agronomy

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Increasing Planting Density and Optimizing Irrigation to Improve Maize Yield and Water-Use Efficiency in Northeast China

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Abstract: We investigated the effects of variety, planting density, and irrigation amount on grain yield, water-use efficiency (WUE), and evapotranspiration (ETc). The trial was conducted in Tong Liao, Inner Mongolia, from 2021 to 2022, with compact variety Dika159 (DK159) and conventional variety Zhengdan958 (ZD958) as the test materials. The planting density was set to 6.0×10^4 plants/ha (D1, local farmer planting density) and 9.0×10^4 plants/ha (D2), with five irrigation levels: 450 mm (W_{450}, irrigation amount used by local farmers, CK); 360 mm (W_{360}); 270 mm (W_{270}); 180 mm (W_{180}); and 90 mm (W_{90}). The results indicate that the yield and WUE of variety DK159 increased by 7.48% and 5.00%, compared to ZD958, respectively. Increasing planting density enhanced yield by 13.32–15.57% in maize yield and 9.55–11.47% in WUE. Maize yield exhibited a trend of increasing linearly with the irrigation amount before reaching a plateau, reaching a maximum (16.62–17.39 t/ha) and high WUE (2.45–2.49 kg/m^3) with DK159-D2-W_{270}. The highest water consumption intensity occurred during the silking stage to the milk stage for different densities and varieties. The results indicate that selecting compact varieties, increasing planting density, and optimizing irrigation amount through integrated drip irrigation and water fertilizer can effectively improve maize yield and WUE.

Keywords: spring maize; varieties; planting density; irrigation; yield; water-use efficiency

Citation: Shen, D.; Wang, K.; Zhou, L.; Fang, L.; Wang, Z.; Fu, J.; Zhang, T.; Liang, Z.; Xie, R.; Ming, B.; et al. Increasing Planting Density and Optimizing Irrigation to Improve Maize Yield and Water-Use Efficiency in Northeast China. *Agronomy* **2024**, *14*, 400. https://doi.org/10.3390/agronomy14020400

Academic Editor: Ivan Francisco Garcia Tejero

Received: 12 January 2024
Revised: 8 February 2024
Accepted: 18 February 2024
Published: 19 February 2024

1. Introduction

The global population is expected to reach over nine billion by 2050, with global food demand predicted to increase steadily at the same time, and as a consequence, the world may face food shortages in the coming decades [1,2]. Under limited land and water resources at the global scale, improving the productivity of land per unit area or water crop per unit area may offer an effective approach to meet the food demand of future population increases [3]. As the largest food crop in both China and the world, high and stable maize yields are closely related to the country's food security [4]. Therefore, in the supplementary irrigation areas of Northeast China, increasing maize yield and reducing agricultural water use have become urgent agricultural issues that need to be addressed.

The impact of density on the grain varies with the genotypic variety [5,6]. This is because different varieties and densities create different canopy structures and population productivity. In particular, compact density-tolerant varieties can construct an ideal canopy structure with a high light interception rate, increase the photosynthetic area, and improve population productivity [7,8]. Planting density significantly affects maize yield [9,10], with the latter increasing with planting density [11–13]. In addition, previous research has shown that the WUE of maize initially increases and subsequently decreases with increasing planting density, and thus, increasing planting density can improve the WUE of maize [14,15].

Irrigation is an important factor affecting crop production. Particularly in irrigated agricultural areas, excessive irrigation or water stress will reduce grain yield [16–18]. Studies have shown that the ETc of maize can be reduced by mulching film and straw [19,20] or employing drip irrigation rather than flood irrigation to reduce crop ETc and increase crop yield, thus improving WUE [21]. Compared with traditional flood irrigation, the integration of drip irrigation with water and fertilizer has a marked effect on saving water and increasing production [22,23] as it facilitates the transport of water and nutrients close to the crop roots according to the water and fertilizer needs for crops via pressure pipes. Thus, water and nutrients are effectively absorbed and utilized by crops, thereby improving crop yield and realizing the efficient use of water and fertilizer.

Limited groundwater resources significantly impede agricultural development. Drip irrigation technology represents an emerging water-saving technique. Utilized by farmers primarily as a convenient method for irrigation rather than a yield-increasing water-saving technology, drip irrigation faces numerous challenges due to water scarcity issues such as irrational irrigation regime designs. Currently observed mixed varieties and low planting density contribute to the excessive consumption of irrigated water, resulting in suboptimal yield levels. Therefore, this study aims to (1) elucidate how different maize varieties, planting densities, and integrated drip irrigation affect maize yield, ETc, and WUE and (2) determine the optimal comprehensive drip irrigation system for different maize populations. The findings can provide a theoretical foundation for enhancing both maize productivity and WUE and aid in formulating improved irrigation systems for the supplementary irrigation area of Northeast China.

2. Materials and Methods

2.1. Site Description

Two years of field experiments were conducted in Qianjiadian Town, Horqin District, Tongliao City, Inner Mongolia (longitude and latitude: 43°43′ N, 122°26′ E; altitude: 174 m) from 2021 to 2022. The region belongs to a semi-arid continental monsoon climate, with an accumulated temperature $\geq$ 10 °C of 3000–3300 °C. The annual sunshine duration is 2500–2800 h, and the frost-free period is 150–169 days. Table 1 reports the rainfall, average temperature, and sunshine hours during the two-year maize growth period. The soil is sandy clay loam: sand 48.00%, clay 7.99%, and loam 44.01%. The soil organic matter content in the 0–60 cm soil layer is 23.88 g/kg, alkali hydrolyzed nitrogen is 87.50 mg/kg, available phosphorus is 6.92 mg/kg, available potassium is 196.90 mg/kg, the soil bulk density is 1.30 g/cm^3, and the field capacity is 34.13%.

Table 1. Precipitation, average temperature, and sunshine hours during the 2021–2022 maize-growth period.

