

Article

# Optimized Water and Fertilizer Management of Mature Jujube in Xinjiang Arid Area Using Drip Irrigation

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**Abstract:** Studying water–fertilizer coupling effects in a drip irrigation system is critical for sustainable agricultural development in arid areas, such as that of Xinjiang in China, to find out the optimized water and fertilizer management. Therefore, a two-year field experiment was conducted to find out how the combination of three levels of irrigation quotas and three levels of fertilizer amounts would affect the physiological and growth indexes of jujube, as well as ascertain the differences between drip irrigation and flood irrigation. The results showed that the interacted and coupled effects of irrigation and fertilization influenced most of the physiological indicators and growth indexes. On the other hand, the physiological and growth indexes were increased after transferring flood irrigation to drip irrigation, as the maximum chlorophyll content (CC) and photosynthetic nitrogen use efficiency (PNUE) values increased on average by 6.00%, and 11.39% in 2016, and 1.47% and 6.83% in 2017, respectively. Undoubtedly, inappropriate water and fertilizer management had negative impacts on jujube growth and yield. Based on the treatments and results in this paper, low fertilizer and moderate irrigation would be the best choice. The crop yield, irrigation water use efficiency (iWUE), and fertilizer partial productivity (PFP) increased by 6.77%, 29.48%, and 193.62% in 2016, and similar increments were also found in 2017 of 6.17%, 78.72%, and 133.06%, respectively. This indicated that fertilizer efficiency was promoted along with water use, and in turn, the water amounts were adjusted by the amount of fertilizer that was applied. Based on a comprehensive consideration of the physiological and growth indexes, a mathematical model was established, and the optimized irrigation and fertilizer amounts of jujube in northern Xinjiang area were found to be 815 mm and 400 kg ha<sup>-1</sup> (with N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O proportioned at 2–1–1.5). The results that were obtained in this paper would provide theoretical reference to the sustainable development of jujube plantation using drip irrigation in the arid areas.

**Keywords:** mature Jujube; water and fertilizer management; northern Xinjiang arid area

## 1. Introduction

Jujube (*Zizyphus jujube mill*) is one of the most important economical crops in the northern desert of Xinjiang area in China, and it has become one of the Chinese's favorite fruits due to its good taste, sufficient nutrition, and medical value [1]. The planting area of jujube in Xinjiang has reached  $4.3 \times 10^5$  hm<sup>2</sup>, which has made it the most planted fruit in China. However, the majority of jujube are still using flood irrigation, and the irrigation quota exceeds 1000 m<sup>3</sup>/mu, leaving merely 9.5% applying drip irrigation. The traditional flood irrigation applied to a jujube plantation has disadvantages in its

water-usage efficiency (WUE), production efficiency, and effects on the ecological environment [2]. On the contrary, drip irrigation is a high-efficiency water-saving irrigation method that directly supplies water and nutrients to the root of crops. As an extreme water shortage has always been the key barrier of agriculture in this area, scholars have increasingly paid more and more attention to drip irrigation technology [3].

Some related results indicated that different crops and soil types all showed positive responses to drip irrigation, compared with the traditional flood irrigation, as the crop yield increased to some extent [4]. Fertigation is the other critical factor that affects water and nutrient supplements, and thus affects crop yield and WUE [5]. In general, the rational management of water–fertilizer showed positive impacts on improving water and fertilizer management [6,7]. The effects of water and fertilizer on crop growth are not isolated, but instead interact with each other, and show a coupling effect [8]. Some scholars have explored multiple crops using drip irrigation and fertilization, such as wheat [9], cotton [10], and fruit trees [11,12]. Although the results were different as the irrigation quota and fertilizer requirement were obviously different for each type of crop studied, these studies determined that reasonable irrigation and fertilization was beneficial to the improvement of the physiological characteristics and yield of crops. Although several scholars studied the effects of irrigation or fertilizer on the jujube plantation, limited results were related to deficit irrigation [13,14] and drip irrigation [15], and no direct results were reported on the water–fertilizer interaction using the drip irrigation system, especially in extremely arid areas, such as Xinjiang province in China [1]. The difference between drip irrigation and flood irrigation were also unknown.

Based on these, a two-year field experiment was conducted to study the effects of different water and fertilizer treatments on the physiological growth and yield of jujube in Xinjiang, China. The study aims to find out the optimized water–fertilizer management of jujube in northern Xinjiang area, and thus provide guidance for the sustainable development of the jujube plantation using drip irrigation in the arid areas.

## 2. Materials and Methods

### 2.1. Experimental Site

The experiment was conducted at Alar agricultural irrigation experiment station, Xinjiang, China (40°34'28'' N, 81°14'12'' E, altitude 1015 m, Figure 1), which has a typical extreme continental arid climate. The experiment was carried out in 2016 and 2017, the average annual rainfall was 67 mm (May–October), and the average sunshine hours and temperature were 2865 h and 10.7 °C, separately. Local groundwater was below 3.5 m, and the atmospheric pressure, ground temperature, effective radiation, minimum relative humidity, and solar radiation were automatically monitored and recorded using a meteorological station (TRM-ZS2). Figure 2 represents the rainfall and reference evapotranspiration during the experiment. Besides, the organic matter, total nitrogen, available P, and available K, were 3.81 g·kg<sup>-1</sup>, 0.47 mg·kg<sup>-1</sup>, 9.4 mg·kg<sup>-1</sup>, and 68 mg·kg<sup>-1</sup> in the upper 0.2 m soil layer, respectively, and the other soil properties are shown in Table 1.

