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Optimal Irrigation Levels Can Improve Maize Growth, Yield, and Water Use Efficiency under Drip Irrigation in Northwest China

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Abstract: Drip irrigation systems are becoming more and more mature, and are presently extensively applied to increase crop yield and water use efficiency. In order to investigate the effects of irrigation quota on maize growth, the grain yield, and the water use efficiency (WUE), a field experiment with four irrigation quotas (T1 420 mm, T2 480 mm, T3 540 mm, and T4 600 mm) was conducted from 2013 to 2021 in Xinjiang, China. The results showed significant changes in maize growth, yield, and WUE in response to different irrigation quotas. The plant height, leaf area index, soil and plant analyzer development (SPAD), dry matter accumulation, yield, and harvest index of maize at different irrigation quotas all showed a 'single peak curve', and its change was closely related to the irrigation level. The growth index, dry matter accumulation, yield, and irrigation water use efficiency with T3 were the highest. The dry matter transfer efficiency, contribution of dry matter translocation to grain, and the harvest index with T3 showed a significant increase of 13.86%, 26.06%, 29.93%, and 7.62% compared to T1, respectively. In comparison to T1, T2, and T4, the yield of T3 increased by 32.17%, 13.54%, and 11.27%, respectively, and the WUE increased by 16.56%, 6.49%, and 23.70%, respectively. The significant correlations established between the maize yield and irrigation quotas could be simulated by a Kuznets-style relation. The maize yield was negatively correlated with irrigation quotas. When the irrigation quota (x) was 539.12 mm, the maize yield (y) was 16043.92 kg·hm^{-2}. These results demonstrate that the optimized irrigation quota (540 mm) can effectively improve the growth, yield, and WUE of drip irrigation maize in northwest China. Meanwhile, it can provide a theoretical reference and data support for the optimal amount of irrigation for drip irrigation maize in Xinjiang China.

Keywords: drip irrigation; maize; irrigation quotas; dry matter accumulation; yield; water use efficiency

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1. Introduction

Maize (*Zea mays* L.) is known as the 'king of the grain' in the 21st century [1]. China plays a significant role in global maize production [2]. Maize growth and yield is closely linked to water resources; it is generally believed that a water deficit markedly inhibits maize growth and yield. Since the 1970s, climatic change and economic growth have resulted in a rapid decrease in water [3]. Shortages of water resources are a common problem in agriculture production worldwide, as well as one of the most important ecological factors restricting crop productivity. Furthermore, water shortages threaten the deterioration of these existing challenges, and further undermine efforts to reduce poverty and improve food security [4].

Northwest China is a typical irrigation agricultural area, with sufficient sunshine, drought, and less rain [5]. In Northwest China, irrigation water is a critical factor for agricultural development. At present, agricultural irrigation water consumption accounts for more than 60% of the total water consumption in northwest China [6]. Water shortages have affected agricultural production in northwest China [7]. With the increasing demand for water resources, their efficient use is being emphasized [8]. The issue of how to make economic and effective use of water resources and implement reasonable irrigation measures are at the core of agricultural production. Therefore, it is imperative to optimize irrigation in arid and semi-arid areas in order to improve unit water yield. Drip irrigation technology is a new type of surface irrigation technology, used to adapt to the development of water-saving agriculture [9]. As a trade-off, optimizing irrigation use to reduce the amount of irrigation is essential for improving the yield of unit water, so as to obtain higher water use efficiency [10].

Drip irrigation is now commonly used for maize cultivation to increase crop yield and water use efficiency in China [11]. Drip irrigation slowly drips water and fertilizer directly into crop root soil through high frequency irrigation, forming an ellipsoid or spherical wetting body in the root zone [12]. Drip irrigation has had effective yield-increasing and water-saving effects [13]. A reasonable irrigation quota can save agricultural water while achieving a high yield [14]. When the irrigation quota is too high, the respiration of maize roots is limited and the physiological progress is affected [15]. When the irrigation quota is too low, it cannot meet the crop's needs for basic physiological development, resulting in a substantial reduction in yield [16]. Scholars have carried out numerous studies on irrigation schedule optimization. Greaves [17] designed five irrigation quotas for maize and concluded that water deficit irrigation had no significant effect on yield, but greatly improved irrigation water use efficiency. Wang [18] found that a drip irrigation quota of 54 mm can improve irrigation water use efficiency without significantly reducing the crop yield of cotton in north Xinjiang. Wang [18] found that in northern Xinjiang, when the drip irrigation quota was 54 mm, the irrigation water use efficiency could be improved without significantly reducing cotton yield. Han [19] optimized the maize irrigation system in the Heihe River basin based on the Aqua Crop-RS model. That study found that compared with full irrigation, the irrigation quota decreased by 0–657 mm, water use efficiency increased by 4.13–5.13%, and water use efficiency increased by 69–91%. WUEET is increased by 4.13–5.13% and WUEI rises by 69–91%. Zhang [20] found that high grain yield (15.7–19.1 $Mg \cdot hm^{-2}$), WUE (2.47–2.77 $kg \cdot m^{-3}$), and economic return (1691.6–2605.7 US$\$ \cdot hm^{-2}$) were achieved at an irrigation quota of 540 mm. were achieved when the irrigation quota was 540 mm. The study by Tang [21] showed that the yield of maize increased with the increase in irrigation quota, but when the irrigation quota exceeded 600 mm, the yield did not significantly increase in the southern region of Xinjiang. The appropriate irrigation quota for maize was 525–600 mm.

The cultivation of high-yield maize requires sufficient water, heat, etc. [10]. Water is the most dynamic factor in determining yield [22]. Insufficient or excessive irrigation water will limit the yield of maize [23]. At present, many scholars study the effect of different irrigation modes on maize yield and water use efficiency [24]. There are few studies on the impact of drip irrigation quota on maize in northwest China. In order to investigate the effects of irrigation quota on maize growth, the grain yield, and WUE, a field experiment with four irrigation quotas was conducted from 2013 to 2021 in northwest China. This study used a comparative test in the same research area for many years. Our aim was to optimize the irrigation quota for maize. Our hypothesis was that optimal irrigation levels can improve maize growth and enhance WUE under drip irrigation in Xinjiang, China. The research results are helpful for optimizing efficient water-saving irrigation, increasing maize yield, and providing theoretical support for sustainable agricultural development in northwest China.

