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Optimizing Planting Density to Increase Maize Yield and Water Use Efficiency and Economic Return in the Arid Region of Northwest China

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Abstract: High grain yield and water use efficiency (WUE) are the key goals when producing maize (*Zea mays* L.) under irrigation in arid areas. Increasing the planting density and optimizing irrigation are important agronomic practices for increasing the maize grain yield and WUE. A two-year field experiment was conducted to investigate the effects of planting density and irrigation on the maize grain yield, WUE, and economic return of spring maize under a mulch drip irrigation system in Xinjiang, Northwest China. The experiment included four irrigation levels and five planting densities. The results showed that the reduction of irrigation decreased the yield and evapotranspiration (ET_c) but improved the WUE. Increasing the planting density increased the ET_c, but there was a quadratic curve relationship between yield and WUE and planting density. Treatment with 600 mm of water and 12 plants m^{-2} obtained the highest grain yield (21.0–21.2 t ha^{-1}) and economic return (3036.0 USD ha^{-1}) and a relatively high WUE (2.64–2.70 kg kg^{-1}). Therefore, a reasonable increase in planting density and an appropriate reduction of irrigation combined with drip irrigation under a mulch system can simultaneously achieve high yields and economic return and high WUE in maize production.

Keywords: maize; grain yield; water use efficiency; evapotranspiration; economic return

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Citation: Zhang, G.; Shen, D.; Ming, B.; Xie, R.; Hou, P.; Xue, J.; Wang, K.; Li, S. Optimizing Planting Density to Increase Maize Yield and Water Use Efficiency and Economic Return in the Arid Region of Northwest China. *Agriculture* **2022**, *12*, 1322. https://doi.org/10.3390/agriculture12091322

Academic Editor: Mercè Llugany

Received: 18 July 2022
Accepted: 25 August 2022
Published: 27 August 2022

1. Introduction

As the global population is increasing and is expected to reach more than 9 billion by 2050, global food demand will continue to increase and could result in severe food shortages [1,2]. With the acceleration of urbanization, the area of cultivated land is decreasing. Only a continuous increase in the grain yield per unit area of the existing agricultural land can meet the rapid growth of food consumption demand. Maize (*Zea mays* L.) is one of the most important grain crops around the globe and plays an important role in ensuring food security [3]. Therefore, the high and stable yield of maize has become the key to ensuring food security.

Irrigation is an important way to improve crop yields and ensure food security. Currently, irrigated agricultural land accounts for 20% of the total global agriculture land use but provides 40% of the total global food supply [4]. Water security is the basis for food security, and a scarcity of water resources leads to variable grain production, which is considered to be the source of severe food crises [5]. However, conserving irrigation water and increasing water use efficiency (WUE) are effective methods for sustainable agricultural development [6]. Furthermore, improving WUE has become a critical factor in balancing water shortages and maintaining high and stable agricultural yields [7].

WUE can be improved by increasing the yield per unit of water consumed or by reducing the amount of water consumed per unit of grain produced [5]. Studies have shown that reducing water consumption by optimizing irrigation, irrigation frequency, and deficit irrigation further improves the WUE of maize [8–11]. In addition, studies have shown that mulching with plastic film or straw can also save water and improve the efficiency of water production [12,13]. Previous studies pursued water savings to improve WUE without considering synergistic improvements in maize yield [14,15]. However, producing higher maize yields with limited water may be a new way to further improve WUE.

Increasing the planting density can increase the interception of light by the crop canopy, canopy productivity, dry matter accumulation, and grain yield within a certain range and is one of the most straightforward ways to increase maize yield [16–19]. A study showed that maize yield could be increased by 5.59% across China if the planting density was increased by 25% in China [20], and research showed that the contribution of plant density to maize yield gain ranges from 8.5% to 17.0% [21]. However, high-density hybrid maize tends to consume more soil water to achieve higher grain yield [22]. Increasing the plant density has been found to increase the consumption of water [23]. More irrigation may be required to obtain high yields. Thus, it is possible that the plant density affects WUE [24]. However, few studies have reported the effects of different maize plant densities on WUE.

As one of the major agricultural countries of the world, with the largest population, China feeds 20–22% of the world's population using only 7% of the world's arable land, and the available water supply per person is 25% of the world's per capita average [2]. Food supply must be increased by 30% by 2030 to meet the demand from a growing population [5]. However, the land and water resources that are the foundation of food production are limited, and food security is under double the amount of pressure. Maize is planted over the largest area and has the highest yield per unit area in China. Maize has a relatively high requirement for water, which causes regions with inadequate supplies of water to develop efficient water management practices to maximize yield and ecological and economic benefits. In arid regions where water resources are extremely scarce, such as Xinjiang in Northwest China, government departments have issued agricultural water restriction policies. The process of effectively improving the yield and WUE of maize under limited irrigation is a major problem that needs to be solved. Therefore, the objectives of this study were (1) to determine the effects of irrigation levels and planting densities on grain yield, WUE, and economic returns of spring maize under mulch drip irrigation and (2) to establish a method to determine the optimal irrigation level and planting density by quantifying the response of maize grain yield, WUE, and economic returns to achieve a trade-off between an increase in maize yield and a decrease in WUE.

