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Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China

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ABSTRACT

Maize production in arid areas of Northwest China is seriously limited by water supply. Conserving irrigation water and increasing water use efficiency (WUE) are effective methods for sustainable agricultural development. The objectives of this study were to optimize irrigation water use, grain yield, WUE, and economic return of super high yield maize in a drip irrigation and plastic film mulch system in Xinjiang. Experiments were conducted in Qitia County, Xinjiang, and included four drip irrigation treatments: T1, 600 mm (CK); T2, 540 mm; T3, 480 mm; and T4, 420 mm. Six density-tolerant maize hybrids were planted in 2014 and 2015. Grain yield and economic return did not significantly change in response to a 10% decrease in irrigation level, whereas evapotranspiration decreased and WUE increased (4.61%–6.66%). High grain yield (15.7–19.1 Mg ha^{-1}), WUE (2.47–2.77 kg m^{-3}), and economic return (1691.6–2605.7 US$ ha^{-1}) were achieved under the T2 treatment. The combined techniques of drip irrigation, plastic film mulching, and increased planting density improved yield. Quadratic relationships were found between irrigation level and grain yield and between irrigation level and economic return. Irrigation level and evapotranspiration were negatively correlated with WUE. Maximum economic return and irrigation level were linearly related with the price of water. Taking into account grain yield, economic return, and ecological effects, an irrigation amount of 540 mm is optimal for drip irrigation-–plastic film mulching systems in arid areas.

1. Introduction

Irrigated agriculture is the largest single source of fresh water use, consuming about 70%–75% of the world's freshwater. Increasing global population, demand for food, livestock feed, and biofuel coupled with global climate change are putting increasing pressure on freshwater resources (Wallace, 2000; Rosegrant et al., 2009). Water scarcity is a major factor limiting crop growth and yield in arid and semiarid agricultural areas (Bozkurt et al., 2006; Hao et al., 2015). Maize (*Zea Mays* L.) is the most widely grown crop in China, maize accounting for 35.3% of total grain production in 2012. Maize is also important for livestock feed and industrial materials. However, maize production is restricted by low yield. At present, the average yield of maize is close to 6.0 Mg ha^{-1} (Li et al., 2016) in China. Therefore, achieving high maize yield is important for ensuring food security (Li and Wang, 2008, 2009; Grassini et al., 2011). To meet the projected basic human requirements in 2020, Chinese grain production will need to exceed 550 billion kg, with maize accounting for 53.1% of total grain production. It is important to increase crop yield per unit water and land, but soil, water, climate, and other factors restrict sustainable grain production. Generally, farmers tend to use excessive amounts of irrigation water to ensure maximum yield, resulting in low WUE and economic return.

In arid regions, irrigation water is the major limiting resource for agricultural yield. Water use efficiency is an important indicator for evaluating the water-saving efficiency of irrigated field crops (Kang et al., 2000; Kiziloglu et al., 2009; Deng et al., 2006; Rudnick et al., 2016; Kang et al., 2017). In a study by Liu et al. (2011), WUE was 1.60 kg m^{-3} when grain yield reached 9.5 Mg ha^{-1}. Fan et al. (2017) reported maize yield of 6.5 t ha^{-1} corresponding to WUE of 1.24 kg m^{-3}. Low WUE is a common problem throughout the world. Howell et al. (1997) reported maize WUE ranging from 1.08 to 1.62 kg m^{-3} and yield from 13 to 14 t ha^{-1}. Yazar et al. (2009)

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reported an average WUE of 1.80 kg m^{-3} and the maximum grain yield of 10.4 t ha^{-1} for maize in Turkey. In a study by Bozkurt et al. (2011), average maize grain yield varied from 1.9 to 10.4 t ha^{-1} and the maximum WUE was 1.77 kg m^{-3}. However, few studies have evaluated the economic return in response to increased WUE. Irrigation level can affect maize growth and grain yield as number of kernels per ear or kernel weight (Gavloski et al., 1992; Cakir, 2004; Payero et al., 2009; Bozkurt et al., 2011; Karasu et al., 2015). Irrigation regimes affect evapotranspiration and maize grain yield. Some studies have suggested that maize yield is a linear function of seasonal evapotranspiration (Payero et al., 2006, 2008; Kuscu et al., 2013; Kresović et al., 2016). Therefore, reducing irrigation level and improving water use efficiency are critically important to sustainable agriculture.

Water-saving irrigation measures can influence crop growth, yield, and WUE. Many techniques have been suggested for improving the yield, WUE and economic return of maize. Some scholars have discussed various water-saving irrigation technologies for reducing agricultural water use (Bassetti and Westgate, 1993; Cakir, 2004; Hassanli et al., 2009; Payero et al., 2009). Some studies have reported using straw mulching and tillage to increase soil moisture and rainfall storage (Tao et al., 2015; Cai et al., 2015). However, these approaches reduce land use efficiency and increase labor costs.

Xinjiang Province is a typical arid-semiarid region, characterized by low rainfall and high evaporation. Irrigation water shortages limit crop production, and combining drip irrigation with plastic film mulching is therefore a developing technique in this region. This method was originally developed for the production of cotton, and it was later applied to maize and other crops. As of 2012, the technique had been applied to a total area of 204.8 million ha. In Xinjiang, the maize cultivation area increased from 50.2×10^4 ha in 2002 to 86×10^4 ha in 2012. At present, drip irrigation–plastic film mulching is widely used in maize production (Fig. 1). Drip irrigation, whereby water is frequently applied to a small area near growing plants, generally results in strong crop development while limiting soil evaporation and percolation depth (Chen et al., 2015). Drip irrigation increases crop yield and WUE compared with sprinkler and furrow irrigation (Yohannes and Tadesse, 1998; Cetin and Bilgel, 2002; Ibragimov et al., 2007; Hassanli et al., 2009). Plastic mulching is also widely used for reducing soil evaporation and enhancing yield (Zhao et al., 2016; Wu et al., 2017; Fan et al., 2017). Combining mulching with drip irrigation is a new comprehensive agricultural technology that can efficiently supply irrigation water, fertilizers, and pesticides, and has been widely studied in recent years (Qin et al., 2016; Liu et al., 2017; Tian et al., 2017). Some scholars have studied the effects of drip irrigation–plastic film mulching on crop production (e.g., cotton (Du et al., 2008; Ning et al., 2015; Tian et al., 2017), and potato (Yang et al., 2017)). However, little information on grain yield, WUE, and economic return exists for high-yield (> 15 Mg ha^{-1}) maize in similar systems of China. Over recent years, the area of high-yield (> 15 Mg ha^{-1}) spring maize has increased gradually in Northwest China (Li et al., 2015a,b; Wang et al., 2012). However, the relationship between maize grain yield and irrigation level has not been clearly defined, and WUE and economic returns typically are low for drip irrigation–plastic film mulching systems. Therefore, the objectives of this study were to (i) investigate changes in maize grain yield, WUE, and economic return in a drip irrigation–-plastic film mulching system; and (ii) to explore the optimal irrigation regime for high-yield spring maize production.

