient based on UNL recommendations and carefully measured site-specific nitrogen credentials and nitrogen requirements. This strategy, when combined with well-distributed wetting events potentially ensured maximum plant N uptake, and rendered minimal opportunity for N loss, eventually making TN or NT nitrogen management strategies more or less equivalent. Although the imposed irrigation and N timing treatments did not have a consistent impact on LAI, this does not imply that the growth and development was not affected, and other parameters of growth and productivity have to be evaluated. The peak LAI among irrigation methods clearly varied consistently, especially in FI method. Overall, the observations of maize LAI measured in this research are in accordance with LAI measured previously under various irrigation methods (Irmak and Djaman 2016a, 2016b) and irrigation levels (Djaman et al., 2013) in the same site. Barideh et al. (2018) reported that the highest maize LAI rate was observed under conventional irrigation method as compared to alternate partial root-zone irrigation and fixed partial root zone irrigation. Khalili et al. (2020) also reported that the maize LAI was decreased at 50% irrigation level significantly ($p = 0.05$) compared to 100% irrigation level on maize under alternate furrow irrigation system.

3.4. Treatment impacts on physiological development and stem diameter

The two growing seasons had similar time (i.e., DAP) on reaching the three maize stages (i.e., V8, VT and R3) that was planned to receive the in-season N applications. Across irrigation methods (i.e., CP and SDI) and treatments, maize reached V8, VT and R3 growth stages around 48, 73 and 89 DAP (June 22, July 17, and August 2, respectively) in 2016 growing season and it reached V8, VT and R3 stages around 43, 74 and 92 DAP (June 23, July 24, and August 11, respectively) in 2017. N treatments (i.e., pre-plant N application and in-season N applications), irrigation treatments, and methods did not affect maize growth and development in terms of time required reaching the aforementioned stages. The results from the averaged LAI of irrigation treatments, including RFT conditions, for a given year and N treatment demonstrated that there was a difference in LAI magnitude N treatments (i.e., higher LAI in NT-1 and NT-2 over TN) at CP and SDI methods (Figs. 9b, d, 10b and d). However, the differences were larger between the irrigation treatments for the given N treatment (Figs. 9a, c, 10a, c, 11a, and c). Moreover, the initiation of the changing in LAI magnitudes varied, depending on the irrigation level coupled with given nitrogen treatment, irrigation method, and year (Figs. 9, 10, and 11). In the past three decades, researchers have used stem diameter changes in plant water assessment and plant response to different environmental variables and management. Stem diameter was shown to be related to the plant water status (Klepper et al., 1971; Molz and Klepper, 1972; Jarvis, 1975). In this research, stem diameter was measured to evaluate the agronomic traits. Larger plant stem diameter usually indicates more reserves and energy accumulation, thus more and a better grain filling. Also, it tends to provide a support structure for the ears. The largest stem diameter of 2.39 (FIT-NT-1), 2.43 (60% FIT-NT-1), and 2.25 (FIT-TN) cm was observed at CP, SDI, and FI methods in 2016 growing season, respectively; and 2.83 (60% FIT-NT-2), 2.79 (80% FIT-TN), and 2.46 (80% FIT-TN) cm at CP, SDI, and FI methods in 2017, respectively (Table 3). There were no significant differences ($p > 0.05$) between the treatments within CP and FI, except few pairwise combinations that had a significant difference in SDI in the 2016 growing season (Table 3). However, there were some pairwise differences between the treatments at CP and SDI in 2017 growing season. A possible explanation for this might be that the plants were not impacted by the water deficit in 2016 as it was more pronounced in 2017 growing season. Also, the inconsistency observed between the fields and years may be due to the soil spatial variability and, as a result, variations in soil water distribution and re-distribution from irrigation and/or rainfall. There was not a significant ($p > 0.05$) three-way interaction between all the variables when comparing TN treatment across all methods. However, the two-way interactions (irrigation method by year interaction and the year by irrigation treatment interaction) were both significant ($p < 0.05$). All irrigation methods showed significantly higher values in 2017 growing season than 2016 growing season for a given irrigation method. In comparison of irrigation methods, there was only one significant difference in 2017 growing season. For example, the averaged stem diameter across TN treatments and irrigation levels in the SDI was significantly higher than CP and FI; also, plants in CP field had significantly higher stem diameter than those in FI field. Considering all three N timing application strategies across CP and SDI, the four-way and three-way interactions were not significant. When comparing the years by irrigation method for the same N treatments, stem diameters were significantly higher in 2017 than in 2016. Kang et al. (2000) found that maize stem diameter showed no significant differences among three irrigation methods of alternate furrow irrigation, fixed furrow irrigation, and conventional furrow irrigation, and three levels of irrigation amounts in maize production in an arid area environment. Rasool et al. (2020) in experiments to study the behavior of deficit drip irrigation system under three four irrigation levels of 100%, 90%, 75% and 60% of ETc, respectively, and furrow irrigation system. They reported that maize stem diameter had slight differences among 100%, 90%, and 75% of ETc under surface drip irrigation system whereas they observed a notable decrease in 60% ETc and furrow irrigation system.