Month	Precipitation (mm)		Average Temperature (°C)		Sunshine Hours (h)	
	2021	2022	2021	2022	2021	2022
May	4.8	46.4	19.5	17.2	7.4	7.6
June	28.8	168.9	21.8	21	7.8	7.6
July	105.4	75.5	25.6	24.4	7.4	7.4
August	154.6	64.9	21.4	22.1	14.3	14.3
September	32.8	10.1	16.9	17.5	12.9	12.6
Total or average	326.4	365.8	21	20.4	10	9.9

2.2. Experimental Design

The experiment adopted a split area design, with varieties as the main area, planting density, and irrigation amount as the secondary area. Dika159 (DK159, compact variety) and Zhengdan958 (ZD958, conventional variety) were adopted. The two-year planting densities were set to 6.0×10^4 plants/ha (D1, planting density of local farmers, plant spacing 27.8 cm, average row spacing 60 cm) and 9.0×10^4 plants/ha (D2, plant spacing 18.5 cm, average row spacing 60 cm). Five irrigation amounts were set, namely 450 mm (W_{450}, local farmer irrigation, CK), 360 mm (W_{360}), 270 mm (W_{270}), 180 mm (W_{180}), and 90 mm (W_{90}). The plot area was 72 m^2 (6 m $\times$ 12 m), and each plot was replicated three times.

2.3. Field Management

The planting date of the 2021 and 2022 year experiment was May 10, and the harvest date was October 10. We adopted a wide and narrow row planting (40 + 80 cm), a shallowly buried drip irrigation, and an integrated fertilization system. The shallowly buried drip irrigation belt was placed in the middle of the narrow row, furrowed, and shallowly buried at a depth of 2–4 cm. Figure 1 presents the planting mode. The drip irrigation belt was made of an internal patch drip irrigation belt, with a 30 cm spacing between drip heads, a 0.1 MPa design working pressure, Q = 2.8 L/h drip flow, and groundwater as the irrigation water. Moreover, we employed drip emergence technology. One day after seeding, 45 mm of drip water was used to promote seed germination and improve the uniformity of the maize population. Irrigation and fertilization began 54 days after seeding, and the whole growth period was irrigated seven times. A total of 270 kg/ha of pure nitrogen, 120 kg/ha of pure phosphorus (P_2O_5), 150 kg/ha of pure potassium (K_2O), and 15 kg/ha of zinc sulfate ($ZnSO_4$) were applied during the two-year growth period. Phosphorus and potassium were applied once as seed fertilizer, while 75 kg/ha of pure nitrogen was applied as seed fertilizer, and the remaining nitrogen was applied six times during the growth period. All weeds, pests, and diseases in the experimental site were effectively prevented or controlled.

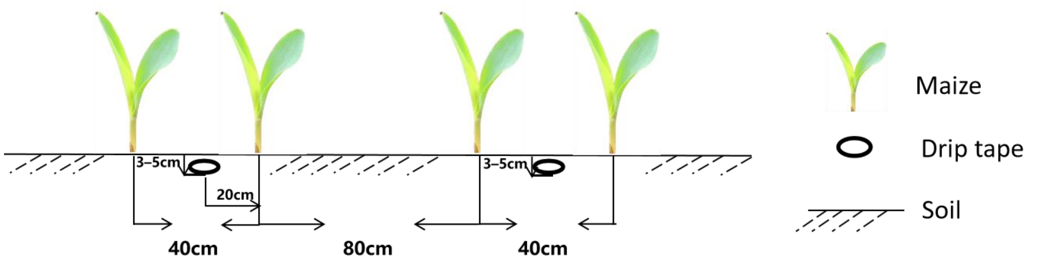

Figure 1. Relative positions of row spacing and drip tape.

2.4. Sampling and Measurements

Soil-moisture content in the 20 cm thick soil layers (0–100 cm) was measured using the oven-drying method and a time domain reflector (TDR, TRIME-T3, IMKO Micromodultechnik GmbH, Ettlingen, Germany). Three 100 cm long tubes were deployed under the drip tape in all treatments after sowing in each season. Samples were collected before sowing and physiological maturity, after rainfall, and one day before and after irrigation. Before sowing and physiological maturity, soil moisture content was measured using the oven-drying method. Record soil moisture content during the sowing (SW), 12-leaf spreading period (V12), silk spinning period (VT), milk ripening period (R3), wax ripening period (R4), and ripening period (R6), and calculate water consumption and intensity during each stage.

Maize actual evapotranspiration ETc (mm) was calculated during the growing season using the soil water balance equation as follows [13]:

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

where ETc is evapotranspiration (mm) during the growing season; I is the amount of applied irrigation water (mm); P is precipitation (mm); Cr is capillary rise (mm); Dp is percolation (mm); Rf is runoff (mm); and ΔS is the change in soil water storage (mm).

In Equation (1), Cr is considered to be zero, runoff is assumed to be insignificant as the field was flat, and Dp is also considered to be negligible because the soil water content below 100 cm did not reach field capacity on any sampling date.

In this study, daily water-consumption intensity (DWCI, mm/d) in Equation (2) and phase water-consumption coefficient (Kp) in Equation (3) were both used to identify the highest water-consumption period (water-sensitive period) of maize as follows:

$$\text{DWCI} = \text{WCp}/\text{GPd} \tag{2}$$

where WCp is the water consumption phase (mm) during a given growth period, and GPd is the duration (in days) of a given growth period.

$$\text{Kp} = \text{WCp}/\text{ETc} \times 100 \tag{3}$$

where Kp is the phase water-consumption coefficient (%) during a specific growth period, WCp is the phase water consumption (mm), and ETc is the total crop evapotranspiration (mm) during the entire growing season.

The WUE (kg/m^3) was represented as the grain yield (t/ha) per unit of ETc (mm).

Irrigation-water-use efficiency (IWUE, kg/m^3) was calculated as grain yield (t/ha) per unit of irrigation water used (mm). Equations (4)–(6) were used to calculate the WUE, IWUE, and rainfall utilization rate (PUE, kg/m^3):

$$\text{WUE} = \text{GY}/\text{ETc} \times 100 \tag{4}$$

$$\text{IWUE} = \text{GY}/\text{I} \times 100 \tag{5}$$

$$\text{PUE} = \text{GY}/\text{P} \times 100 \tag{6}$$

where GY is grain yield (t/ha), ETc is crop evapotranspiration (mm), and P is rainfall during the growth period (mm).

