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Water-Yield Relationship Responses of Maize to Ridge-Furrow Planting Systems Coupled with Multiple Irrigation Levels in China's Horqin Sandy Land

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Abstract: Water scarcity threatens the sustainability of irrigated agriculture in semi-arid regions, and ridge-furrow planting systems (RFPS) can be a prospective rainwater harvesting approach. In this study, we aimed to develop a promising water-saving strategy to boost maize productivity and water use efficiency (WUE). In 2017, we carried out a field experiment to study the effects of various RFPS with multiple irrigation levels on the yield-water relationship of maize (*Zea mays* L.). Eleven treatments were set up: RFPS with film mulching on both ridges and furrows and without water supply after seed emergence, abbreviated as QF; RFPS with film mulching on continuous ridges, abbreviated as MD, including SMD, MMD, and LMD (S, M, and L—three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season); RFPS without film mulching, abbreviated as DD, including SDD, MDD, and LDD; conventional flat planting with no film mulching, abbreviated as GG, including SGG, MGG, and LGG; localized full irrigation (actual amount of irrigation excessively exceeding the quantity needed), abbreviated as NM. A positive linear relationship (R^2 = 0.95–1), a quadratic curve, and a negative linear relationship were observed between the irrigation water level and actual crop evapotranspiration (ET_c), grain yield, and WUE, respectively. The ET_c of QF (292 mm) was substantially lower than that of the other treatments ($p < 0.01$), saving 649 mm of irrigation water and increasing the yield by 2.24% compared with those of NM. Meanwhile, the WUE and irrigation water use efficiency (IWUE) of QF reached maximums of 6.3 and 47.36 kg m^{-3}, respectively, which were significantly higher than those of other treatments ($p < 0.001$). The results showed that planting in an RFPS with film mulching on both ridges and furrows (a ridge-to-furrow ratio of 50:30, with a 38 mm irrigation level) is suitable for maize to obtain high yield and reduce irrigation water use significantly.

Keywords: ridge-furrow planting systems; evaportranspiration; crop coefficiency; yield; water use efficiencies

1. Introduction

In arid and semi-arid regions, the annual crop evapotranspiration (ET_c) greatly exceeds the total precipitation, and approximately 50% of the total evapotranspiration occurs through the soil surface. Farmland irrigation is obtained mainly from groundwater [1], and over-exploitation of this resource can result in water unavailability. The total water requirement for maize (*Zea mays* L.), the third most important cereal food crop globally, varies from 500 to 800 mm during the entire growing season [2]. Water scarcity can affect maize growth and reduce grains per ear and kernel weight, ultimately reducing grain yield [3–6]. The degree of yield reduction due to drought stress is dependent on drought severity and the growth stage at which it occurs, e.g., reduced irrigation frequency early in the cropping season [7,8] and drought occurring just before anthesis [9], and during silking and grain filling. Intermediate and severe drought stresses at critical growth stages reduce grain yield by 70–90%. Moreover, the length of maize growing season can be extended by delayed flowering (7 days) and ripening (5 days) due to drought [10].

Employing supplemental irrigation to avoid drought stress during critical growth stages has been reported to increase yield and water use efficiency (WUE) (e.g., yield divided by ET_c) [11–13]. Furthermore, maize yield of 5.6, 10.1, and 11.8 Mg ha^{-1} has been recorded in rain-fed, supplemental irrigation, and full irrigation, respectively. However, the WUE was reduced with full irrigation compared with that under rain-fed and supplemental irrigation conditions [14,15]. Additionally, developing suitable water-saving countermeasures for agriculture is also an effective approach to produce relatively stable, even maximize, grain yields in regions with limited water supply. Recent studies reflect the increasing interest in sprinkler, drip, and subsurface drip irrigation [16]. Drip irrigation has been shown to reduce soil surface evaporation and irrigation frequency [17] and increase irrigation efficiency by 90% [18]. Subsurface drip irrigation can allocate water more effectively [19,20]. Alternatively, mulching has been increasingly practiced in agriculture to increase crop yield by increasing precipitation use efficiency [21] and soil temperature, and by conserving soil moisture [22–26]. Mulching practices include flat plastic covering [27], plastic film mulching on ridges [28–30], and ridge-furrow mulching with alternate ridges and furrows [31].

Elucidating the crop yield–water relationship has been a major focus in maize, and it is necessary to determine irrigation strategies when water supply is scarce [32]. Methods used to improve the WUE are anticipated to increase the efficiency of water delivery and water use by plants. Irrigation water use efficiency (IWUE), i.e., yield divided by seasonal irrigation, is commonly used to estimate the threshold of water delivery to optimize management scheduling [33]. The range of IWUE depends on irrigation frequency and pattern, plant density, and microclimate conditions [34,35]. Moreover, the reference crop evapotranspiration (ET_o) is a measurement of water use for a reference crop, and the crop co-efficient (k_c) takes into account the crop type and crop development to adjust the ET_o for that particular crop.

Irrigated maize is the dominant annual crop in Horqin Sandy Land, located in the semi-arid area of Southeastern Inner Mongolia, which is severely desertified [36]. Farmland irrigation is heavily dependent on groundwater, the availability of which is highly limited in this region. Furthermore, water-saving measures are rarely employed, and flood irrigation is widely adopted by local farmers. During the maize growing season, soil evaporation typically accounts for 22–30% of total crop evaporation resulting from poor irrigation [37,38]. Excessive or inadequate irrigation has a significant negative effect on grain yield and the WUE of maize. Therefore, the objective of the present study was to: (1) quantify the ET, yield potential, and WUE under various ridge-furrow planting systems (RFPS) with multiple irrigation levels and (2) elucidate the optimum RFPS pattern, with the maximum grain yield and WUE, to reduce groundwater use in Horqin Sandy Land.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out from April to September, 2017, at the Naiman Desertification Research Station of the Chinese Academy of Sciences (42°58′ N, 120°43′ E; 360 m a.s.l.), located in the eastern part of the Inner Mongolia Autonomous Region, China (Figure 1). Naiman is a desertification-threatened area in the southwest of Horqin Sandy Land [39], with a continental semi-arid monsoon climate. The experimental site, with sandy soil texture sensitive to wind erosion, has a mean annual precipitation of approximately 360 mm (262 mm in this growing season), annual mean evaporation of approximately 1950 mm, and an annual mean temperature of 6.4 °C, with a minimum monthly average of −13.5 °C in January and a maximum of 23.8 °C in July. In addition, the wind direction is predominantly from the northwest in winter and south-to-southwest in the summer and autumn, with annual wind speeds ranging from 3.2 to 4.1 m s^{-1}. At a soil depth of 0–30 cm, soil organic carbon content, pH (1:2.5 water), and electrical conductivity (1:5 water) before planting were 2.48 g kg^{-1}, 9.23, and 62.73 µS cm^{-1}, respectively. The field water capacity was 12.77%, wilting point 5.4%, water saturation 30.24%, saturated hydraulic conductivity 0.93 mm min^{-1}, and bulk density 1.55 g cm^{-3}.

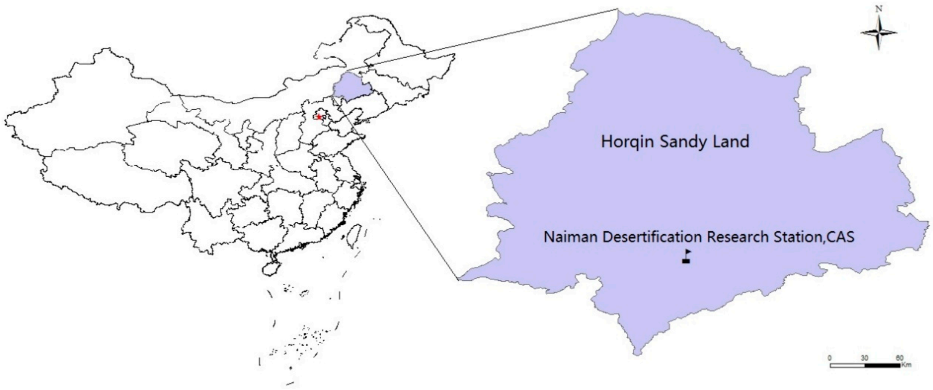

Figure 1. Location of Naiman desertification research station in China.