3.5. Relationship between maize LAI and plant height

Field measurements of plant LAI can be difficult and more complex task than measuring plant height, which is a very simple process. Thus, experimentally established relationships between plant height and LAI can be used as a more practical approach to estimate LAI and as an index to quantify plant growth rate. The relationships between the two variables developed in this research can provide opportunity to estimate LAI from plant height under different irrigation levels and N management strategies under different irrigation methods, which has not been done previously. However, the limitation of this approach raises up at the point when LAI starts to decrease, while plant height remains relatively constant after it reaches its maxima. Strong linear relationships were observed between LAI and plant height in all irrigation and N treatments and all irrigation methods and years (**Figs. 12, 13 and 14**). The slopes across N and irrigation treatments for a given irrigation method increased from RFT to FIT and ranged from 2.05 to 2.21 for CP, from 2.16 to 2.27 for SDI, and from 1.82 to 1.94 for FI. Another significant aspect is that the slopes for the pooled data were similar between TN and NT nitrogen treatments in CP and SDI methods (Fig. 12k and l for TN and 17k and l for NT). This suggests that there was no considerable N treatment impact on the LAI vs. plant height relationship thereby on the magnitude of the slope value. The slopes were higher in CP and SDI than FI. This could be due to greater LAI values corresponding with the plant height values in the beginning of the 2017 growing season than in 2016 and this inconstancy in FI likely to be related mainly to the lower irrigation efficiency (data not shown) in FI as compared with the CP and SDI. This means that the soil moisture in the plant root zone in FI is susceptible to a greater distribution variability in FI than in CP and SDI and this potentially led to increased plant growth variation in plant height vs. LAI relationship. Soil moisture distribution variability is normalized or less with CP and SDI methods, especially in the FIT, than in FI. The main reason for this is that plants uptake soil water more uniformly in FIT irrigation level in the CP and SDI than FI. In accordance with the present results, previous studies by other researchers (Pieri and Fuchs, 1990; Sadek et al., 2006; Djaman et al., 2013) also demonstrated linear and strong relationships between plant height and LAI for cotton and maize. However, no research quantified these relationships for maize for different irrigation and nitrogen management under three different irrigation methods under the same management and environmental conditions.

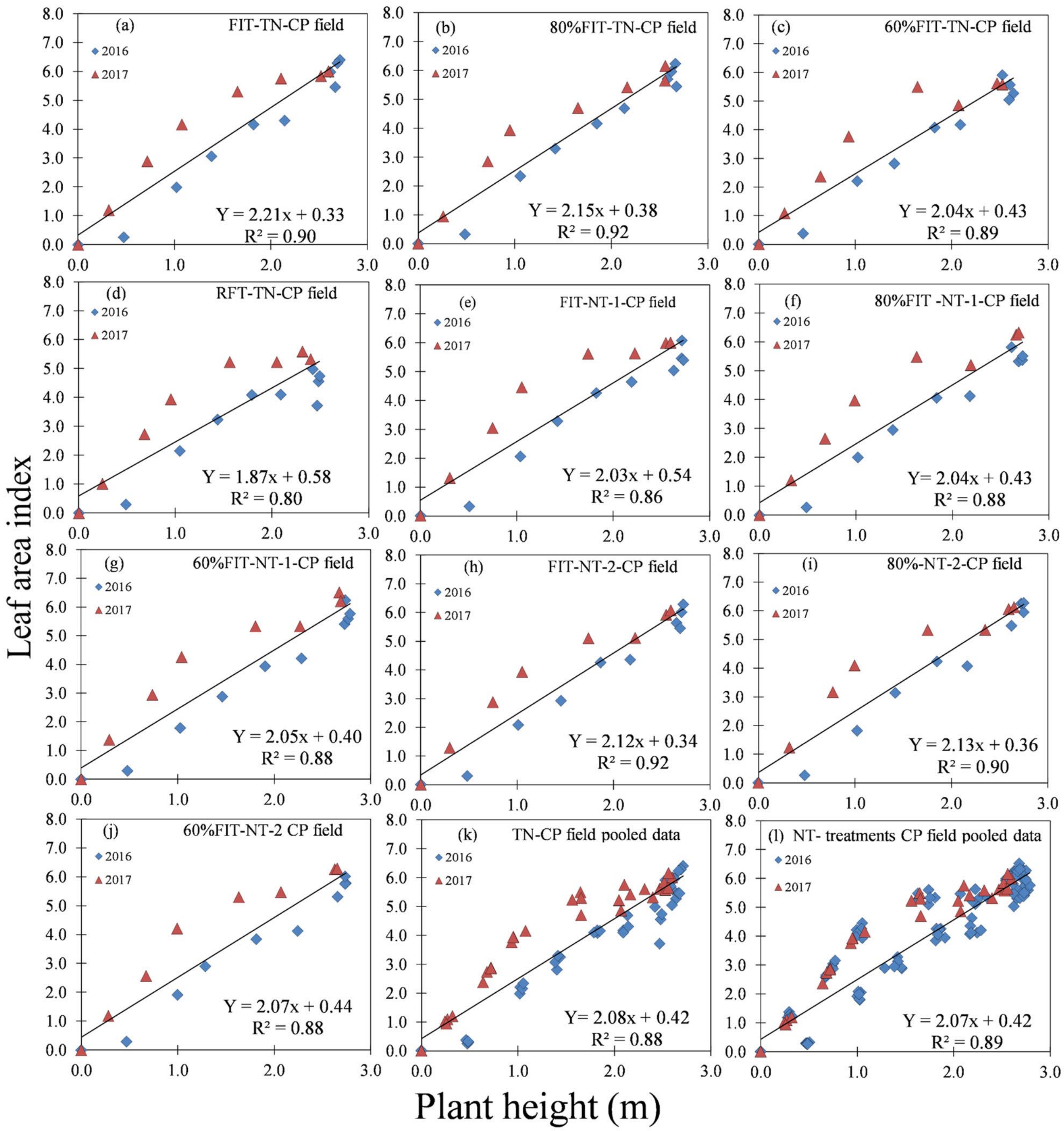


Fig. 12. Relationship between plant height and leaf area index (LAI) by irrigation level and nitrogen treatments and for the pooled data from 2016 and 2017 growing seasons in the center pivot (CP) field from emergence to the time when crop attained maximum height. Each data point represents an average of 10 measurements.