**Table 1.** Soil properties used in the experiment.

Soil Layer/cm	Soil Type	Field Moisture Capacity/(g·g <sup>-1</sup> )	Soil Bulk Density/(g·cm <sup>-3</sup> )	Soil Density/(g·cm <sup>-3</sup> )	Soil Total Porosity/%	Capillary Porosity/%
0–20	loamy sand soil	0.19	1.51 ± 0.03	2.05 ± 0.08	47.6 ± 1.35	45.28 ± 0.78
20–40	sand soil	0.20	1.57 ± 0.03	1.89 ± 0.05	42.11 ± 1.45	40.12 ± 0.98
40–60	loamy sand soil	0.19	1.53 ± 0.04	1.43 ± 0.06	43.27 ± 0.42	41.02 ± 0.87
60–80	sand soil	0.20	1.58 ± 0.07	2.09 ± 0.05	41.74 ± 1.05	39.24 ± 0.66

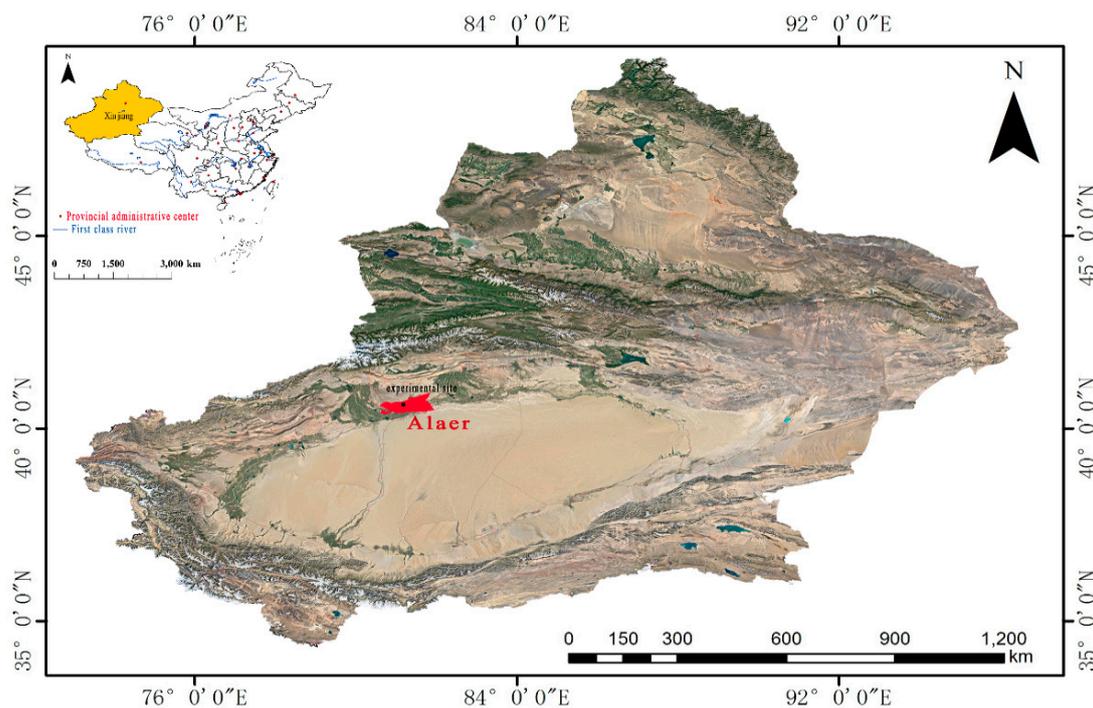


Figure 1. The location of the experimental site.

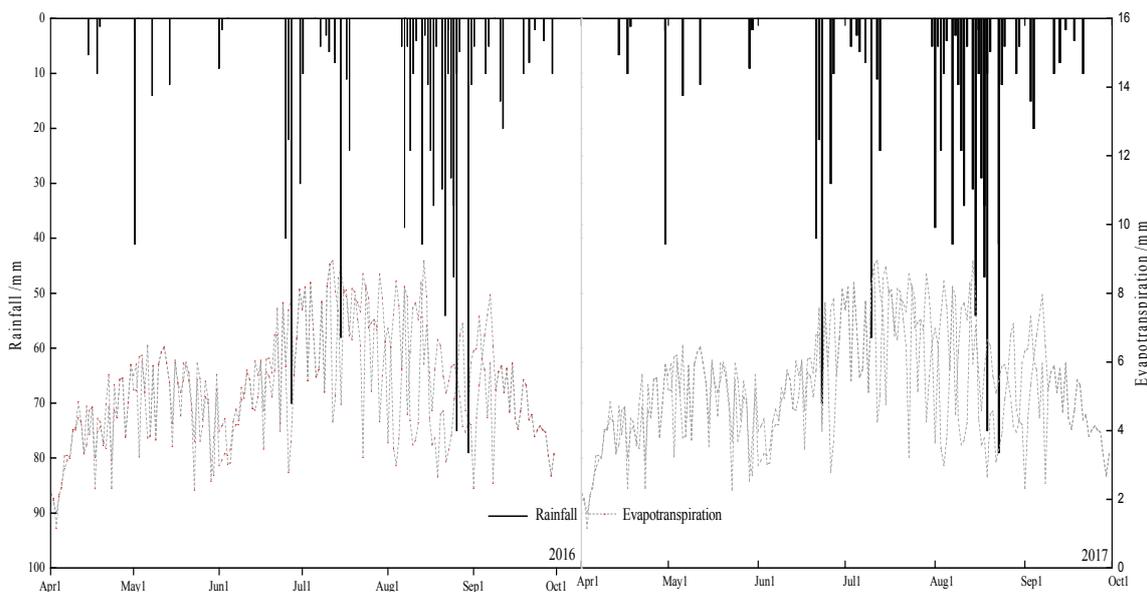


Figure 2. Reference evapotranspiration and rainfall during the experiment.

### 2.2. Field Experiment Layout

Eight-year-old mature jujube trees (*Zizyphus Jujube Mill*) were selected for the experiment. They were planted in 2008 and grafted in 2009, and flood irrigation was applied until 2015. The annual irrigation and fertilization amounts (N–P–K) were 1020 mm and 600–300–450 kg ha<sup>-1</sup>, respectively. Their water and fertilizer management transferred from flood irrigation to drip irrigation on 2016 (Figure 3). The wide–narrow row-planting mode was applied, which means that the distance between jujube rows were 200 cm (wide row) and 80 cm (narrow row) by turns. Each row of jujube was irrigated with two driplines centered in narrow rows with 40 cm on each side. Jujube was planted at constant intervals of 80 cm in each row, and the emitter spacing was 30 cm. The overall layout of the experiment was displayed in Figure 4. The drip irrigation system was operated under the constant working

pressure of 0.10 MPa and was 20 m in length, and the rated outflow of each emitter was  $2 \text{ L h}^{-1}$  with an internal diameter of 12 mm.

