Article

Optimal Irrigation Levels can Improve Maize Growth, Yield, and Irrigation 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 present extensively applied to increase crop yield and water use efficiency in Xinjiang, northwest China. To investigate the effects of irrigation quota on maize growth, the grain yield, and the irrigation water use efficiency (IWUE), a field experiment with four irrigation quotas (T1 4200$m^3 \cdot hm^{-2}$, T2 4800$m^3 \cdot hm^{-2}$, T3 5400$m^3 \cdot hm^{-2}$ and T4 6000$m^3 \cdot hm^{-2}$.) were conducted from 2013 to 2021 in Xinjiang China. The results showed significant changes in maize growth, yield, and irrigation water use efficiency in response to different irrigation quotas. The plant height, leaf area index, SPAD, biomass, 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 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 irrigation water use efficiency (IWUE) increased by 2.80%, 0.93% and 23.63% respectively. The significant correlations established between the maize yield and irrigation quotas could be simulated by kuznets-style relation. The maize yield was negative correlated with irrigation quotas, When the irrigation quota (x) was 5376.73$m^3 \cdot hm^{-2}$, the maize yield (y) was 15841.00$m^3 \cdot hm^{-2}$. These results demonstrate that the optimized irrigation quota (5400$m^3 \cdot hm^{-2}$ treatment) can effectively improve the growth, yield and irrigation water use efficiency of drip irrigation maize in Northwest China. In the meanwhile, it can provide theoretical reference and data support for the optimal irrigation amount of drip irrigation maize in Northwest Xinjiang.

Keywords: drip irrigation; maize; irrigation quotas; biomass; yield; irrigation water use efficiency

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 water deficit markedly inhibits maize growth and yield. Since the 1970s, climatic change and economic growth have

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resulted in a decrease rapidly in water [3]. Water resources shortage is a common problem in agriculture production world-wide and is 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 total water consumption in northwest China [6]. Water shortages have affected agricultural production in northwest China [7]. With stimulating demand for water resources, the efficient use of water resources is being emphasized [8]. How to make economic and effective use of water resources and implement reasonable irrigation measures are the core issues of agricultural production. Therefore, it is imperative to optimize irrigation in arid and semi-arid areas to improve unit water yield. Drip irrigation technology is a new type of surface irrigation technology to adapt to the development of water-saving agriculture [9]. As a trade-off, optimizing irrigation use to reduce the amount of irrigation to improve 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 made effective yield increasing and water saving effects [13]. Reasonable irrigation quota can save agricultural water while achieving high yield [14]. When the irrigation quota is too high, the respiration of maize roots will be limited and the physiological progress will be affected [15]. When the irrigation quota is too low, it cannot meet the 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 drip irrigation quota 540m^3·hm^{-2} can improve irrigation water use efficiency without significantly reducing crop yield of cotton in north Xinjiang. Han [19] optimized the maize irrigation system in Heihe River Basin based on the Aqua Crop-RS model, that study found compared with full irrigation, irrigation quota decreased by 0-657mm, water use efficiency increased by 4.13%-5.13%, and water use efficiency increased by 69%-91%. Sefer [20] found that under the yield level of 10370kg·hm^{-2}, the maize yield increased with the increase of irrigation quota. Tang [21] studies showed that the yield of maize increased with the increase of irrigation quota, but when the irrigation quota exceeded 6000m^3·hm^{-2}, the yield did not increase significantly in the southern region of Xinjiang.

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

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2. Materials and Methods

A field experiment was conducted investigation experiment of whole growth stages of maize from 2013 to 2021 in experimental station for crop water use of ministry of agriculture 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 452.80m, an average annual temperature of 22.46 ℃ and the average annual evaporation is 1942mm. The maximum/minimum temperatures and monthly effective rainfall for the growth season in nine years during the maize growth periods are shown in Fig.1. According to the FAO/UNESCO system, the soil type is a calcaric fluviso [25]. The physicochemical properties of the soil were similar in nine years (Table 1).