2. Materials and methods

2.1. Experiment station and description

Field experiments were conducted at Qitai Farm (Qitai, Xinjiang Province, China (Fig. 2)) during the 2014 and 2015 growing seasons. The region has a temperate arid climate. Geographical and meteorological conditions are shown in Table 1. Meteorological data for the maize growing season in 2014 and 2015 were obtained from meteorological stations located near the experimental station (Table 2). The soil at the station is light loam, and its physicochemical properties were listed in Table 3.

2.2. Experimental design and field management

A split-plot design was used with maize variety as the main plot factor and irrigation level as the sub-plot factor. Surface drip irrigation and plastic film mulching techniques were adopted. Each treatment was replicated three times. The area of each plot was 48 m^2 (length: 7.27 m, width: 6.60 m). Water movement between plots was prevented by burying waterproof membranes to a depth of 1 m below the soil surface between each plot and by setting up a wide 1-m buffer zone between plots. The planting density was 12×10^4 plants ha^{-1}. Plants were seeded in alternating wide-narrow row patterns (alternating row spaces of 70 and 40 cm, respectively). Before sowing, drip tape was applied, followed by plastic film with punch holes for seedling growth. According to the hole to play the planting. A joint planter was used to synchronize these procedures (Fig. 1). To ensure uniform planting density, maize precision planters (ACME-BZQ, ACME, China) were used to manually sow the seeds to an average depth of 5.0 cm. Seeds were planted along each row and covered with thin soil. The plastic film was transparent with a width of 70 cm and a thickness of 0.01 mm (Tianye

Fig. 1. Joint planter applying drip tape, plastic film, punch holes and sowing.

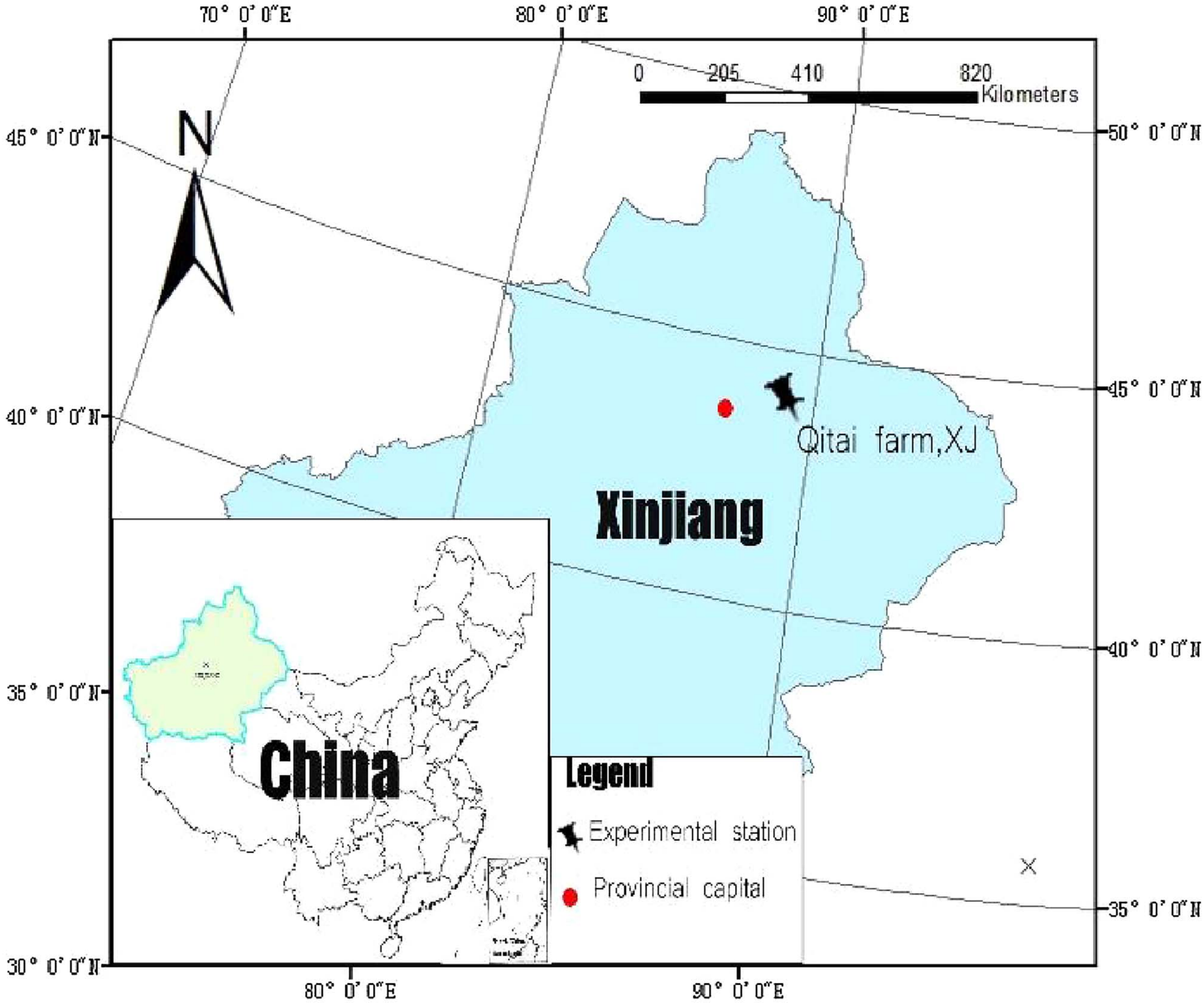

Fig. 2. Map of Xinjiang experimental station.