2. Materials and Methods

2.1. Experimental Region and Site

Field experiments were conducted in 2016 and 2017 at the Qitai Farm Experimental Station of the Chinese Academy of Agricultural Sciences (43°50′ N, 89°46′ E, altitude: 1020 m) in Xinjiang, China. The region is characterized by a typical, temperate, arid climate, minimal rainfall, and abundant sunshine, and it has a large diurnal temperature range. From 2008 to 2017, the annual mean accumulated solar radiation was 1648 MJ m^{-2}; the total precipitation was 144.5 mm; the evaporation was 2176 mm; the frost-free period was approximately 181 d; and the mean temperature was 18.5 °C during the maize growing season. The total precipitation was 208.2 and 166.0 mm during the maize growing season in 2016 and 2017, respectively. The daily reference ET_o was determined using the FAO Penman–Monteith method [25]. The meteorological data were obtained from the meteorological stations nearby. Figure 1 shows the average air temperature, precipitation, and reference evapotranspiration (ET_o) during the whole duration of the maize growing period in 2016 and 2017.

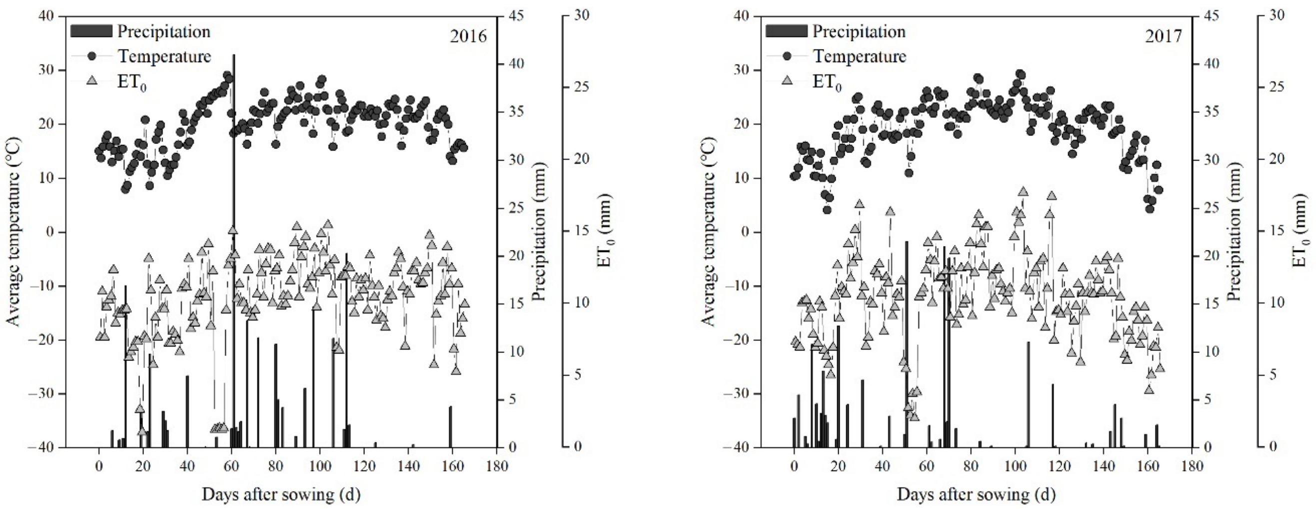


Figure 1. Precipitation, average air temperature, and reference evapotranspiration during the maize growing season.

The soil texture was sandy loam [8]. The soil profile contained 14.9 g kg^{-1} total organic matter, 72.5 mg kg^{-1} alkaline N, 49.7 mg kg^{-1} Olsen P, and 99.7 mg kg^{-1} available K. In the 0–120 cm soil profile, the average bulk density was 1.32 g cm^{-3}, the average field capacity was 30.2% (cm^3 cm^{-3}), and the wilting point was 11.3% (cm^3 cm^{-3}). These physical and chemical properties of the soil were measured at the beginning of each field experiment.

2.2. Experiment Design and Field Management

The experiment was designed as a split-plot design with irrigation as the main plot factor and planting density as the sub-plot factor. Three irrigation levels were used in 2016: 360 mm (W1), 480 mm (W2), and 600 mm (W3). W3 was the common level of irrigation. Four irrigation levels were used in 2017: 360 mm (W1), 480 mm (W2), 600 mm (W3), and 720 mm (W4). The four planting densities in 2016 were 7.5 plants m^{-2} (D1), 10.5 plants m^{-2} (D3), 12.0 plants m^{-2} (D4), and 13.5 plants m^{-2} (D5). D1 was the planting density used by the local farmers. Five planting densities were included in 2017: 7.5 plants m^{-2} (D1), 9.0 plants m^{-2} (D2), 10.5 plants m^{-2} (D3), 12.0 plants m^{-2} (D4), and 13.5 plants m^{-2} (D5). Xianyu335 (XY335), a maize hybrid that is widely planted in China, was used in both experimental years. Plants were seeded in alternating wide and narrow rows (alternating row widths of 70 and 40 cm, respectively) [6,7]. The area of each plot was 66 m^2 (10 m long and 6.6 m wide), and each type of plot had three replicates. Water movement between the plots was prevented by waterproof membranes, which were used to partition the plots vertically and by 1 m wide buffer zones between the plots.

