

Article

Estimation of Evapotranspiration of a Jujube/Cotton Intercropping System in an Arid Area Based on the Dual Crop Coefficient Method

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Abstract: An accurate estimation of crop evapotranspiration (ET_c) in intercropping is critical for a theoretical basis for formulating an intercropping irrigation system of fruit trees and improving the soil moisture condition of orchards in arid regions of Southern Xinjiang. Herein, observational data such as soil moisture and plant physiological indicators were measured in jujube/cotton intercropping in the Aksu region from 2015 to 2017. The evapotranspiration of single-crop jujube and cotton was estimated using the modified dual crop coefficient method. Then, based on the proportion of intercropping crops, the soil water stress coefficient was introduced to estimate the evapotranspiration of the jujube/cotton intercropping. The results show that the model has good applicability to simulate single-crop jujube and cotton, and jujube/cotton intercropping. However, compared with single cropping, the accuracy of simulated daily evapotranspiration was decreased. In addition, adjusting the cotton irrigation amount caused the simulation accuracy to further decrease. From the perspective of interspecies complementarity and competition, cotton dominated the intercropping system and had better tolerance to external environmental changes than jujube trees. Intercropping had negative effects on jujube trees in general, and very obvious positive effects on cotton. Based on the 3-year crop yield, 5-year-old jujube trees are recommended for intercropping. During this time, the yield of cotton under the effect of interspecific complementation increased by 26.47%, and the yield of intercropping jujube was similar to that of single crop. As the jujube tree age increases, the effect of increasing cotton production gradually diminishes. The jujube trees also had a significant reduction in yield due to interspecific competition. Our research supports the dual crop coefficient method as appropriate to estimate crop ET_c in intercropping and may be further used to improve irrigation scheduling for jujube/cotton intercropping.

Keywords: intercropping; dual crop coefficient; water balance method; evapotranspiration

1. Introduction

With the rapid development of the forest and fruit industries in Xinjiang province, China, jujube trees are becoming a new pillar of the local economy. Large areas of orchards have been established by farmers. However, young jujube trees produce little fruit, and their economic benefits are often negative, so some farmers use intercropping to relieve economic pressure. Due to the lack of scientific guidance on irrigation systems, fruit trees are vulnerable to great impacts of climate and low agricultural output [1], leading to low enthusiasm for planting new trees among farmers. Thus, it is particularly important to establish a scientifically informed irrigation system and achieve higher water use efficiency in order to develop the forest and fruit industry in Xinjiang, China.

Intercropping is an efficient way to utilize land for farmers. Due to its comprehensive use of land nutrients, water, light, thermal energy, and other agricultural resources [2,3], it has attracted more and



more attention. Wu et al. [4] and He et al. [5] used stable isotope methods to test whether intercropping could improve the water use of rubber trees. It has been found that the agroforestry systems have stable internal microclimatic environments or higher resistance and they retained much more soil water and improved the water use efficiency. Ling et al. [6] studied the effects on root-zone soil water for intercropping. The results showed that both agroforestry systems clearly improved soil water at depths of 0–20 cm and 20–60 cm under jujube trees. Different crops need different soil water intensities in the vertical direction, which is the main factor to reduce the intensity of interspecific competition. Li et al. [7] studied the different irrigation quota of jujube/cotton intercropping. They found that an appropriate irrigation quota is beneficial to cotton growth and land use efficiency. Land use efficiency in the jujube/cotton intercropping system was higher than the monoculture system. Thus, a better

production capacity could be reached [8]. Due to the fact that monitoring of evapotranspiration of crops in fields is restricted by many uncontrollable factors, the establishment of an evapotranspiration mathematical model is one of the most effective methods to solve this problem. At present, the constant usage models include Penman–Monteith method (P–M) [9], Shuttle–Wallace method (S–W) [10], and dual crop coefficient method [11]. S–W method can improve the simulation accuracy by adding another model parameter (canopy surface resistance and soil surface resistance). It is mostly used in sparse planting mode. In addition, measurement errors of some parameters of S–W method have a high impact on simulation accuracy, which makes the model complex [12]. For the P–M method, the simulation accuracy is lower than that of the dual crop coefficient model because it cannot effectively distinguish the effects of soil evaporation and crop transpiration.

understanding of transpiration was used to help investigate if irrigation can be improved and optimal