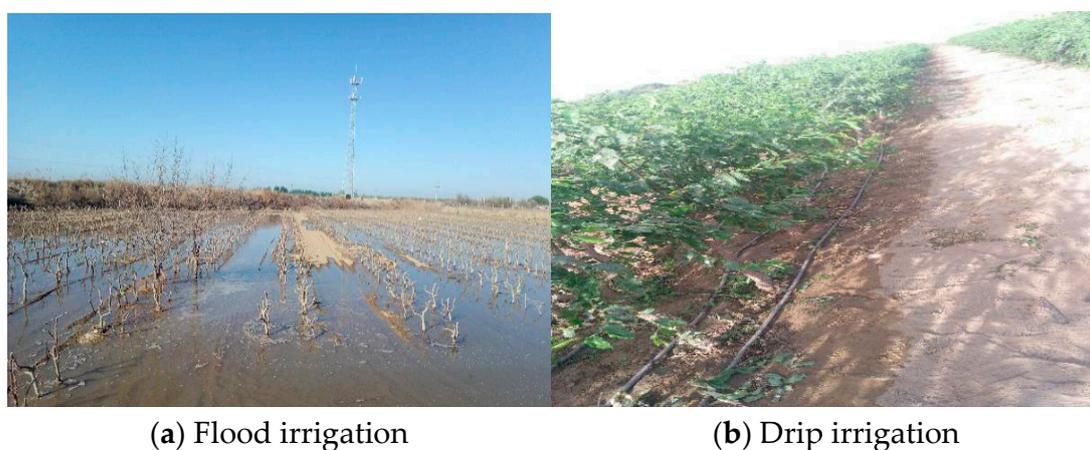


Figure 3. Different irrigation methods of jujube.

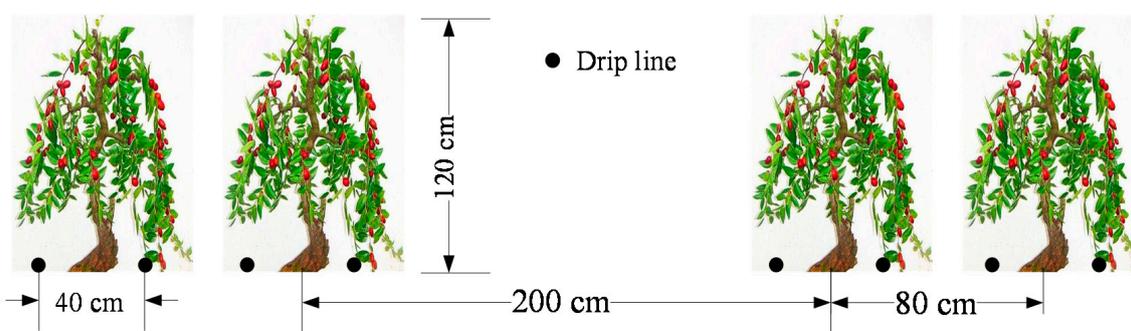


Figure 4. Planting patterns of jujube.

### 2.3. Experiment Design

To find out the optimized water and fertilizer management of jujube when changing from traditional flood irrigation to drip irrigation, two factors and three levels of treatments were set up for two years. The irrigation quota and fertilizer amount (N:P:K = 2:1:1.5 based on local agricultural management) were defined as the two factors. In 2016, three levels were included in irrigation amounts as 620 mm (W1), 820 mm (W2), and 1020 mm (W3), and the fertilizer treatments were  $450 \text{ kg ha}^{-1}$  (F1),  $900 \text{ kg ha}^{-1}$  (F2), and  $1350 \text{ kg ha}^{-1}$  (F3). In 2017, irrigation amounts were 570 mm (W1), 770 mm (W2), and 970 mm (W3), and the fertilizer treatments were  $410 \text{ kg ha}^{-1}$  (F1),  $860 \text{ kg ha}^{-1}$  (F2), and  $1310 \text{ kg ha}^{-1}$  (F3), respectively. These values were based on the comprehensive consideration of local evaporation, seeding time, and the flood irrigation references. The traditional flood irrigation was treated as control check (CK), and thus, there were 10 treatments in total for the orthogonal experiment, and three replications for each treatment. The detailed water and fertilizer managements during the experiment are shown in Table 2. During the experiment, fertilization was conducted both for 30 min after operation began and 30 min before irrigation stopped.

**Table 2.** Irrigation and fertilizer managements in jujube.

Year	Growth Stage	Period	Irrigation Treatment/mm			Fertilization Treatment/kg ha <sup>-1</sup>			Flood Irrigation		Irrigation Times	Fertilization Times
			W1	W2	W3	F1	F2	F3	W	F		
2016	Budding and shooting	04/30–06/20	70	110	150	90	180	270	150	270	1	1
	Flowering	06/21–07/20	160	200	240	120	240	360	240	360	2	2
	Fruiting	07/21–08/17	160	200	240	120	240	360	240	360	2	2
	White maturity	08/18–09/18	160	200	240	120	240	360	240	360	2	2
	Fully maturity	09/19–10/30	70	110	150	—	—	—	150	—	1	0
2017	Budding and shooting	05/05–06/15	60	100	140	80	170	260	140	260	1	1
	Flowering	06/16–07/15	150	190	230	110	230	350	230	350	2	2
	Fruiting	07/16–08/06	150	190	230	110	230	350	230	350	2	2
	White maturity	08/07–09/16	150	190	230	110	230	350	230	350	2	2
	Fully maturity	09/17–11/05	60	100	140	—	—	—	140	—	1	0

## 2.4. Measurements and Methods Applied

### 2.4.1. Crop Growth

The  $I_{SL}$  were measured on 5 May 2016 for the first time, and continued until 10 July with the constant interval of seven days. In 2017, the two indicators were first measured on 10 May, and continued until 15 July with same interval. During each measurement, five jujube trees were selected, and  $I_{SL}$  was measured with the tapeline.