2. Materials and Methods

2.1. Experiment Site

A field experiment was conducted for the purpose of investigating the whole growth stages of maize from 2013 to 2021. This occurred in an experimental station of the Ministry of Agriculture, studying the use of water for crops, in Shihezi City, Xinjiang, China (86°09′ E, 45°38′ N). The experimental field was located in the western suburbs of Shihezi, with an elevation of 452.80 m, an average annual temperature of 22.46 °C, and an average annual evaporation of 1942 mm. The depth of the water table in this area is relatively high, varying from 2 to 3 m over different years. The maximum/minimum temperatures and monthly effective rainfall for the growth season over the nine-year maize growth periods are shown in Figure 1. The maximum/minimum temperatures and monthly effective rainfall for the growth season in nine years during the maize growth periods are shown in Figure 1.

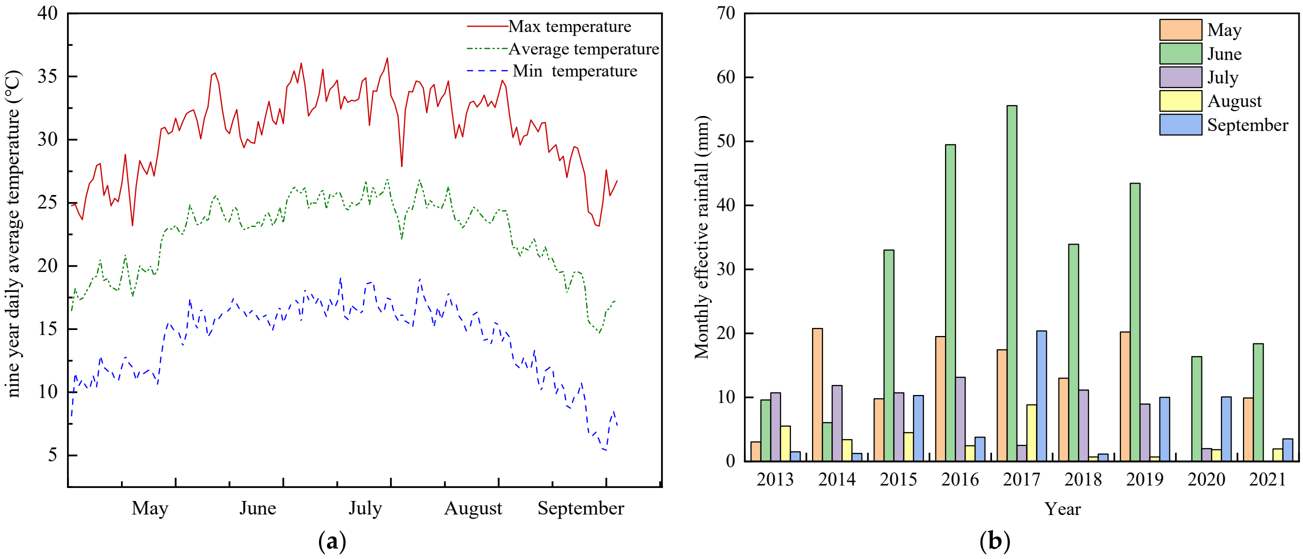


Figure 1. Meteorological variation during maize growth periods from 2013 to 2021. (**a**) Daily average temperature. (**b**) Monthly effective rainfall.

Soil properties at the test site were measured between the depths of 0 and 100 cm prior to maize planting in the first season. The soil type is a grey desert soil [25]. Nine-year averages of the soil's physicochemical properties are shown in Table 1. The quality of the irrigation water is shown in Table 2.

Table 1. The physicochemical properties of soil in the station.

Soil Depth (cm)	Organic Matter ($g{\cdot}kg^{-1}$)	Total Nitrogen ($g{\cdot}kg^{-1}$)	Olsen-P ($mg{\cdot}kg^{-1}$)	Avail.K ($mg{\cdot}kg^{-1}$)	Bulk Density ($g{\cdot}cm^{-3}$)	Saturated Volumetric Water Content (%)	pH
0–20	16.79	1.44	26.52	415.98	1.56	32.01	8.19
20–40	17.92	1.40	26.76	416.78	1.67	33.14	8.20
40–60	16.74	1.38	23.56	354.65	1.72	33.26	8.16
60–80	8.16	1.03	8.13	246.37	1.74	34.54	8.14
80–100	7.04	0.80	6.15	214.47	1.76	35.67	8.16

Table 2. Irrigation water quality.

Index	Total Hardness (mg/L) ($CaCO_3$)	Mineralization Degree (mg/L)	(NH_4-N) (mg/L)	Permanganate Index (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)	Phenol
Content	155	367	<0.05	13.53	92.09	25.53	<0.002

2.2. Experimental Design

Conducted through a completely randomized design, the experiment comprised four irrigation quotas (T1 420 mm, T2 480 mm, T3 540 mm, and T4 600 mm), which referred to irrigation quantities of the local farmers. Considering the marginal effect of different irrigation quotas, the 12 plots were separated from adjacent plots by 2.2 m-wide isolation strips, and each plot (110 m^2) was 20 m long and 5.5 m wide. In each plot, a water reading meter and a fertilizer tank were installed in order to monitor the amount of irrigation water, fertilizer, N, P, and K that were applied, respectively. irrigation water and fertilizer that were applied, respectively. Fertilization was carried out with irrigation and all treatments had the same management, which began after 30 min of irrigation and ended 30 min before irrigation stopped. The irrigation water was supplied by underground water. The irrigation and fertilization levels in each growth period are shown in Table 3. Drip irrigation maize sowing, harvesting, and sampling time are shown in Table 4.

Table 3. Irrigation and fertilization in different periods.