Table 1
Location and meteorological conditions for the experimental station.

Station	Location		Meteorological Conditions					
	North Latitude	East Longitude	Altitude (m)	Cumulative Sunshine hours (h)	≥10 °C Accumulated Temperature (°C)	Frost-free Duration (d)	Precipitation (mm)	Evaporation (mm)
Qitai	43°50′	89°46′	946.2	2841	3025.8	158	202.5	2141

Note: 16-year (2000–2015) mean values of annual meteorological variables were obtained from meteorological stations near the experimental station.

Table 2
Precipitation, average air temperature, and sunshine hours during 2014 and 2015 maize growing seasons.

Month	Precipitation (mm)			Average temperature (°C)			Sunshine hours (h)		
	2014	2015	2000–2015 average	2014	2015	2000–2015 average	2014	2015	2000–2015 average
April	40.6	18.8	19.2	9.8	11.9	10.6	7.9	9.1	8.8
May	41.4	43.9	21.5	17.2	18.8	17.1	9.8	9.2	9.7
June	43.8	76.5	18.7	21.1	20.8	21.7	9.2	9.3	10.0
July	45.6	27.4	33.1	23.2	25.2	23.0	9.1	11.0	9.6
August	30.0	57.4	25.2	22.2	22.7	21.7	9.1	10.2	9.6
September	62.0	47.4	17.1	15.4	13.9	15.6	7.5	8.3	9.0
October	12.5	10.3	13.1	8.2	8.4	7.3	7.9	7.2	7.6
Total/average	275.9	281.7	148.0	16.7	17.4	16.7	8.6	9.2	9.2

Table 3
Soil physicochemical properties (0–60 cm depth) at the experimental station.

Parameter	pH	Organic matter (g kg^{-1})	Alkaline-N (mg kg^{-1})	Olsen-P (mg kg^{-1})	Available K (mg kg^{-1})	Bulk density (g cm^{-3})	Field capacity (g g^{-1})
Average	7.9 ± 0.2	15.0 ± 0.3	46.3 ± 1.3	16.4 ± 0.8	297.6 ± 5.4	1.5 ± 0.1	0.239

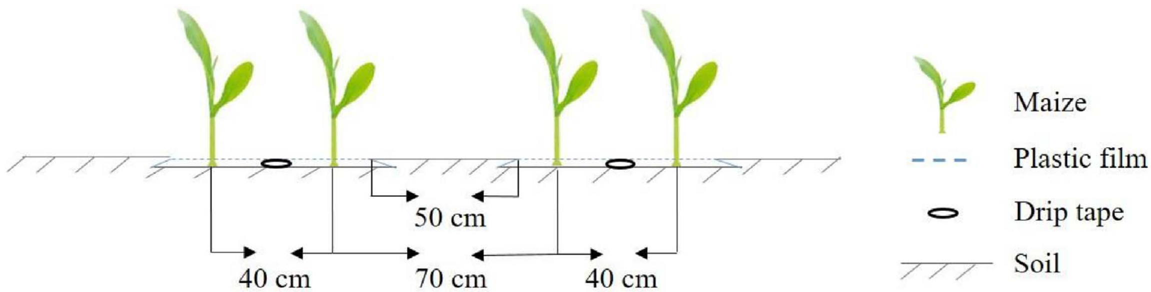

Fig. 3. Sketch showing the relative positions of row spacing, drip tape, and plastic film.

Inc., China). Rainwater could infiltrate the soil via the seedling holes or bare soil. The planting pattern was the same for both years (Fig. 3). There were six sheets of plastic film per plot, with 50 cm bare soil between each sheet. Each sheet of plastic had two rows of maize. There was 10 cm between the edge of the plastic film and the first row of maize. The spacing between rows was 40–70–40 cm, which is a commonly used pattern in this region, and the spacing between plants within a row was 15 cm. Maize was irrigated with a drip irrigation system, and irrigation water was pumped from groundwater. The drip irrigation system included single wing labyrinth drip tape 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 (Tianye Inc., China). Discharge and pressure were stable due to careful design and management. Each plot was connected to a high precision water meter (LXS-40F, Ningbo, China) and control valve. The irrigation level was determined based on the local irrigation quota. We used the local irrigation level as the control (CK), and decreased this level by 10%, 20%, and 30% to determine the reduced irrigation levels. Four irrigation levels were used in 2014 and 2015: T1, 600 mm (CK); T2, 540 mm; T3, 480 mm; and T4, 420 mm. Three local, density-tolerant maize hybrids were used in 2014: Zhongdan909 (ZD909), Liaodan565 (LD565) and Ningyu721 (NY721); and three local, high-yield, density-tolerant maize hybrids were used in 2015: Zhengdan958 (ZD958), Xianyu335 (XY335), and KWS3564 (KWS3564). All experimental maize was sown on 18 April 2014 and 14 April 2015, and harvested on 20 October 2014 and 18 October 2015. One day after sowing, all experimental plots were irrigated (60 mm). Because the surface soil moisture content (0–20 cm) was low (14.2%–14.5%) before sowing in both years, irrigation was needed after sowing to assure uniform, rapid germination. To prevent late lodging and harden seedlings, no irrigation was conducted from sowing to V10. Beginning 60 d after sowing, single water applications (60, 53.33, 46.67, and 40 mm) were applied to the T1–T4 treatments at 10 d intervals (total of nine applications). Irrigation intervals and duration were in accordance with local field management practices. Based on the chemical profile of the soil and a maximum expected yield of 18 Mg ha^{-1} (Hou et al., 2012), base fertilizers were applied at rates of 150 kg ha^{-1} N (as urea), 300 kg ha^{-1} P_2O_5 (super phosphate), and 120 kg ha^{-1} K_2O (potassium sulfate) prior to sowing. Additional urea (600 kg ha^{-1} N) was applied during the growing stage to ensure a non-limiting supply of nutrients. All weeds, diseases, and pests in the experimental plots were controlled.

2.3. Sampling and measurements

2.3.1. Evapotranspiration and water use efficiency

Soil moisture content in 20 cm soil layers (0–100 cm) was measured with the oven drying method and a Time-Domain Reflector (TDR, TRIME-T3, Germany). Samples were collected before planting and after harvest, as well as one day before and after irrigation. No runoff was observed during the experiments.