Maize was sown on 18 April and 21 April in 2016 and 2017, respectively, and harvested on 18 October in both 2016 and 2017. A joint planter was used to lay drip tapes and plastic film before the seeds were sown. According to the plant spacing of different planting densities, maize precision seeders (ACME-BZQ; ACME, Shandong, China) were used to manually sow the seeds to an average depth of 3.0 cm. Seeds were planted along each row and covered with 2.0 cm thin soil [7]. The transparent plastic film (Tianye, Inc., Xinjiang, China) was 70 cm wide and 0.01 mm thick and used in both years. Irrigation and fertilization were performed using an integrated water-fertilizer system under drip irrigation under plastic film in both years. The irrigation water was supplied by underground water. The drip irrigation system included single-wing labyrinth drip tape (Tianye, Inc.) placed in the middle of each narrow row. The dripper spacing was 30 cm, and the flow rate was 3.2 L h^{-1} at an operating pressure of 0.1 MPa. A high-precision water meter (LXS-32F; Ningbo Water Meter Inc., Ningbo, China), pressure meter, and control valves were installed in each plot to ensure accurate discharge and stable pressure. All the experimental plots were irrigated with 15 mm of water after sowing to ensure uniform and rapid germination.

No irrigation was applied to the hardened seedlings for the first 60 days after sowing. Single water applications of 38.33, 51.67, 65.0, and 78.33 mm were applied to the W1, W2, W3, and W4 treatments, respectively, at 9–10 d intervals throughout the whole irrigation period for a total of nine applications. In both years, 69 kg ha^{-1} of N, 99 kg ha^{-1} of P, and 37.5 kg ha^{-1} of K were applied before sowing. An additional 276 kg N ha^{-1} was applied during the whole irrigation period. All the weeds, diseases, and pests in the experimental plots were controlled.

2.3. Sampling and Measurements

After maize physiological maturity, 5 m long sections of the middle four rows of maize in each plot were manually harvested. The total numbers of plants and ears were counted. Twenty ears were collected from the middle four rows in each plot, and the number of kernels was counted on each ear. The grain yield and kernel weight were expressed at 14% moisture.

The ET_c was calculated by means of the soil water balance [6,8]:

$$ET_c = I + P + Cr - Rf - Dp \pm \Delta S \quad (1)$$

where I (mm) is irrigation; P (mm) is precipitation; Cr (mm) is capillary rise; Rf (mm) is runoff; Dp (mm) is percolation; and ΔS (mm) is the change in soil water storage. Cr was zero because the groundwater table was 80 m below the soil surface. Rf was also assumed to be insignificant because the field was flat, and Dp was considered negligible because the soil water content below 120–140 cm did not reach field capacity on any sampling date.

The soil moisture content (SMC) was measured in 20 cm thick soil layers (0–120 cm deep) using the oven-drying method and a time-domain reflector (TDR; TRIME-T3, IMKO, GmbH, Ettlingen, Germany). Three 150 cm long TDR tubes were deployed under the drip tape in each plot after sowing.

WUE was calculated using the following equation [6]:

$$WUE = Y/ET_c \quad (2)$$

where Y is the grain yield (kg ha^{-1}), and ET_c (mm) is the evapotranspiration for the entire growing season.

The economic return (NR) was assessed as follows:

$$\text{Economic return (USD ha}^{-1}) = G_b - S_c - I_c - O_c \quad (3)$$

$$G_b = Y \times P_{gy} \quad (4)$$

$$S_c = \text{Planting density} \times P_s \quad (5)$$

$$I_c = \text{Irrigation amount} \times P_{we} \quad (6)$$

where G_b is the grain yield benefit; P_{gy} is maize price, 0.241 USD kg^{-1}; S_c is the seed cost, P_s is seed price, 0.001704 USD $grain^{-1}$; I_c is the water electricity cost, P_{we} is the water electricity price, 0.071 USD m^{-3}; and O_c is other inputs, including the machinery operating cost, 593.2 USD ha^{-1}, plastic mulch cost, 86.9 USD ha^{-1}, agricultural insurance cost, 75.8 USD ha^{-1}, irrigation equipment cost, 268 USD ha^{-1}, fertilizer cost, 347.2 USD ha^{-1}, pesticide cost, 21.3 USD ha^{-1}, and labor cost, 5.1 USD ha^{-1}. The exchange rate between RMB and USD was 0.142.