Treatment/Period		Seedling Stage	Jointing Stage	Bell-Mouth Stage	Heading Stage	Flowering Stage	Silking Stage	Grain Formation Stage	Milk-Ripe Stage	Maturity Stage	Total
Irrigation quantity (mm)	T1	13.7	53.6	53.6	53.6	53.6	53.6	50.9	45.5	41.9	420.0
	T2	16.4	60.0	60.0	60.0	60.0	60.0	60.0	56.4	47.2	480.0
	T3	16.4	69.1	69.1	69.1	69.1	69.1	65.5	58.2	54.4	540.0
	T4	19.0	75.5	74.5	75.5	74.5	75.5	75.5	70.0	60.0	600.0
Fertilizer amount (kg·hm^{-2})	Urea	0.0	81.8	81.8	90.9	81.8	81.8	72.7	54.5	0.0	545.3
	Monoammonium phosphate	36.4	36.4	45.5	45.5	45.5	27.3	18.2	18.2	0.0	273.0
	Potassium sulphate	0.0	18.2	27.3	27.3	36.4	22.7	18.2	13.6	0.0	163.7

Table 4. Maize sowing, harvesting, and sampling time.

Years	Sowing Date	Harvest Date	Flowering Stage	Maturity Stage
2013	8th May	20th September	18th July	23th August
2014	5th May	22nd September	13th July	26th August
2015	2nd May	25th September	15th July	24th August
2016	30th April	24th September	17th July	25th August
2017	7th May	28th September	20th July	28th August
2018	28th April	27th September	18th July	25th August
2019	30th April	22nd September	14th July	22nd August
2020	26th April	1st October	15th July	2nd September
2021	7th May	24th September	19th July	27th August

A joint planter was used to lay drip tapes, film, and sow. Its planting density was $1.26 \times 10^5/\text{hm}^2$ in the experiment. The plants were sown with alternating wide and narrow rows of 0.8 and 0.3 m. The spacing between plants within a row was 14.4 cm (Figure 2, the spacing between the drip tapes was 110 cm).

2.3. Material

The green maize variety "ZD958", which is commonly planted in northern China, was used as the experimental variety. Zhengdan 958 was the offspring of inbred Zheng 58 and Chang 7–2 (deposition number 20000009), which are approved in China. In this study, the seeds of Zhengdan 958 were provided by Beijing Denong Seed Technology Co., Ltd. (Beijing, China) Experimental research and field studies on plants complied with relevant institutional, national, and international guidelines and legislation. The urea (N $\geq$ 46.4%, granules) used in the experiment was produced by Xinlianxin Co., Ltd. (Xinjiang, China). Monoammonium phosphate (N $\geq$ 12%, $P_2O_5 \geq$ 61%, powder) was produced by Guizhou Kai Phosphorus Group Co., Ltd. (Guiyang, China). Potassium sulfate was produced by Luobupo Potassium Salt Co., Ltd. (Xinjiang, China).

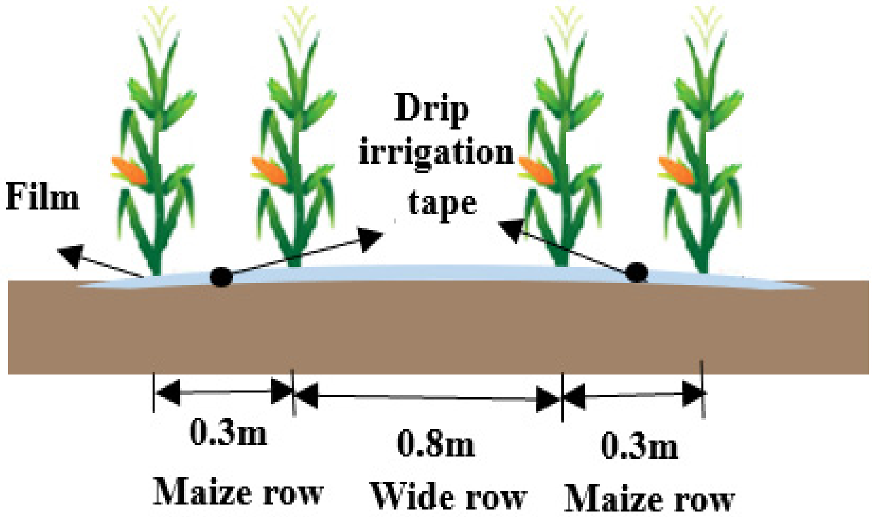


Figure 2. Schematic diagram of cultivation mode for maize.

The source of the irrigation water was a deep well with a depth of 100 m; the salinity of the water was 0.2–0.3 g·L^{-1}. The type of drip irrigation belt was a single wing labyrinth drip-irrigation belt (WDF16/2.6–100) produced by Xinjiang Tianye Company (Shihezi, China). The wall thickness was 0.18 mm, the inner diameter was 16 mm, the drip hole spacing was 300 mm, the rated flow was 2.0 L·h^{-1}, and the working pressure was 0.1–0.15 MPa.

2.4. Sampling and Measurements

2.4.1. Stand Growth Index

Plant height [26]: Ten maize plants with similar growth were randomly selected from each treatment at flowering and maturity stages, and the height from the ground to the top of the maize plant was measured using a tape measure.

Leaf area index (LAI) [27]: ten plants with similar growth vigor were randomly selected from each treatment at flowering and maturity stages. Leaf area: using destructive sampling, the length and width of the leaves were measured with a tape measure, then multiplied by 0.75 to calculate the leaf area per plant.

$$\text{LAI} = \text{Leaf area per plant} \times \text{Number of maize plants per unit of land area/Unit land area}$$

SPAD: the SPAD-502 chlorophyll meter (Minolta, Osaka, Japan) was used to randomly determine the three ear leaves of 20 maize plants, and plants continuously selected at flowering and maturity stages.

Dry matter determination: At the flowering and maturity stages, four representative maize plants with stable growth were randomly selected from the third film and the fourth film in each plot. The above-ground parts of the plants were removed from the base of the plants and divided into leaves, stems, and reproductive organs [28]. The leaves and other organs were packed in paper sampling bags, marked, placed in an oven, kilned at 105 °C for 30 min, dried to a constant weight at 75 °C, and weighed and recorded on a balance with an accuracy of 0.01.