Total water consumption or actual evapotranspiration (ET_c, mm) was calculated during the growing season using the soil water balance equation (Rana and Katerji, 2000; Kresovic et al., 2016):

$$ET_c = I + P + C_r - R_f - D_p \pm \Delta S \quad (1)$$

where ET_c is evapotranspiration (mm) during the growing season, I is amount of irrigation water applied (mm), P is precipitation (mm), C_r is capillary rise (mm), D_p is percolation (mm), R_f is runoff (mm), and ΔS is change in soil moisture content (mm).

In Eq. (1), C_r was considered to be zero because the groundwater table were 70–80 m below the surface; runoff was also assumed to be insignificant because the field was flat; and D_p was considered negligible because the soil water content below 60 cm did not reach field capacity on any sampling date.

Eqs. (1) and (2) were used to determine WUE (kg m^{-3}) (Du et al., 2008; Payero et al., 2008; Kresovic et al., 2016):

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

where GY is grain yield (kg ha^{-1}), and ET_c is total actual evapotranspiration (mm) calculated from Eq. (1).

2.3.2. Grain yield

At the physiological maturity stage, an area of 8 m^2 (central four rows of each plot, 2 m long) from 3 plots was harvested manually and grain mass was measured. The total number of plants and ears were counted, and the number of ears per plant was determined. Twenty ears were collected from the middle four rows of each plot at physiological maturity. Grain per ear was counted for each ear. Grain weight was determined by drying three samples of 1000 kernels at 80 °C for 3 d to constant weight. The remaining grains were air-dried and weighed. Grain yield was expressed at 14% moisture content and used in statistical analyses and efficiency calculations.

2.3.3. Economic analysis

Economic return was assessed using the following equations:

$$\text{Economic return (US\$ ha}^{-1}) = \text{grain yield benefit (US\$ ha}^{-1}) - \text{Toal cost (US\$ ha}^{-1}) \quad (3)$$

$$\text{Grain yield benefit (US\$ ha}^{-1}) = \text{GY (kg ha}^{-1}) \times \text{maize price (US\$ kg}^{-1}) \quad (4)$$

Toal cost (US\$ ha^{-1}) = land use fee (US\$ ha^{-1}) + machinery operating cost (US\$ ha^{-1}) + irrigation equipment cost (US\$ ha^{-1}) + fertilizer cost (US\$ ha^{-1}) + pesticide cost (US\$ ha^{-1}) + seed cost (US \$ ha^{-1}) + labor cost (US\$ h^{-1}) + electricity cost ($m^3\ ha^{-1}$) + water cost ($m^3\ ha^{-1}$) (5)

$$\text{Electricity cost } (m^3\ ha^{-1}) = x\ (m^3) \times \text{electricity price (US\$ } m^{-3}) \quad (6)$$

$$\text{Water cost } (m^3\ ha^{-1}) = x\ (m^3) \times \text{WP (US\$ } m^{-3}) \quad (7)$$

Economic return estimate:

$$Y_{GY} = a\,x^2 + bx + c \quad (8)$$

$$Y_{ER} = Y_{GY} \times \text{maize price} - \text{Toal cost (US\$ } ha^{-1}) \quad (9)$$

where GY is grain yield (kg ha^{-1}), Y_{ER} is economic return (US\$ ha^{-1}), x is irrigation amount, and WP is water price. Economic return was highest when the water cost was zero. Y_{ER} was calculated based on the relationship between grain yield and irrigation level (Eq. 8). Eq. (8) was substituted into Eq. (4), and the result was substituted into Eq. (3) to obtain the relationship between water price, irrigation level, and economic return (Eq. (9)).

Note: Fixed production inputs including: Land use fee, 660.8 US \$ ha^{-1}; Machinery operating cost, 231.3 US\$ ha^{-1}; Irrigation equipment cost, 321.6 US\$ ha^{-1}; Pesticide cost, 55.1 US\$ ha^{-1}; Fertilizer cost, 338.6 US\$ ha^{-1}; Seed cost, 242.3 US\$ ha^{-1}; Maize price, 0.28 US \$ kg^{-1} (2014) and 0.25 US\$ kg^{-1} (2015); Labor cost, 2.2 US\$ h^{-1}; Electricity price, 0.03 US\$ m^{-3}; Water price, 0.04 US\$ m^{-3}.

Data required for the economic return calculation were collected from a survey of local farms during both study years.

2.4. Statistical analysis

Analysis of variance (ANOVA) was performed to test for differences in yield, WUE, and ET_c among irrigation treatments. Correlation analysis was conducted with SPSS 18.0 software to determine the relationships between grain yield and irrigation level, evapotranspiration; between water use efficiency and irrigation level, evapotranspiration; and between irrigation level and total cost, economic return. Means were compared using Fisher's least significant difference tests at $p < 0.05$ (LSD 0.05).

3. Results

3.1. Grain yield, yield components, water use efficiency, and evapotranspiration

Grain yield ranged from 16.2 to 19.4 Mg ha^{-1} (T1), 15.7 to 19.1 Mg ha^{-1} (T2), 14.2 to 18.3 Mg ha^{-1} (T3), and 14.1 to 17.6 Mg ha^{-1} (T4) over both growing seasons (Table 4). The grain yield of T1 was not significantly difference from that of T2, but both were significantly higher compared with T3 and T4. Irrigation level did not significantly impact the effective ear number. Irrigation level had a significant impact on kernel number per ear, which decreased as irrigation level was reduced. Kernel number per ear for fully irrigate maize (T1) was significantly higher compared with the other treatments. 1000-kernel weight decreased as irrigation level was reduced. The highest grain yield (19.4 Mg ha^{-1}) of all the treatments in this study was 143% higher than the average yield (8.0 Mg ha^{-1}) in Xinjiang, 224% higher than the average yield (6.0 Mg ha^{-1}) in China, and 72.8% higher than the average yield (11.3 Mg ha^{-1}) in America. The high grain yield was achieved by the chosen planting patterns for density-tolerant high-yield maize hybrids, which increased the planting density; the combination of drip irrigation–plastic film mulching; and the integrated management of water and fertilizer applied to a small area near the plant root system. The planting pattern avoided water and nutritional stress that usually occur under high planting density and improved light availability. Water use efficiency increased as irrigation level decreased, whereas evapotranspiration increased as irrigation level increased. Grain yield was not significantly reduced when irrigation level and evapotranspiration decreased by 10% (T2), but WUE significantly increased. Grain yield did not increase with ET_c, but WUE decreased as ET_c increased (Table 4). These results suggest that using high irrigation levels throughout the season increases water consumption but does not lead to higher grain yield.