At physiological maturity, an area of 36 m^2 (10 m $\times$ 3.6 m) from each plot was harvested manually, and the grain mass was measured. The plants and ears were counted, and the number of ears per plant was determined. Grain moisture content was determined with a portable moisture meter (PM8188A, Taizhou Weikete Instrument Co., Ltd., Taizhou, China). Grain yield was determined at a 14% moisture content.

2.5. Statistical Analysis

Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA), SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA), and Origin 2022 (Origin Lab Corporation, Northampton, MA, USA) were adopted for the calculations of the data and the preparation of the plots, respectively. Analysis of variance was used to test for differences in yield, WUE, and ETc. Correlation analysis was performed with SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Means were compared using Fisher's least significant difference tests with $p < 0.05$.

3. Results

3.1. Grain Yield, Evapotranspiration, and Water-Use Efficiency

Yield, WUE, and ETc were affected by maize varieties, planting density, and irrigation amount (Table 2). Across the two years, the yield (WUE) of DK159 was 5.37–7.48% (5.0–5.69%) higher than that of ZD958. Furthermore, the yield (WUE) of treatment D2 was 15.89–16.90% (9.75–15.29%) higher than that of treatment D1.

Table 2. Yield, evapotranspiration, water-use efficiency, irrigation-water-use efficiency, and precipitation-use efficiency.

Year	Variety	Density	Treatments	Yield (t/ha)	ETc (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	PUE (kg/m^3)
2021	DK159	D1	W_{90}	11.16 b	485.13 e	2.51 a	5.51 a	3.44 b
			W_{180}	13.92 a	594.40 d	2.44 b	3.44 b	4.47 a
			W_{270}	13.94 a	625.03 c	2.30 c	2.29 c	4.48 a
			W_{360}	13.93 a	706.80 b	2.05 d	1.72 d	4.47 a
			W_{450}	13.91 a	788.67 a	1.84 e	1.43 e	4.47 a
		D2	W_{90}	12.20 c	494.43 e	2.54 a	6.02 a	3.77 c
			W_{180}	14.85 b	568.30 d	2.51 b	3.67 b	4.39 b
			W_{270}	17.39 a	694.23 c	2.48 c	2.86 c	5.35 a
			W_{360}	17.33 a	756.1 b	2.29 d	2.14 d	5.34 a
			W_{450}	17.33 a	796.13	2.18 e	1.71 e	5.34 a
	ZD958	D1	W_{90}	10.62 b	478.13 e	2.43 a	5.24 a	3.27 b
			W_{180}	13.17 a	557.87 d	2.36 b	3.25 b	4.07 a
			W_{270}	13.24 a	633.30 c	2.09 c	2.18 c	4.08 a
			W_{360}	13.26 a	691.80 b	1.92 d	1.64 d	4.08 a
			W_{450}	13.22 a	776.82 a	1.70 e	1.31 e	4.08 a
		D2	W_{90}	11.13 c	478.43 e	2.54 a	5.50 a	3.44 c
			W_{180}	14.2 b	564.30 d	2.47 b	3.51 b	4.29 b
			W_{270}	16.01 a	657.23 c	2.44 c	2.64 c	4.94 a
			W_{360}	16.01 a	705.10 b	2.27 d	1.98 d	4.94 a
			W_{450}	15.95 a	784.13 a	2.03 e	1.58 e	4.92 a
2022	DK159	D1	W_{90}	11.63 b	513.72 e	2.37 a	5.75 a	3.18 b
			W_{180}	13.44 a	599.88 d	2.24 b	3.32 b	3.67 a
			W_{270}	13.37 a	659.12 c	2.03 c	2.20 c	3.66 a
			W_{360}	13.41 a	695.43 b	1.96 d	1.66 d	3.66 a
			W_{450}	13.43 a	754.73 a	1.78 e	1.33 e	3.67 a
		D2	W_{90}	12.31 c	497.04 e	2.57 a	6.08 a	3.36 c
			W_{180}	14.73 b	561.23 d	2.54 b	3.54 b	3.92 b
			W_{270}	16.62 a	640.47 c	2.49 c	2.64 c	4.38 a
			W_{360}	16.67 a	728.09 b	2.30 d	1.98 d	4.39 a
			W_{450}	16.65 a	770.04	2.19 e	1.58 e	4.38 a
	ZD958	D1	W_{90}	11.22 b	501.33 e	2.23 a	5.54 a	3.08 b
			W_{180}	12.90 a	588.88 d	2.19 b	3.18 b	3.53 a
			W_{270}	13.00 a	663.82 c	1.96 c	2.14 c	3.56 a
			W_{360}	13.03 a	715.27 b	1.88 d	1.61 d	3.56 a
			W_{450}	13.00 a	765.44 a	1.70 e	1.28 e	3.56 a
		D2	W_{90}	11.89 c	472.04 e	2.47 a	5.78 a	3.12 c
			W_{180}	13.55 b	560.23 d	2.41 b	3.35 b	3.71 b
			W_{270}	15.54 a	649.47 c	2.38 c	2.56 c	4.25 a
			W_{360}	15.41 a	722.09 b	2.10 d	1.90 d	4.22 a
			W_{450}	15.47 a	774.04 a	2.00 e	1.53 e	4.23 a

Note: different letters indicate statistical differences at $p < 0.05$ within the same planting density. D1, 6.0×10^4 plants/ha; D2, 9.0×10^4 plants/ha. ETc, evapotranspiration; WUE, water-use efficiency; IWUE, irrigation-water-use efficiency; PUE, precipitation-use efficiency.