2.4.2. Grain Yield and Yield Components

At the maturity stage, 20 ears were taken from the middle two rows of each plot, and the grain number per ear was counted. By randomly selecting 10 plants from each plot, the grain number and row number data were recorded, and then the average was calculated. A total of 1000 seeds were randomly selected from the seed batches of each plot, and the weight of the seeds was determined using an electronic balance scale. The ear number, grain moisture content, and grain yield were also determined for each plot. Grain yield and kernel weight were expressed at 14% moisture content.

2.4.3. Data Analysis

Yield (kg hm^{-2}) = 20 grain weight (g)/20 panicles × 126,000/1000 × [1-grain moisture content (%)]/(1–14%) [29].

Harvest index (%) = yield/aboveground biomass × 100 [30].

Dry matter translocation (kg·hm^{-2}) = stem and leaf dry matter at flowering stage—stem and leaf dry matter at maturity stage;

Dry matter transfer efficiency (%) = dry matter translocation/stem and leaf dry matter at flowering stage × 100;

Contribution of dry matter translocation to grain (%) = dry matter translocation/grain yield × 100 [31].

2.4.4. Water Use Efficiency (WUE) [32]

Seasonal evaporate-transpiration (*ET*) was estimated using the water balance approach [32].

$$ET = P + I + C_p - D_p - R_f - \Delta S$$

where *P*, precipitation; *I*, irrigation; *Cp*, contribution through capillary rise from groundwater; *Dp*, deep percolation; *Rf*, runoff. ΔS = Sf − Si, change in the soil water storage in the profile, where Si represents soil water storage in the profile at sowing and Sf represents soil water storage in the profile at harvest.

Since the groundwater was relatively deep (2–3 m), *Cp* was assumed to be negligible. *Dp* was considered to be negligible beyond 90 cm due to negligible changes in the soil moisture storage below a soil depth of 90 cm. There was no runoff (*Rf*) from the field, as all of the plots were provided with bunds. Δ*S* indicates that the soil water storage at the time of sowing is similar to that at the time of harvest, which can be ignored. Thus,

$$ET = P + I$$
$$WUE = Y/ET$$

where *Y* is the grain yield of maize.

Irrigation Water Use Efficiency (*IWUE*)

Calculation formula of irrigation water use efficiency (kg·m^{-3}) is [24].

$$IWUE = Y/I$$

In the formula, *Y* is the yield per unit area (kg·hm^{-2}), and *I* is the irrigation amount of maize growth period (mm).

2.5. Statistical Analysis

All data were statistically analyzed using SPSS 25.0, including one-way ANOVA and multiple mean comparison using the least significant difference (LSD) test (α = 0.05). The figures were prepared via Origin 2018 and Excel 2016.

3. Results

3.1. Growth Index

Irrigation quotas significantly ($p < 0.05$) affected the maize growth index (Figure 3). With the increase in irrigation quotas, the growth indices of maize at the flowering and maturity periods first increased, but then decreased, and the effects were the most obvious at a quota of 540 mm (T3). In comparison to T1, T2, and T4, the plant height at the flowering stage of T3 increased by 9.78%, 5.00%, and 2.32%, and that at the maturity stage increased by 7.90%, 4.36%, and 1.68%, respectively. The leaf area index showed that at the flowering stage, T3 treatment was 16.39% and 12.89% higher than T1 and T2, and T4 treatment was 10.89% and 7.56% higher than T1 and T2, respectively. At the maturity stage, T3 was 17.48% and 10.68% higher than T1 and T2, and T4 was 12.58% and 6.07% higher, respectively. At the flowering and maturity stages, T3 resulted in 9.46% and 5.95% higher SPAD compared with T1, and 4.22% and 5.78% higher SPAD compared with T2, respectively. Plant height, leaf area index, and SPAD have specific functional relationships.

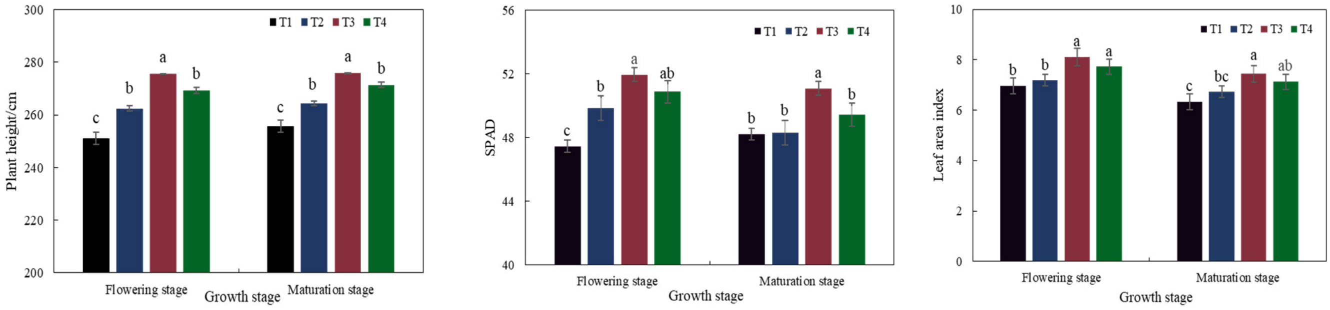


Figure 3. Effects of different irrigation quotas on plant height, SPAD, and leaf area index of maize. Note: Different lowercase letters indicate that there are significant differences between different treatments of each index in the same growth period.