### 2.4.2. Photosynthetic Characteristics

Leaf photosynthetic characteristics, including  $P_n$ ,  $G_s$ ,  $C_i$ , and  $T_r$  were measured on 30 July 2016 and 25 July 2017, respectively. Validation experiment was conducted between 10:00 and 20:00 on 31 July 2016 and 25 July 2017, on three expanded upper canopy leaves of each tree (five trees for each treatment) with the Li-6400 Portable Photosynthetic System (manufactured by Li-Cor Inc., Lincoln, NE, USA). This system was equipped with a red/blue light source (6400-02B LED).

### 2.4.3. Chlorophyll and Nitrogen Contents

In this experiment, the chlorophyll content (CC) was measured by Minolta SPAD 502 m. Three jujube trees were selected for each treatment, and the upper, middle, and lower leaves of each tree were measured. Each treatment totaled nine leaves and took the average. Then, the CC was separated from the plant at 105 °C for 30 min, and then dried at 80 °C to constant quality. Then, the leaf nitrogen content (NC) was measured by a semi-micro Kjeldahl method [16]. Photosynthetic nitrogen use efficiency (PNUE) was calculated by  $P_n/NC$  [17].

### 2.4.4. Water and Fertilizer Efficiency and Crop Yield

The irrigation water use efficiency (iWUE) (unit:  $kg \cdot m^{-3}$ ) was calculated according to the method used by Kuslu et al. [18]. The fertilizer partial productivity (PPF) (unit:  $kg \cdot kg^{-1}$ ) referred to the method that was used by Ierna et al. [19]. The jujube yield was measured with five trees and took their average value. Then, its EI was calculated using the method applied by Badr et al. [20], which was based on the difference between the yield of treatments and CK.

### 2.4.5. Water and Fertilizer Optimization Method

The binary quadratic regression equation was applied for optimized water and fertilizer management. Y was regarded as the dependent variable (Y), and the irrigation amount (W) and fertilizer amount (F) were treated as the independent variables.

### 3. Results and Analysis

#### 3.1. Effects of Water–Fertilizer Treatments on the Physiological Indicators

The effects of the different water and fertilizer treatments on the physiological indicators ( $P_n$ ,  $T_r$ ,  $G_s$ ,  $C_i$  CC, and PNUE) are shown in Table 3.

Seen from Table 3, the  $P_n$ ,  $T_r$ ,  $G_s$ , and  $C_i$  values of different water and fertilizer treatments ranged within 7.26~8.94  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , 3.15~3.86  $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , 0.31~0.49  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , and 447.5~707.41  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , respectively, in 2016. Similar values were acquired in 2017 as 7.54~8.51  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , 3.24~3.68  $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , 0.36~0.48  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , and 568.48~678.22  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , respectively. The maximum values were all observed in W2F1 treatment for two years, and they were larger than those of CK by 3.65~12.61%, 3.67~17.32%, 6.67~8.89%, and 10.66~19.30%, respectively. These results indicated that the medium irrigation quota was helpful to improve the efficiency of lower-level fertilizer and resulted in the most positive effects on these four indexes. Generally speaking, the  $P_n$ ,  $T_r$ ,  $G_s$ , and  $C_i$  values were significantly affected by an irrigation quota of ( $p < 0.01$ ), but their dynamic responses to fertilizer amounts failed to reach a significant level ( $p < 0.05$ ). As the effects of irrigation were higher than fertilization, their coupling effects also reached the significant level ( $p < 0.05$ ).

Meanwhile, the CC of different water and fertilizer treatments ranged from 43.17  $\text{mg}\cdot\text{g}^{-1}$  (W1F3) to 53.00  $\text{mg}\cdot\text{g}^{-1}$  (W3F3) in 2016, and from 44.2  $\text{mg}\cdot\text{g}^{-1}$  (W1F3) to 51.81  $\text{mg}\cdot\text{g}^{-1}$  (W3F3) in 2017. The minimum and maximum values were obtained in the same treatments. Compared with W1F3 and CK, the CC value under W3F3 treatment was increased by 17.22~22.77% and 1.47~6.00%, respectively. The CC was not affected by the fertilizer level, as the effects of the irrigation quota were much more significant. However, the maximum and minimum PUNE were obtained in different treatments, which were W1F2 (1.95  $\mu\text{molCO}_2\cdot\text{g}^{-1}\cdot\text{Ns}^{-1}$ ) and W2F2 (2.25  $\mu\text{molCO}_2\cdot\text{g}^{-1}\cdot\text{Ns}^{-1}$ ) in 2016, and turned out to be W1F1 (1.96  $\mu\text{molCO}_2\cdot\text{g}^{-1}\cdot\text{Ns}^{-1}$ ) and W2F1 (2.19  $\mu\text{molCO}_2\cdot\text{g}^{-1}\cdot\text{Ns}^{-1}$ ) in 2017. A small irrigation quota seemed to be beneficial for improving the PUNE. However, their effects were combined with those of different fertilizer treatments. According to the significant test, the effect of merely irrigation or fertilization on these three indicators that were mentioned above was not significant ( $p < 0.05$ ), but their interactions on CC and PUNE reached significant values ( $p < 0.01$ ).