In 2021, the yields of treatments DK159-D1-W_{180} and ZD958-D1-W_{180} were higher than those of treatment W_{90} by 24.73% and 24.01%, respectively, while no significant differences were observed with those of treatments W_{270}, W_{360}, and W_{450}. In addition, the yields of DK159-D2-W_{270} and ZD958-D2-W_{270} were not significantly different from those of treatments W_{450} and W_{360} but increased by 17.10% and 42.54% compared to W_{90} and by 12.74% and 43.85% compared with W_{180}, respectively. Moreover, the WUE of DK159-D1-W_{180} and ZD958-D1-W_{180} was higher than that of W_{450} by 32.61% and 38.82%, respectively. Similarly, the WUE of DK159-D2-W_{270} and ZD958-D2-W_{270} were 20.10% and 19.68% higher than that of W_{450}, respectively.

In 2022, the yields of treatments DK159-D1-W_{180} and ZD958-D1-W_{180} were higher than those of treatment W_{90} by 15.56% and 14.97%, respectively, while no significant differences were observed with those of treatments W_{270}, W_{360}, and W_{450}. The yields of DK159-D2-W_{270} and ZD958-D2-W_{270} were not significantly different from those of treatments W_{450} and W_{360}, but increased by 12.74% and 43.85% compared to W_{90}, and by 35.01% and 30.70% compared with W_{180}, respectively. Moreover, the WUE of DK159-D1-W_{180} and ZD958-D1-W_{180} was significantly higher than that of W_{450} by 25.84% and 28.82%, respectively. Similarly, the WUE of DK159-D2-W_{270} and ZD958-D2-W_{270} were 19.14% and 13.33% higher than that of W_{450}, respectively.

ETc was observed to increase significantly with the irrigation amount during the two-year growth period, while IWUE decreased significantly as the irrigation amount increased. PUE increased with the irrigation amount, with values optimized and stabilizing for treatment W_{180} under D1 and for treatment W_{270} under D2. The results indicate that increasing the planting density of the same variety can enhance maize yield and WUE. In addition, selecting densely planted varieties with the same density can also increase maize yield and WUE, and appropriately reducing the irrigation amount can reduce ETc, increase WUE, and maintain a stable yield.

Year, variety, density, and irrigation have significant effects on maize yield, ETc, WUE, IWUE, and PUE ($p < 0.05$) (Table 3). The average grain yield (WUE) in 2021 is 2.02% (3.65%) higher than in 2022, DK159 is 6.03% (5.01%) higher than ZD958, and D2 is 16.38% (12.38%) higher than D1. The interactions between year and variety, variety and density, year and variety and density, as well as the interaction between year, variety, and irrigation amount, and the interrelationships between the four factors have a significant impact on yield, ETc, and WUE. The interaction between variety and density has no effect on IWUE and PUE. The impact of research years on maize yield and water-use efficiency may be due to different levels and stages of rainfall during the growth period. During the critical growth period of maize, long-term rainy weather can affect maize yield and water-use efficiency.

Table 3. Analysis of variance of year, variety, density, and irrigation amount on yield, water-use efficiency, evapotranspiration, irrigation-water-use efficiency, and precipitation-use efficiency.

Variation Source	Yield (t/ha)	ETc (mm)	WUE (kg/m^3)	IWUE (kg/m^3)	PUE (kg/m^3)
Year (Y)	**	**	**	**	**
Varieties (V)	**	**	**	**	**
Density (D)	**	**	**	**	**
Irrigation (I)	**	**	**	**	**
Y × V	**	**	**	**	**
Y × D	*	**	**	*	**
Y × I	**	**	**	**	**
V × D	**	**	*	ns	ns
V × I	**	**	**	**	**
D × I	**	**	**	**	**
Y × V × D	**	**	**	ns	**
Y × V × I	**	**	**	**	**
Y × D × I	**	**	**	**	**
V × D × I	**	**	**	**	**
Y × V × D × I	**	**	**	**	**

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

3.2. Correlation of Grain Yield with Evapotranspiration and Irrigation Amount

As irrigation amount and ETc increase, the grain yield follows a "linear plateau" pattern (Figures 2 and 3). The relationships between grain yield and irrigation amount and between grain yield and evapotranspiration are shown in Tables 4 and 5, respectively. In 2021, the yield was maximized at 13.24 t/ha under ZD958-D1 (182.47 mm irrigation amount and 559.39 mm ETc), at 15.99 t/ha under ZD958-D2 (234.48 mm irrigation amount and 613.31 mm ETc), at 14.07 t/ha under DK159-D1 (180.22 mm irrigation amount and 595.66 mm ETc), and at 17.35 t/ha under DK159-D2 (264.91 mm irrigation amount and 638.20 mm ETc).

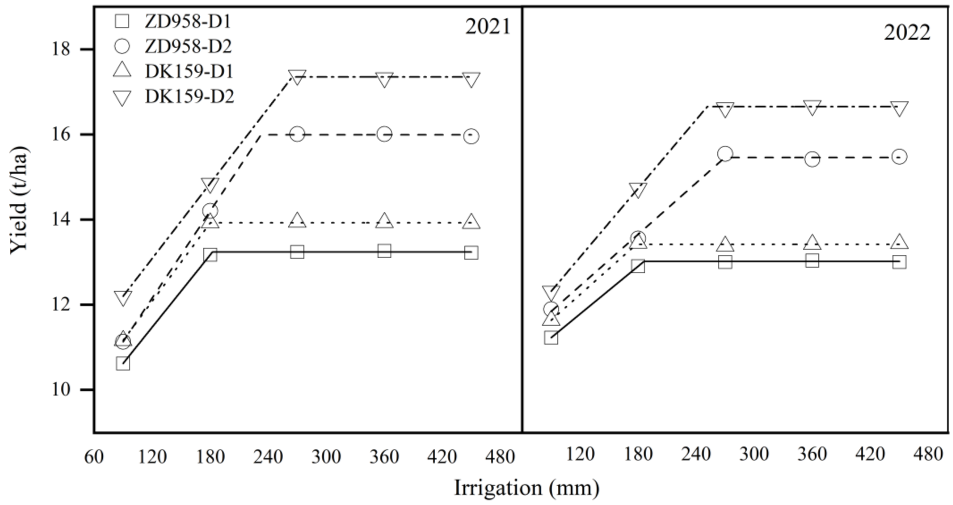

Figure 2. Relationship between maize grain yield and irrigation amount.