Dry Matter Accumulation

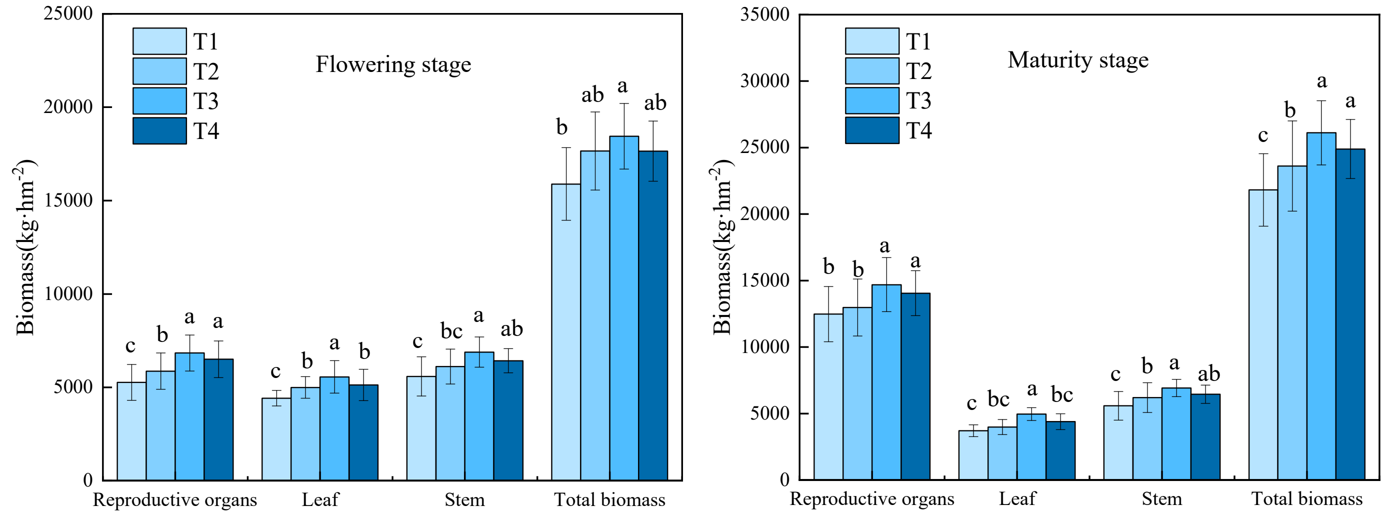
Irrigation quotas significantly affected the dry matter accumulation of maize at the flowering and maturity stages. The biomass of the leaves, stems, and reproductive organs of maize at different irrigation quotas all showed a 'single peak curve', and the changes were closely related to the irrigation level (Figure 4). In comparison to T1, T2, and T4, the biomass of the reproductive organs of the T3 maize increased by 29.91%, 16.62%, and 5.26%, the biomass of the stems of T3 increased by 23.27%,12.68%, and 7.24%, the biomass of the leaves of T3 increased by 25.69%, 11.21%, and 8.33%, and the total biomass increased by 16.09%, 4.47%, and 45.43% at the flowering stage, respectively (Figure 4—Left). The biomass of the reproductive organs and stems, as well as the total biomass of T3 at the maturity stage, were significantly higher than those of T1 and T2, and there was no significant difference between T3 and T4. The biomass of the reproductive organs of T3 was higher than that of T1 and T2 by 17.76% and 13.26%, the biomass of the stems increased by 23.98% and 11.71%, and the total biomass increased by 19.69% and 10.57%, respectively. The leaf biomass of T3 was significantly higher than that of the plants which underwent other treatments; it increased by 33.76%, 24.48%, and 12.96%, respectively (Figure 4—right). Dry matter accumulation at the flowering and maturity stages of maize showed that the assimilation ability of the T3 maize to carbohydrate was stronger than that of the plants which underwent other treatments. The irrigation quota and dry matter accumulation were fitted and analyzed, and it was found that they have specific functional relationships. The dry matter accumulation at maturity was negatively correlated with irrigation quotas: $y = -0.2094\,x^2 + 233.14\,x - 39386$, $R^2 = 0.9039$. When the irrigation quota (x) was 556.69 mm, dry matter accumulation (y) was 25,505.87 kg·hm^{-2}.

3.2. Grain Yield and Harvest Index

3.2.1. Yield and Its Components

The results in Table 5 demonstrate that, with the exception of row number per ear, the irrigation quotas significantly influenced the maize yield and components. The yield and the components of maize, at different irrigation quotas, all showed a 'single peak curve', and the change was closely related to the irrigation level. Ear diameter, kernel number per row, row number per ear, thousand-kernel weight, and yield were factors which we considered. In comparison to T1, T2, and T4, the ear diameter of the T3 maize increased by 6.80%, 4.57%, and 3.01%, its kernel number per row increased by 7.52%, 4.90%, and 2.93%, its thousand-kernel weight increased by 9.51%, 5.93%, and 6.61%, and its yield increased by 32.17%, 13.54%, and 11.27%, respectively. The significant correlations established between the maize yield and irrigation quotas could be simulated by Kuznets-style relation. The maize yield was negatively correlated with irrigation quotas: $y = -0.2593\,x^2 + 279.59x - 59323$,

$R^2 = 0.9222$. When the irrigation quota (x) was 539.12 $m^3 \cdot hm^{-2}$, the maize yield (y) was 16,043.92 $kg \cdot hm^{-2}$.



Left: Dry matter accumulation of maize at flowering stage Right: Dry matter accumulation of maize at maturity stage

Figure 4. Dry matter accumulation of maize under drip irrigation quotas: Left is dry matter accumulation of maize at flowering stage; right is dry matter accumulation of maize at maturity stage. Note: Different lowercase letters indicate that the dry matter of each part of the maize at the same growth period is significantly different between different treatments.

Table 5. Yield and components of maize under different irrigation quotas.