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

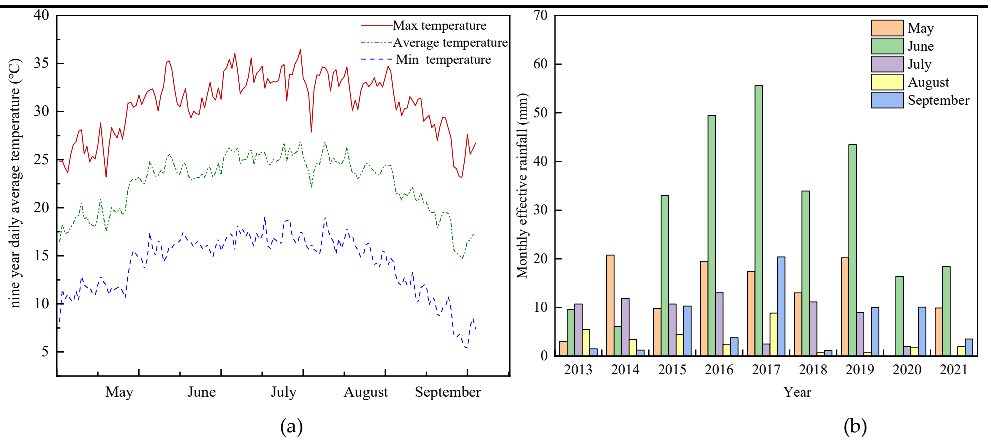

Figure 1. Meteorological variation during maize growth periods from 2013 to 2021. (a) Daily average temperature. (b) Monthly effective rainfall.

2.2. Experimental Design

Conducted through a completely randomized design, the experiment comprised of four irrigation quotas (T1 4200$m^3{\cdot}hm^{-2}$, T2 4800$m^3{\cdot}hm^{-2}$, T3 5400$m^3{\cdot}hm^{-2}$ and T4 6000$m^3{\cdot}hm^{-2}$), which refer to the local farmer irrigation quantity. Considering the marginal effect of different irrigation quotas, the 12 plots were separated from adjacent plots by 2.2m-wide isolation strips, and the size of each plot(110m^2) was 20m long and 5.5m wide. In each plot, water reading meter and fertilizer tank were installed to monitor the amount of irrigation water and fertilizer N P K applied, respectively. Fertilization was carried out with irrigation and all treatments kept the same management, which was started 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 is shown in Table 2.

Sowing dates were 8th May,2013, 5th May,2014, 2nd May,2015, 30th April,2016, 7th May,2017, 28th April, 2018, 30th April, 2019, 26th April,2020, 7th May, 2021. Harvest dates

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were 20th September,2013, 22nd September,2014, 25th September,2015, 24th September,2016, 28th September,2017, 27th September,2018, 22nd September,2019, 1st October,2020, 24th September, 2021. A joint planter was used to lay drip tapes, film and sow. Its planting density was $1.26\times10^5/hm^2$ in the experimental. 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 14.4cm. respectively (Fig.2, the spacing between the drip tapes was 110cm).

Table 2. 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 ($m^3\cdot hm^{-2}$)	T1	136.4	536.4	536.4	536.4	536.4	536.4	509.1	454.5	418.0	4200.0
	T2	163.6	600.0	600.0	600.0	600.0	600.0	600.0	563.6	472.8	4800.0
	T3	163.7	690.9	690.9	690.9	690.9	690.9	654.5	581.8	545.5	5400.0
	T4	191.0	754.5	745.5	754.5	745.5	754.5	754.5	700.0	600.0	6000.0
Fertilizer amount ($kg\cdot hm^{-2}$)	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

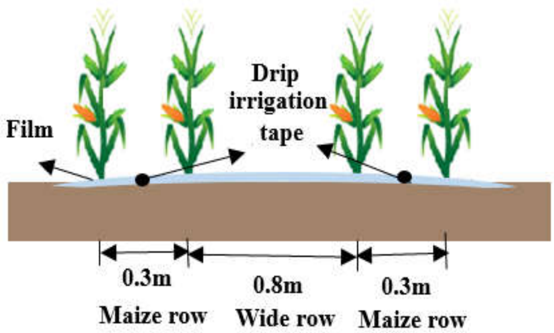

Figure 2. Schematic diagram of cultivation mode for maize.

2.3. Material

The tested maize Zhengdan958 was bred by Henan academy of agricultural sciences. Urea (N≥46.4%, granules) used in the experiment was produced by Xinlianxin Co, Ltd. (Xinjiang, China). Monoammonium phosphate (N≥12%, P_2O_5≥61%, powder) is produced by Guizhou Kai Phosphorus Group Co., Ltd. (Guiyang, China). Potassium sulfate is produced by Luobupo Potassium Salt Co., Ltd. (Xinjiang, China). Type of drip irrigation belt was a single-wing labyrinth drip irrigation belt produced by Xinjiang Tianye company (Shihezi, China). The wall thickness was 0.18mm, the inner diameter was 16mm, the drip hole spacing was 300mm, the rated flow was $2.0L\cdot h^{-1}$, and the working pressure was 0.1-0.15MPa.