2.2. Experimental Layout and Treatment Description

The trial was laid out in a completely randomized plot design, comprising eleven treatments with four replicates. Each plot was 12 m long and 3 m wide, with an area of 36 m^2. The following treatments were used (Table 1): (1) RFPS with film mulching on both ridges and furrows, and without irrigation after seed emergence (irrigation after sowing to guarantee seed initiation), abbreviated as QF; (2) RFPS with film mulching on continuous ridges with three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season, abbreviated as SMD, MMD, and LMD; (3) RFPS without film mulching, with three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season, abbreviated as SDD, MDD, and LDD; (4) conventional flat planting without film mulching, with three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season, abbreviated as SGG, MGG, and LGG; and (5) full irrigation (actual irrigation amount excessively exceeding the amount of water needed) during the whole growing season, defined as NM. Flood irrigation was used with QF and GG, and drip irrigation was used with MD and DD during the whole growing season. Detailed plot arrangement is shown below.

Table 1. The specific trial layout in maize growing seasons.

Treaments	Description	Ridge	Furrow	Row Spacing	Plant Spacing
QF	Ridge-furrow mulching system	Plastic film mulch	Plastic film mulch	0.8 m	0.22 m
MD	Drip irrigation under plastic film	Plastic film mulch	No mulch	0.6 m	0.22 m
DD	Subsurface drip irrigation	No mulch	No mulch	0.6 m	0.23 m
GG	Conventional flood irrigation	No mulch	No mulch	0.6 m	0.24 m

Notes: QF represents RFPS with film mulching on both ridges and furrows and without water supply after seed emergence; MD represents RFPS with film mulching on continuous ridges; DD represents RFPS without film mulching; GG represents conventional flat planting with no film mulching.

For QF, each ridge was 50 cm wide × 35 cm high, and each furrow was 30 cm wide, with three ridges and four furrows per plot. An optimum ridge-to-furrow ratio is imperative to develop a more effective RFPS. The ridge-to-furrow ratio was 50:30 (50 cm ridge width, and 30 cm furrow width). One week prior to planting, the ridges were banked up with soil and the furrows served as the planting areas. Fertilizer was spread evenly over the furrows and then ploughed into the soil at a depth of 8 cm. The covering materials were strips of plastic film (transparent and black polyethylene film, 1 m wide, and 0.008 mm thick), which were laid tightly and continuously against the ridge and furrow surfaces, ensuring the two successive plastic film edges overlapped by 20 cm, and then covered tightly with soil. The maize was seeded in the middle of each furrow using drill seeding. The plots were 100 cm apart.

For both MD (SMD, MMD, and LMD) and DD (SDD, MDD, and LDD), each ridge was 80 cm wide × 35 cm high, and each furrow was 40 cm wide, with two ridges and three furrows per plot. The ridge-to-furrow ratio was 80:40. Maize was planted in the ridges on the ridge edges of two rows, with 22 cm between each plant. For MD, strips of plastic film (1 m wide and 0.008 mm thick) were laid tightly against the ridge surfaces, and the two edges were covered with soil before sowing, while furrows were kept uncovered. Crops were irrigated by drip irrigation. Black polyethylene drip tapes were buried 1 cm below the mulch of MD, and 5 cm below the soil surface in DD, in an east-west direction, with adequate water being supplying directly to the crop root zone. These procedures reduced water loss by soil evaporation, which is a main characteristic of drip irrigation under plastic film and subsurface drip irrigation systems compared to other irrigation systems (including sprinkler and surface irrigation). The drip lines were installed in the middle of the ridge width. Emitter spacing was 0.15 m on the drip lines, with a 1 L h^{-1} emitter discharge rate. Groundwater for irrigation was measured continuously by the flowmeters, with a water-supplied pressure of 0.2 MPa (Figure 2A). Drip lines were 12 m long in an east-west direction. The drip emitters were pressure-compensated, adjusting the discharge and providing a constant flow rate under, for example, variable pressure and slope, providing uniform water application [40].

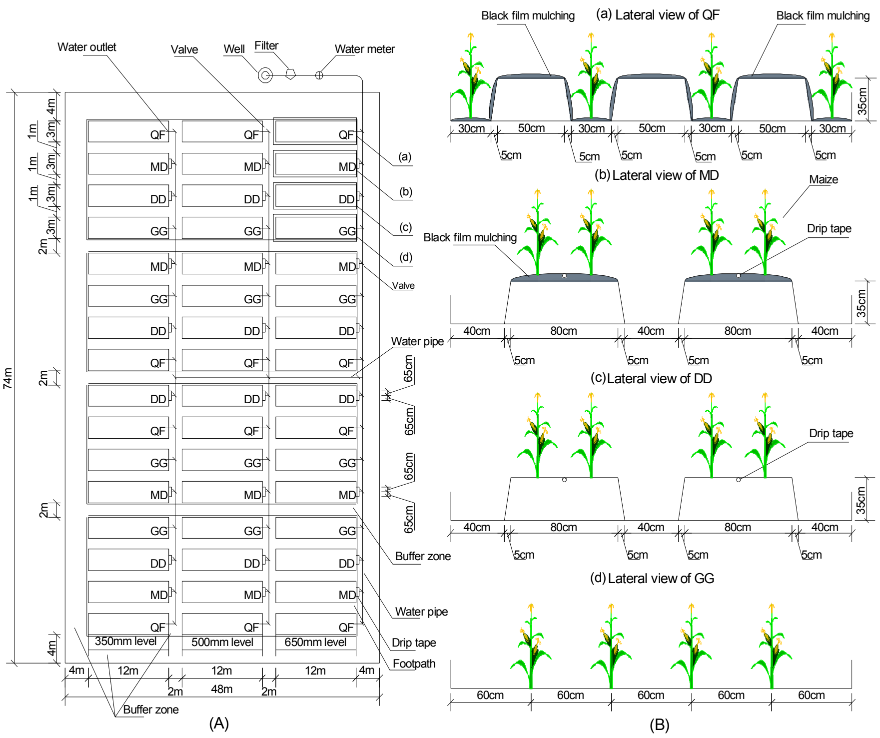

Figure 2. Schematic diagrams for field experimental plot layout showing four replicated blocks, and four randomly assigned treatments. Plot size: Width 3 m (4 rows at 0.8 m spacing in QF, and at 0.6 m spacing in MD, DD, and GG). (**A**) represents schematic diagrams of the test field. (**B**) represents profile diagram of treatments. Length 12 m. Total area (36 m^2); 1m buffers among plots, 4 m buffers between crops and on field edges.

For GG (SGG, MGG, and LGG), the crop was flat planted without the other water conservation measures (plastic black film mulching), with 22 cm between each plant and 60 cm row spacing (Figure 2B).