**Table 3.** Effects of water–fertilizer treatments on photosynthetic characteristics.

Years	Treatments	$P_n/\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	$T_r/\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	$G_s/\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	$C_i/\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	$C_c/\text{mg}\cdot\text{g}^{-1}$	$\text{PNUE}/\mu\text{mol}\cdot\text{CO}_2\cdot\text{g}^{-1}\text{Ns}^{-1}$
2016	W1F1	7.26 ± 0.07 f	3.15 ± 0.06 b	0.31 ± 0.01 c	447.50 ± 2.78 f	49.2 ± 0.85 b	1.96 ± 0.16 c
	W1F2	7.82 ± 0.12 e	3.17 ± 0.02 b	0.33 ± 0.02 c	519.89 ± 3.38 e	44.5 ± 1.25 c	1.96 ± 0.08 c
	W1F3	7.73 ± 0.04 e	3.19 ± 0.05 b	0.35 ± 0.10 c	365.07 ± 5.11 g	43.2 ± 0.38 c	2.15 ± 0.02 b
	W2F1	8.93 ± 0.03 a	3.86 ± 0.01 a	0.49 ± 0.02 a	707.41 ± 4.48 a	52.2 ± 0.51 ab	2.20 ± 0.04 a
	W2F2	8.34 ± 0.08 cd	3.68 ± 0.02 a	0.47 ± 0.04 ab	639.25 ± 3.45 b	44.9 ± 0.58 c	2.25 ± 0.04 a
	W2F3	8.43 ± 0.03 c	3.76 ± 0.02 a	0.45 ± 0.02 b	710.42 ± 2.79 a	52.6 ± 1.77 ab	1.99 ± 0.07 c
	W3F1	8.24 ± 0.05 d	3.27 ± 0.06 b	0.35 ± 0.02 c	631.01 ± 2.52 b	51.9 ± 0.58 ab	2.03 ± 0.02 c
	W3F2	8.67 ± 0.13 b	3.40 ± 0.06 b	0.36 ± 0.02 c	592.06 ± 2.04 c	43.8 ± 0.77 c	2.19 ± 0.03 a
	W3F3	8.41 ± 0.09 cd	3.28 ± 0.05 b	0.44 ± 0.03 b	536.53 ± 1.44 d	53.0 ± 0.69 a	1.97 ± 0.03 c
	CK	7.93 ± 0.15 e	3.29 ± 0.04 b	0.45 ± 0.27 b	639.26 ± 2.56 b	50.0 ± 0.53 ab	2.03 ± 0.06 b
2017	W1F1	7.54 ± 0.05 c	3.24 ± 0.05 bc	0.36 ± 0.01 c	568.48 ± 2.78 d	44.2 ± 0.74 d	1.96 ± 0.05 c
	W1F2	7.78 ± 0.09 c	3.28 ± 0.04 bc	0.32 ± 0.02 c	597.89 ± 4.31 c	46.5 ± 1.17 c	1.99 ± 0.07 c
	W1F3	8.05 ± 0.06 bc	3.09 ± 0.03 c	0.42 ± 0.10 bc	604.19 ± 6.48 c	46.9 ± 0.98 c	2.06 ± 0.03 b
	W2F1	8.51 ± 0.04 a	3.68 ± 0.06 a	0.48 ± 0.02 a	678.22 ± 4.48 a	51.5 ± 0.74 a	2.19 ± 0.05 a
	W2F2	8.49 ± 0.07 ab	3.57 ± 0.07 b	0.41 ± 0.04 ab	659.69 ± 3.45 ab	46.6 ± 0.78 c	2.14 ± 0.03 ab
	W2F3	8.36 ± 0.06 cb	3.49 ± 0.06 b	0.45 ± 0.02 b	654.42 ± 6.74 ab	51.6 ± 1.47 ab	1.90 ± 0.05 c
	W3F1	8.41 ± 0.08 b	3.54 ± 0.06 b	0.46 ± 0.02 ab	648.27 ± 3.75 b	50.9 ± 0.14 b	2.11 ± 0.04 ab
	W3F2	8.39 ± 0.08 b	3.48 ± 0.03 b	0.45 ± 0.02 b	652.34 ± 3.48 ab	44.4 ± 0.87 cd	2.12 ± 0.06 ab
	W3F3	8.35 ± 0.10 b	3.39 ± 0.02 b	0.44 ± 0.03 b	649.26 ± 5.10 b	51.8 ± 0.79 a	2.06 ± 0.04 b
	CK	8.21 ± 0.09 b	3.45 ± 0.06 b	0.45 ± 0.03 b	635.19 ± 3.07 b	51.1 ± 0.93 ab	2.05 ± 0.05 b
Significant Analysis							
2016	W (irrigation)	10.35 *	63.20 **	13.90 **	13.43 **	1.93	0.79
	F (fertilization)	0.39	0.10	0.15	0.17	0.20	0.12
	W × F	77.55 **	10.52 **	10.60 **	1251.19 *	10.87 **	7.89 **
2017	W (irrigation)	11.72 *	54.69 **	25.49 **	19.48 **	0.86	0.99
	F (fertilization)	0.45	0.69	0.75	0.48	0.22	0.24
	W × F	100.55 **	25.44 **	16.46 **	69.13 *	14.59 **	10.01 **

Note: The data in the Table 3 is mean value ± standard error, different letters indicate significant difference between treatments ( $p < 0.05$ ). \* and \*\* in the significance test represent reached significant values under  $p < 0.05$  and  $p < 0.01$ , respectively.

### 3.2. Effects of Water–Fertilizer Treatments on the Growth Indexes and Crop Yield

The effects of different water and fertilizer treatments on the growth indexes are shown in Table 4.