Year	Treatment	Ear Diameter (mm)	Kernel Number per Row	Row Number per Ear	1000-Kernel Weight (g)	Yield ($kg \cdot hm^{-2}$)
2013	T1	42.01 ± 2.11 b	35.26 ± 3.69 b	14.26 ± 0.89 b	322.65 ± 23.83 c	10,495.01 ± 1063.83 c
	T2	43.67 ± 4.54 ab	35.87 ± 1.83 ab	14.54 ± 0.59 b	329.14 ± 28.11 bc	12,841.24 ± 987.93 b
	T3	44.11 ± 1.45 a	36.52 ± 2.22 a	16.27 ± 0.67 a	346.63 ± 31.03 a	15,852.10 ± 1293.72 a
	T4	43.09 ± 3.69 ab	35.90 ± 2.81 ab	14.91 ± 1.05 b	333.17 ± 34.69 b	15,601.48 ± 1168.72 ab
2014	T1	43.21 ± 1.35 c	35.92 ± 2.75 ab	15.19 ± 1.01 a	319.83 ± 25.17 c	11,702.33 ± 968.15 c
	T2	44.67 ± 1.58 ab	35.96 ± 2.11 ab	14.83 ± 0.88 ab	339.12 ± 22.95 b	13,366.67 ± 1473.38 ab
	T3	45.94 ± 1.29 a	36.14 ± 3.61 a	15.26 ± 0.27 a	358.2 ± 18.37 a	14,404.35 ± 1185.43 a
	T4	44.90 ± 1.53 ab	35.93 ± 1.98 ab	14.74 ± 0.83 ab	345.27 ± 25.55 b	12,833.21 ± 1277.49 bc
2015	T1	44.30 ± 1.97 c	29.50 ± 3.09 b	12.60 ± 0.95 bc	335.58 ± 34.03 c	13,916.40 ± 2026.18 b
	T2	47.22 ± 1.34 ab	33.35 ± 1.95 ab	12.80 ± 0.98 bc	365.74 ± 29.18 bc	14,842.01 ± 1567.29 b
	T3	49.24 ± 1.74 a	35.24 ± 2.49 a	14.05 ± 0.48 a	393.92 ± 21.86 a	16,515.66 ± 2617.32 a
	T4	48.05 ± 3.19 a	30.85 ± 1.09 b	13.65 ± 1.00 ab	337.29 ± 17.84 c	14,288.22 ± 1632.62 b
2016	T1	43.42 ± 1.36 c	29.75 ± 2.69 b	13.43 ± 0.43 b	350.88 ± 21.07 b	12,308.60 ± 1178.62 b
	T2	44.00 ± 1.61 bc	33.30 ± 1.14 ab	14.75 ± 1.41 a	365.43 ± 26.76 b	15,511.86 ± 1365.48 b
	T3	48.55 ± 1.75 a	34.60 ± 0.75 a	14.90 ± 0.50 a	376.14 ± 33.57 a	16,843.50 ± 1634.13 a
	T4	45.50 ± 0.43 b	33.05 ± 2.83 ab	14.60 ± 0.86 a	354.94 ± 72.73 b	15,063.40 ± 1549.37 b
2017	T1	46.18 ± 2.04 b	31.90 ± 2.14 c	14.65 ± 0.61 a	324.00 ± 27.39 c	12,831.30 ± 1375.19 bc
	T2	46.66 ± 1.59 ab	34.05 ± 1.47 ab	14.71 ± 0.88 a	330.50 ± 37.18 b	14,236.02 ± 1467.28 b
	T3	47.01 ± 1.38 a	34.75 ± 1.64 a	14.90 ± 0.64 a	345.75 ± 31.29 a	16,739.75 ± 1275.74 a
	T4	47.97 ± 1.04 a	35.45 ± 0.94 a	13.90 ± 0.48 ab	325.75 ± 35.44 bc	14,877.88 ± 1128.48 b
2018	T1	46.51 ± 1.78 b	32.10 ± 1.89 b	14.00 ± 0.86 a	325.425 ± 19.91 b	12,622.08 ± 1022.43 b
	T2	46.85 ± 2.73 b	32.45 ± 2.25 b	14.30 ± 0.50 a	322.2 ± 15.62 b	15,041.43 ± 1793.74 b
	T3	49.00 ± 3.49 a	35.65 ± 3.85 a	14.30 ± 0.30 a	347.225 ± 36.72 a	16,320.98 ± 1317.82 a
	T4	44.85 ± 1.17 c	34.45 ± 3.51 ab	13.80 ± 0.77 a	324.475 ± 14.55 b	15,788.32 ± 1082.73 ab

Table 5. *Cont.*

Year	Treatment	Ear Diameter (mm)	Kernel Number per Row	Row Number per Ear	1000-Kernel Weight (g)	Yield (kg·hm^{-2})
2019	T1	43.57 ± 0.11 a	34.75 ± 1.94 b	16.42 ± 0.93 b	323.50 ± 41.75 b	12,315.23 ± 1367.05 b
	T2	43.55 ± 0.08 a	33.05 ± 1.52 ab	16.11 ± 0.36 b	329.25 ± 40.56 a	13,164.46 ± 1506.54 b
	T3	43.64 ± 0.19 a	35.90 ± 2.62 a	25.25 ± 0.72 a	326.00 ± 29.86 a	16,408.04 ± 1480.95 a
	T4	43.47 ± 0.08 a	33.35 ± 2.94 ab	15.84 ± 1.03 b	323.25 ± 16.07 b	13,866.91 ± 2277.41 b
2020	T1	42.83 ± 1.88 c	31.05 ± 1.59 a	14.7 ± 0.38 a	329.14 ± 39.01 c	13,818.51 ± 700.42 c
	T2	43.51 ± 0.99 bc	31.40 ± 0.21 a	14.80 ± 0.53 a	333.73 ± 33.29 bc	15,775.93 ± 2026.60 bc
	T3	49.55 ± 1.54 a	31.30 ± 0.90 a	14.93 ± 1.10 a	369.91 ± 59.09 a	18,800.32 ± 1653.87 a
	T4	47.82 ± 1.06 ab	32.80 ± 0.73 a	14.91 ± 0.82 a	346.58 ± 30.21 b	16,053.01 ± 2651.63 b
2021	T1	43.63 ± 0.45 b	30.55 ± 0.60 b	13.78 ± 0.37 a	329.50 ± 26.34 c	12,827.10 ± 1446.74 b
	T2	43.98 ± 1.83 b	30.33 ± 2.09 b	13.85 ± 0.13 a	340.00 ± 19.05 b	16,565.66 ± 1056.69 b
	T3	45.52 ± 0.83 a	32.53 ± 2.09 a	14.02 ± 0.13 a	372.50 ± 16.40 a	17,247.86 ± 614.30 a
	T4	44.54 ± 1.96 b	31.93 ± 1.73 ab	13.95 ± 0.51 a	344.75 ± 16.33 b	15,658.92 ± 1971.10 b
Mean	T1	43.96 ± 1.45 c	32.31 ± 2.26 c	14.34 ± 0.71 b	328.95 ± 28.72 c	12,537.40 ± 1238.73 c
	T2	44.90 ± 1.81 bc	33.31 ± 1.62 bc	14.52 ± 0.70 ab	339.46 ± 28.08 b	14,593.92 ± 1471.44 b
	T3	46.95 ± 34.74 a	34.74 ± 2.24 a	15.99 ± 0.53 a	359.59 ± 30.91 a	16,570.28 ± 1452.59 a
	T4	45.58 ± 33.75 b	33.75 ± 2.06 ab	14.48 ± 0.82 ab	337.28 ± 29.27 bc	14,892.37 ± 1637.73 b

Note: different lowercase letters indicate significant differences between different treatments of the same indicator.