2.3. Agronomic Management

The experimental field had a 0.5% slope from west to east. The field was rectangular, measuring 74 m in a north-south direction and 48 m in an east-west direction. The *Zea mays.* L. cv. Jingke 958 variety was chosen as the tested cultivar for all the treatments and was planted on 26 April 26 at a depth of 5 cm. The field was tilled approximately 1 week before sowing. At the time of tilling, a basal dose of fertilizer was spread evenly over the topsoil at a rate of 375 kg ha^{-1} of diammonium phosphate (N-P_2O_5-K_2O, 18-46-0) based on the N and P requirements; the fertilizer was applied in spade slits to avoid loss over the soil surface and sprinkled near the maize roots to ensure full absorption by the crops. One day before sowing, ridges and furrows were constructed alternately in each plot and mulching was applied. Plant populations averaged 60,000 plants ha^{-1} and did not vary by treatment. Plants emerged on 7 May, and the crops were harvested on 11 September. We considered the growing season to be the period from maize emergence to harvest. The field was managed as a ridge-till in the growing season, and pesticide, insecticide, herbicide, and fertilizer were applied uniformly to the entire field as needed. After harvesting in 2017, the ridge and furrow configurations were left in the field to be re-built in the following year. Weeds were controlled manually. Plots were spaced 1m apart to minimize water movement among treatments, and a buffer channel 1 m wide was provided in the neighborhood of experimental fields to avoid edge effects.

2.4. Irrigation Scheduling of Crop Growth Stages

In our study, the maize growing season could be divided into seeding, jointing, heading, filling, and ripening stages. Based on the different maize water requirements for each growth stage, water supply was distributed as the percentage of the total designed water supply (Table 2), and the actual irrigation regimes are shown in Table 3. Furthermore, the plants were irrigated on days with no or low wind (<1.5 m s^{-1}) to achieve uniform irrigation. Precipitation was measured with a standard pluviometer. The amount of irrigation for each growth stage was the designed water supply amount minus precipitation (during the period between irrigation events). The local irrigation water was assumed to be 157.5 mm on 29 April, 105 mm on 30 June, 115.5 mm on 13 July, 83.5 mm on 23 July, 105 mm on 17 August, and 120.75 mm on 3 September, producing a total of 687 mm.

Table 2. The designed water supply scheduling in different growth stages for treatment MD, DD, and GG.

Growth Stage	Total Designed Water Supply (%)	Total Water Supply Amount (mm)		
		650 mm	500 mm	350 mm
Seeding-Jointing Stage	15.0	98	75	53
Jointing-Heading Stage	35.0	228	175	123
Heading-Filling Stage	22.0	143	110	77
Filling-Ripening Stage	28.0	182	140	98

As can be seen in Table 3, with a low total water supply (350 mm), the actual water supply amount from the filling to the ripening stage was significantly higher than the designed water supply threshold (98 mm), severely affecting the accuracy of the trial results—this was likely related to the precipitation data. The maximum daily precipitation on 3 August 2017 (100.47 mm) was significantly higher than from May to September 2006–2016 (50 mm) (Figure 3), and therefore it was an extreme precipitation event, and the total water supply amount could be modified as needed to the three irrigation levels (650 mm, 500 mm, and 400 mm).

Table 3. The irrigation regimes across the growing season (April–September 2017).

Growth Stage	Precipitation	Irrigation (Excepting Precipitation)	QF	SMD	SDD	SGG	MMD	MDD	MGG	LMD	LDD	LGG
Seeding–Jointing Stage	**26 April–28 April**						0.0					
		28 April–1 May	38.82	38.79	38.80	38.84	38.93	38.94	39.12	38.74	39.04	38.75
	2 May–22 May						29.9					
		23 May–25 May	N	28.40	28.51	28.60	6.00	5.98	5.94	N	N	N
	23 May–8 June						0.6					
	Total Irrigation from Seeding to Jointing Stage		69.37	97.74	97.86	97.99	75.48	75.47	75.61	69.29	69.59	69.30
	Irrigation Deviation		0.00	+0.24	+0.36	+0.49	+0.48	+0.47	+0.61	+16.79	+17.09	+16.80
Jointing–Heading Stage		**9 June–13 June**	N	113.48	113.45	113.24	87.04	87.11	86.94	44.41	44.12	44.37
	14 June–24 June						5.5					
		25 June–27 June	N	51.40	51.44	51.35	38.35	38.27	38.33	25.21	25.16	25.20
	25 June–15 July						54.7					
	Total Irrigation from Jointing to Heading Stage		60.12	225.00	225.01	224.71	185.51	185.50	185.33	129.74	129.40	129.69
	Irrigation Deviation		0.00	−2.5	−2.49	−2.79	+10.51	+10.50	+10.33	+7.24	+6.90	+7.19
Heading–Filling Stage		**16 July–20 July**	N	97.8	97.86	98.02	62.85	62.79	62.96	44.11	44.34	44.17
	20 July–28 July						35.7					
	Total Irrigation from Heading to Filling Stage		35.67	133.47	133.53	133.69	98.52	98.46	98.63	79.78	80.01	79.84
	Irrigation Deviation		0.00	−9.53	−9.47	−9.31	−11.48	−11.54	−11.37	+2.78	+3.01	+2.84
Filling–Ripening Stage	**29 July–4 August**						100.5					
		5 August–7 August	N	30.38	30.41	30.34	4.37	4.33	4.40	N	N	N
	5 August–8 September						34.8					
	Total Irrigation from Filling to Ripening Stage		135.24	165.62	165.58	165.58	139.61	139.57	139.64	135.24	135.24	135.24
	Irrigation Deviation		0.00	−16.38	−16.42	−16.42	−0.39	−0.43	−0.36	+37.24	+37.24	+37.24
Total Water Supply (Irrigation Plus Precipitation) in Whole Growing Season (No Decimals)			300	622	622	622	499	499	499	414	414	414
Total Precipitation in Whole Growing Season							261.6					
Total Irrigation (Excepting Total Precipitation) in Whole Growing Season (No Decimals)			39	360	360	360	238	238	238	153	153	153

Note: N represents no irrigation; + represents irrigation increment compared to water supply scheduling in different growth stages (Table 2) and needs to be subtracted from the next time of irrigation; − represents irrigation loss compared to water supply scheduling in different growth stages (Table 2), and need to be added at the next time of irrigation. QF represents RFPS with film mulching on both ridges and furrows, and without irrigation after seed emergence (irrigation after sowing to guarantee seed initiation); SMD, MMD, and LMD represents RFPS with film mulching on continuous ridges with three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season; (3) SDD, MDD, and LDD represents RFPS without film mulching, with three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season; (4) SGG, MGG, and LGG represents conventional flat planting without film mulching, with three water supply (irrigation plus precipitation) levels of 650 mm, 500 mm, and 350 mm during the whole growing season. The date between precipitation and irrigation is continuous because the precipitation during the days of irrigation is automatically counted as the amount of precipitation in the interval between that irrigation and the next irrigation.