**Table 4.** Effects of water–fertilizer treatments on yield indexes.

Cropping Year	Treatments	I <sub>SL</sub> /mm	Y/kg ha <sup>-1</sup>	iWUE/kg·m <sup>-3</sup>	PPF/kg·kg <sup>-1</sup>	EI/%
2016	W1F1	48 ± 2.08 c	5450 ± 104.58 d	7.57 ± 0.15 b	12.11 ± 0.54 b	—
	W1F2	51 ± 2.08 bc	4661 ± 85.58 e	6.47 ± 0.12 c	5.53 ± 0.25 d	-14.48
	W1F3	53 ± 1.53 bc	5879 ± 84.79 c	8.17 ± 0.25 a	4.75 ± 0.36 d	7.87
	W2F1	54 ± 2.08 b	6956 ± 125.79 a	7.87 ± 0.14 ab	16.12 ± 0.58 a	33.14
	W2F2	58 ± 1.53 b	6803 ± 84.89 b	7.38 ± 0.19 b	8.06 ± 0.44 c	24.83
	W2F3	56 ± 1.53 b	5799 ± 55.65 c	6.29 ± 0.16 c	4.69 ± 0.35 d	6.40
	W3F1	57 ± 1.53 b	5603 ± 89.81 cd	5.19 ± 0.15 d	12.45 ± 0.66 b	2.81
	W3F2	64 ± 1.00 a	4894 ± 95.73 e	4.53 ± 0.14 e	5.81 ± 0.45 d	-10.20
	W3F3	59 ± 1.53 ab	5414 ± 105.23 d	5.01 ± 0.21 d	4.37 ± 0.22 d	-0.66
CK	61 ± 1.46 ab	6796 ± 89.78 b	6.31 ± 0.12 c	5.49 ± 0.12 d	24.70	
2017	W1F1	49 ± 1.52 c	5651 ± 97.85 d	13.89 ± 0.15 b	13.78 ± 0.54 b	—
	W1F2	51 ± 1.70 c	5798 ± 106.46 e	14.25 ± 0.12 c	6.74 ± 0.25 d	2.60
	W1F3	50 ± 2.03 c	6047 ± 88.69 c	14.86 ± 0.25 a	4.62 ± 0.36 d	7.01
	W2F1	55 ± 1.25 b	7056 ± 111.45 a	13.74 ± 0.14 ab	17.20 ± 0.58 a	24.86
	W2F2	57 ± 1.26 b	6803 ± 109.48 b	13.25 ± 0.19 b	7.91 ± 0.44 c	20.38
	W2F3	56 ± 1.73 b	6716 ± 78.95 c	13.07 ± 0.16 c	5.12 ± 0.35 d	18.84
	W3F1	60 ± 1.26 a	6841 ± 97.58 cd	10.57 ± 0.15 d	16.68 ± 0.66 b	21.06
	W3F2	62 ± 2.00 a	5984 ± 108.44 e	9.24 ± 0.14 e	6.96 ± 0.45 d	5.89
	W3F3	58 ± 1.25 ab	6144 ± 97.52 d	9.50 ± 0.21 d	4.69 ± 0.22 d	8.72
CK	61 ± 2.00 a	6648 ± 91.42 b	8.31 ± 0.12 c	7.38 ± 0.12 d	24.70	
Significant Analysis						
2016	W (irrigation)	8.46 *	4.71	11.32 **	0.20	/
	F (fertilization)	0.70	0.41	0.17	29.01 **	/
	W × F	78.12 **	78.01 **	155.82 **	758.71 **	/
2017	W (irrigation)	10.11 *	1.59	9.48 *	0.22	/
	F (fertilization)	0.41	0.13	0.14	18.75 **	/
	W × F	56.89 **	98.46 *	205.49 **	544.17 **	/

Note: The data in the Table 4 is the mean value ± standard error; different letters indicate significant difference between treatments ( $p < 0.05$ ). \* and \*\* in the significance test represent reaching significant values under  $p < 0.05$  and  $p < 0.01$ , respectively.

As shown in Table 4, I<sub>SL</sub> values were 48~49 cm (W1F1) to 62~64 cm (W3F2) in 2016 and 2017, and I<sub>SL</sub> values under W3F2 treatment were 26.53~51.32% and 3.33~21.58% larger than those of W1F1 and CK. Seen from the results obtained, the irrigation quota was more related to I<sub>SL</sub>, as more irrigated water were helpful to obtain larger I<sub>SL</sub> values, and the effects of irrigation quotas on the differences of I<sub>SL</sub> values reached a significant level ( $p < 0.05$ ), while those of fertilizer amounts failed. However, their coupling effects were enhanced to significant impacts under the significant level of  $p < 0.01$ . On the other hand, Y<sub>max</sub> and Y<sub>min</sub> were acquired in W2F1 (7256 kg·ha<sup>-1</sup>) and W1F2 (4661 kg·ha<sup>-1</sup>), while that of Y<sub>CK</sub> was 6976 kg·ha<sup>-1</sup> in 2016. Similar results were obtained in 2017. Besides, the highest PFP values were in both W2F1 treatments for two years, and it was 133.06~193.62% higher than that of CK (5.49 kg·kg<sup>-1</sup>). However, the highest iWUE value was obtained under W1F3 treatment in both 2016 and 2017 (8.17 kg·m<sup>-3</sup> and 14.86 kg·m<sup>-3</sup>), which increased by 29.48% and 78.72% when compared with CK (6.31 kg·m<sup>-3</sup> and 8.31 kg·m<sup>-3</sup>). The improving effect (EI) of W1F2, W3F2, and W3F3 treatments were negative values, and the EI<sub>max</sub> was acquired in W2F1 treatment (33.14% and 24.86%). Based on the two-year data analysis, the iWUE was significantly affected by irrigation quotas ( $p < 0.05$ ), the PFP was significantly influenced by fertilizer amounts ( $p < 0.01$ ), and they were both significantly affected by the coupling effects of water–fertilizer ( $p < 0.01$ ). Besides, the crop yield was significantly affected neither by the irrigation quota nor the fertilizer amount; only their interaction reached the significant level ( $p < 0.01$ ).

### 3.3. Optimized Water and Fertilizer Managements of Jujube in the Xinjiang Area

Based on the results mentioned above, the impact of water and fertilizer managements on physiological indicators and growth indexes varied among different treatments. The corresponding yield effect model was obtained by regression in Equation (1), and the optimized results of the yield model were shown in Figure 5. According to Equation (1), the interaction coefficient of water and fertilizer was a positive value, which meant that the positive impacts were increasing. Seen from Figure 5, the effect of the water and fertilizer coupling model showed a bimodal surface; the relatively higher yield was acquired with either low fertilizer or high fertilizer amount when irrigated with a moderate quota. Low fertilizer and moderate irrigation would be a better choice, as the maximum yield was acquired as  $6.87 \text{ Mg ha}^{-1}$ , and the optimized irrigation quota should be 815 mm while applying fertilizer with the amount of  $400 \text{ kg ha}^{-1}$ .

$$Y = 4.8 \times 10^{-6} \times F^2 - 3.1 \times 10^{-5} \times W^2 + 1.4 \times 10^{-6} \times W \times F + 5.0 \times 10^{-2} \times W - 1.0 \times 10^{-2} \times F - 10.0 \quad (R^2 = 0.85) \quad (1)$$

where Y represents the jujube yield ( $\text{kg ha}^{-1}$ ); W is the irrigation quota (mm), and F is the fertilizer amount ( $\text{kg ha}^{-1}$ ).