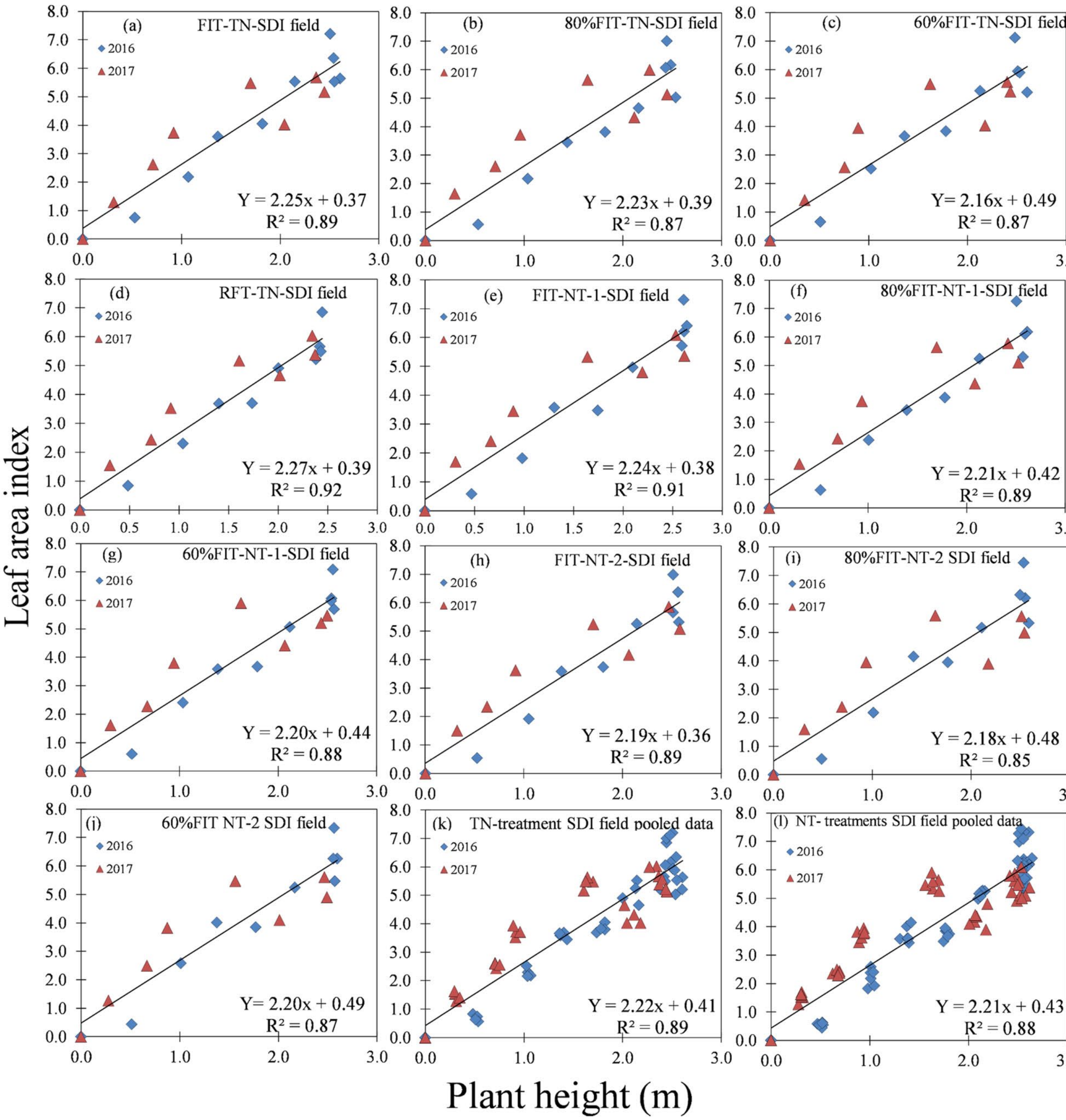


Fig. 13. Relationship between plant height and leaf area index (LAI) by irrigation level and nitrogen treatments and for the pooled data from 2016 and 2017 growing seasons in the subsurface drip irrigation (SDI) field from emergence to the time when crop attained maximum height. Each data point represents an average of 10 measurements.