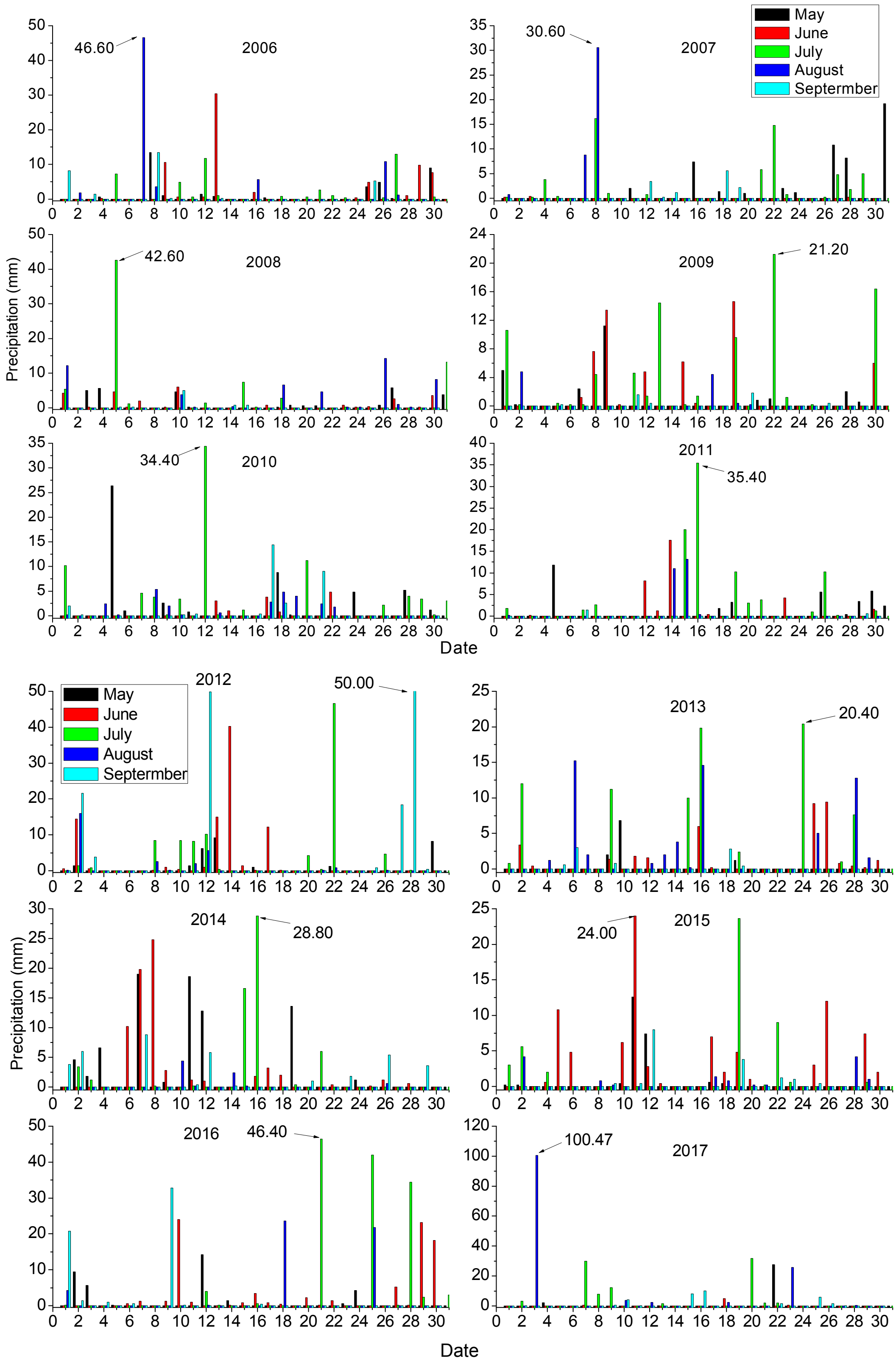

Figure 3. The mean precipitation diurnal variations during maize growing season (from May to September) in experimental fields at the Naiman Desertification Research Station of the Chinese Academy of Sciences, Naiman, China, from 2006 to 2017.

2.5. Estimations of Water Uses of Indicators

Maximum air temperature (T_{max}), minimum air temperature (T_{min}), mean air temperature (T_{mean}), net solar radiation (R_n), relative humidity (RH), wind speed at 2 m height (U_2), latitude (Ψ), latent heat (λ), soil heat flux (G) were obtained from the long-term meteorological monitoring station located in the experimental site.

Grain yield (maize of every plot) was harvested at the maturity stage, and 6 ears that grew successfully were selected randomly in each plot. Grains per ear, ear length, and diameter were calculated by counting the number of grains per ear, measuring tape, and vernier calliper, respectively. Yield components of plots were averaged as the final values of each treatment. Subsequently, drying the grain for constant weight at 85 °C, weighted by an electric balance for hundred grain weight and grain yield, and grain yields were converted to a standard grain water content of 15.5% wet basis [41].

ET_c was calculated daily during the growing season by the soil water balance equation (Equation (1)) [42]:

$$ET_c = I + P + C_r - D_w - R_f \pm \Delta s \tag{1}$$

in which ET_c is the actual evapotranspiration (mm), I is the amount of irrigation water applied (mm), P is the precipitation (mm), C_r is the capillary rise (mm), D_w is the amount of drainage water (mm), R_f is the amount of runoff (mm), and $\triangle s$ is the change in the soil moisture content(mm). The soil moisture content measurement was used by the conventional oven-dry method in soil layers (0–20, 20–40, 40–60, 60–80 and 80–100cm). No runoff was observed during the trials. Capillary rise was considered negligible due to the deep-water table level. Drainage water included precipitation under the effective rooting depth, according to the soil water content measurements in soil layer at the effective rooting depth, was determined.

Water use efficiency (kg m^{-3}) was calculated by dividing grain yield (kg ha^{-1}) by evaportranspiration (mm) [43].

ET_c is the product of the evapotranspiration of a reference crop (ET_o) and a crop coefficient (k_c). ET_o was calculated using the weather data as input to the Penman-Monteith equation and the k_c is used to adjust the estimated ET_o for the reference crop at different growth stages.

ET_o was calculated per day during the growing season by using the FAO Penman-Monteith equation. The FAO Penman-Monteith equation is given by Allen et al. [44]:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}\mu_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \tag{2}$$

in which ET_o is the reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), μ_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (k Pa), e_a is actual vapor pressure (k Pa), $e_s - e_a$ is saturation vapor pressure deficit (k Pa), D is the slope of the saturation vapor pressure curve (k Pa/°C), and c is psychrometric constant (k Pa/°C). Meteorological parameters needed to calculate ET_o were derived from a local meteorological station.

The crop coefficient (k_c) is the ratio of ET_c to ET_o, and k_c was estimated with the following equations [45]:

$$k_c = ET_c/ET_o \tag{3}$$

Water use efficiency (WUE, kg m^{-3}) and irrigation water use efficiency (IWUE, kg m^{-3}) were calculated as

$$WUE = \frac{Y}{ET_c} \tag{4}$$

$$IWUE = \frac{Y}{I} \tag{5}$$

in which Y = yield (kg ha^{-1}), ET_c = seasonal crop evapotranspiration (mm), and I = seasonal irrigation (mm).

2.6. Statistical Analysis

Analysis of variance (ANOVA) was performed using SPSS 17.0 software to evaluate the effects of various patterns of RFPSs and irrigation levels on the grain yield components of maize. We used a two-way ANOVA to analyze grain yield, WUE, and IWUE responses to various patterns of RFPS with different irrigation levels. Differences among means in water use indicators and yield components were evaluated for significance using least significant differences (LSD) at the 5% and 1% probability levels. Figures were generated using Origin 8.0. All statistical analyses, including correlations among water-use characteristics and yield components, were computed using the SPSS software.

3. Results and Discussion

3.1. Water Use Characteristics

As shown in Table 4 and Figure 4, ET_o of the growing season was 501mm, overall, ET_c, k_c, and daily water use increased with irrigation in all treatments. Total ET_c and k_c of QF presented minimum values of 292 mm and 0.58, respectively, being significantly different to those of the other treatments ($p < 0.05$). In contrast, the maximum total ET_c and k_c values were recorded with NM, likely due to an adequate soil water supply during the growing stage, showing values of 942 mm and 2.38, respectively, and the average daily water use reached 6.83 mm d^{-1}, significantly higher than with the other treatments ($p < 0.01$). This result was substantially higher than that observed by Istanbulluoglu et al. [46], who reported ET_c values for maize of 586 mm with full irrigation, indicating that RFPS may be useful for preventing evaporation. However, a value of 174 mm for the ET_c for non-irrigated maize was recorded by Dagdelen et al. [47], which was lower than that of QF; this was responsible mostly for regional difference, maize variety, and irrigation approach. The ET_c of MD and DD varied in the range of 412 ± 48 mm–598 ± 32 mm, of which decreasing ratio was between 46.17% and 49.32%, compared to drip irrigated maize of Oktem et al. [48], confirming that RFPS and subsurface drip irrigation had a higher capacity for water conservation (Figure 4).