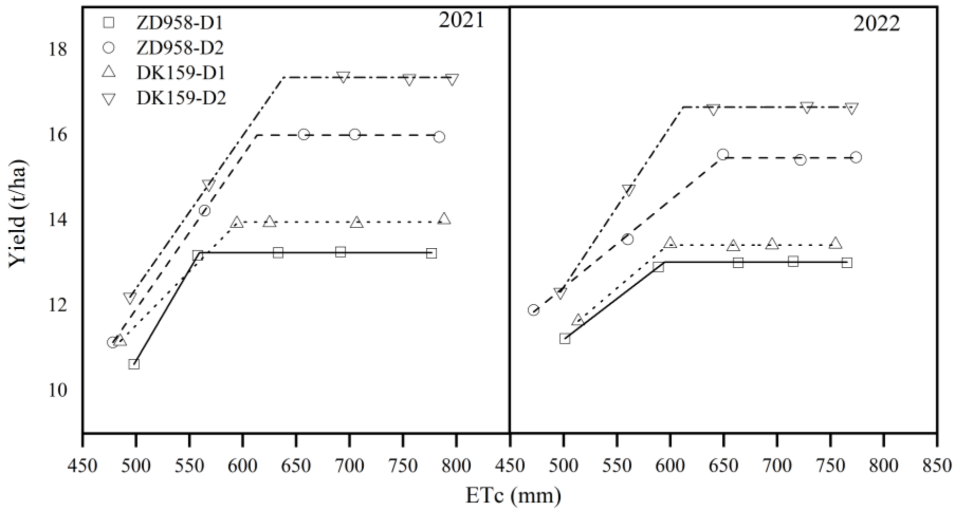

Figure 3. Relationship between maize grain yield and evapotranspiration.

Table 4. Fitting equation of the relationship between irrigation amount and maize yield.

Year	Variety	Density	Fitting Equation	Determination Coefficient R^2
2021	ZD958	D1	y = 0.067x + 8.07, x < 182.47; y = 13.24, x ≥ 182.47	0.99 **
		D2	y = 0.077x + 8.06, x < 234.48; y = 15.99, x ≥ 234.48	0.99 **
	DK159	D1	y = 0.034x + 8.40, x < 180.22; y = 13.93, x ≥ 180.22	0.99 **
		D2	y = 0.077x + 9.55, x < 264.91; y =17.35, x ≥ 264.91	0.98 **
2022	ZD958	D1	y = 0.019x + 9.54, x < 185.89; y = 13.01, x ≥ 185.89	0.99 **
		D2	y = 0.020x +10.02, x < 269.59; y = 15.45, x ≥ 269.59	0.99 **
	DK159	D1	y = 0.020x + 9.80, x < 178.04; y = 13.41, x ≥ 178.04	0.99 **
		D2	y = 0.027x + 9.89, x < 251.28; y = 16.65, x ≥ 251.28	0.91 **

Note: **, significant at $p < 0.01$.

Table 5. Fitting equation of the relationship between ETc and maize yield.

Year	Variety	Density	Fitting Equation	Determination Coefficient R^2
2021	ZD958	D1	$y = 0.043x - 10.67, x < 559.39; y = 13.24, x \geq 559.39$	0.99 **
		D2	$y = 0.036x - 6.10, x < 613.31; y = 15.99, x \geq 613.31$	0.99 **
	DK159	D1	$y = 0.025x - 1.13, x < 595.66; y = 13.96, x \geq 595.66$	0.99 **
		D2	$y = 0.036x - 5.52, x < 638.20; y = 17.35, x \geq 638.20$	0.98 **
2022	ZD958	D1	$y = 0.019x + 1.6, x < 594.61; y = 16.65, x \geq 594.61$	0.99 **
		D2	$y = 0.020x + 2.19, x < 648.62; y = 13.41, x \geq 648.62$	0.99 **
	DK159	D1	$y = 0.021x + 0.72, x < 597.60; y = 15.46, x \geq 597.60$	0.99 **
		D2	$y = 0.038x - 6.43, x < 612.07; y = 16.65, x \geq 612.07$	0.99 **

Note: **, significant at $p < 0.01$.

In 2022, the yield was maximized at 13.01 t/ha under ZD958-D1 (185.89 mm irrigation amount and 594.61 mm ETc), at 15.45 t/ha under ZD958-D2 (269.59 mm irrigation amount and 648.62 mm ETc), at 13.41 t/ha under DK159-D1 (178.04 mm irrigation amount and 597.60 mm ETc), and 16.65 t/ha under DK159-D2 (251.28 mm irrigation amount and 612.07 mm ETc). Beyond this irrigation amount, the ETc continues to increase without inducing a significant increase in yield, resulting in ineffective water consumption. Therefore, reducing irrigation amounts for different maize populations can effectively reduce ETc and improve water production efficiency.

3.3. Correlation of Water-Use Efficiency with Evapotranspiration and Irrigation Amount

The WUE of different varieties and densities decreased linearly with the increase in irrigation amount and ETc (Figures 4 and 5). The relationships between WUE and irrigation amount and between WUE and evapotranspiration are shown in Tables 6 and 7, respectively. The WUE of DK159 was higher than that of ZD958. For the same variety, the WUE of the D2 planting density exceeded that of D1. The results indicate that reducing irrigation amount to the optimal value could effectively reduce ETc during the growth period, yet the yield did not decrease significantly, thus improving the WUE. Increasing planting density also improved the WUE of maize.