2.4. Statistical Analysis

Data calculation was performed in Microsoft Excel 2019 (Redmond, WA, USA). A two-way analysis of variance (ANOVA) was used to test for differences in harvested ear, kernel no. per ear, 1000-kernel weight, and grain yield as a function of irrigation and planting density. Multiple comparisons were made using Tukey–Kramer tests at $p < 0.05$. Regression analysis was performed with SPSS 21.0 (SPSS Inc., Chicago, IL, USA) to determine the relationship between yield and irrigation and planting density and WUE and irrigation and planting density. The figures were plotted in SigmaPlot 12.5 (Systat Software, Inc., San Jose, CA, USA).

3. Results

3.1. Grain Yield and Yield Components

The grain yield increased as the irrigation level increased (Table 1). However, there was no significant difference in grain yield between W3 and W4. The increase in irrigation did not affect the number of harvested ears, but it significantly increased the number of kernels per ear and 1000-kernel weight. However, there was no significant difference in the number of kernels per ear and 1000-kernel weight between W3 and W4. As the planting density increased, the grain yield first increased and then decreased under different irrigation levels. Planting density had a significant effect on maize yield. The ear number increased significantly with the increase in planting density, while the kernel number per ear and 1000-grain weight decreased under different irrigation levels. In both years, at W1, planting density D3 achieved the highest yield of 18.6–18.7 t ha^{-1}; at W2, planting density D3 achieved the highest yield of 20.6–20.8 t ha^{-1}; at W3, planting density D4 achieved the highest yield of 21.0–21.2 t ha^{-1}; and, at W4, planting density D4 achieved the highest yield of 21.0 t ha^{-1}. Compared with the local production of W3D1 or W4D1, W3D4 significantly increased the maize yields by 13.7% and 13.4%, respectively. The grain yield was significantly affected by year ($p < 0.01$), irrigation ($p < 0.01$), planting density ($p < 0.01$), irrigation × planting density ($p < 0.01$), and year × irrigation × planting density ($p < 0.05$) (Table 2). The grain yield was higher in 2017 than in 2016. This difference in yield could be owing to the greater number of rainy days in 2016 and the reduction in sunshine during the grain-filling stage.

Table 1. Harvested ear, kernel no. per ear, 1000-kernel weight, and grain yield of maize under different irrigation and planting densities in 2016 and 2017.

Year	Irrigation Level	Plant Density	Harvested Ear (Plants m^{-2})	Kernel No. per Ear	1000-Kernel Weight (g)	Grain Yield (t ha^{-1})
2016	W1	D1	7.6 ^{d}	571.4 ^{a}	360.0 ^{a}	16.4 ^{d}
		D3	10.1 ^{c}	465.4 ^{b}	348.7 ^{b}	18.7 ^{a}
		D4	11.6 ^{b}	451.3 ^{b}	335.9 ^{c}	18.4 ^{b}
		D5	13.1 ^{a}	390.6 ^{c}	327.6 ^{d}	17.7 ^{c}
	W2	D1	7.5 ^{d}	621.8 ^{a}	368.9 ^{a}	18.3 ^{c}
		D3	10.1 ^{c}	510.6 ^{b}	353.4 ^{b}	20.6 ^{a}
		D4	11.6 ^{b}	493.7 ^{b}	343.3 ^{c}	20.5 ^{a}
		D5	13.1 ^{a}	475.2 ^{b}	335.8 ^{d}	20.0 ^{b}
	W3	D1	7.6 ^{d}	672.4 ^{a}	370.1 ^{a}	18.4 ^{c}
		D3	10.2 ^{c}	547.6 ^{b}	355.5 ^{b}	20.7 ^{b}
		D4	11.6 ^{b}	527.9 ^{b}	349.9 ^{c}	21.0 ^{a}
		D5	13.1 ^{a}	504.0 ^{b}	343.4 ^{d}	20.5 ^{b}