Table 4. Maximum air temperature (T_{max}), minimum air temperature (T_{min}), mean air temperature (T_{mean}), net solar radiation (R_n), relative humidity (RH), wind speed at 2 m height (U_2), latitude (Ψ), latent heat(λ), Soil heat flux (G), and reference crop evapotranspiration (ET_o) for the months of April–September at Naiman, China in April–September, 2017.

Date	T_{max} (°C)	T_{mean} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	U_2 (m/s)	Ψ (rad)	λ (MJ kg^{-1})	G (MJ m^{-2})	R_n (MJ m^{-2})	ET_o (mm)
April [a]	23.42	16.57	8.90	48.80	12.60	2.26	42.93	2.47	0.54	6.75	22
May	26.55	18.99	11.05	69.81	20.19	1.73	42.93	2.46	0.05	8.04	129
June	30.93	24.06	17.77	87.43	36.40	1.25	42.93	2.45	0.09	9.10	114
July	31.00	24.67	18.95	96.81	46.94	1.04	42.93	2.44	−0.01	9.87	118
August	26.52	19.50	13.39	96.07	38.28	0.98	42.93	2.45	−0.14	7.70	88
September [b]	28.31	21.26	14.49	81.72	32.20	1.26	42.93	2.46	0.06	5.82	30

Note: [a] Calculated from the data between 26 and 30 April. [b] Calculated from the data between 1 and 11 September.

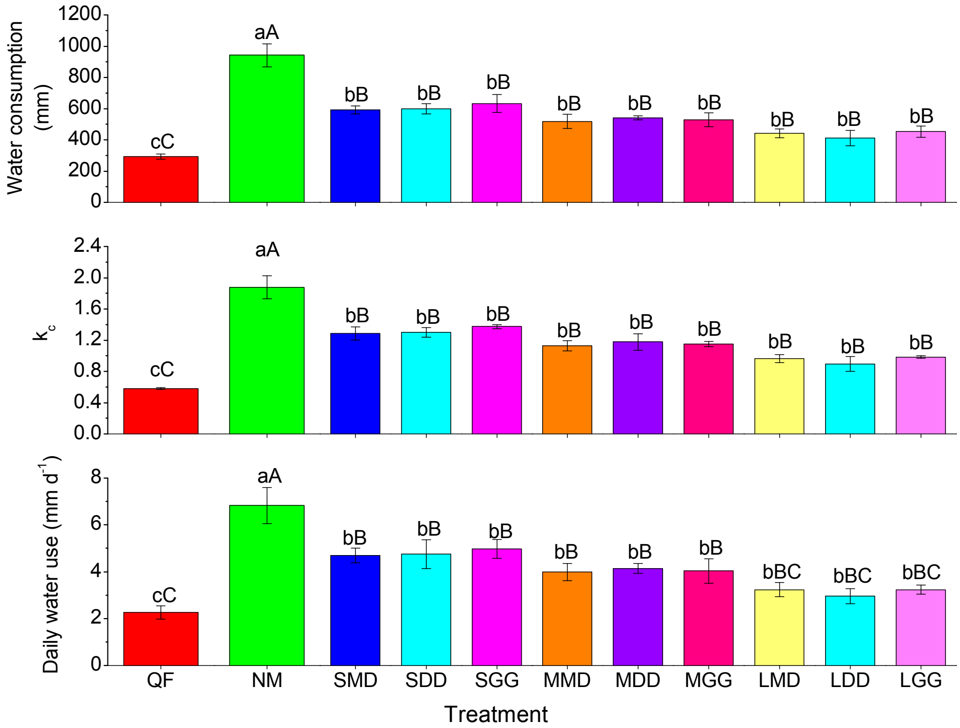

Figure 4. ET_c, reference crop coefficiency (k_c), daily water use changes in April–September 2017. QF represents RFPS with film mulching on both ridges and furrows, without water supply after seed emergence; MD represents RFPS with film mulching on continuous ridges; DD represents RFPS without film mulching; GG represents conventional flat planting no film mulching; NM refers to local sufficient irrigation (actual irrigation amount excessively exceed water needed). S refers to high water supply level (650 mm), M refers to moderate water supply level (500 mm), and L refers to low water supply level (400 mm) (the same below). Values represent means ± SE (n = 12). Bars labeled with different letters (lowercase, capital) differed remarkably among the treatments ($p \leq 0.05$, $p \leq 0.01$).

The maize growing period with QF, MD, and DD was shorter than with NM by approximately 10, 12, and 7 days, respectively. However, the growing period with GG was delayed, suggesting that, under flood irrigation, the level of maize irrigation must be above 622 mm for proper growth (Figure 5).

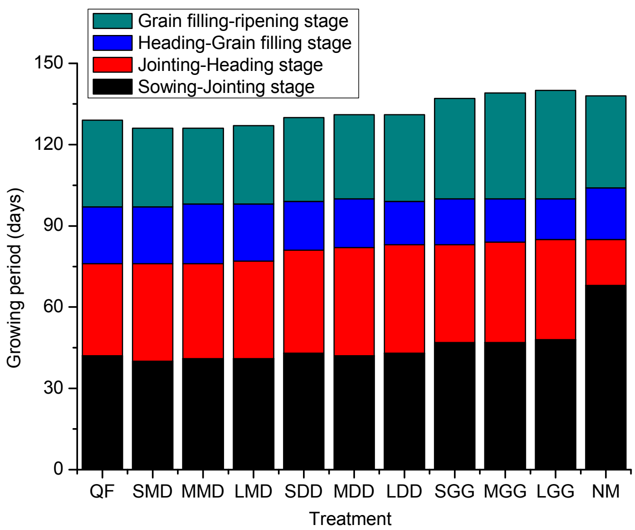

Figure 5. Growth period of maize in 2017. It was expressed as the bar chart and was comprised of sowing, jointing, heading, grain filling, and ripening stage.

3.2. Yield Components Analysis

The number of rows per ear, 100 grain weight, grains per ear, and cob weight were significantly related to grain yield [49]. Grain yield can be reduced by decreasing yield components (grain number and grain weight) [32]. In our study, ear length, ear diameter, and grains per ear with QF increased by 10.64%, 8.09%, and 13.05%, respectively, compared to NM. Considering water-saving approaches under the same irrigation level, the yield was in the order DD > MD > GG, and significant differences were found between DD, MD, and GG ($p < 0.01$). Similarly, considering a single irrigation level with the same water-saving approach, grain yield was consistent in the order of 360 mm > 237 mm > 152 mm, but the differences were not significant.

The maximum grain yield occurred with the DD treatment and with the 360 mm irrigation level, with a value of 21,197.37 kg ha^{-1}, an increase of 17.84% compared to NM; however, the maximum grain yield did not occur at or near maximum WUE, and the rate of yield increase was lower than in Li et al. [39] at 49.0% with the 295 mm irrigation level. This lower rate was likely due mostly to geographical differences, plant per hectare, and irrigation pattern. There were no pronounced differences in yield between SDD, MDD, and LDD. If no irrigation water is considered (QF, except for irrigation after sowing), grain yield attained 18390.5 kg ha^{-1}, significantly higher than that of Yildirim et al. [50], fully explaining the yield-increasing effect of the RFPS. The yield with MD and DD with the 360 mm, 237 mm, and 152 mm irrigation levels increased by different degrees (3.91–17.84%), and the irrigation amount was reduced by 43.49%, 65.31%, and 87.14%, respectively, compared to NM, achieving the goal of saving water and increasing yield. However, this result was not consistent with that reported by Dagdelen et al. [47], namely, that yield was markedly affected by the drip irrigation application rate. When the amount of applied water through drip irrigation was reduced by 25%, the yield decreased by approximately 17.1%. However, reducing irrigation by up to 50% resulted in a 34.1% lower yield than with full irrigation. This contradiction could be due to plant pattern (RFPS in our study) and the contribution of planting density (Figure 6).