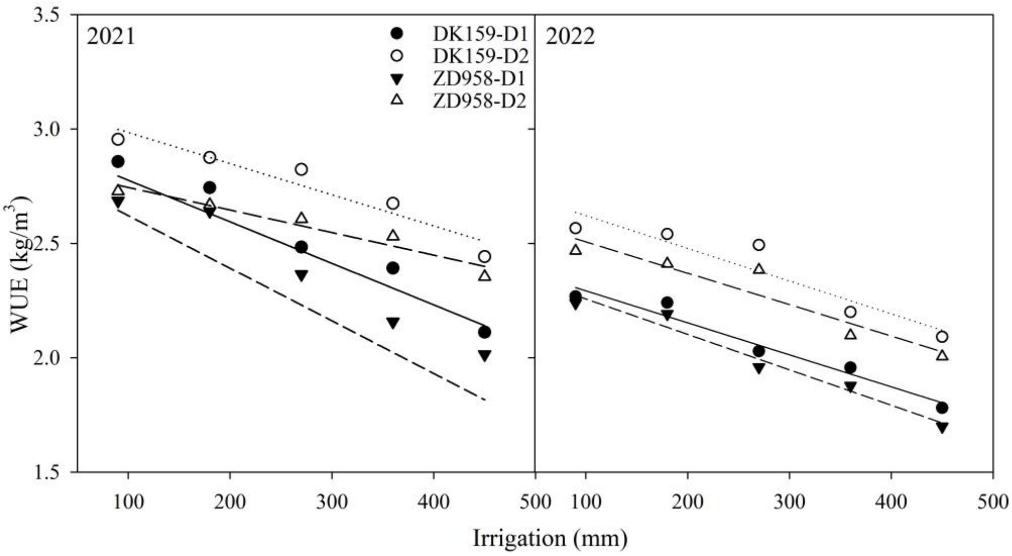

Figure 4. Relationship between water-use efficiency and irrigation amount.

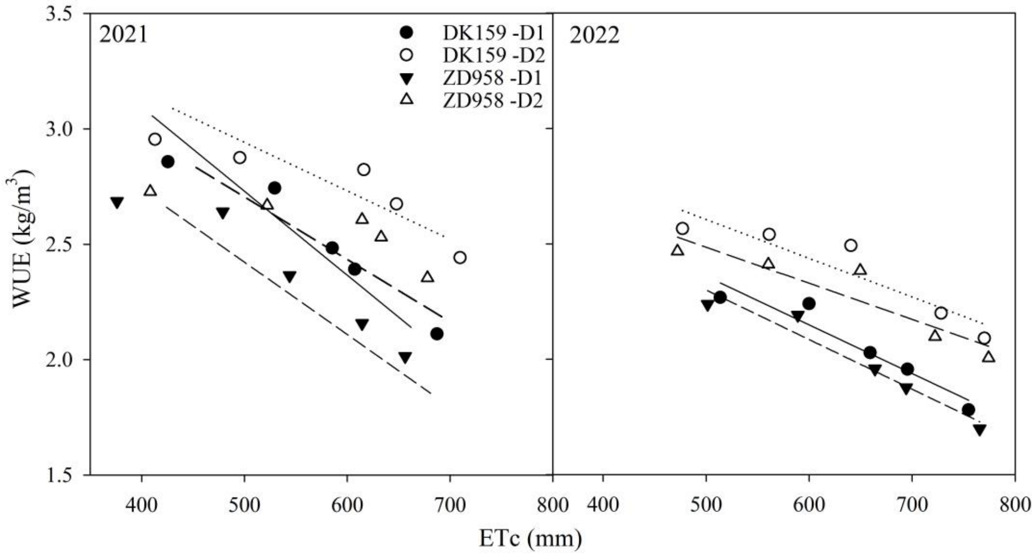

Figure 5. Relationship between water-use efficiency and evapotranspiration.

Table 6. Fitting equation of the relationship between irrigation amount and WUE.

Year	Variety	Density	Fitting Equation	Determination Coefficient R^2
2021	ZD958	D1	y = −0.001x + 2.84	0.94 **
		D2	y = −0.002x + 2.92	0.97 **
	DK159	D1	y = −0.002x + 3.12	0.92 **
		D2	y = −0.002x + 3.07	0.98 **
2022	ZD958	D1	y = −0.002x + 2.92	0.97 **
		D2	y = −0.001x + 2.84	0.94 **
	DK159	D1	y = −0.002x + 3.07	0.98 **
		D2	y = −0.002x + 3.12	0.92 **

Note: **, significant at $p < 0.01$.

Table 7. Fitting equation of the relationship between WUE and ETc.

Year	Variety	Density	Fitting Equation	Determination Coefficient R^2
2021	ZD958	D1	y = −0.003x + 3.73	0.92 **
		D2	y = −0.001x + 3.25	0.77 **
	DK159	D1	y = −0.003x + 4.18	0.94 **
		D2	y = −0.002x + 3.62	0.81 **
2022	ZD958	D1	y = −0.002x + 3.37	0.94 **
		D2	y = −0.002x + 3.27	0.85 **
	DK159	D1	y = −0.002x + 3.41	0.91 **
		D2	y = −0.002x + 3.45	0.86 **

Note: **, significant at $p < 0.01$.

3.4. Change in Daily Water Consumption Intensity

The water consumption of different varieties and planting densities increases with the increase in irrigation amount within two years (Figure 6). The daily water consumption intensity of each irrigation treatment exhibited a single peak curve with the advancement of the growth process, reaching a maximum at stage VT-R3, followed by stage V12-VT. This indicates that the VT period is key for maize water demand, and ensuring a sufficient water content before and after the VT period can ensure the normal growth of maize. In the VT-R3 stage, the water consumption intensity for the optimal irrigation amount

(180 mm) in the D1 treatment ranged from 5.72 to 6.12 mm/d, while the water consumption intensity for the optimal irrigation amount (270 mm) in the D2 treatment ranged from 6.53 to 7.14 mm/d. Under all treatments, the average daily water consumption intensity of treatment D2 was 2.16% higher than that of treatment D1. Increasing planting density also increased evapotranspiration, yet the increase in evapotranspiration was not as large as that of yield (Table 2). This further reveals that increasing planting density improved WUE.