Table 1. *Cont.*

Year	Irrigation Level	Plant Density	Harvested Ear (Plants m^{-2})	Kernel No. per Ear	1000-Kernel Weight (g)	Grain Yield (t ha^{-1})
2017	W1	D1	7.5 ^{e}	626.3 ^{a}	421.5 ^{a}	16.3 ^{c}
		D2	8.8 ^{d}	576.4 ^{ab}	409.4 ^{b}	17.6 ^{b}
		D3	10.3 ^{c}	554.5 ^{b}	403.4 ^{b}	18.6 ^{a}
		D4	11.6 ^{b}	452.9 ^{c}	386.5 ^{c}	18.9 ^{a}
		D5	13.2 ^{a}	406.6 ^{c}	384.2 ^{c}	17.8 ^{b}
	W2	D1	7.5 ^{e}	665.0 ^{a}	444.0 ^{a}	18.6 ^{c}
		D2	8.9 ^{d}	612.5 ^{ab}	423.7 ^{b}	19.3 ^{b}
		D3	10.3 ^{c}	575.5 ^{b}	416.8 ^{b}	20.8 ^{a}
		D4	11.6 ^{b}	491.5 ^{c}	399.5 ^{c}	20.7 ^{a}
		D5	13.2 ^{a}	483.1 ^{c}	392.5 ^{d}	20.4 ^{a}
	W3	D1	7.5 ^{e}	675.3 ^{a}	446.3 ^{a}	18.7 ^{c}
		D2	8.9 ^{d}	644.3 ^{ab}	422.5 ^{b}	19.5 ^{b}
		D3	10.3 ^{c}	596.4 ^{b}	412.8 ^{c}	20.8 ^{a}
		D4	11.6 ^{b}	525.5 ^{c}	412.4 ^{c}	21.2 ^{a}
		D5	13.2 ^{a}	505.4 ^{c}	406.3 ^{c}	20.7 ^{a}
	W4	D1	7.5 ^{e}	666.0 ^{a}	438.5 ^{a}	18.6 ^{c}
		D2	8.8 ^{d}	639.5 ^{ab}	421.3 ^{b}	19.6 ^{b}
		D3	10.3 ^{c}	590.5 ^{b}	410.1 ^{c}	20.8 ^{a}
		D4	11.6 ^{b}	522.9 ^{c}	411.5 ^{c}	21.0 ^{a}
		D5	13.2 ^{a}	519.8 ^{c}	401.1 ^{d}	20.8 ^{a}

Note: W1, W2, W3, and W4 represent irrigation levels of 360, 480, 600, and 720 mm, respectively. D1, D2, D3, D4, and D5 represent planting densities of 7.5, 9.0, 10.5, 12.0, and 13.5 plants m^{-2}, respectively. Means within a column and for the same site followed by different letters are significantly different at $p < 0.05$.

Table 2. Levels of significance in an analysis of variance (ANOVA) for the main factors, which included irrigation level and planting density and the two-way interactions between harvested ear, kernel no. per ear, 1000-kernel weight, and grain yield.

Source of Variation	Harvested Ear	Kernel No. per Ear	1000-Kernel Weight	Grain Yield
2016				
Irrigation (W)	ns	**	**	**
Planting density (D)	**	**	**	**
D × W	ns	ns	**	**
2017				
W	ns	**	**	**
D	**	**	**	**
D × W	ns	ns	**	*
Y	**	**	**	**
Y × W	ns	ns	**	ns
Y × D	*	**	**	ns
Y × W × D	ns	ns	*	*

Note: ns, not significant; * $p < 0.05$; ** $p < 0.01$.

3.2. Evapotranspiration

Irrigation and planting density significantly affected the ET_c of maize during the growth period. The ET_c increased with the increase in irrigation and planting density (Figure 2). In both years, the ET_c in W1 decreased by 13.4–14.6%, 18.6–21.9%, and 22.4% compared with W2, W3, and W4, respectively. Compared with D1, the ET_c of D2, D3, D4, and D5 significantly increased by 1.9%, 4.8–8.2%, 6.7–9.6%, and 9.9–14.4%, respectively.

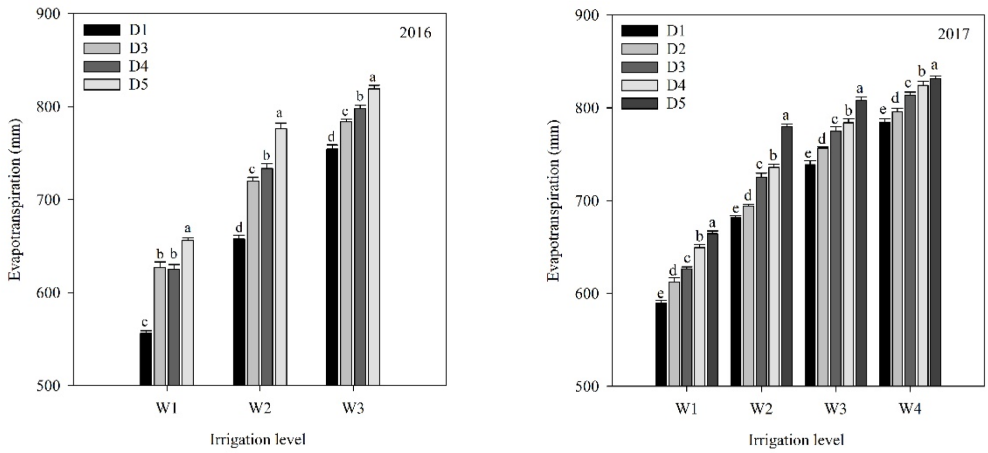


Figure 2. Changes of evapotranspiration under different irrigation levels and planting densities during the 2016 and 2017 maize growing seasons. W1, W2, W3, and W4 represent irrigation levels of 360, 480, 600, and 720 mm, respectively. D1, D2, D3, D4, and D5 represent planting densities of 7.5, 9.0, 10.5, 12.0, and 13.5 plants m^{-2}, respectively. Means within a column and for the same site followed by different letters are significantly different at $p < 0.05$.