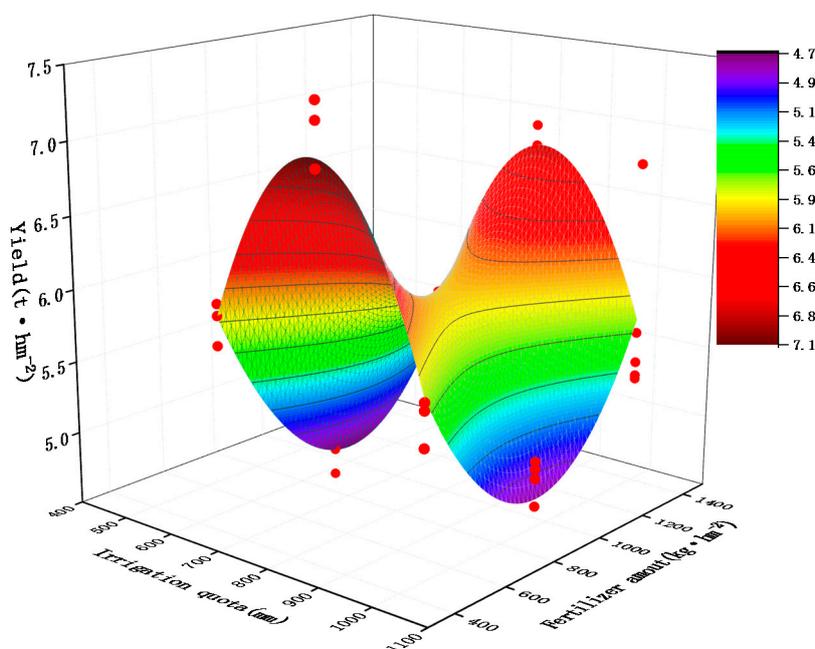


Figure 5. Water–fertilizer optimization based on maximum jujube yield.

## 4. Discussion

Water and fertilizer management is critical to crop production, especially for agriculture in arid areas [21]. When the coupling effects of water and fertilizer are optimized, the crop yield is significantly increased [20]. The key of water and fertilizer coupling is “using water to promote fertilizer [and] using fertilizer to adjust water”. In recent years, water–fertilizer management has become a hot research topic, especially when applying water-saving technology [22,23]. However, the related studying results related to jujube plantations are lacking.

In this paper, water and fertilizer interaction showed significant effects on jujube CC, NC, and PNUE, which indicated that fertilizer efficiency was promoted by the irrigation water, and in turn the amount of water that was needed was adjusted by the fertilizer applied, on the condition that neither water nor fertilizer showed significant impacts. We failed to find results on jujube CC, NC, and PNUE in the arid area, but the trend that we observed was consistent with the results of the wheat photosynthetic characteristics under water and fertilizer coupling conditions that were reported

by Wang et al. [24]. After applying the drip irrigation technology in 2016, the maximum CC, NC, and PUNE values increased on average by 6.00%, 9.49%, and 11.39%, respectively, upon comparing those using flood irrigation in 2015, which indicated the great improvement due to changing the irrigation method. Although these contents continued to increase after application in the second year of 2017, the increasing rates decreased to 1.47%, 3.37%, and 6.83%, respectively, as they were compared with those using drip irrigation. Meanwhile, neither excessive irrigation nor deficit irrigation was beneficial for photosynthetic characteristics, and the best effects occurred at the low fertilization level, which was similar to the results of Li et al. [25] and Zhou et al. [26]. Compared with flood irrigation, fertigation with drip irrigation could not only promote the nutrient absorption of crops, it could also improve the utilization rate of water fertilizer [21,27]. The results in this paper also showed that the highest yield was obtained with moderate irrigation and low fertilization treatment (W2F1) using drip irrigation, when the iWUE and PFP reached higher levels.

On the other hand, some scholars argued whether the net photosynthetic rate could increase crop yield significantly, especially under water stress conditions [28]. Actually, photosynthesis and the transpiration of jujube were directly affected by stomatal conductance, as leaves could control the jujube net photosynthetic rate and transpiration rate through the opening size of stomatal conductance. Therefore, it is important to study the relations between  $P_n$  and other indicators. In this paper, we studied the quantitative relations between physiological indicators and growth indexes (Figure 6). The results showed that  $P_n$ ,  $T_r$ , and  $G_s$  were closely related ( $R^2 > 0.84$  \*\*,  $p < 0.01$ ). Meanwhile, a significant linear relation was found between  $P_n$  and  $I_{SD}$  ( $R^2 = 0.52$ \*,  $p < 0.05$ ), while those of  $P_n$  and  $I_{SL}$  failed ( $R^2 = 0.26$ ,  $p < 0.05$ ). On the other hand, the realization of photosynthesis depends on the absorption of light energy obtained by chlorophyll. Seen from Figure 6,  $P_n$  had linear relations with CC and NC ( $R^2 > 0.39$ \*,  $p < 0.05$ ). Among them, CC was not only the most important pigment for the photosynthesis of crops, it was also the basic substance of the photosynthesis of plants [29]. We also found linear relations between leaf CC and NC ( $R^2 = 0.97$  \*\*,  $p < 0.01$ ).

Through the experiment, we acquired some meaningful results on how water–fertilizer management would affect jujube growth and yield. However, there were still some issues to study in the future: (1) the experiment was conducted with three irrigation quotas and three fertilizer amounts according to the local planting mode. More water and fertilizer gradients are needed, especially with higher irrigation and fertilization levels, in order to identify the most appropriate water–fertilizer management; (2) long-term experiment verifications are needed to find out the water–fertilizer coupling treatments after we turned flood irrigation to drip irrigation in the Xinjiang area. Besides, their effects on a healthy soil and microorganism community are also unknown.