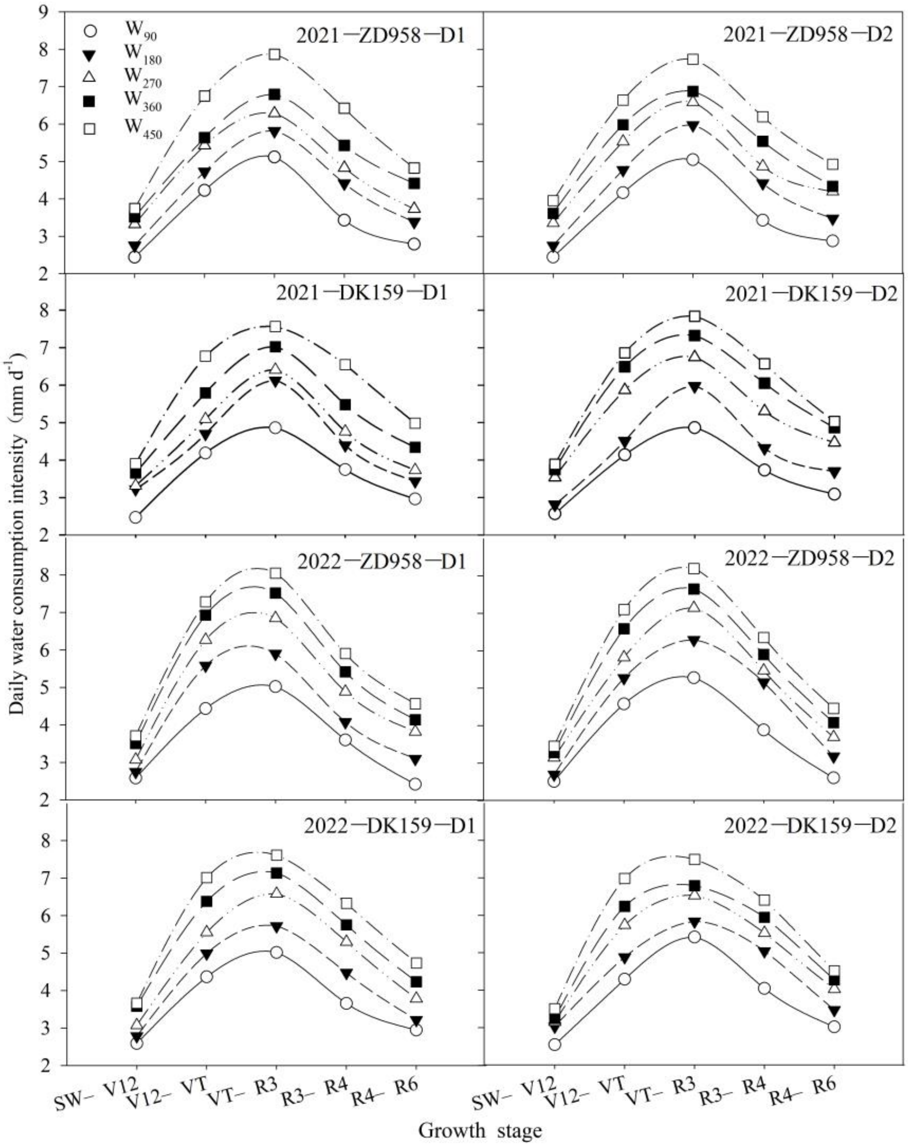

Figure 6. Daily water consumption intensity during the reproductive stage. In the *x*-axis, SW denotes sowing, V12 denotes the 12-unfolded-leaves stage, VT denotes silk emergence, R3 denotes milk ripening, R4 denotes wax ripening, and R6 denotes maturity.

3.5. Dynamics of the Phase Water-Consumption Coefficient

The two-year average Kp value of each treatment exhibited different trends across the growth period (Figure 7). We can divide the growth period into five growth stages according to the growth of maize, namely, SW–V12 (31.4133.64%), V12–VT (13.94–14.49%), VT–R3 (20.02–20.60%), R3–R4 (17.19–18.78%), and R4–R6 (14.46–15.29%). Stage SW–V12 has the highest Kp value, followed by VT–R3. This may be attributed to the different rainfall amounts and growth days in the growth stage, which affects the water consumption and subsequently impacts the Kp value.

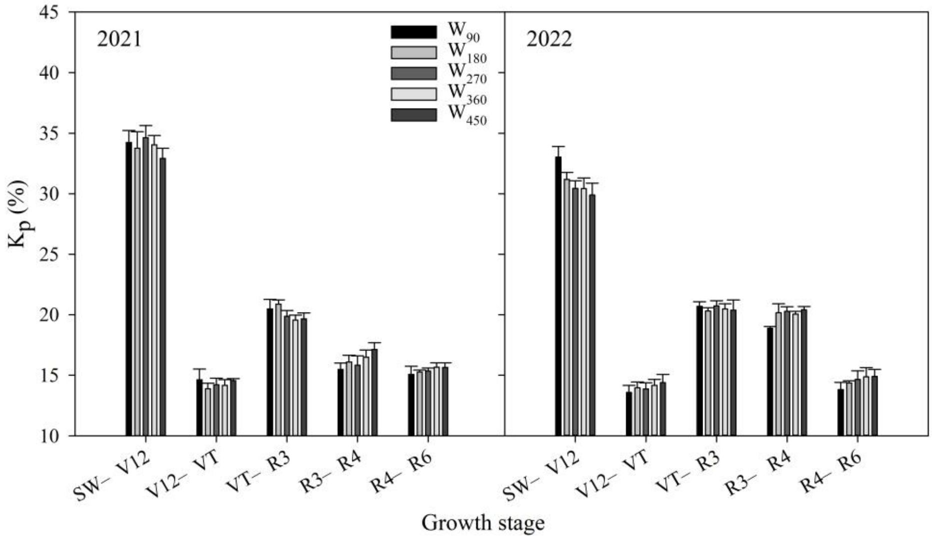

Figure 7. Dynamics of the phase water-consumption coefficient.