3.3. Water Use Efficiency

In the 2016 and 2017 maize growing seasons, the WUE increased as irrigation level decreased. WUE first increased and then decreased with plant density (Figure 3). At W1, the WUE of D3 reached its maximum (2.90–2.98 kg m^{-3}). At W2, D3 obtained a high WUE (2.81–2.86 kg m^{-3}); at W3 irrigation, D3 and D4 obtained high WUE values (2.64–2.70 kg m^{-3}), and there was no significant difference between D3 and D4. At W4, D3 and D4 obtained high WUE (2.55–2.56 kg m^{-3}). This shows that, under the conditions of limited irrigation, optimal planting obtains a high WUE.

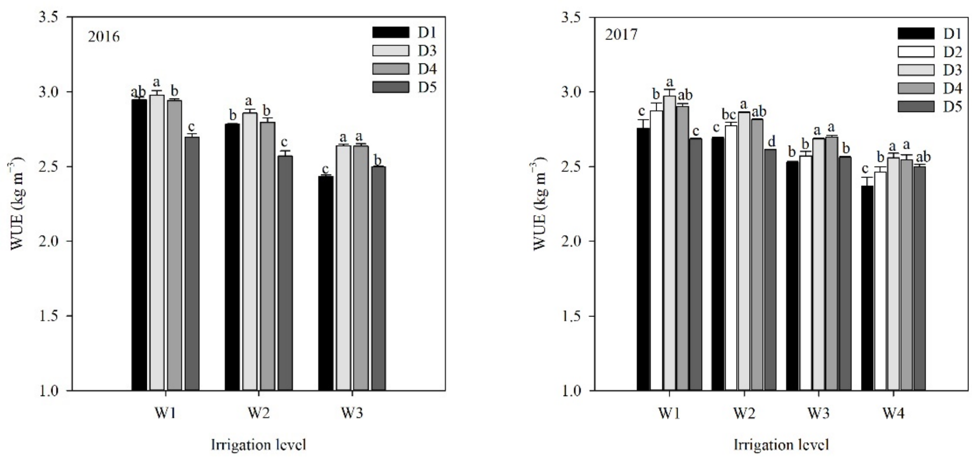


Figure 3. Changes of water use efficiency under different irrigation levels and planting densities during the 2016 and 2017 maize growing seasons. WUE, water use efficiency. W1, W2, W3, and W4 represent irrigation levels of 360, 480, 600, and 720 mm, respectively. D1, D2, D3, D4, and D5 represent planting densities of 7.5, 9.0, 10.5, 12.0, and 13.5 plants m^{-2}, respectively. Means within a column and for the same site followed by different letters are significantly different at $p < 0.05$.

3.4. Economic Return

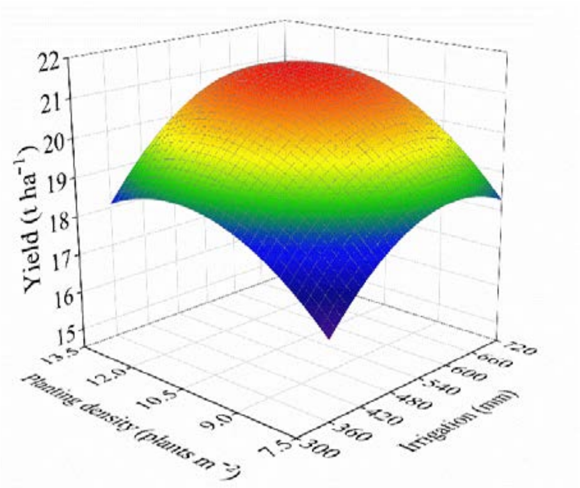
Irrigation and planting density primarily affected seed, water, and electricity costs (Table 3). During the two years, the total cost increased with increasing irrigation and planting density owing to water and seed costs. Economic returns first increased and then decreased with plant density. Maximized total income, total cost, and economic return were achieved at W3D4.

Table 3. Economic returns of maize under different irrigation and planting densities.