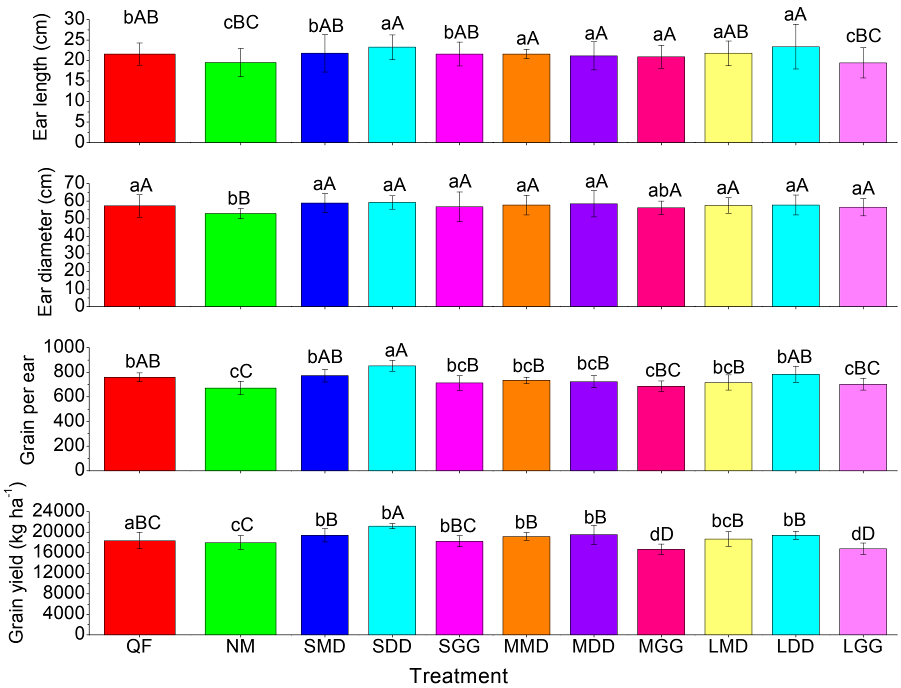

Figure 6. Characteristics of grain yield components during the growing season in 2017 (ear length, ear diameter, grains per ear, and grain yield). Lowercase and uppercase letters indicate significant differences according to $LSD_{0.05}$ and $LSD_{0.01}$, respectively (n = 12). Vertical bars indicate standard errors of means. Bars labeled with different letters (lowercase, uppercase) differed remarkably among the treatments.

Crop WUE is generally determined as the economic yield divided by the seasonal crop evapotranspiration, and the IWUE is the economic yield divided by the total irrigation water applied. QF had the largest WUE and IWUE of 6.33 kg m^{-3} and 47.36 kg m^{-3}, respectively, substantially higher than the results of Ko and Piccinni [51], and the greatest WUE (1.6–2.0 kg m^{-3}) was recorded with the 456 mm irrigation level and the other water-saving approaches in our study. Therefore, the QF treatment was appropriate for maintaining, even increasing, yield, and maximizing savings in irrigation. Next was DD at the 152 mm irrigation level, in which WUE and IWUE were 4.72 kg m^{-3} and 12.71 kg m^{-3}, respectively, an increase of 33.33% and 116.16%, respectively, compared to the 360 mm irrigation level. In brief, WUE and IWUE were coincident with irrigation levels in the order of 38 mm > 152 mm > 237 mm > 360 mm > 687 mm, contradicting previous results showing that maize WUE decreased with decreasing levels of irrigation, with no significant differences in WUE being observed among different irrigation levels [10,52]. Overall, our study showed that ET_c, WUE, and IWUE ranged between 292–632 mm, 2.89–6.33 kg m^{-3}, and 5.39–47.36 kg m^{-3}, respectively; however, Koksal and Kanber [53] reported that when ET_c levels in maize were between 631 and 723 mm, WUE and IWUE ranged between 1.38 and 1.80 kg m^{-3} and 0.87 and 3.19 kg m^{-3}, respectively, indicating that WUE and IWUE were greatly improved in our study (Figure 7).

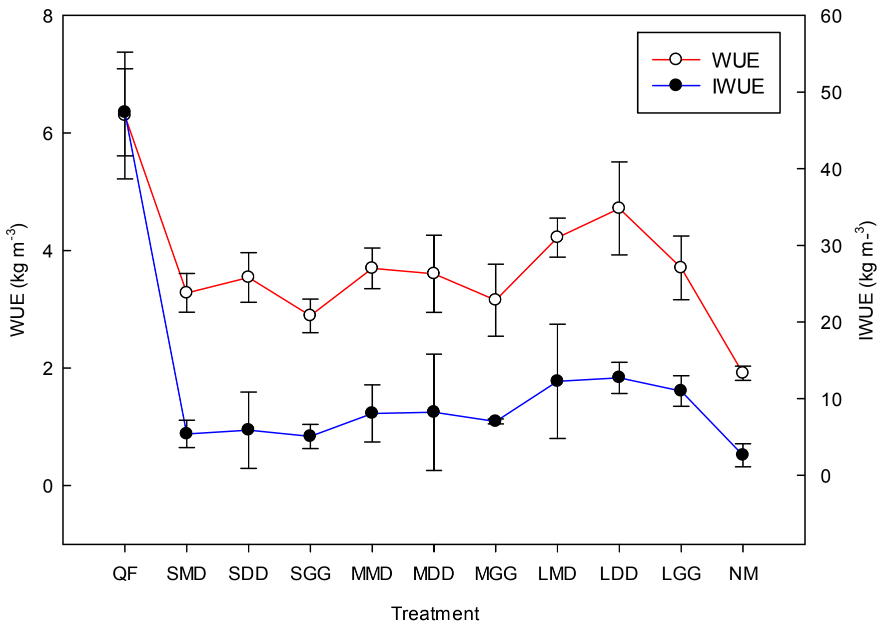

Figure 7. Trends of WUE and IWUE. Vertical bars indicate standard errors of means.

3.3. The Relationships between Irrigation Water and Yield Components

Curve relationships were found between irrigation amount and yield components, as seen in Figure 8. Moosavi [54] reported that reducing the amount of irrigation led to a decrease in ear diameter and length, but only within an irrigation threshold of 0–400 mm. The maximum ear length, ear diameter, grains per ear, and yield values were all recorded between the 300 and 400 mm irrigation levels, corroborating the results in Figure 6; with irrigation levels above 400 mm, the values decreased with increasing irrigation amounts, consistent with the results presented in Table 5, indicating that the correlation coefficients between ET_c and yield components were negative. Therefore, excessive irrigation did not increase yield, and the yield components of maize were higher between 0 and 100 mm than between the 600 and 700 mm irrigation level thresholds. In addition, grain number is closely related to maize yield, and the number of grains per ear is a yield component that varies markedly with irrigation water amounts [55]. It was relatively close to similar findings in Table 2 that Yield was greatly positively affected by grains per ear, and a curvilinear relationship existed between yield and irrigation water, which was consistent with Farré and Faci [4] and Cetin and Bilgel [56].

However, a good linear relationship between yield and irrigation water applied in maize has also been reported in other studies [48,57], with the likely reason for these different results being that the relationships between yield and irrigation water varied with season and location.