3.2. Relationship between grain yield and irrigation level, evapotranspiration

The relationship between irrigation level and grain yield could be described with a quadratic curve (Fig. 4a). Grain yield did not significantly decrease under an irrigation level of 540 mm. In addition, ET_c significantly influenced grain yield. The relationship between grain yield and ET_c was quadratic over irrigation levels ranging from 420 to 600 mm (Fig. 4b). ET_c for T2 was significantly lower than that for T1, but grain yield did not significantly differ between these two treatments. However, when irrigation level was reduced to 480 mm, grain yield significantly decreased and ET_c was significantly decreased. As a result, ET_c was relatively low, but grain yield was relatively high for T2.

3.3. Relationships between water use efficiency and irrigation level, evapotranspiration

Water use efficiency significantly increased with decreasing irrigation level (Fig. 5a) and with decreasing ET_c (Fig. 5b). Therefore, decreasing irrigation and ET_c were beneficial to WUE.

3.4. Relationships between irrigation level and total cost, economic return

Total cost linearly increased with irrigation level (Fig. 6a), and the relationship between irrigation level and economic return could be described by a quadratic curve (Fig. 6b). Economic return did not significantly differ between T2 and T1; thus, a 10% reduction in irrigation amount did not significantly reduce economic return, but saved irrigation water and irrigation water costs (labor, water, and electricity costs). Considering economic return, the most reasonable irrigation level was 540 mm.

3.5. Relationships between water price and economic return

We found a linear relationship between water price and economic return (Fig. 7). Economic return was highest when the cost of water was zero for the T2 treatment. Economic return of T2 was also highest when water price increased from 0 to 4.11 US\$ mm^{-1}. Economic return of T1 was highest when water price increased from 4.11 to 4.74 US\$ mm^{-1}. The economic return for all irrigation treatments (T4, 420 mm; T3, 480 mm; T2, 540 mm and T1, 600 mm) was zero when the water price rose to 4.74, 4.57, 4.60 and 4.10 US\$, respectively.

3.6. Analysis of optimal economic return

The effect of irrigation level on maize production and economic return was investigated by analyzing the change in water price assuming all other costs remain constant. The mean value of data required for the economic return calculation was substituted into Eq. (9) to obtain the equation $Y_{ER} = -0.0155\,x^2 + (18.62 - WP)\,x - 3124.1$ (x is irrigation amount; WP is water price). The relationship between water price and irrigation level can be deduced under the condition of maximum economic return. Irrigation level and economic return decreased as the water price of increased (Fig. 8). The relationships between water price and irrigation level and economic return can be expressed as follows: $y_{irrigation} = -32.26WP + 600.7$; $y_{ER} = 16.13\ WP^2 - 600.65$

Table 4
Grain yield, yield components, crop evapotranspiration and water use efficiency of maize under different treatments in 2014 and 2015.

Years	Treatments		Ear number (10^4 ha^{-1})	Grains per ear	1000-grain weight (g)	Grain yield (Mg ha^{-1})	Water use efficiency (kg m^{-3})	Crop evapotranspiration (mm)
2014	ZD909	T4	10.8a	463.3b	307.9c	14.1b	2.61a	538.3d
		T3	10.2a	494.7ab	311.1b	14.2b	2.44b	583.9c
		T2	10.8a	496.0ab	322.5a	15.7a	2.47b	634.6b
		T1	10.3a	533.3a	323.5a	16.2a	2.40c	677.0a
	LD565	T4	11.0a	429.3b	339.0c	14.5c	2.74a	529.6d
		T3	10.9a	452.7a	354.2b	16.0b	2.69b	592.4c
		T2	11.3a	457.3a	366.1a	17.5a	2.77a	630.8b
		T1	10.7a	460.0a	357.0b	16.3b	2.29c	710.3a
	NY721	T4	10.6a	490.7b	316.7b	14.9b	2.72a	549.8d
		T3	10.2a	512.0ab	319.0b	15.2b	2.62b	580.5c
		T2	10.5a	522.7a	338.9a	16.9a	2.61b	647.9b
		T1	10.6a	528.0a	343.1a	17.4a	2.58b	673.4a
2015	ZD958	T4	11.4a	378.0b	319.6c	16.4c	2.69a	610.0d
		T3	11.4a	435.9a	341.4b	17.8b	2.68ab	662.6c
		T2	11.2a	460.6a	340.3b	19.0a	2.67b	709.5b
		T1	11.5a	489.8a	350.8a	19.0a	2.57c	739.2a
	XY335	T4	11.8a	414.0b	293.5d	16.4c	2.71b	605.6d
		T3	11.3a	425.0b	317.8c	18.3b	2.78a	656.2c
		T2	11.4a	468.2ab	365.1b	19.1a	2.71b	707.0b
		T1	11.0a	515.2a	385.0a	19.4a	2.53c	767.0a
	KWS3564	T4	11.5a	410.4c	318.0c	17.6c	2.93a	601.2d
		T3	11.3a	471.0bc	337.5b	18.2b	2.84b	641.4c
		T2	11.5a	513.5ab	346.9a	19.0a	2.73c	694.3b
		T1	11.5a	572.4a	354.2a	19.3a	2.65d	731.0a

Note: Means within a column followed by different letters are significantly different at $P < 0.05$.