The dual crop coefficient method, based on water balance theory, is used to simulate soil evaporation and plant transpiration [11] by dividing crop coefficients into basic coefficients and soil evaporation coefficients. Due to its simplicity and stability, this method has been used for field crops and some fruit trees [13,14]. It is the most common method of estimating farmland evapotranspiration (ET) and has been recognized by many scholars [15–18]. Paredes et al. [19] used the dual crop coefficient method to model water use. Calibration was performed by minimizing differences between measured and simulated soil water content with a root mean square error representing 2% of the measured mean. The calibrated basal crop coefficients for the initial, mid-season, and end-season were respectively 0.15, 1.15, and 1.10. Li et al. [20] used the dual coefficient method to simulate the evapotranspiration of corn. The results showed that evapotranspiration calculated by the dual crop coefficient method had a positive correlation with those values obtained by water balance methods, and the root mean square error was about 10 mm. In addition, the adjustment of the crop coefficient curve based on locally observed data is needed to achieve an accurate estimate of actual water requirements [21].

At present, there are many studies on estimating evapotranspiration by the dual crop coefficient method, but there are few reports on crop evapotranspiration in arid areas, especially those dealing with fruit trees in intercropping mode. In this study, evapotranspiration during the crop growth period was determined using the water balance method and a jujube/cotton intercropping system from 2015 to 2017. The present study aimed to: (1) use the dual crop coefficient method to simulate the compound evapotranspiration of jujube, cotton, and jujube/cotton intercropping in an arid region; (2) analyze how evapotranspiration during intercropping changes during and between years, in order to provide a theoretical basis for formulating an intercropping irrigation system of fruit trees and improving the soil moisture condition of orchards in arid regions of Southern Xinjiang.

2. Materials and Methods

2.1. Study Site

This study was carried out in the experimental base of Xinjiang Agricultural University in Aksu region of Xinjiang from 2015 to 2017 (80°14′ E, 41°16′ N). This region has a continental temperate

arid desert climate, with a wide temperature difference between day and night. The annual average total solar radiation is 544.115~590.156 kJ·cm⁻². The annual average sunshine hours is 2855~2967 h. The frost-free period is 205~219 d. The annual average precipitation is 74.4 mm. The annual average temperature is 11.2 °C. The annual average effective accumulated temperature is 3950 °C. The upper layer of soil (0~50 cm) is dominated by silty loam, and the lower layer (50~100 cm) is dominated by fine sand. The average dry bulk density is 1.39 g·cm⁻³. The field water holding capacity is 28%. The burial depth of groundwater is more than 10 m [22].

2.2. Study Design

The tested crops were cotton No. 49 Xinluzhong and 5-year-old jujube trees (2015). Cotton was sowed in mid-April and harvested in early November. Jujube trees entered the germination stage in late April and were harvested in mid-November. Jujube tree spacing was 1 m, and row spacing was 4 m. The drip irrigation belt was placed 30 cm away from each side against the tree trunk. Cotton was planted with four rows of one film and one belt. The distance between drippers of the drip irrigation belt was 20 cm, and the dripper flow rate was 1.38l/h. The film was 1.5 m wide and 0.05 mm thick. Plant spacing was 8 cm. The row spacing was 20-40-20 cm. The planting pattern is shown in Figure 1. Five treatments were performed in the experiment, one for jujube, one for cotton, and three for jujube/cotton intercropping according to the irrigation amount of jujube and cotton. The irrigation schedule for each treatment is shown in Table 1, and three replicates were set up for each treatment. The experimental designs for 2015, 2016, and 2017 are the same. However, the experimental field was irrigated at fixed irrigation time points by the fixed irrigation quota method from 2015 to 2016. In 2017, the P–M method [11] was used to guide irrigation in the experimental field and the irrigation period was 7 days. The irrigation amount was determined by the cumulative evapotranspiration of the previous irrigation cycle. The jujube crop coefficient was calculated as reported by Hong et al. [23]. The cotton crop coefficient was calculated as reported by Zhang et al. [24] and Ma et al. [25]. The fertilization and crop management were determined based on the local conditions.



Figure 1. Jujube/cotton intercropping pattern.

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lable I.	Irrigation	system of the	e jujube, co	otton, and	jujube/cotton	single intercro	pping model.