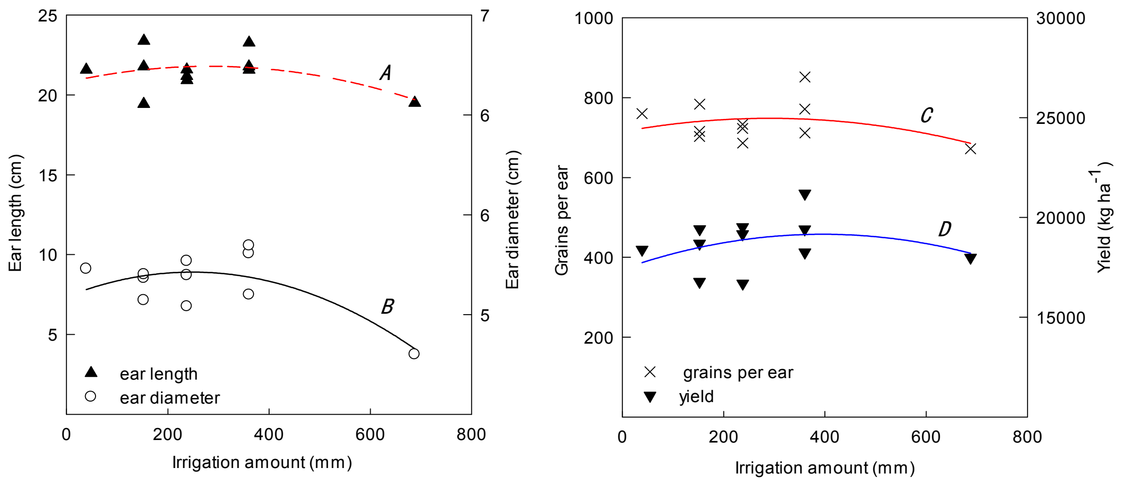

Figure 8. The relationships between irrigation water and ear length, ear diameter, and grains per ear, as well as grain yield. *A*, *B*, *C*, and *D* represents changes of ear length, ear diameter, grains per ear, and yield with irrigation water, respectively.

Table 5. Results from two-way ANOVA of the effect of various patterns of RFPS and irrigation levels on ET_c, k_c, and daily water use.

Descriptions	***df***	**ET_c (mm)**		**k_c**		**Daily Water Use (mm d^{-1})**	
		F	**P**	**F**	**P**	**F**	**P**
Water-saving approach	2	3014.287 **	0	13.694 **	0	32.302 **	0
Irrigation level	2	162843.122 **	0	449.809 **	0	4548.837 **	0
Water-saving approach × Irrigation level	4	2366.463 **	0	3.080 *	0.043	38.672 **	0

Note: F represents F-statistics; P represents significant value. ** means the significant difference at the level of 0.01; * means the significant difference at the level of 0.05.

3.4. The Relationships between Irrigation Amount and Water Use Characteristics

As seen in Table 2, ET_c, k_c, and daily water use were significantly affected by irrigation levels. ET_c, k_c, and daily water use were linearly proportional to the amount of irrigation water ($R^2 \geq 0.95$); the relationship between ET_c and k_c and daily water use were also positively linear, and R^2 was between 0.98 and 1 (Figure 9). Therefore, the increases in ET_c, k_c, and daily water use were closely associated with increased irrigation amounts (Table 4). Consequently, these results confirm that ET_c, k_c, and daily water use were coincident with irrigation levels in the order of 687 mm > 360 mm > 238 mm > 153 mm > 39 mm. ET_c and k_c were 292 mm and 0.58, respectively, with the irrigation level of 39 mm, and were significantly lower than with other irrigation levels ($p < 0.01$). Kiziloglu et al. [58] determined that the k_c for the whole maize growing season to be 1.01–1.1, in agreement with our results showing a k_c between 1.15–1.22 with a 360 mm level of irrigation. The greater the amount of irrigation water applied above 360 mm, the bigger the k_c.

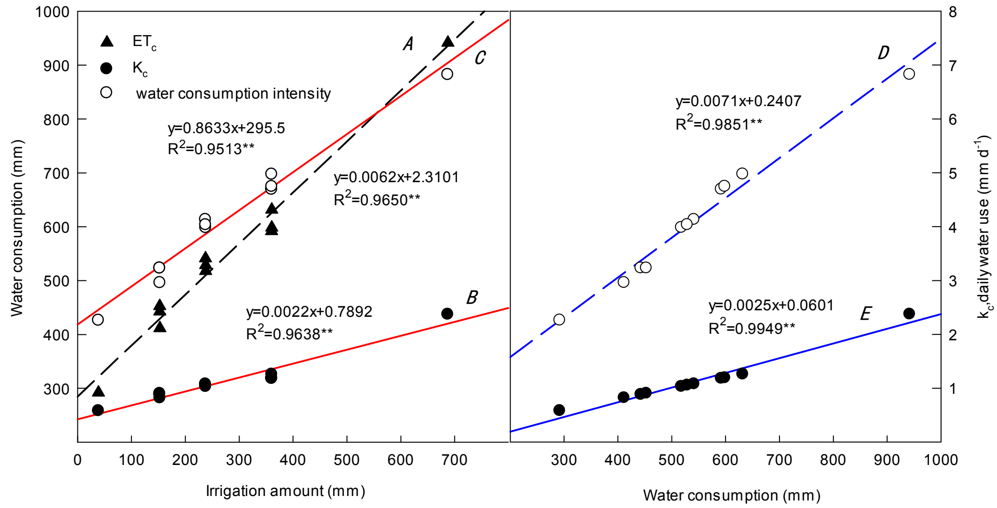

Figure 9. The relationships between irrigation water and water use characteristics. *A*, *B*, and *C* denote changes of ET_c, k_c, and daily water use with irrigation water. *D* and *E* denote changes of daily water use and k_c with irrigation water.

3.5. The Relationships between Irrigation Water and WUE, IWUE

As described in Table 6, WUE and IWUE were greatly affected by irrigation levels and were linearly related to irrigation water. WUE and IWUE declined with increasing irrigation levels (Figure 10), and there was a significant negative correlation between ET_c and WUE and IWUE, as shown in Table 7. Therefore, WUE and IWUE were coincident with irrigation levels in the order of 39 mm > 153 mm > 238 mm > 360 mm > 687 mm.

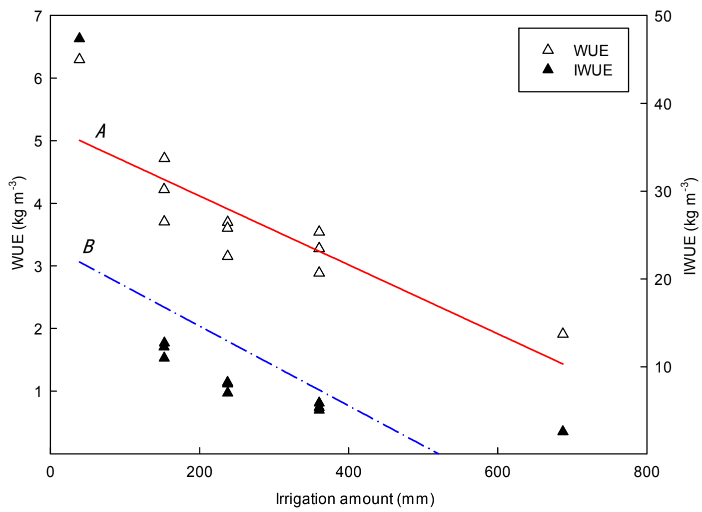

Figure 10. The relationships between irrigation amount and WUE, IWUE. *A* and *B* represent changes of WUE, IWUE with irrigation water, respectively.

Table 6. Results from two-way ANOVA of the effect of various patterns of RFPS and irrigation levels on yield, WUE and IWUE.

Descriptions	*df*	Yield (kg ha^{-1})		WUE (kg m^{-3})		IWUE (kg m^{-3})	
		F	**P**	**F**	**P**	**F**	**P**
Water-saving approach	2	6.270 **	0.009	10.749 **	0.001	6.233 **	0.009
Irrigation level	2	1.608	0.228	21.535 **	0	168.879 **	0
Water-saving approach × Irrigation level	4	0.176	0.948	0.826	0.526	0.410	0.799

Note: F represents F-statistics; P represents significant value. ** means the significant difference at the level of 0.01.