2.4. Sampling and Measurements

2.4.1. Stand Growth Index

Plant height [26]: Ten maize plants with the same 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 with a tape.

Leaf area index (LAI) [27]: Ten plants with the same 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, multiplied by 0.75 to calculate the leaf area per plant.

LAI = Leaf area per plant × Number of maize plants per unit of land area/Unit land area

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

Dry matter determination: At the flowering and maturity 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℃ for 30min, dried to a constant weight at 75℃, and weighed and recorded on a balance with an accuracy of 0.01.

Field sampling and investigation were conducted at the flowering stage (18th July, 2013, 13th July, 2014, 15th July, 2015, 17th July, 2016, 20th July, 2017, 18th July, 2018, 14th July, 2019, 15th July, 2020, and19th July, 2021) and maturity stage (23th August, 2013, 26th August, 2014, 24th August, 2015, 25th August, 2016, 28th August, 2017, 25th August, 2018, 22nd August, 2019, 2nd September, 2020, and 27th August, 2021) of maize.

2.4.2. Grain Yield and Yield Components

At the maturity stage of maize, 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. 1000 seeds were randomly selected from the seed batches of each plot, and the weight of the seeds was weighed with an electronic balance. 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 × 126000 / 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. 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}), I is the irrigation amount of maize growth period (m^3·hm^{-2}).

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2.5. Statistical Analysis

All data were statistically analyzed using SPSS 25.0, including one-way ANOVA, 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 Parameters

3.1.1. Growth Index

Irrigation quotas significantly ($p < 0.05$) affected the maize growth index (Fig 3). With the increase of irrigation quotas, the growth indices of maize at the flowering and maturity period first increased but then decreased, and the effects were the most obvious at the quotas of 5400$m^3 \cdot hm^{-2}$(T3). In comparison to T1, T2 and T4, the plant height at flowering stage of T3 increased by 9.78%, 5.00% and 2.32%, and that at maturity period increased by 7.90%, 4.36% and 1.68% respectively. Leaf area index showed that at flowering stage, T3 treatment was 16.39% and 12.89% higher than T1 and T2, and T4 was 10.89% and 7.56% higher than T1 and T2, respectively. At maturity stage, T3 was 17.48% and 10.68% higher than T1 and T2, and T4 was 12.58% and 6.07% higher. At flowering and maturity stage, T3 resulted in 9.46% and 5.95% higher SPAD compared with T1, 4.22% and 5.78% higher SPAD compared with T2, respectively. Plant height, leaf area index, and SPAD have specific functional relationships.

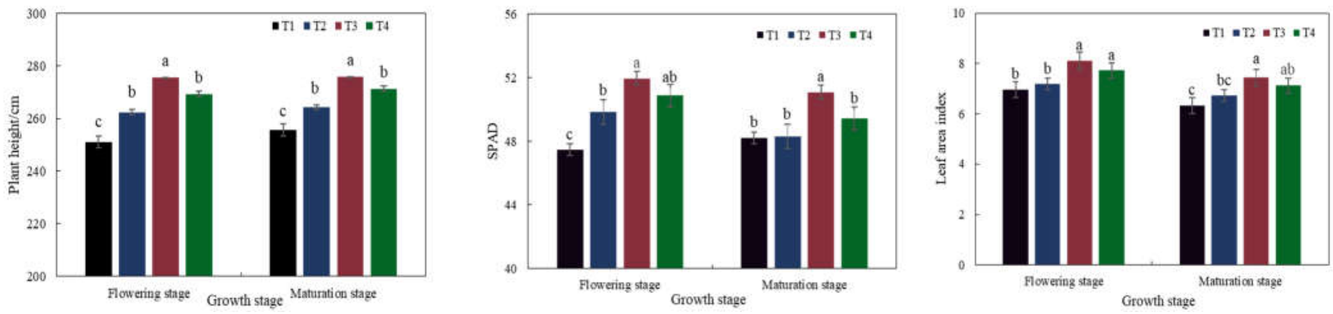

Figure 3. Effects of different irrigation quotas on plant height, SPAD and leaf area index of maize.