Jujube	Growing Stage	Spring Irrigation	Sprout Leaves	Flowering	Fruit Setting	Fruit Enlargement	Fruit Mature	Whole
Irrigation quota	2015–2016 2017	40 mm 40 mm	70 mm 52 mm	140 mm 217 mm	70 mm 52 mm	105 mm 110 mm	35 mm 0	460 mm 471 mm
Cotton	Growing Stage	Spring Irrigation	Seedling	Budding	Flowering	Boll Setting	Boll Opening	Whole
Irrigation	2015-2016	75 mm	0 mm	112.5 mm	112.5 mm	75 mm	37.5 mm	412.5 mm
quota	2017	75 mm	0 mm	128 mm	84 mm	98 mm	30 mm	415 mm

Z2: Single cropping of jujube, the irrigation quota for jujube trees is shown in the table. Z2M2: Jujube/cotton intercropping, the irrigation quota for cotton trees is shown in the table. Z1M2: Jujube/cotton intercropping, jujube trees caused a reduction of irrigation by 50% and no change in cotton. Z2M1: Jujube/cotton intercropping, jujube trees remain unchanged, and cotton reduced irrigation by 50%. M2: Single cropping of cotton, the irrigation quota for cotton trees is shown in the table.

2.3. Measurements

2.3.1. Crop Growth Indicators

After 20 days from the seedling stage and the bud stage, 10 cotton plants and 3 jujube trees were randomly selected in the test plot, and the plant height was measured with a ruler every other week until the end of the growing period. Then, we fit a quadratic function to daily plant height of cotton and jujube.

2.3.2. Crop Evapotranspiration

Previous studies have shown that root water uptake of young jujube mainly concentrated on the 0–100 cm soil layer [26–28], so this paper mainly studied the changes of soil moisture in the root zone of 0–100 cm jujube trees. The evapotranspiration of jujube root zone was calculated by water balance method:

$$ET_c = I + P - \Delta S - R - D \tag{1}$$

where ET_c is crop evapotranspiration (mm), *I* is the irrigation amount (mm), *P* is the rainfall amount (mm), ΔS is the change in soil water storage (mm), *R* is the surface runoff (mm), and *D* is the deep percolation (mm).

We assumed that the surface runoff was 0 mm, due to the use of drip irrigation. We assumed that the deep leakage was 0 mm, due to the fact that groundwater depth was over 10 m. Soil water storage was measured using the TRIME-IPH(TRIME-PICO-IPH, Channel tech, China) soil moisture measurement system. The determination time was before and after each irrigation and after each rainfall. If a crop had a change in growth stage, we measured soil moisture again. The exact location of instrument is shown in Figure 2.



(a) Single-crop jujube.

Figure 2. Cont.



(c) Jujube/cotton intercropping.

Figure 2. Location of measurement of soil moisture content points.

2.3.3. Crop Yield

At the end of the full growth period, 10 m² cotton and 10 jujube trees yields were collected in each test plot to calculate crop yield.

2.3.4. Meteorological Parameters

Meteorological data were measured every 30 min using a Watchdog (model 2700, spectrum Technologies, Inc, Aurora, Illinois, IL, USA) small automatic weather station to automatically observe temperature, radiation, rainfall, and other commonly used meteorological data.

2.4. Calculation of Evapotranspiration Using the Dual Crop Coefficient Method

According to the dual crop coefficient method recommended by FAO-56, the formula for calculating evapotranspiration under a single cropping mode is as follows:

$$ET = (K_S \cdot K_{cb} + K_e) ET_0 \tag{2}$$

where ET is the evapotranspiration (mm·d⁻¹), K_{cb} is the base crop coefficient, K_e is the evaporation coefficient of the soil surface evaporation, K_s is the water stress coefficient, and ET_0 is reference crop evapotranspiration (mm·d⁻¹). It is calculated from the meteorological data of the test field [11]. For other parameter determination methods, refer to Allen et al. [11].

2.5. Parameter Correction for the Dual Crop Coefficient Method

Based on the 2016 water balance method, the crop and soil parameters such as K_{cb} , p, Z_e , TEW, and REW in the dual crop coefficient method were corrected based on the evapotranspiration of single-crop jujube and cotton. In order to ensure that the model parameters were applicable to many regions, FAO-56 recommended standard values are based on a semi-humid area [11]. In the southern part of Xinjiang, China, the annual rainfall is much lower, resulting in increasing crop evapotranspiration. The basic crop coefficient of cotton increased by 10%~20% [29,30]. There is no reference value for the basic crop coefficient for jujube in FAO-56. In this study, the initial value of the basic crop coefficient in the middle stage of jujube growth was basically 1 under full irrigation, so the basic crop coefficient of jujube should also be adjusted to about 1. The soil water consumption coefficient (p) was mainly determined by crop species and external environment. The soil water consumption coefficient may decrease by 10%~25% [11] due to the test area environment.