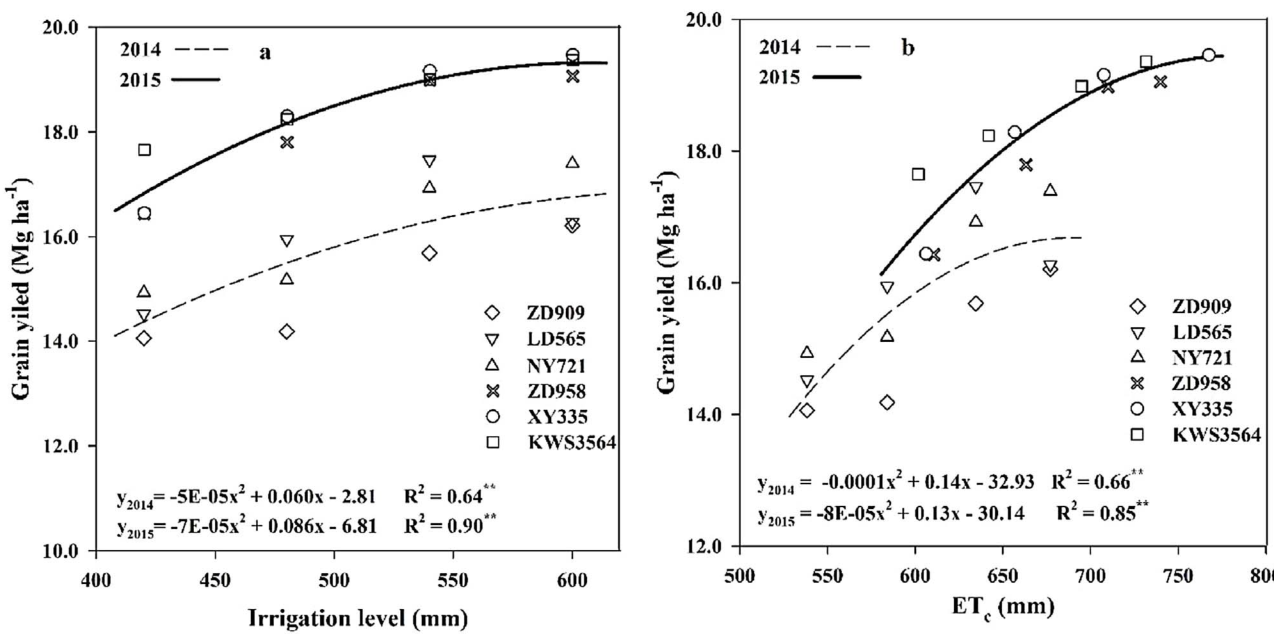

Fig. 4. Relationships between grain yield and (a) irrigation level, (b) evapotranspiration.

WP + 2467.8 (0 < WP < 18.62). Maximum economic return corresponds to the optimal irrigation level. When the water price is 4.70 US $ mm^{-1}, irrigation level was 449 mm and economic return was zero.

4. Discussion

Grain yield showed a quadratic relationship with irrigation level and ET_c (Fig. 4a and b), which is similar to the results of previous studies (Yazar et al., 1999; Payero et al., 2006; Xiao et al., 2008a,b; Payero et al., 2008; Bozkurt et al., 2011; Djaman et al., 2013; Irmak et al., 2016; Kresovic et al., 2016). In our study, evapotranspiration varied from 529.4 to 739.2 mm and grain yield ranged from 14.1 to 19.4 Mg ha^{-1}. One reason for the high yield obtained in this study is high planting density, which is an effective way to increase maize yield (Grassini et al., 2011; Xue et al., 2016; Li et al., 2015a). Though water is limited in arid areas, light levels are high. Sufficient light is conducive to the accumulation of photosynthetic products and improvements in yield; thus, high-density crops can make full use of light resources to increase photosynthetic rates. Plastic film mulching is an effective method for increasing crop productivity in dryland agriculture (Wu et al., 2017). Relative to non-mulched plots, mulching significantly increased soil temperature and moisture during the early growth stages, increased grain yield by 28.3% and 87.5%, and improved WUE by 23% and 91% in 2010 and 2011, respectively (Bu et al., 2013). Furthermore, compared with furrow irrigation (irrigation level of 764.6 mm), drip irrigation under plastic film mulching (irrigation level of 444.4 mm)

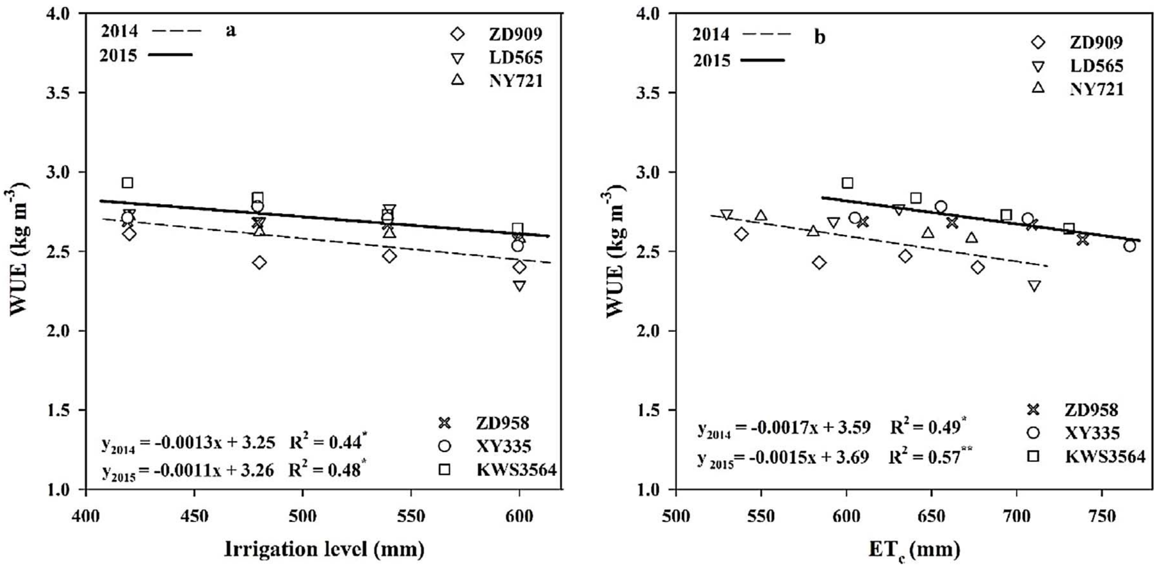

Fig. 5. Relationships between water use efficiency and irrigation level (a), evapotranspiration (b).