3.1.2. Dry matter Accumulation

Irrigation quotas significantly affected the biomass accumulation of maize at the flowering and maturity period. The leaves, stems, and reproductive organs biomass of maize at different irrigation quotas all showed a "single peak curve", and its change was closely related to the irrigation level (Fig 4). In comparison to T1, T2 and T4, the reproductive organs biomass of T3 increased by 29.91%, 16.62% and 5.26%, the stems biomass of T3 increased by 23.27%,12.68% and 7.24%, the leaves biomass of T3 increased by 25.69%, 11.21% and 8.33%, and that the total biomass increased by 16.09%, 4.47% and 45.43% at flowering stage, respectively. The reproductive organs, stem and total biomass of T3 at maturity stage were significantly higher than those of T1 and T2, and there was no significant difference between T3 and T4. The reproductive organs biomass under T3 was higher than T1 and T2 by 17.76% and 13.26%, the stem biomass increased by 23.98% and 11.71% and total biomass increased by 19.69% and 10.57%, respectively. The leaf biomass of T3 was significantly higher than other treatments, increased by 33.76%, 24.48% and 12.96%, respectively (Fig.4b). Dry matter accumulation at flowering and maturity stages of maize showed that the assimilation ability of maize to carbohydrate under T3 was stronger than that under other treatments. The irrigation quota and dry matter accumulation were fitted and analyzed. Those have specific functional relationships. The dry matter accumulation at maturity was negative correlated with irrigation quotas, $y=-0.0021x^2+23.314x-39386$, $R^2=0.9039$. When the irrigation quota (x) was 5550.95$m^3 \cdot hm^{-2}$, dry matter accumulation (y) was 25321.45$kg \cdot hm^{-2}$.

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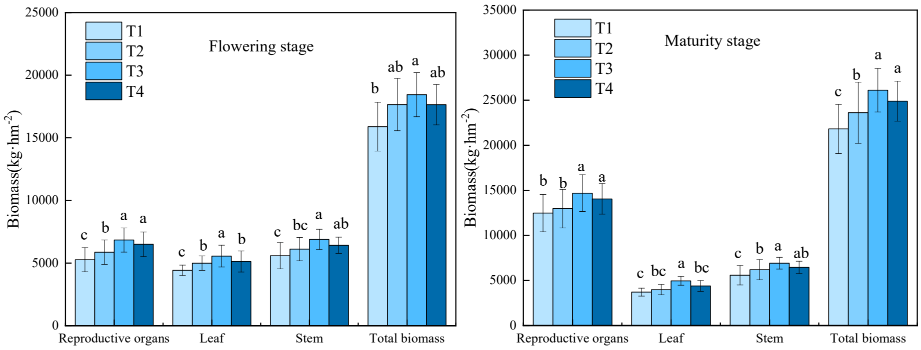

a. b

Figure 4. Biomass accumulation of maize under drip irrigation quotas. **a**. Biomass accumulation of maize at flowering stage; **b**. Biomass accumulation of maize at maturity stage.

3.2. Grain Yield and Harvest index

3.2.1. Yield and Its Components

The results in Table (3) demonstrate that, With the exceptions of row number per ear, the irrigation quotas significantly influenced the maize yield and their components. The yield and its components of maize at irrigation quotas all showed a "single peak curve", and its change was closely related to the irrigation level. Ear diameter, kernel number per row, row number per ear, thousand-kernel weight and yield. In comparison to T1, T2 and T4, the ear diameter of T3 increased by 6.80%, 4.57% and 3.01%, the kernel number per row of T3 increased by 7.52%, 4.90% and 2.93%, the thousand-kernel weight of T3 increased by 9.51%, 5.93% and 6.61%, and that the yield of T3 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 negative correlated with irrigation quotas, $y=-0.0026x^2+27.959x-59323$, $R^2=0.9222$. When the irrigation quota (x) was 5376.73m^3·hm^{-2}, the maize yield (y) was 15841.00kg·hm^{-2}.