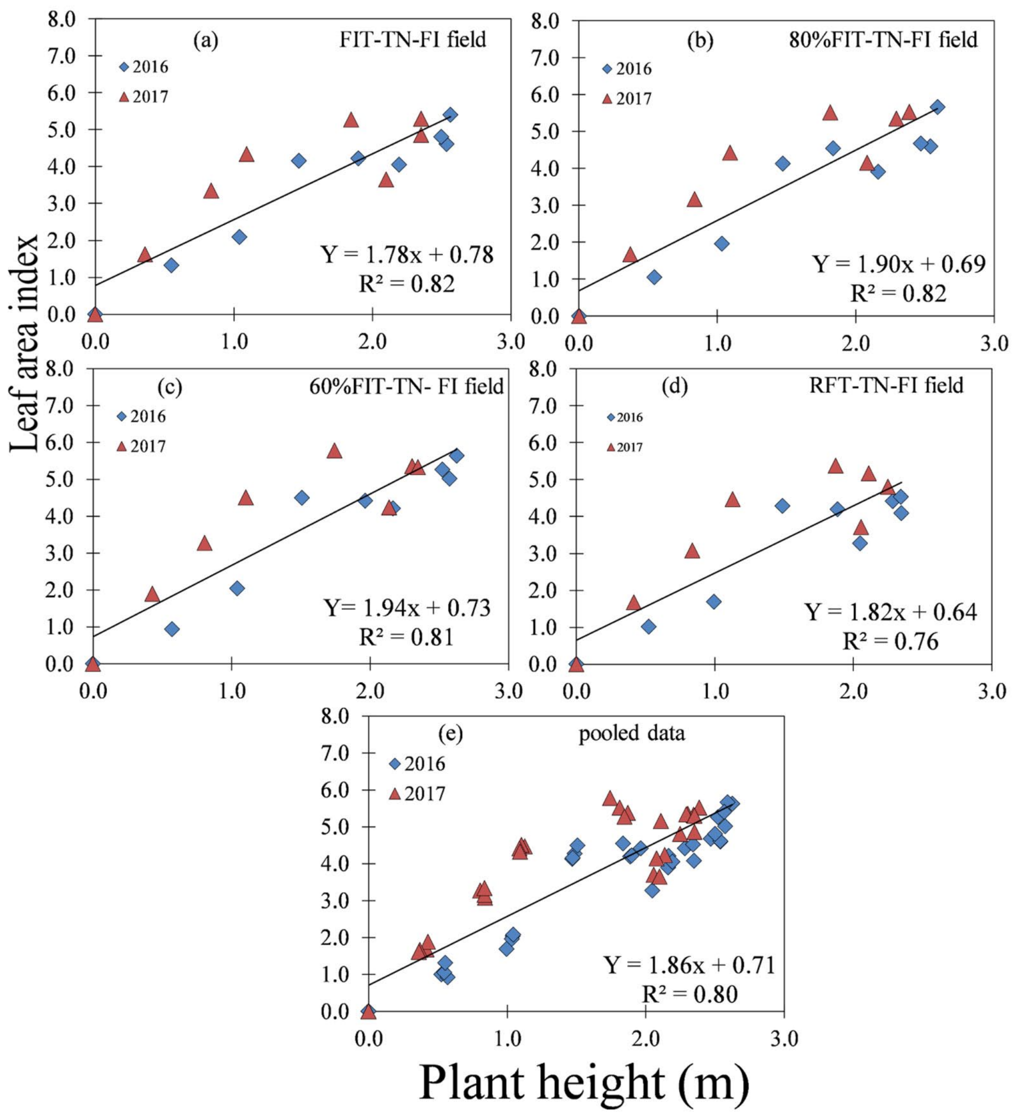


Fig. 14. Relationship between plant height and leaf area index (LAI) by irrigation level and nitrogen treatments and for the pooled data from 2016 and 2017 growing seasons in the furrow irrigation (FI) field from emergence to the time when crop attained maximum height. Each data point represents an average of 10 measurements.

3.6. Irrigation and nitrogen treatments and irrigation methods impacts on maize grain yield

Maize grain yields across all the treatments ranged from 9.6 to 16.6 Mg ha^{-1} (CP), 9.1–16.4 Mg ha^{-1} (SDI), and 9.8–15.2 Mg ha^{-1} (FI) in 2016; and from 9.3 to 17.0 Mg ha^{-1} (CP), 10.9–16.1 Mg ha^{-1} (SDI), and 7.9–14.0 Mg ha^{-1} (FI) in 2017 (Table 3). For all treatments, the grain yield exhibited an upward trend with increasing applied irrigation amount. The highest grain yields were measured in the FIT irrigation level across all N treatments (i.e., TN, NT-1, and NT-2) in all three irrigation methods in both years (Table 3). However, the highest grain yield of 17.0 Mg ha^{-1} was observed in CP in 2017. Grain yields were notably altered by irrigation levels for the TN nitrogen and NT nitrogen treatments for the given irrigation method, and general trend was increasing in grain yield with an increase in irrigation amount (Table 3).

Generally, average grain yield across all treatments, including both CP and SDI, were marginally (1.6%) higher in 2017 than in 2016 and grain yields between the two growing seasons were not significant ($p > 0.05$) for the same treatments as a result of the same maize variety, same agronomic practices, and similar weather parameters (i.e., solar radiation, and GDD). Although the total amount of irrigation and rainfall was higher in 2017, the uneven rainfall distribution in 2016 led to an insignificant impact on grain yield production. One of the reasons of higher yield in 2017 is that cooler T_{max} during the reproductive stage coupled with relatively cooler T_{min} for the growing season and higher VPD (data not shown). High air temperatures (>30 °C) during the reproductive stage may limit photosynthesis process and adversely affect grain filling and hot nights may also reduce grain production by increasing respiration process (using sugar as energy rather than kernel production) and that is why maize prefers cooler nights with ambient temperatures of around 15.5 °C. However, FI showed significantly higher ($p < 0.05$) yields in 2016 than that in 2017 (Table 3), which primarily associated with the soil at that specific site. This might suggest that the most combination and concentration of mineral nutrients were adequately available in the soil in the 2016 growing season and relatively consumed or even leached mobile nutrients in 2017 because of the higher amount of seasonal total irrigation amount applied.