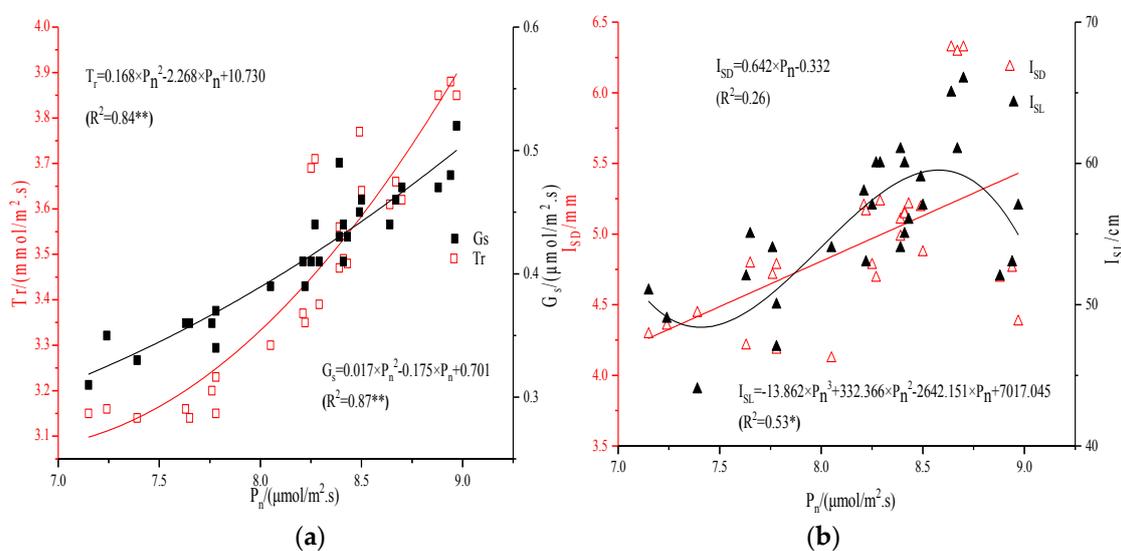
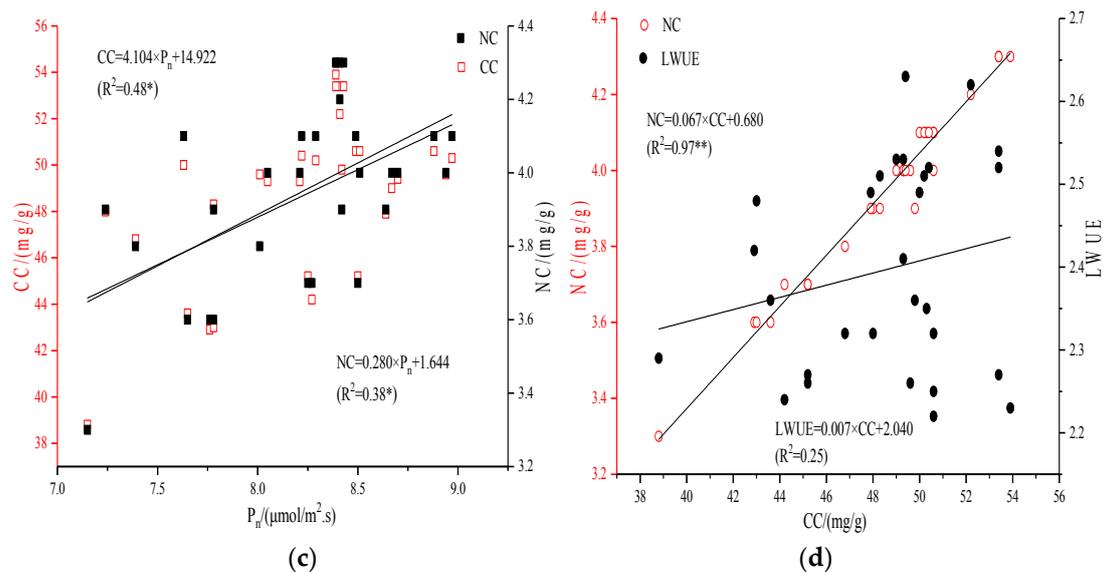


Figure 6. Cont.



**Figure 6.** Quantitative relations between physiological indicators and growth indexes. (a) The relationship between  $P_n$  and  $T_r$ ,  $G_s$ ; (b) The relationship between  $P_n$  and  $I_{SD}$ ,  $I_{SL}$ ; (c) The relationship between  $P_n$  and CC, NC; (d) The relationship between CC and NC, LWUE.

## 5. Conclusions

When planting jujube in the Xinjiang area using drip irrigation and integrating fertilization, most of the physiological indicators and growth indexes were not significantly affected merely by the irrigation quota nor the fertilizer amounts; only the water–fertilizer interaction showed significant effects. The physiological indicators and growth indexes were increased when transferring flood irrigation to drip irrigation. After applying drip irrigation technology, fertilizer efficiency was promoted with the irrigation water input, and in turn, the water requirements were adjusted by the fertilizer applied. However, inappropriate water and fertilizer management would show negative impacts on jujube growth and yield. Among the treatments in this paper, low fertilizer and moderate irrigation would be the best choice. Therefore, the optimized irrigation and fertilizer amounts of jujube in northern Xinjiang area should be 815 mm and 400 kg ha<sup>-1</sup>, on the basis of a comprehensive consideration of physiological indicators and growth indexes.

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**Conflicts of Interest:** The authors declare that there is no conflict of interest.

## Abbreviations

$P_n$ , net photosynthetic rate;  $G_s$ , stomatal conductance;  $C_i$ , intercellular CO<sub>2</sub> concentration;  $T_r$ , transpiration rate;  $I_{SL}$ , length increment; PFP, partial fertilizer productivity; PNUE, photosynthetic nitrogen use efficiency; iWUE, irrigation water use efficiency; NC, nitrogen content; CC, chlorophyll content; EL, improving effect.

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