can save an average of 41.9%, increase cotton yield by 23.2%, and improve water use efficiency by 70.7% (Fan et al., 2012). Tang et al. (2014) showed that, compared with furrow irrigation (average irrigation level of 900 mm), drip irrigation under plastic film mulching (irrigation level of 600 mm) can increase maize yield by 47.3%, and drip irrigation levels of 300–450 mm can conserve irrigation water (50%–66.7%); thus, the most suitable drip irrigation level for maize is 525–600 mm in southern Xinjiang. The conventional furrow irrigation level to achieve a maize yield of 15000 kg ha^{-1} is 650–750 mm (Dong et al., 1998); compared with this level, combined drip irrigation–mulching systems save 26.2%–36.0% of water. Compared with traditional irrigation methods, drip irrigation–plastic film mulching is an effective technology to conserve water and achieve high yield. Increasing density will increase competition for water and fertilizer resources, but drip irrigation and plastic film mulching can help avoid this limitation. In our experiments, water, fertilizer, and pesticides were frequently and evenly applied to a small area near plant roots, effectively controlling maize growth, insect pests, and diseases. This technique also can limit soil evaporation and deep percolation (Liu et al., 2017), thereby conserving water and increasing yield (Deng et al., 2006; Kuscu et al., 2013; Qin et al., 2016; Liu et al., 2017; Tian et al., 2017). Therefore, the cultivation techniques of close planting, plastic film mulching, and combined drip irrigation can help increase production, save water, and improve water use efficiency by optimizing the use of light resources. In our study, grain yield decreased when irrigation level was reduced by 20% (T3) but it was not significantly affected by a 10% reduction (T2). This agrees with the previous result that soil water deficit induced during certain periods of the crop season can save water while maintaining yield (Kang et al., 2000; Kuscu and Demir, 2013). High soil moisture content resulted in high ET but did not lead to higher grain yield (Liu et al., 2017). However, reducing the irrigation level significantly reduced evapotranspiration, indicating that evapotranspiration is inefficient under high irrigation levels. In summary, 540 mm (T2) is the optimal irrigation level under the current irrigation regime.

The ultimate goal of agricultural irrigation is to maximize production per unit of crop water consumption, and it is essential to develop a suitable irrigation schedule to achieve this (Zhang et al., 2008). During the two study years, WUE was highest for T4 (2.61 and 2.93 kg m^{-3}, respectively), but yield (14.1, 16.4 Mg ha^{-1}) and ET$_c$ (538.3,

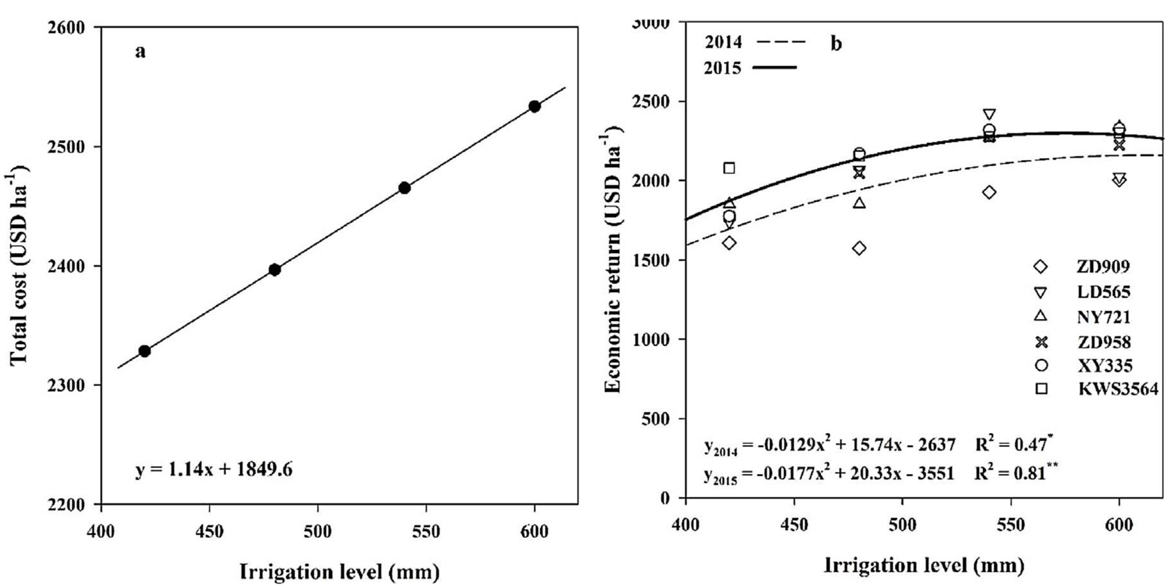

Fig. 6. Relationship between irrigation level and total cost (a) and economic return (b).

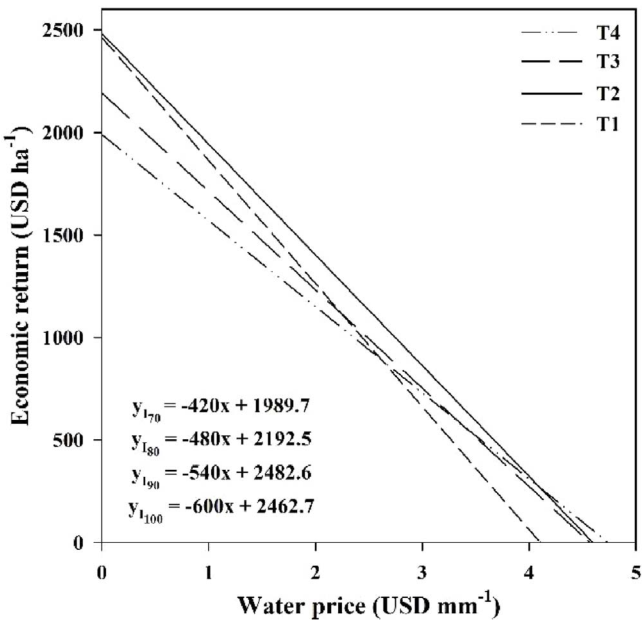

Fig. 7. Relationship between water price and economic return.