In most cases, the coefficient of variance (CV) values of the grain yields, calculated by the ratio of the standard deviation of the grain yield to the mean of the grain yield, were relatively small, indicating small variations between the replications of a given treatment (Table 3). The CV values of grain yield for the three irrigation methods, treatments, and two years were below 20% (except the RFT treatment in the SDI in 2016), indicating low yield variability between the replications. There were relatively high CV values in the FI method/field in 2017 in addition to the RFT treatment in SDI in 2016. The three type tests of fixed effects showed that the irrigation treatments ($p = 0.0006$) and the irrigation method x year interaction ($p < 0.0024$) were significant on grain yield production. Average grain yield across the irrigation levels (i.e., FIT, 80% FIT, and 60% FIT) for the TN treatment at the given irrigation method within a year, showed significant differences between FI and CP, and it was 8.1% and 25.5% higher in CP in 2016 and 2017, respectively. Also, between FI and SDI, which had 8.1% and 23% higher yield in SDI in 2016 and 2017, respectively. This could be due to FI having higher irrigation depths applied and lower irrigation efficiency because of the difficulties on ensuring uniform distribution of water with the FI method as compared with CP and SDI methods as well as less water storage in the plant root zone and higher water losses through deep percolation and surface run-off (data not shown) in the FI method as compared with SDI and CP methods. Moreover, the irrigation efficiency for the FI method is approximately 45–65%, as compared with 75–85% for the CP and > 95% for the SDI methods. Therefore, this higher water losses in the FI method may cause increased N leaching from the plant root zone, which can negatively affect maize N uptake and grain yield. There was no significant difference ($p > 0.05$) within a year between SDI and CP methods in any of the growing season. When grouping the irrigation levels across the irrigation methods and years, there were significant yield differences between 60% FIT and 80% FIT and 60% FIT and FIT irrigation treatments. There was no significant difference between the 80% FIT and FIT treatments.

In comparison between three N levels (TN, NT-1, and NT-2) in the SDI and CP irrigation methods, and FIT, 80% FIT, and 60% FIT irrigation levels for both years, the statistical tests of fixed effects showed that three irrigation treatment was significant ($p = 0.0001$) on grain yield production, while the irrigation method x year interaction (p = 0.0551) was not significant. Moreover, significant differences were found between years within irrigation method in CP (p = 0.0121, higher yield in 2017) and between CP and SDI (p = 0.0012, higher yield in CP) in 2017. These findings indicate that maize grain yields under CP with combined N treatments can be optimized the irrigation methodology and N timing applications strategies interactions on maize grain yields more effectively than in SDI in 2017. However, the grouped N treatments need further investigation to unravel the actual N treatment impact on yield, as explained in the next paragraph. Furthermore, there were significant differences between all levels of the irrigation treatment, between 60% FIT and 80% FIT (p = 0.0001, higher yield in 80% FIT) and between 60% FIT and FIT (p = 0.0001, higher yield in the FIT) as well as between 80% FIT and FIT (p = 0.0101, higher yield in the FIT).

Grouping NT-1 and NT-2 vs. TN treatment across the irrigation levels, and years, in CP and SDI methods, it was found that the irrigation treatment (p = 0.0001) and irrigation method x nitrogen interactions were significant (p = 0.0453), while irrigation method x year interaction (p = 0.0581) was not significant. The NT-1 and NT-2 nitrogen treatments had significantly higher grain yields than TN treatment at both irrigation methods of CP and SDI. Moreover, NT-1 and NT-2 nitrogen treatments in CP method had significantly higher grain yields than in SDI. Finally, there were significant differences between all three irrigation levels and higher yields in the 80% FIT than 60% FIT and in the FIT than 80% FIT irrigation levels. These results indicate that the lower yield in the TN treatment in both SDI and CP as compared with grouped NT N treatments was a result of the possibility of N loss via leaching when it applied as a one-time application at preplant. Therefore, the N was not available adequately as compared with split N application methods, which maintained N readily available for crops throughout the growing season and plants had more opportunity to access N as needed. On the other hand, there was no significant difference between NT-1 and NT-2; therefore, NT-1 can be considered as a preferred management practice, which could maximize the economic return by saving the fourth time side-dress N application at R3 growth stage. The TN-1 yielded 4.3% higher in the CP than that in SDI method and the TN-2 was similar between SDI and CP.

The individual seasonal statistical analysis for CP, SDI and FI method is presented in Table 3. In FI, maize grain yields ranged from 9.8 to 15.2 Mg ha^{-1} and from 7.9 M to 14.0 Mg ha^{-1} in 2016 and 2017 growing seasons, respectively. The highest grain yields of 15.2 and 14.0 Mg ha^{-1} were observed in the 2016 and 2017 growing season, respectively (Table 3). The three type tests of fixed effects showed that both irrigation treatment and year were significant on grain yield production with p-values of 0.0001 and 0.00175, respectively. The FI method did not have any significant difference ($p > 0.05$) among the three irrigation levels of 60% FIT, 80% FIT and FIT in both years. However, RFT was significantly lower ($p < 0.05$) than 60% FIT, 80% FIT and FIT levels in both growing seasons as explained previously (Table 3). Pooled grain yields data showed that the comparisons in the 60% FIT irrigation level were significantly different between the two years and higher in 2016 than 2017; also, it was marginally significantly ($p = 0.0495$) different between 60% FIT and FIT irrigation levels (higher grain yield with FIT). The statistical analysis with more data points may increase values in the upper and lower limit; as a result, the yield response was clearly shown in the pooled data in the 60% FIT. However, there was no significant difference between 80% FIT and FIT because the pooled yield results were similar and, as a result, the 80% FIT irrigation level can be recommended as an effective management practice in water-limiting areas.