4. Discussion

The variety, planting density, and irrigation regime are important agricultural measures that affect crop production. Previous research has shown that optimizing agronomic measures can effectively improve crop yield and WUE [24]. In this study, under a 6.0×10^4 plants/ha density and 180 mm irrigation, the yields of ZD958 and DK159 reached 12.90–13.17 t/ha and 13.44–14.07 t/ha, respectively. Additionally, under a 9.0×10^4 plants/ha density and 270 mm irrigation, the yields of ZD958 and DK159 reached 15.54–16.01 t/ha and 16.62–17.39 t/ha. It is obvious that the yield of DK159 is higher than that of ZD958. Similarly, DK159 had higher WUE than ZD958 at the same planting density and irrigation conditions (Table 1). The main reason is due to the genetic gain in grain yield of maize varieties. Previous research revealed that the yield of variety MC670 was maximized (24.95 t/ha) under a 13.5×10^4 plants/ha high density and 600 mm irrigation in Xinjiang, China. Under the same water and fertilizer conditions, compared with other varieties, MC670 not only produced a high yield but also synergistically improved the water and fertilizer utilization efficiency [25]. Breeding makes a significant contribution to potential grain yields [26]. However, under high-density (D2) conditions, the increase in yield and WUE of DK159 was higher than that of the control variety ZD958. This difference may be linked to the plant type characteristics of maize populations. The DK159 variety is compact, while the control variety is loose. Compact varieties are more conducive to dense planting, light energy interception, and improved yield and resource utilization efficiency [27–29]. Furthermore, compared with 6.0×10^4 plants/ha, the 9.0×10^4 plants/ha plant density achieved a 14.45% higher grain yield and a 10.51% higher WUE. The yield and WUE of D2 were significantly higher than that of D1 under the same variety and irrigation conditions (Table 1), indicating that increasing planting density improved yield and WUE, which is similar to previous studies [11,13]. Previous studies have reported an increase in planting density as the most effective way to improve maize yield per unit area [13,30,31]. Moreover, under the same variety and planting density conditions, maize yield exhibited a trend of increasing linearly with the irrigation amount before reaching a plateau (Figure 2); WUE decreased with increased irrigation (Figure 4). Compared with the control irrigation of 450 mm, maize yield was not significantly reduced by appropriately reducing to 180 mm and 270 mm of irrigation for D1 and D2, respectively. While ETc declined and the WUE increased. This indicates that decreasing the irrigation amount can improve the WUE while ensuring yield. This is similar to the results obtained by previous studies [16,32,33]. This study showed that the grain yield was maximized (16.62–17.39 t/ha) at 9.0×10^4 plants/ha with a density of 270 mm irrigation with DK159. In the same ecological area, Yang et al. [34] showed that under a 7.6×10^4 plants/ha density and 210 mm irrigation, the yield of NH 101 reached

12.27 t/ha. The average yield of Yang et al. was 7.69% and 31.31% lower than the DK159-D1-W_{180} and DK159-D2-W_{270} treatments in this study, respectively. Liu et al. [11] showed that the selection of density-tolerant varieties combined with densification improved maize yield and WUE, which agrees with our results. However, the yield in this study was significantly higher than that of Liu et al., mainly due to the high planting density in this study. Therefore, the selection of an appropriate variety, density, and irrigation amount can improve the yield of maize and resource utilization efficiency.

The daily water consumption intensity of each irrigation treatment exhibited a single peak curve with the advancement of the growth process, reaching a maximum at stage VT-R3. We found that ET_a and the daily water consumption intensity increased with rising planting density. The main reason may be that ET_a is closely related to planting density and LAI [35]. Furthermore, we found that the daily water consumption intensity increases with the increase in irrigation amount, which was similar to the results of a previous study [36]. In addition, scholars have reported the water consumption mode coefficient (Kp) to vary with climate zones, reaching its maximum during the SW-V12 stage in semi-arid regions [36]. This is similar to the results of this study. We also determined the Kp value to exhibit the largest proportion in the SW–V12 stage, followed by VT–R3. Water consumption of maize is influenced by climate, variety, planting density, and irrigation amount; therefore, there are differences in the water consumption intensity of maize in different ecological regions. Therefore, according to the water demand regulation of different maize populations, irrigation according to demand can achieve high yield, reduce ineffective water consumption, and further improve water-use efficiency.

Changes in cropping practices are an effective way to increase maize yield and WUE. Previous studies have shown that in the same region, integrated drip irrigation with water and fertilizer has increased maize yield and WUE by 1.4–6.2% and 20.5–27.5%, respectively, compared to conventional flood fertilization [23]. However, in this study, the yield and WUE of DK159-D2-W270 increased by 20.6% and 54.7% compared to Yang et al.'s [23] conventional flood fertilization (planting density, 7.5 plants/m^2; irrigation amount, 450 mm) average yield (14.1 t/ha) and WUE (1.61 kg/m^3). The main reason is that this study adopted compact varieties, and increasing the planting density ensures the high yield of maize populations, while the integration of drip irrigation with water and fertilizer solves the problems of water and fertilizer supply and demand. As a consequence, the productivity of the crop population is improved, as well as the yield and water and fertilizer utilization rate. Therefore, under the integrated mode of shallow buried drip irrigation, selecting compact density-tolerant varieties and appropriately increasing planting density can improve maize yield and WUE.

5. Conclusions

In the supplementary irrigation area of Northeast China, under the condition of integrated water and fertilizer with shallow drip irrigation, maize yield exhibited a trend of increasing linearly with the irrigation amount before reaching a plateau, reaching a maximum (16.62–17.39 t/ha) and high WUE (2.45–2.49 kg/m^3) with DK159-D2-W270. Therefore, under the condition of integrated water and fertilizer with shallow drip irrigation, selecting compact varieties, increasing planting density, and optimizing irrigation amount can effectively improve maize yield and the WUE.

Author Contributions: G.Z., K.W., R.X. and S.L. conceived and designed the experiment; D.S., L.Z., L.F., Z.W., T.Z., J.F., Z.L., J.L. and X.K. performed the experiments; D.S., G.Z., B.M., P.H. and J.X. analyzed the data; D.S. wrote the paper; G.Z. and S.L. revised the final draft manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by grants from the National Natural Science Foundation of China (M2142005), the China Postdoctoral Science Foundation (2020M670547), and the Inner Mongolia Science and Technology Major Project (2021ZD0003).

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

Acknowledgments: The authors thank the reviewers for their valuable comments and suggestions.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

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