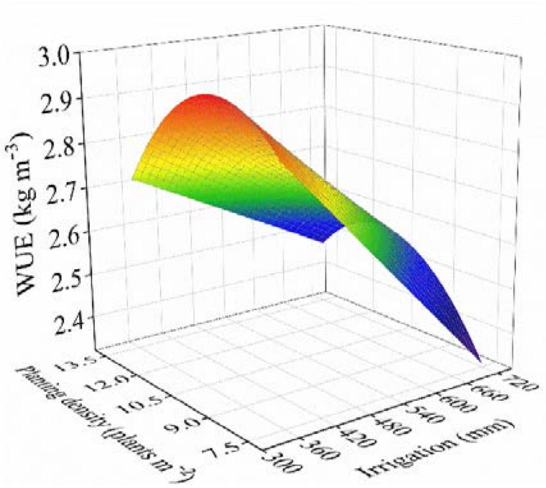
Irrigation	Density	Seed Cost (USD ha^{-1})	Water Cost (USD ha^{-1})	Total Cost (USD ha^{-1})	Total Income (USD ha^{-1})	Economic Return (USD ha^{-1})
W1	D1	127.8	255.6	1810.9	3942.6	2131.7
	D2	153.4	255.6	1836.5	4246.3	2409.8
	D3	178.9	255.6	1862.0	4502.1	2640.1
	D4	204.5	255.6	1887.6	4497.1	2609.5
	D5	230.0	255.6	1913.2	4288.2	2375.0
W2	D1	127.8	340.8	1896.1	4454.3	2558.1
	D2	153.4	340.8	1921.7	4650.1	2728.4
	D3	178.9	340.8	1947.2	4990.3	3043.0
	D4	204.5	340.8	1972.8	4975.0	3002.2
	D5	230.0	340.8	1998.4	4869.4	2871.0
W3	D1	127.8	426.0	1981.3	4470.3	2489.0
	D2	153.4	426.0	2006.9	4698.4	2691.5
	D3	178.9	426.0	2032.4	5006.9	2974.5
	D4	204.5	426.0	2058.0	5094.0	3036.0
	D5	230.0	426.0	2083.6	4968.5	2885.0
W4	D1	127.8	511.2	2066.5	4487.6	2421.1
	D2	153.4	511.2	2092.1	4732.1	2640.0
	D3	178.9	511.2	2117.6	5028.7	2911.1
	D4	204.5	511.2	2143.2	5064.5	2921.3
	D5	230.0	511.2	2168.8	5011.8	2843.1

3.5. Evaluation of Optimized Irrigation and Planting Density

Irrigation and planting density significantly affected the grain yield and WUE of maize (Figure 4). To determine the optimum irrigation and planting density, a regression analysis was performed for maize grain yield (Figure 4a). The predicted maximum grain yield was 21.2 t ha^{-1} (635.1 mm and 11.9 plants m^{-2}). In addition, these calculations that evaluated WUE established the relationship between irrigation and planting density and WUE (Figure 4b). The relationship between irrigation and planting density and grain yield and WUE is highly significant ($p < 0.01$) (Table 4).



(**a**) Grain yield



(**b**) WUE

Figure 4. Relationship between grain yield (**a**) and water use efficiency (**b**) of maize under different irrigation and planting density treatments. WUE, water use efficiency.

Table 4. Regression equations for the response variables of grain yield and water use efficiency (WUE) of maize under different irrigation and planting density treatments.

Response Variable	Regression Equation	R^2
Grain yield (t ha^{-1})	$Z_{Yield} = -3.437 \times 10^{-5}x^2 - 0.1302y^2 + 0.03929x + 2.869y + 3.667 \times 10^{-4}xy - 8.344$	0.961 **
WUE (kg m^{-3})	$Z_{WUE} = 1.389 \times 10^{-7}x^2 - 0.01976y^2 - 0.002751x - 0.336y + 1.417 \times 10^{-4}xy + 2.061$	0.964 **

Note: x represents the planting density; and y represents the irrigation level. ** $p < 0.01$.

4. Discussion

4.1. Effect of Irrigation and Planting Density on Maize Yield

Irrigation and increases in planting density are important agronomic practices for increasing the maize grain yield. Previous studies showed that irrigation affects the yield by affecting the growth, kernel number per ear, or kernel weight of maize [26–28]. However, planting density can improve the population quality and productivity by coordinating the relationship between individual plants and the population. Since the planting density increases the number of harvested ears and the kernel number per ear, the 1000-kernel weight decreases [17,29]. However, grain yield has been found to exhibit a quadratic response to plant density, and there is an optimum plant density [7,29,30]. We found similar results. However, most of these studies only considered the single factor of irrigation level or planting density and ignored the interaction between them. Our results show that the optimal planting density varies under different irrigation levels, i.e., in an arid area, where light, fertilizer, and other management practices are the same, the improvement of the optimum planting density of maize depends on the availability of water. In this study, W3D4 obtained the highest grain yield (21.0–21.2 t ha^{-1}), while W3D4 did not differ significantly from W4D4 and W4D5 and was higher than W3D5. This shows that the most suitable planting density required for this variety to achieve maximum yields was D4, which provided satisfactory amounts of irrigation water. Compared with the local production of W3D1 or W4D1, W3D4 significantly increased the maize yields by 13.7% and 13.4%, respectively. As a result, the increased planting density significantly increased the maize grain yield without any increase in irrigation water. In addition, with climate change, groundwater resources in arid areas are facing major challenges. Agricultural water limitation is an inevitable measure in the future, which raises the question of how to balance the contradiction between food production and water shortage. Our results confirm that, under limited amounts of irrigation, water-saving technology combined with the optimal planting density can effectively improve the yield of maize and improve the water production efficiency. This may be an effective way to solve the contradiction between water shortage and food production in the future.