In SDI method, maize grain yields ranged from 9.1 to 16.0 Mg ha^{-1} in TN treatment; 16.0–16.8 Mg ha^{-1} in TN-1; and 16.0–16.8 Mg ha^{-1} in NT-2 in 2016. Yield ranged from 10.9 to 16.1 Mg ha^{-1} in TN treatment; 15.9–16.5 Mg ha^{-1} in TN-1; and 16.4–16.7 Mg ha^{-1} in NT-2 in 2017. Superior grain yields were obtained for NT treatments of NT-1 and NT-2 at the three irrigation levels as compared with TN treatment, and the year effect was not significant ($p = 0.5964$) on grain yield production. Thus, the statistical analysis was tested the pooled data between the irrigation treatments within each of the different nitrogen treatments, which indicated that the crop responded to treatments similarly. The simple effect comparisons did not show any significant differences between the N treatments within each irrigation level. On the other hand, there were significant differences between the irrigation levels within each of the different nitrogen treatments. Therefore, NT treatments showed a significant difference between 60% FIT and FIT levels at TN-1 and between RFT and 60% FIT, 80% FIT and FIT levels. The results confirm that the NT-1 is an effective practice to maximize yield production under the SDI method with 60% FIT and 80% FIT irrigation levels.

In CP method, maize grain yields ranged from 9.6 to 16.6 Mg ha^{-1} in TN treatment; 16.4–17.3 Mg ha^{-1} in TN-1; and 16.2–17.3 Mg ha^{-1} in NT-2 in 2016. Yield ranged from 9.3 to 17.0 Mg ha^{-1} in TN treatment; 16.5–17.8 Mg ha^{-1} in TN-1; and 16.6–17.6 Mg ha^{-1} in NT-2 in 2017. The NT-1 and NT-2 treatments at three irrigation levels were performed superiorly as compared with TN treatment. Similar to the SDI method, the year effect was not significant ($p = 0.1733$). Hence, the statistical analysis was tested the pooled data and showed that there were some significant differences between the N treatments within some of the irrigation levels. For example, at three irrigation levels of 60% FIT, 80% FIT and FIT there were significant differences in NT-1 vs. TN and NT-2 vs. TN treatment, with higher yields in both NT treatments. Also, there were more significant differences between the irrigation levels within each N treatments as compared with the SDI method whereas the irrigation levels within each of the different nitrogen treatments showed significant differences. For example, in the NT-1, there was only one significant difference between 60% FIT and FIT, while in the NT-2 there were significant differences between 60% FIT and 80% FIT; and between 60% FIT and FIT. When comparing the grain yield in the FIT irrigation level with the results of Djaman et al. (2013) at the same research site and irrigation method, the grain yields were higher in this current research by 12% than the measured value of 15.5 Mg ha^{-1} in the NT-1 and NT-2 in 2016 and 13.5–15% than the measured value of 15.5 Mg ha^{-1} t at NT-1 and NT-2 in 2017, respectively. Similarly, our results were higher 23.5% (CP-NT-1) to 13% (CP-NT-2) in 2016, and 27% (CP-NT-1) to 26% (CP-NT-2) in 2017, respectively, than a result of a research conducted by Irmak et al. (2019) at the same location under linear-move sprinkler irrigation system. These results cast a new light on both NT-1 and NT-2 N management that they perform better than TN, especially NT-2 had greater yield than NT-1. The TN showed that the statistical differences were found between RFT and 60% FIT, 80% FIT and FIT irrigation levels with RFT treatment having lower yields at FIT and also between 60% FIT and FIT irrigation level with 60% FIT having lower yields than FIT. These results indicate that the CP method maximized N availability when it applied via the system (fertigation), because the system tends to apply N uniformly over the entire field and that may lead to maximize N availability in the soil (especially topsoil) profile.

3.7. Spatial grain yield and frequency distribution

While the treatment-mean grain yields depict plot-aggregated crop response to irrigation amount and N fertilizer timing, it is worthwhile to decipher the spatial distribution of yield response across the fields. The high-resolution yield monitoring capabilities of the harvester allowed for analytically quantifying the distribution characteristics and mapping grain yield in each field. The yield monitor data was interpolated using inverse distance weighing technique in ArcMap 10.7 (ESRI, Redlands, CA). Grain yield maps clearly demonstrate the spatial variability that was encountered upon harvest because of treatment imposition in 2016 and 2017 (**Figs. 15a and 16a**). Moreover, the maps also allow for a fair comparison of how each field performed across the two growing seasons and bring out the year-to-year variability. variation in the frequency distribution of maize grain yield was considerably affected by the methodology of the given irrigation system and the combination of the weather variables for the given season. Both maps (2016 and 2017) had some areas of yield variation that were not management-driven, but rather other error sources such as reduced yields from center pivot tracks and irregular harvester maneuvers around permanently installed instrumentation in the field. These erroneous data points were removed before analyzing the frequency distribution of grain yields in each field. The frequency distribution of grain yields achieved in each field in 2016 and 2017 are shown in Figs. 15b and 16b. The frequency distribution (Figs. 15b and 16b) analyzed and classified 39617, 12632, and 1924 grid cells for the CP, SDI, and FI fields, respectively, into grain yield bins of 2 Mg ha^{-1}, ranging from 0 to 18 Mg ha^{-1}.