Table 3. Yield and its 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·hm^{-2})
2013	T1	42.01±2.11b	35.26±3.69b	14.26±0.89b	322.65±23.83c	10495.01±1063.83c
	T2	43.67±4.54ab	35.87±1.83ab	14.54±0.59b	329.14±28.11bc	12841.24±987.93b
	T3	44.11±1.45a	36.52±2.22a	16.27±0.67a	346.63±31.03a	15852.10±1293.72a
	T4	43.09±3.69ab	35.90±2.81ab	14.91±1.05b	333.17±34.69b	15601.48±1168.72ab
2014	T1	43.21±1.35c	35.92±2.75ab	15.19±1.01a	319.83±25.17c	11702.33±968.15c
	T2	44.67±1.58ab	35.96±2.11ab	14.83±0.88ab	339.12±22.95b	13366.67±1473.38ab
	T3	45.94±1.29a	36.14±3.61a	15.26±0.27a	358.2±18.37a	14404.35±1185.43a
	T4	44.90±1.53ab	35.93±1.98ab	14.74±0.83ab	345.27±25.55b	12833.21±1277.49bc
2015	T1	44.30±1.97c	29.50±3.09b	12.60±0.95bc	335.58±34.03c	13916.40±2026.18b
	T2	47.22±1.34ab	33.35±1.95ab	12.80±0.98bc	365.74±29.18bc	14842.01±1567.29b
	T3	49.24±1.74a	35.24±2.49a	14.05±0.48a	393.92±21.86a	16515.66±2617.32a
	T4	48.05±3.19a	30.85±1.09b	13.65±1.00ab	337.29±17.84c	14288.22±1632.62b
2016	T1	43.42±1.36c	29.75±2.69b	13.43±0.43b	350.88±21.07b	12308.60±1178.62b
	T2	44.00±1.61bc	33.30±1.14ab	14.75±1.41a	365.43±26.76b	15511.86±1365.48b
	T3	48.55±1.75a	34.60±0.75a	14.90±0.50a	376.14±33.57a	16843.50±1634.13a
	T4	45.50±0.43b	33.05±2.83ab	14.60±0.86a	354.94±72.73b	15063.40±1549.37b

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2017	T1	46.18±2.04b	31.90±2.14c	14.65±0.61a	324.00±27.39c	12831.30±1375.19bc
	T2	46.66±1.59ab	34.05±1.47ab	14.71±0.88a	330.50±37.18b	14236.02±1467.28b
	T3	47.01±1.38a	34.75±1.64a	14.90±0.64a	345.75±31.29a	16739.75±1275.74a
	T4	47.97±1.04a	35.45±0.94a	13.90±0.48ab	325.75±35.44bc	14877.88±1128.48b
2018	T1	46.51±1.78b	32.10±1.89b	14.00±0.86a	325.425±19.91b	12622.08±1022.43b
	T2	46.85±2.73b	32.45±2.25b	14.30±0.50a	322.2±15.62b	15041.43±1793.74b
	T3	49.00±3.49a	35.65±3.85a	14.30±0.30a	347.225±36.72a	16320.98±1317.82a
	T4	44.85±1.17c	34.45±3.51ab	13.80±0.77a	324.475±14.55b	15788.32±1082.73ab
2019	T1	43.57±0.11a	34.75±1.94b	16.42±0.93b	323.50±41.75b	12315.23±1367.05b
	T2	43.55±0.08a	33.05±1.52ab	16.11±0.36b	329.25±40.56a	13164.46±1506.54b
	T3	43.64±0.19a	35.90±2.62a	25.25±0.72a	326.00±29.86a	16408.04±1480.95a
	T4	43.47±0.08a	33.35±2.94ab	15.84±1.03b	323.25±16.07b	13866.91±2277.41b
2020	T1	42.83±1.88c	31.05±1.59a	14.7±0.38a	329.14±39.01c	13818.51±700.42c
	T2	43.51±0.99bc	31.40±0.21a	14.80±0.53a	333.73±33.29bc	15775.93±2026.60bc
	T3	49.55±1.54a	31.30±0.90a	14.93±1.10a	369.91±59.09a	18800.32±1653.87a
	T4	47.82±1.06ab	32.80±0.73a	14.91±0.82a	346.58±30.21b	16053.01±2651.63b
2021	T1	43.63±0.45b	30.55±0.60b	13.78±0.37a	329.50±26.34c	12827.10±1446.74b
	T2	43.98±1.83b	30.33±2.09b	13.85±0.13a	340.00±19.05b	16565.66±1056.69b
	T3	45.52±0.83a	32.53±2.09a	14.02±0.13a	372.50±16.40a	17247.86±614.30a
	T4	44.54±1.96b	31.93±1.73ab	13.95±0.51a	344.75±16.33b	15658.92±1971.10b
Mean	T1	43.96±1.45c	32.31±2.26c	14.34±0.71b	328.95±28.72c	12537.40±1238.73c
	T2	44.90±1.81bc	33.31±1.62bc	14.52±0.70ab	339.46±28.08b	14593.92±1471.44b
	T3	46.95±34.74a	34.74±2.24a	15.99±0.53a	359.59±30.91a	16570.28±1452.59a
	T4	45.58±33.75b	33.75±2.06ab	14.48±0.82ab	337.28±29.27bc	14892.37±1637.73b