3.2.2. Harvest Index

The results in Table 6 demonstrate that the irrigation quotas significantly influenced the biomass transfer and related indicators. With the increase in irrigation quotas, dry matter transport and correlative indicators of maize first increased, but then decreased, and the effects were the most obvious at a quota of 540 mm (T3). The dry matter translocation of the T3 maize was 13.86%, 13.29%, and 9.95% higher than that of T1, T2, and T4, and the grain contribution increased by 29.93%, 6.96%, and 11.31%, respectively. The dry matter transfer efficiency of T3 was higher than that of T1 and T2; it increased by 26.06% and 14.88%, and the harvest index increased by 7.62% and 3.11%, respectively. In general, T3 was superior to other treatments in dry matter translocation, dry matter transfer efficiency, grain contribution, and harvest index, and was more beneficial for improving maize yield.

Table 6. Effect on harvest index of maize under different irrigation quotas.

Treatment	Dry Matter at Flowering Stage (kg·hm^{-2})	Dry Matter at Maturity (kg·hm^{-2})	Dry Matter Translocation (kg·hm^{-2})	Dry Matter Transport Efficiency (%)	Grain Contribution (%)	Harvest Index (%)
T1	15,890.05 ± 1738.37 c	21,814.93 ± 1188.26 c	6569.02 ± 1555.33 c	53.43 ± 22.60 c	40.00 ± 20.44 c	60.10 ± 14.17 c
T2	17,657.26 ± 1899.31 bc	23,613.32 ± 1371.05 b	6601.98 ± 1200.16 bc	58.63 ± 26.12 bc	48.59 ± 22.75 bc	62.73 ± 8.59 b
T3	18,447.08 ± 1107.74 a	26,110.00 ± 1906.50 a	7479.68 ± 1587.54 a	67.36 ± 21.52 a	51.97 ± 16.94 a	64.68 ± 19.07 a
T4	17,645.46 ± 1968.47 bc	24,893.06 ± 1434.82 b	6802.67 ± 1968.47 b	65.96 ± 22.77 ab	46.69 ± 22.79 bc	64.25 ± 4.51 a

Note: different lowercase letters indicate significant differences between different treatments of the same indicator.

3.3. Water Use Efficiency (WUE)

Water use efficiency (WUE) is the standard for comparing the economy of agricultural water use units under different irrigation quotas (Table 7). The WUE of maize at different irrigation quotas showed a 'single peak curve', and the changes were strongly associated with the irrigation levels. The IWUE of the T3 maize was better than that of T2 and T4; the IWUE of T3 increased by 0.94% and 19.50%, respectively. The WUE of T3 was 16.56%, 6.49%, and 23.70% higher than that of T1, T2, and T4, respectively. The WUE of maize was lower when the irrigation water was too high, and T3 improved the WUE of maize compared with other treatments, demonstrating its water-saving effect. The WUE was negatively correlated with irrigation quotas: $y = -7e^{-5}x^2 + 0.0729x - 15.349$, $R^2 = 0.8931$. When the irrigation quota (x) was 520.71 mm, the WUE (y) of the maize was 3.07 kg·m^{-3}.

Table 7. WUE of drip irrigated maize under different irrigation quotas.

Year	Treatment	Irrigation Amount in Maize Growth Period (mm)	Yield ($kg \cdot hm^{-2}$)	IWUE ($kg \cdot m^{-3}$)	WUE ($kg \cdot m^{-3}$)
2013	T1	420	10,495.01 c	2.50 c	2.33 b
	T2	480	12,841.24 b	2.68 b	2.52 ab
	T3	540	15,852.10 a	2.94 a	2.79 a
	T4	600	15,601.48 ab	2.60 b	2.48 ab
2014	T1	420	11,702.33 c	2.79 a	2.33 b
	T2	480	13,366.67 ab	2.79 a	2.55 ab
	T3	540	14,404.35 a	2.67 ab	3.08 a
	T4	600	12,833.21 bc	2.14 b	2.00 c
2015	T1	420	13,916.40 b	3.35 a	2.56 ab
	T2	480	14,842.01 b	3.09 b	2.71 ab
	T3	540	16,515.66 a	3.06 b	3.03 a
	T4	600	14,288.22 b	2.38 c	2.14 b
2016	T1	420	12,308.60 b	3.41 a	2.42 b
	T2	480	15,511.86 b	3.23 b	2.73 ab
	T3	540	16,843.50 a	3.12 b	3.10 a
	T4	600	15,063.40 b	2.51 c	2.19 c
2017	T1	420	12,831.30 bc	3.29 a	2.44 ab
	T2	480	14,236.02 b	2.97 ab	2.43 ab
	T3	540	16,739.75 a	3.04 ab	2.81 a
	T4	600	14,877.88 b	2.48 b	2.11 b
2018	T1	420	12,622.08 b	3.48 a	2.55 b
	T2	480	15,041.43 b	3.13 ab	2.79 ab
	T3	540	16,320.98 a	3.02 ab	3.03 a
	T4	600	15,788.32 ab	2.63 b	2.39 c
2019	T1	420	12,315.23 b	3.41 a	2.54 b
	T2	480	13,164.46 b	2.74 bc	2.34 b
	T3	540	16,408.04 a	3.04 b	3.04 a
	T4	600	13,866.91 b	2.31 c	2.03 c
2020	T1	420	13,818.51 c	3.77 a	3.01 ab
	T2	480	15,775.93 bc	3.29 b	3.09 ab
	T3	540	18,800.32 a	3.48 b	3.31 a
	T4	600	16,053.01 b	2.68 c	2.55 b
2021	T1	420	12,827.10 b	3.29 a	2.95 b
	T2	480	16,565.66 b	3.45 a	3.22 ab
	T3	540	17,247.86 a	3.19 ab	3.52 a
	T4	600	15,658.92 b	2.61 b	2.47 c
Mean	T1	420	12,537.40 c	3.49 a	2.57 b
	T2	480	14,593.92 b	3.15 b	2.88 ab
	T3	540	16,570.28 a	3.18 b	3.08 a
	T4	600	14,892.37 b	2.56 c	2.35 b

Note: different lowercase letters indicate significant differences between different treatments of the same indicator.