Comparing CP and SDI fields across Figs. 15a and 16a, it can be deduced that grain yields were higher in 2017 than 2016, due to conducive weather conditions explained earlier in Section 3.6. Although this difference was statistically insignificant when averaged across the fields, on a finer spatial scale, it was found that substantially greater

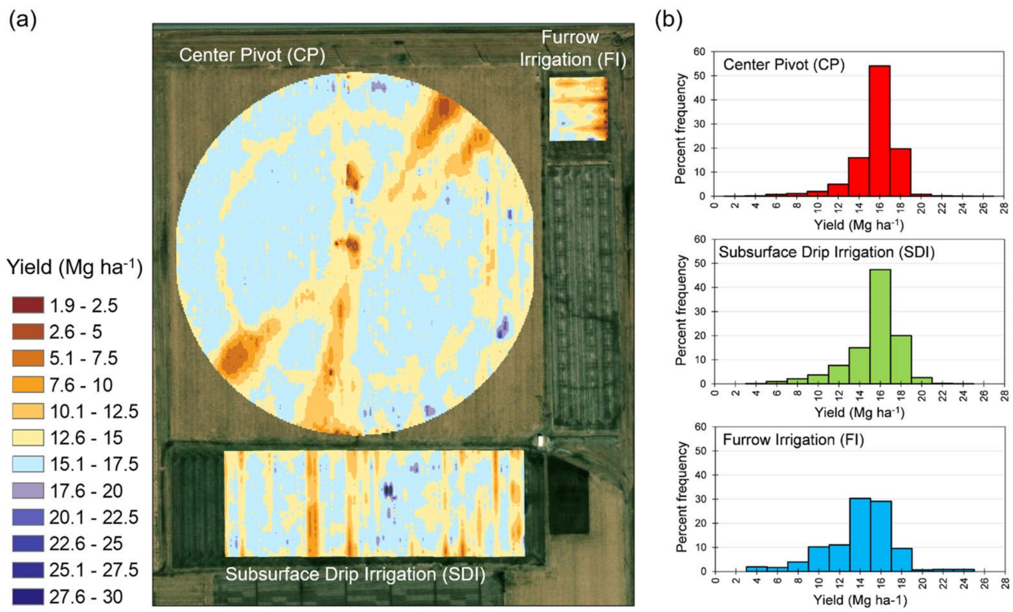


Fig. 15. Maize grain yield (adjusted to 15.5% grain moisture content): (a) and yield frequency distribution (b) across all treatments for 2016 growing season in the center pivot (CP), subsurface drip irrigation (SDI), and furrow irrigation (FI) fields.

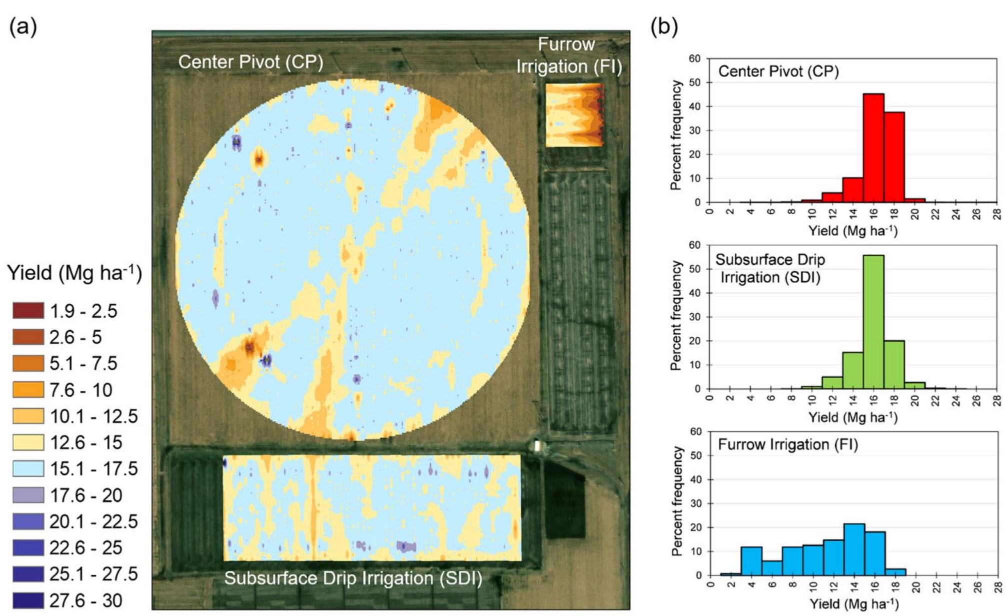


Fig. 16. Maize grain yield (adjusted to 15.5% grain moisture content): (a) and yield frequency distribution (b) across all treatments for 2017 growing season in the center pivot (CP), subsurface drip irrigation (SDI), and furrow irrigation (FI) fields.

proportion of the CP and SDI fields showed greater yields in 2017, than the remainder of both the fields. On the other hand, FI showed greater yields in 2016 than 2017 across majority of the acreage of the field, which was attributed to soil characteristics and nutrient availability (see Section 3.6). This year-to-year difference is also easily detectable from the rainfed treatments (e.g., 4 sectors in CP field corresponding to 0% T), which are darker brown in 2016 than 2017. Also evident is the importance of using broader outer spans for detecting treatment effects in CP, due to the suboptimal irrigation application precision in narrower inner spans. The contrast of crop response to water availability at upstream and downstream ends of the FI field is also visible in both years.