3.2.2. Harvest Index

The results in Table (4) demonstrate that the irrigation quotas significantly influenced the biomass transfer and related indicators. With the increase of irrigation quotas, dry matter transport and correlative indicators of maize first increased but then decreased, and the effects were the most obvious at the quotas of 5400m^{3}·hm^{-2}(T3). The dry matter translocation of T3 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 higher than that of T1 and T2 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, which was more beneficial to improve maize yield.

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Table 4. 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	15890.05±1738.37c	21814.93±1188.26c	6569.02±1555.33c	53.43±22.60c	40.00±20.44c	60.10±14.17c
T2	17657.26±1899.31bc	23613.32±1371.05b	6601.98±1200.16bc	58.63±26.12bc	48.59±22.75bc	62.73±8.59b
T3	18447.08±1107.74a	26110.00±1906.50a	7479.68±1587.54a	67.36±21.52a	51.97±16.94a	64.68±19.07a
T4	17645.46±1968.47bc	24893.06±1434.82b	6802.67±1968.47b	65.96±22.77ab	46.69±22.79bc	64.25±4.51a

3.3. Irrigation Water Use Efficiency

Irrigation water use efficiency (IWUE) is the standard for comparing the economy of agricultural water use units under different irrigation quotas (Fig.5). IWUE of maize at different irrigation quotas showed a "single peak curve", and its change was strongly associated to the irrigation levels. The effects were the most obvious at the quotas of 5400m^3·hm^{-2}(T3). In comparison to T1, T2 and T3, the IWUE of T4 reduced by 20.27%, 22.50% and 23.63%, respectively. In comparison to T1, T2 and T4, the IWUE of T3 increased by 2.80%, 0.93% and 23.63% respectively. The highest IWUE of T3 reached 3.07 kg·hm^{-2}. IWUE of maize was lower when the irrigation water was too high, and T3 improved the IWUE of maize compared with other treatments, which exerted its effect of water saving. The IWUE was negative correlated with irrigation quotas, $y=-4e^{-7}x^2+0.0043x-7.2394$, $R^2=0.9249$. When the irrigation quota (x) was 5375.00m^3·hm^{-2}, the maize IWUE (y) was 2.72kg·m^{-3}.

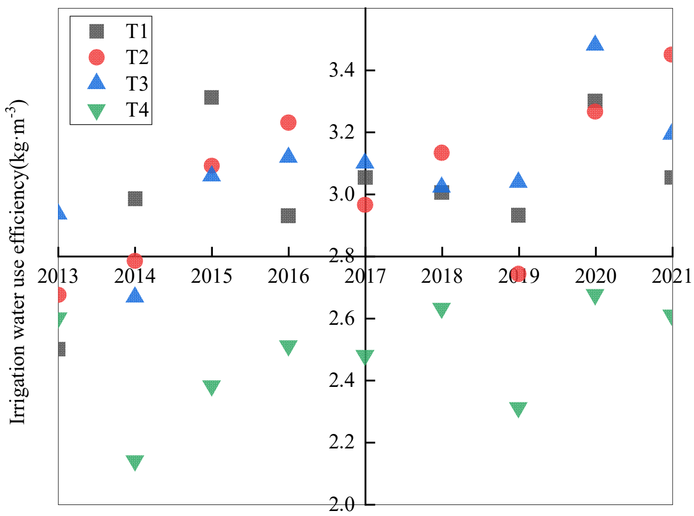

Figure 5. IWUE of drip irrigated maize under different irrigation quotas.