Table 7. Pearson correlations among water use characteristics and yield components.

Descriptions	ET_c (mm)	k_c	Daily Water Use (mm d^{-1})	Ear Length (cm)	Ear Diameter (cm)	Grains Per Ear	Yield (kg ha^{-1})	WUE (kg m^{-3})	IWUE (kg m^{-3})
ET_c (mm)	1								
k_c	1.00 **	1							
Daily water use (mm d^{-1})	0.99 **	0.99 **	1						
Ear length (cm)	−0.38	−0.38	−0.31	1					
Ear diameter (cm)	−0.59	−0.59	−0.5	0.73 *	1				
Grains per ear	−0.31	−0.31	−0.24	0.83 **	0.79 **	1			
Yield (kg ha^{-1})	0.01	0.01	0.08	0.76 **	0.7 *	0.83 **	1		
WUE (kg m^{-3})	−0.9 **	−0.9 **	−0.90 **	0.41	0.53	0.4	0.13	1	
IWUE (kg m^{-3})	−0.68 *	−0.68 *	−0.69 **	0.1	0.23	0.17	−0.09	0.89 **	1

Note: * correlation is significant at the 0.05 level (2-tailed). ** correlation is significant at the 0.01 level (2-tailed).

3.6. The Comparisons of Grain Yield, WUE, and ET_c of Maize

As shown in Table 8, although irrigation water level of our study was not significant, grain yield, WUE, and IWUE were not affected negatively. The irrigation amount was significantly lower compared to Igbadun et al., El-Wahed et al., and Oktem, but the grain yield, WUE, and IWUE were significantly higher. The irrigation amount used in our study was similar to Payero et al. and Sun et al., but the yield, WUE, and IWUE were also significantly higher.

Table 8. The comparisons of grain yield, IWUE, WUE, and ET_c of maize under different irrigation strategies in previous studies compared to this study.

Authors	Irrigation Water (mm)	Grain Yield (kg ha^{-1})	IWUE (kg m^{-3})	WUE (kg m^{-3})	ET_c (mm)	Date
Payero et al. [20]	150	10810–12960	7.21–8.64	1.80–2.05	525	2005
	150	7590–11350	5.06–7.57	1.56–1.92	556	2006
Payero et al. [59]	53–356	8440–10850	2.92–15.93	1.46–1.66	394–650	2005
	22–226	4550–9570	4.13–21.08	0.98–1.49	457–640	2006
Sun et al. [60]	87–162	7164–8110	1.60–1.928	1.58–1.66	449–490	2004
Dağdelen et al. [61]	147–488	5520–11630	2.38–3.75	1.98–2.30	257–434	2003
	149–497	4910–11050	2.22–3.29	1.87–2.00	262–450	2004
Aydinsakir et al. [62]	129–722	1440–7430	1.12–1.67	0.55–1.21	26–737	2013
	129–722	3630–9350	1.29–2.83	1.27–1.57	263–738	2013
Sampathkumar et al. [49]	240–400	4670–7610	1.35–2.68	1.00–1.83	351–538	2008
	231–500	4560–7520	1.04–2.29	0.95–2.1	293–551	2009
El-Hendawy and Schmidhalter [63]	357–596	721–9146	2.02–18.70	1.84–17.57	380–616	2007
Oktem [64]	610–876	8270–13200	1.36–1.59	1.18–1.33	700–1008	1998
	612–889	8340–14350	1.36–1.62	1.19–1.36	701–1071	1999
Ko and Piccinni [51]	211–422	6375–8442	2.00–3.02	0.85–1.20	704–753	2003
	209–418	5477–7879	1.89–2.62	0.43–1.26	626–1289	2003
	116–231	6930–8567	3.71–5.99	0.78–1.03	833–887	2004
Igbadun et al. [12]	400–700	1710–3832	0.43–0.56	0.44–0.71	389–540	2004
	440–750	1625–4349	0.37–0.62	0.41–0.85	396–512	2005
El-Wahed et al. [65]	391–559	4202–10071	0.11–0.18	1.03–1.80	408–560	2009
	477–682	2864 –8047	0.06–0.12	0.60–1.18	477–682	
	391–559	4350–10100	0.11–0.18	1.03–1.81	422–558	2010
	477–682	3055–8047	0.06–0.12	0.64–1.18	477–682	
El-hendawy et al. [66]	357–596	2620–7097	0.73–1.19			2005
	357–596	2657–7309	0.74–1.23			2006
This study	38–360	16685–21197	5.06–47.36	2.89–6.30	292–632	2017

In our study, yield, WUE, and IWUE exhibited a significant improvement that was dependent on irrigation levels, and the values were significantly higher than in previous reports. Relatively few studies have reported greater WUE values than ours, likely related to water-saving approaches and climatic factors. The values we obtained for WUE, IWUE, and yield were achieved using substantially less irrigation water than most studies performed with the same or higher irrigation levels.

4. Conclusions

Interactions between various water-saving approaches and irrigation levels significantly influenced water use and improved grain yield, WUE, and IWUE. These favorable effects advanced growth cycle, promoted grain yield, lowered *ET*, and increased WUE in comparison with those by local flood irrigation. The ET_c and k_c decreased with the irrigation level in the following order 687 > 360 > 238 > 153 > 39 mm, as they were linearly positively proportional to irrigation water (R^2 of 0.95–1). A Quadratic curve relationship was observed between irrigation water level and grain yield. The WUE and IWUE were strongly affected by irrigation water level, and they negatively correlated with the ET_c. In the ridge-furrow planting system with film mulching on both ridges and furrows (the ridge-to-furrow ratio was 50:30 with flood irrigation), the ET_c and k_c with QF were 292 mm and 0.58, respectively, which were significantly lower than those of other irrigation water levels ($p < 0.01$). In this system, the irrigation water was saved by 649 mm, and the yield was increased by 2.24% compared with those in the conventional flat planting system with no film mulching. Furthermore, the WUE and IWUE reached 6.3 and 47.36 kg m^{-3}, respectively, which were substantially higher than those with other water-saving approaches. Furthermore, a quadratic curve relationship was explored between irrigation water and yield. The maximum ear length, ear diameter, grains per ear, and grain yield occurred between the 300 and 400 mm irrigation levels and subsequently decreased with the increase in the irrigation level. With the 360, 238, and 153 mm irrigation levels, the yield of plants with the ridge-furrow planting system without film mulching (drip irrigation) was higher than that with ridge-furrow planting with film mulching on continuous ridges (drip irrigation under black plastic film mulching) or conventional flat planting with no film mulching (flood irrigation). However, although the highest yield (21,197.37 kg ha^{-1}) was recorded with the ridge-furrow planting system without film mulching (drip irrigation) with a 360 mm irrigation level, no significant difference was recorded among 360, 238, and 153 mm irrigation levels; the WUE and IWUE with 153-mm irrigation level were 4.72 and 12.71 kg m^{-3}, respectively, showing increases of 33.33% and 116.16% compared with those of the 360 mm level, respectively.

Among various combinations of water-saving approaches and irrigation levels, the ridge-furrow planting system with film mulching on both ridges and furrows performed best in terms of increasing the yield and promoting the WUE in Horqin Sandy Land of Northeastern China, followed by the ridge-furrow planting system without film mulching (drip irrigation) at the 153-mm irrigation level.

Further studies are needed to reduce labor and mitigate the environmental pollution associated with this technology. In addition, studies are necessary to evaluate the possible large-scale adoption of this technology for different soils or crop cultivars and develop a water-saving strategy to boost maize productivity and water-use efficiency.

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