The frequency distributions (Figs. 15b and 16b) convey the grain yield distribution as affected by various irrigation methods. Among the three irrigation methods, CP and SDI had narrower distributions than FI, which is evident from the mean absolute deviation (MAD) of the data points in Figs. 15b and 16b. MAD was the lowest (implying narrowest distribution) for CP (1.44 Mg ha^{-1}), followed by SDI (1.83 Mg ha^{-1}), and FI (2.42 Mg ha^{-1}) in 2016, whereas it was lowest for SDI (1.21 Mg ha^{-1}), closely followed by CP (1.23 Mg ha^{-1}), and FI (3.51 Mg ha^{-1}) in 2017. The highest frequency of occurrence (proportion of field falling under a given yield bin) was found for the 14–16 Mg ha^{-1} range for both CP and SDI, whereas for FI, 12–14 Mg ha^{-1} range had the highest frequency, very closely followed by 14–16 Mg ha^{-1}. Since all fields had the same proportion of their respective acreages under various treatments, it is interesting to note the contrast among the yield distribution in FI vs. CP and SDI (Figs. 15b and 16b). Against largely symmetric and unimodal distributions observed for CP and SDI, FI had presents a more uniform, and rather bimodal distribution in 2017. This is attributable to the lower irrigation efficiency, higher deep percolation and runoff, and increased N leaching in FI. CP in 2016 and SDI in 2017 had the highest area proportion (~55%) under the peak grain yield bin (14–16 Mg ha^{-1}), whereas FI only had 30% and 21% of area under its peak grain yield bin of 12–14 Mg ha^{-1}, while roughly the same area was under the 14–16 Mg ha^{-1}. This underscores the importance of irrigation efficiency differences among the three irrigation methods, which is highest for SDI, followed by CP and FI. The sub-plot level high resolution yield analysis corroborates earlier observation of decrease in the spread of yield distribution (lowering of MAD) with an increase in irrigation efficiency.

4. Summary and conclusions

The effect of coupled impacts of irrigation rates and N timing management strategies on maize growth, development and yield productivity under different irrigation methods were investigated by field experiments in in a transition zone between sub-humid and semi-arid climates near Clay Center, Nebraska, USA. Results reveal that in all cases, LAI showed higher values in the NT-1 and NT-2 N treatments over TN treatment across the two irrigation methods of CP and SDI in both growing seasons. Irrigation method had a substantial influence on LAI seasonal trends, and it was higher at both irrigation methods of CP and SDI than in FI method across the irrigation levels, N treatments and both growing seasons. The peak LAI values varied between the irrigation methods and years as well as in terms of the time they occurred. There was a statistical difference between the NT nitrogen treatments and TN treatment at both irrigation methods of CP and SDI. Utilizing seasonally averaged LAI approach was better than the peaked LAI approach on reflecting more realistic crop growth development determinations. The CP method had a statistically higher plant height than SDI and FI and SDI method had higher plant height than FI. Stem diameter was not influenced by the irrigation method and N treatment, but was influenced by irrigation level in the CP and SDI in 2017. Grain yields were notably altered by irrigation level for the TN and NT nitrogen treatments for the given irrigation method. Across all treatments and years, yields were statistically higher at both irrigation methods of CP and SDI (similar between CP and SDI) than FI. In general, results suggest that both CP and SDI performed superiorly than FI in terms of maize grain yield production across all irrigation levels (FIT, 80% FIT and 60% FIT) and N application timing treatments. The NT-1 in the 80%FIT showed the best grain yield production among the combination of irrigation level and N application timing treatments. This research has provided deeper quantitative insight in terms of better understanding the irrigation levels and N management vs. crop growth and development variables and grain yield under three different irrigation methods. These research findings can aid in developing best management strategies in terms of maximizing coupled N and water use and effective management, maximizing maize and soil productivity, increasing farmer's profit, enhancing stakeholder awareness and knowledge and equally importantly protecting the environmental quality.

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.

Acknowledgment The work presented in this paper is a part of a long-term research that investigates the fundamentals of coupled irrigation water and nitrogen management strategies on grain yield, water productivity, evapotranspiration, yield production functions, soil-water dynamics and yield response factors, and other productivity variables and environmental relationships for different cropping systems in the Irmak Research Laboratory. The work in this manuscript was included as part of the second author's Ph.D. study while he was a graduate student in the Irmak Research Laboratory under the supervision of Professor Suat Irmak at UNL. The funding and all resources for this research was obtained by Senior Author, Professor Irmak. This research is based upon the work that is partially supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, Professor Suat Irmak's Hatch Project. Professor Irmak thanks his current and former Irmak Research Laboratory team members who assisted in this research. The trade names or commercial products are provided solely for the information of the reader and do not constitute a recommendation for use by the authors or their institutions.

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