4.2. Effect of Irrigation and Planting Density on Evapotranspiration and Water Use Efficiency

Irrigation and planting density are important factors that affect the ET_c of maize. Previous studies showed that high irrigation results in high ET_c and that there is a positive correlation between them [6,11,31]. The ET_c increased when the planting density improved from D1 to D5 under the same level of irrigation. Other studies also found that ET_c increases in response to planting density [23,32]. However, the relationship between maize yield and planting density is a quadratic curve, which indicates that there is a most suitable planting density under the same irrigation amount. If the planting density is too high, the yield will not be significantly increased, and the ineffective transpiration will be increased, which is not conducive to the improvement of water production efficiency. Therefore, in an area of limited irrigation in arid areas, matching a reasonable planting density is conducive to the coordinated improvement of maize yield and water production efficiency. In addition, in this study, W3D4 and W4D4 were compared and reduced the amount of irrigation while reducing ET_c, while the maize yield was not significantly reduced, thereby improving water production efficiency. Therefore, under conditions of the same planting density, optimizing the irrigation amount does not result in a significant change in maize yield. In addition, the amount of ET_c is reduced, which improves the water production efficiency of maize. In this study, W3D4 achieved high yield and water production efficiency, and there was a significant interaction between irrigation depth and planting density. There are abundant light resources in arid areas, which are conducive to increasing planting density [33]. In arid agricultural areas, the shortage of water resources is the primary factor that restricts maize production. When WUE is mainly considered, the optimal planting density can be estimated under low irrigation. WUE is higher for plants with a slight water deficit compared with well-watered plants [34]. The global average WUE per unit water depletion is 1.8 kg m^{-3} for maize [35]. In this study, the WUE of W1D3 reached its maximum (2.90–2.98 kg m^{-3}), 63.3% higher than the global average WUE. Therefore, increasing the planting density increases the WUE of maize. According to the irrigation quota combined with the drip irrigation technology under the mulch film, matching the optimal planting density can effectively improve the yield and water production efficiency of maize.

4.3. Effect of Irrigation and Planting Density on Economic Return

The economic return of maize production is affected by production management procedures, planting density, irrigation, fertilizer, the level of mechanization, and the market price of seeds, grain yield, pesticides, and maize in different years, which is a complex problem worth further discussion [6,19,36]. In this study, the economic return of maize was primarily affected by the irrigation depth and planting density. The economic return first increased and then decreased as the planting density increased under the same irrigation applications owing to changes in the total income caused by maize grain yield. The maximum economic return of 3036.0 USD ha^{-1} was achieved at W3D4, which indicates that the impact of yield on economic return is more significant than the cost of production. Therefore, under conditions of limited irrigation, water-saving irrigation technology combined with the optimal planting density can produce higher grain yields of maize, while improving water production efficiency and economic returns. Under the condition of national food surplus, it may be necessary to consider the sustainability of agriculture, especially in relation to water resources and soil quality. Long-term irrigation and high-density planting may cause soil salinization and soil fertility decline. Then, WUE can be used as the production goal, combined with the conservation tillage, to improve the quality of the soil and achieve the sustainable development of agriculture.

Grain yield and ecological and economic benefits should be comprehensively considered in maize production management [6]. Increasing the planting density can effectively improve maize yield, but it needs more irrigation water to obtain higher yields. Increasing irrigation and planting density can be used in an emergency manner to manage the food demand crisis, but, under the conditions of stable food supply and demand, it is necessary to consider the carrying capacity of the ecological environment, reduce irrigation, reasonably match planting density, improve maize yield and water production efficiency, and balance the contradiction between maize yield and water consumption. Particularly under the condition of limited irrigation in arid areas, using water-saving irrigation technology and matching the optimum planting density to improve the yield, WUE, and economic benefits of maize are effective ways to save water and increase grain yield and can result in the green and sustainable development of agriculture in arid, agricultural areas in the future. In future studies, in order to simultaneously achieve high yields and high WUE in maize, we will explore water requirement regulation in different planting densities of maize, combining irrigation with a crop population's demand for water. In addition, selecting drought resistant, high-yield, and water-efficient maize varieties combined with the optimum planting density is also a possible way to save water and increase grain in the future.

Author Contributions: Conceptualization, G.Z., K.W., R.X. and S.L.; methodology, B.M. and J.X.; software, G.Z. and D.S.; validation, B.M., R.X. and P.H.; formal analysis, B.M.; investigation, G.Z. and D.S.; resources, S.L.; data curation, G.Z. and D.S.; writing—original draft preparation, G.Z. and D.S.; writing—review and editing, G.Z. and B.M.; visualization, G.Z.; supervision, B.M.; project administration, J.X., P.H. and S.L.; funding acquisition, J.X., P.H. and S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by grants from the Agricultural Science and Technology Innovation Program (CAAS-ZDRW202004); Central Public-Interest Scientific Institution Basal Research Fund (no. Y2022XK06); and China Agriculture Research System of MOF and MARA(CARS-02).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors sincerely thank the anonymous reviewers who made valuable comments on this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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