4. Discussion

4.1. Effects of Different Irrigation Quotas on Yield and Growth Index of Drip Irrigation Maize

In arid and semi-arid regions, the water resources directly affect the distribution and growth of crops [33]. Irrigation is a key factor in agricultural development. An appropriate irrigation water quota ensures a high crop yield, resource conservation, and environment-friendly agricultural development [34]. Nevertheless, the continuous supply of additional water does not always increase food production, as some water may be consumed inefficiently through soil evaporation, especially under drought conditions. When the irrigation quota reaches a certain value, the influence of a continuous increase in irrigation amount on the growth index is greatly weakened [35]. Fang [36] found that in the arid oasis farming system, water-saving irrigation (medium and low irrigation) reduced the maize yield by 12.0–28.0% compared with full irrigation of different soils. You [37] found that the plant height and yield components of winter wheat increased with the increase in annual irrigation quotas. However, Jia [38] demonstrated that applying deficit irrigation (375 $m^3 \cdot hm^{-2}$) at the flowering stage (IF) of plants grown under a medium planting density (M:75000 plants$\cdot hm^{-2}$) (MIF) RFRH system can increase biomass and grain yield. Ma [39] found that the maximum and average dry matter accumulation rates in maize plants increased as the irrigation quota increased from 300 to 375 mm. When the irrigation quota was increased to 450 mm, the maximum dry matter growth rate, the maximum average dry matter growth rate, and the yield of maize were all decreased, which is consistent with our results. This study showed that proper irrigation can continuously increase growth index, biomass accumulation, and yield. However, with the continuous increase in the irrigation quota, the growth, dry matter accumulation, and yield of maize decreased. Those studies were conducted in arid regions, and achieved the same results as ours. However, for semi-arid areas, the effect of irrigation on crop yields is not significant, as most rainfall occurs during the growing season [40]. The inconsistency between irrigation optimal irrigation quota may be due to differences in factors such as soil type, maize variety, and climatic conditions.

4.2. Effects of Different Irrigation Quotas on WUE of Drip Irrigated Maize

WUE is an important water use index in crop production. In order to reduce the waste of water resources in agricultural production, it is necessary to study how to achieve a high WUE for crops [41]. Water-saving measures are widely considered to improve the utilization efficiency of water resources, and to further alleviate the crisis of water shortage, especially in arid areas. The development of the drip irrigation technique has enriched the agricultural measures of water-saving irrigation, as it can directly supply water to crops. By adjusting the water supply, the regulation of water and fertilizer can be achieved, which can promote the growth of crops. Drip irrigation quantity is also important; excessive irrigation will reduce WUE, and limited irrigation may lead to higher WUE and lower field-scale ET. Hence, optimizing the irrigation schedule is an important measure for improving the yield and WUE. Wang [42] found that compared with the irrigation amount used for field production (390 mm), an excessive amount of mulched drip irrigation (600 mm) reduced the seed cotton yield, resulting in a decrease in irrigation water use efficiency (IWUE). Wang [42] found that compared with the irrigation amount used for field production (390 mm), when the irrigation amount was 600 mm, the seed cotton yield was reduced, resulting in a decrease in WUE. Zhang [20] found that when the irrigation level was reduced by 10%, the grain yield and economic return did not change significantly, but the evapotranspiration decreased and the WUE increased (4.61–6.66%). The appropriate irrigation amount (540 mm) could obtain a higher WUE level (average: 3.08 $kg \cdot m^{-3}$). Our conclusion is that appropriate irrigation quotas lead to higher WUE levels [43,44]. In our study, the IWUE of maize at irrigation quotas showed a "single peak curve", and its variation was negatively correlated with irrigation level. The effects were the most obvious at the quotas of 540 mm (T3); the highest IWUE of T3 reached 3.18 $kg \cdot m^{-3}$. Drip irrigation, dense planting, and plastic film mulching are effective ways to change the surface resistance, reduce soil evaporation, save water, increase production, and improve WUE. Thus, an appropriate irrigation quota guarantees a high maize yield and improves WUE, resource conservation, and environmentally friendly agricultural development.

The results of this study were obtained under the same soil texture, planting pattern, maize variety, and drip irrigation belt conditions. Further research is needed under other test conditions.

5. Conclusions

(1) From the comparative field observation experiment on four kinds of irrigation quotas under drip irrigation conditions, conducted for 9 consecutive years, it can be considered that the growth, yield, and irrigation WUE of maize are closely related to the irrigation quota. With the increase in irrigation quotas, the growth, yield, and irrigation water use efficiency of maize first increased, but then decreased.
(2) Based on the analysis of each index, the growth index, dry matter accumulation, yields, and WUE with T3 were the highest. In comparison to T1, T2, and T4, the yield of T3 increased by 32.17%, 13.54%, and 11.27%, respectively, and the WUE increased by 16.56%, 6.49%, and 23.70%, respectively.
(3) The significant correlations established between the maize yield and irrigation quotas could be simulated by Kuznets-style relation. When the irrigation quota (x) was 539.12 mm, the maize yield (y) was 16,043.92 kg·hm^{-2}. Hence, optimizing the irrigation quota (540 mm) can effectively improve maize growth, yield, and water use efficiency under drip irrigation in the northwest region of China. In the future, the amount and duration of irrigation should be further optimized in the proposed planting methods, in order to further save water and increase efficiency.

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