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 [32]. Irrigation is a key factor in agricultural development. Appropriate irrigation water quota ensures high crop yield, resource conservation and environment-friendly agricultural development [33]. 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 continuous increase in irrigation amount on growth index is greatly weakened [34]. Fang [35] found that in the arid oasis farming system, water-saving irrigation (medium and low irrigation treatments) reduced maize yield by 12.0-28.0% compared with full irrigation of different soils. You [36] found that the plant height and yield components of winter wheat increased with the increase of annual irrigation quotas. However, Jia [37] demonstrated that applying deficit irrigation (375m^3·ha^{-1}) at the flowering stage (IF) of plants grown under a medium planting density (M:75000plants·ha^{-1}) (MIF) RFRH system can increase biomass and grain yield. Ma [38] found that the maximum and average dry matter accumulation rates in maize plants increased as irrigation quota increased from 3000 to 3750m^3·hm^{-2}, when the irrigation quota was increased to 4500m^3·hm^{-2}, the maximum dry matter growth rate, the maximum average dry matter growth rate, and yield of maize were all decreased with the increase of irrigation quantity, which is consistent with our results. This study showed that proper irrigation can continuously increase the growth index, biomass accumulation and yield. However, with the continuous increase of irrigation quota, the growth, dry matter accumulation and yield of maize decreased. Those studies were done in arid region [38] and concluded 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 [39]. The inconsistency between irrigation optimal irrigation quota be due to differences in factors such as soil type, maize variety and climatic conditions.

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

IWUE 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 high IWUE of crops [40]. Water-saving measures are widely considered to improve the utilization efficiency of water resources and further alleviate the crisis of water shortage, especially in arid areas. The development of drip irrigation technique has enriched the agricultural measures of water-saving irrigation. It can directly supply water for 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 IWUE, and limited irrigation may lead to higher IWUE and lower field-scale ET. Hence, optimizing the irrigation schedule is an important measure to improve the yield and WUE. Wang [41] found that compared with the irrigation amount of field production (390mm), an excessive amount of irrigation (600mm) reduced the seed cotton yield of mulched drip irrigation, resulting in the decrease of irrigation water use efficiency (IWUE). Zhang [42] found that when the irrigation level was reduced by 10%, the grain yield and economic return did not change significantly, while the evapotranspiration decreased and the WUE increased (4.61%-6.66%). The appropriate irrigation amount (540mm) could obtain higher WUE (average 2.62kg·m^{-3}). Our conclusion is that appropriate irrigation quotas lead to higher WUE [43-44]. In our study, the irrigation water utilization efficiency of maize at irrigation quotas showed a “single peak curve”, and its variation was positively correlated with irrigation level, and the effects were the most obvious at the quotas of 5400m^3·hm^{-2}(T3), the highest IWUE of T3 reached 3.07 kg·hm^{-2}. Compared with previous studies, we obtained higher IWUE. The main reason for this result is that we used irrigation water use efficiency (IWUE) rather than water use efficiency (WUE). From 2013 to 2021, the average precipitation in the whole maize growing season (May to September) was 60.27 mm, if rainfall was considered, WUE was 2.76kg·hm^{-2}, which is consistent with previous results [42]. Drip-irrigation, dense planting, plastic film mulching are effective ways to change surface resistance, reduce soil evaporation, save water, increase production, and improve IWUE. Thus, an appropriate of irrigation quotas guarantees high maize yield, improve IWUE, resource conservation and environmentally friendly agricultural development.

5. Conclusions

Through the field comparative observation experiment of four kinds of irrigation quota under drip irrigation condition for 9 consecutive years, it is considered that the growth, yield and irrigation water use efficiency of maize are closely related to the irrigation quota. With the increase of irrigation quotas, the growth, yield, and irrigation water use efficiency of maize first increased but then decreased. Based on the analysis of each index, the growth index, biomass accumulation, yields and irrigation water use efficiency 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, the irrigation water use efficiency (IWUE) increased by 2.80%, 0.93% and 23.63%, the water consumption per millimetre of $1hm^2$ increased by 0.83kg, 0.28kg and 5.86kg, respectively. The significant correlations established between the maize yield and irrigation quotas could be simulated by kuznets-style relation. When the irrigation quota (x) was $5376.73m^3 \cdot hm^{-2}$, the maize yield (y) was $15841.00m^3 \cdot hm^{-2}$. Hence optimizing the irrigation quota ($5400m^3 \cdot hm^{-2}$ treatment) can effectively improve maize growth, yield, and water use efficiency under drip irrigation in the northwest region. In the future, the amount of irrigation and irrigation time should be further optimized in the proposed planting methods to further save water and increase efficiency.

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