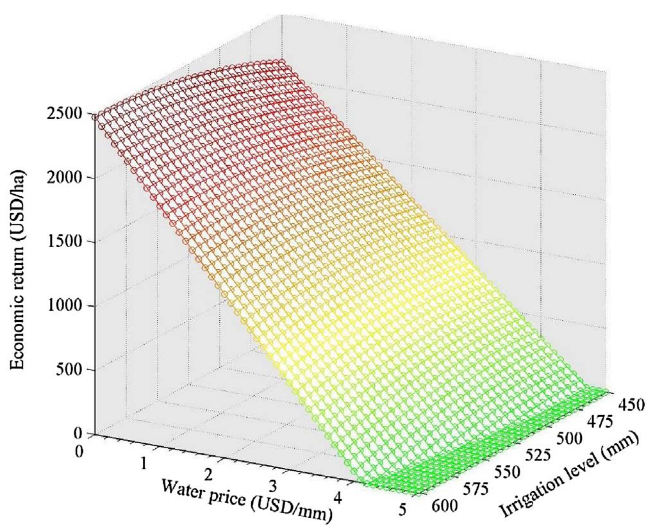

Fig. 8. Relationships between water price and irrigation level and economic return.

610.0 mm) were lowest. In contrast, fully irrigated plants (T1) had high yield (17.5–19.4 Mg ha^{-1}) and ET_c (710.3–767.0 mm) but low WUE (2.29–2.53 kg m^{-3}). WUE was negatively related with irrigation level (Fig. 5a) and ET_c (Fig. 5b), which agrees with the results of previous studies (Kuscu et al., 2013; Chen et al., 2015; Kresović et al., 2016). Zwart and Bastiaanssen (2004) reported a global average WUE per unit water depletion of 1.8 kg m^{-3} for maize. Deng et al. (2006) measured WUE of about 0.46 kg m^{-3} in the north and northwest of China. The WUE in this study was (2.29–2.93 kg m^{-3}). However, the range of WUE obtained in this study was higher than that reported by Yazar et al. (1999) (0.87–1.42 kg m^{-3}), Oktem et al. (2003) (1.04–1.36 kg m^{-3}), Kuscu et al. (2013) (1.40–1.90 kg m^{-3}), and other studies (Bozkurt et al., 2006; Hassanli et al., 2009; Bozkurt et al., 2011; Bouazzama et al., 2012; Irmak et al., 2016). These differences are a result of the relatively high yield of our maize crop and the drip irrigation-plastic film mulching system we employed, which decreased soil evaporation and effectively improved the efficiency of soil water use. This technique can limit deep water percolation and uniformly distribute water in the soil. WUE is influenced by crop yield potential, irrigation method, ET, crop environment, and climatic characteristics. Under the current irrigation system, a 10% reduction in irrigation level reduced ET_c and increased WUE (4.61%–6.66%). This result is similar to previous studies that reported higher WUE for plants with a slight water deficit compared with well-watered plants (Karam et al., 2003; Sun et al., 2006; Kuscu et al., 2013). Thus, reduced irrigation (10%) can maintain high yield by improving WUE and reducing ET_c. We found a quadratic relationship between economic return and irrigation level (Fig. 6b), and economic return was higher compared with values reported by previous studies. Wu et al. (2015) obtained maize grain yield of 10.2 t ha^{-1} under an irrigation level of 75 mm and rainfall level of 636.9 mm in a furrow irrigation system. In this study, the grain yield benefit was 2695 US$ ha^{-1} (domestic market price 0.27 US$ kg^{-1}) and irrigation and rainfall levels were 540 mm and 202 mm. Grain yield benefit was higher (88.2%) compared with the results of Wu et al. (2015) due to the drip irrigation–plastic film mulching systems used in this studys. Tang et al. (2014) compared grain yield (14997.4 kg ha^{-1} and 10178.3 kg ha^{-1}) and economic return (1440.7 US$ ha^{-1} and 790.0 US$ ha^{-1}) for a drip irrigation–plastic film mulching system (irrigation level of 600 mm) and a furrow irrigation system (average irrigation amount 900 mm) in Xinjiang. The grain yield and economic return reported in the current study are higher than the results of Tang et al. (2014) for the drip irrigation system (29.6% and 81.7%, respectively) and furrow irrigation system (91% and 231%, respectively) due to high planting density and high yield. Grain yield, economic return, and ecological effect should be considered when evaluating crop management practices. Considering these factors, the optimal irrigation level (540 mm) can save irrigation water, improve WUE, and maintain high yield and economic return. The economic return of T2 (540 mm) was higher compared with the other treatments when water price increased from 0.40 to 4.11 US$ mm^{-1}. Therefore, this irrigation regime is recommended as a water-saving strategy for similar arid and semi-arid areas throughout the world.

Agricultural drought is becoming a serious threat to crop production (Rosegrant et al., 2009). Shortage of agricultural water resources will cause water prices to rise in arid areas. To reduce water costs, farmers will reduce irrigation level, which will subsequently decrease maize yield and economic return. When water supplies are limited, farmer should maximize economic return per unit water used rather than per land unit. We found a linear relationship between irrigation level and water cost. Maximum economic return (2230.1 US$ ha^{-1}) was achieved when irrigation amount was 587.7 mm and water price was 0.40 US$ mm^{-1}. Irrigation level was 449 mm and economic return was zero when water price was 4.70 US$ mm^{-1}. It is necessary to seek a balance among grain yield, ecological effects, and economic return in agricultural production. A shortcoming of our study was that the maize varieties were not uniform during the two growing seasons, however they were all high density-tolerant varieties. In future studies, we will evaluate the effects of irrigation interval and fertilizer amount of grain yield and economic return of super high-yield maize in a drip irrigation–plastic film mulching system.

5. Conclusions

Grain yield ranged from 16.2 to 19.4 Mg ha^{-1} (T1), 15.7 to 19.1 Mg ha^{-1} (T2), 14.2 to 18.2 Mg ha^{-1} (T3), and 14.1 to 17.6 Mg ha^{-1} (T4); WUE ranged from 2.29 to 2.65 kg m^{-3} (T1), 2.47 to 2.77 kg m^{-3} (T2), 2.44 to 2.84 kg m^{-3} (T3), and 2.61 to 2.93 kg m^{-3} (T4); and economic return ranged from 1761.4 to 2617.6 US$ ha^{-1} (T1), 1691.6 to 2605.7 US$ ha^{-1} (T2), 1361.5 to 2444.1 US$ ha^{-1} (T3), and 1397.1 to 2343.3 US$ ha^{-1} (T4). We combined drip irrigation–plastic film mulching with integrative water, fertilizer, and density techniques, allowing full use of light resources. The optimal irrigation level for this system was 540 mm. Similar management practices can be applied in other arid or semi-arid areas.

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