The model parameters were corrected by a trial-and-error method [33]. First, we kept the soil parameters (Z_e , TEW, REW) unchanged and adjusted the crop parameters (K_{cb} , p); second, we kept the revised crop parameters unchanged and adjusted the soil parameters until the error was minimal and stable. The final calibration parameters are shown in Table 2.

	Relevant Parameters	J	ujube	Cotton		
	Relevant Futuricters	Initial Values	Calibrated Values	Initial Values	Calibrated Values	
	Evaporation depth of surface soil Ze: m	0.10	0.15	0.10	0.15	
Soil parameters	Total evaporative water in Surface Soil TEW: mm	26.00	39.00	26.00	39.00	
	Surface evaporable water Volume REW: mm	11.00	9.00	11.00	9.00	
	K _{cb-int}	0.45	0.40	0.15	0.20	
Crop parameters	K_{cb-mid}	0.85	1.00	1.15	1.20	
Crop parameters	K_{cb-end}	0.60	0.70	0.50	0.50	
	Soil water consumption coefficientp	0.50	0.50	0.65	0.40	

Table 2. Initial and calibrated values of soil parameters and crop-related parameters in dual crop coefficient method model.

2.6. Estimation of the Crop Coefficient under Compound Intercropping

Crop coefficients of intercropping patterns were derived from the two individual crop patterns, and their formulas are as follows [11]:

$$K_{\rm C} = \frac{f_1 h_1 K_{c1} + f_2 h_2 K_{c2}}{f_1 h_1 + f_2 h_2} \tag{3}$$

where f_1 and f_2 are the planting proportions of two crops under intercropping mode, respectively. h_1 and h_2 are the plant heights of two crops, respectively. We estimated daily plant height by fitting the measured data with a quadratic function in this paper. K_{C1} and K_{C2} are the crop coefficients of two crops, respectively. In addition, to reduce the effect of soil water stress on the simulation results, each crop coefficient needs to be multiplied by its respective water stress coefficient (K_s).

2.7. Data Processing and Analysis

In this paper, Office 2019, **DPS 9.5**, and **SPSS 22** were used to analyze data processing, variance analysis and significance test.

3. Results

3.1. Evaluation of Simulation Results in the Dual Crop Coefficient Method

3.1.1. Single-Crop Jujube and Cotton

Table 3 shows the comparison results between the measured and simulated values of evapotranspiration of jujube trees and cotton in 2015 (verification), 2016 (fixed), and 2017 (verification). Compared with other months, the simulation error of jujube and cotton during the middle and late stages of growth (August to September) increased abnormally during the three years. This may be due to the increased water absorption capacity of the root system caused by severe water stress [34,35], which affects the simulation accuracy. The determination and modification of water stress are involved in the dual crop coefficient method, which mainly depends on the soil water consumption coefficient p. For this purpose, based on the 2016 soil moisture content measurement, the soil water consumption coefficient p was calculated. That is, the actual water consumption coefficient p was calculated by inverse analysis based on the measured soil moisture content, the ET_c without water stress in the model, the water consumption in the root layer, and the total effective water content (TAW) in the root layer. We constructed a functional relationship between the root influence error (p_{practice}-p_{simulation}) and the moisture content (TAW-RAW) in the root layer, which is prone to water stress. We included the soil water consumption coefficient p corresponding to the occurrence of water stress ($K_s < 1$) during the whole growth period of jujube trees. For cotton, because the total effective water content (TAW) is affected by the depth of the cotton root layer, the value fluctuates greatly, which is not conducive to model revision. Therefore, in this paper, the relevant data after water control were selected to modify the simulation results from August to September. Its correction function is shown in Figure 3. The corrected simulation results are shown in Table 3. The simulation error statistics are shown in Table 4.

Time			Z2 Trea	tment		M2 Treatment				
	mit	Measurement	Simulation	Simulation Relative (Revise) Error		Measurement	Simulation	Simulation (Revise)	Relative Error	
	May	109.75 ± 5.34	101.34	107.15	-2.36%	37.51 ± 2.88	38.69	38.69	3.13%	
	June	126.37 ± 7.33	128.75	131.34	3.93%	93.7 ± 4.24	84.61	84.61	-9.70%	
2015	July	129.57 ± 5.85	124.22	125.52	-3.12%	133.63 ± 6.31	132.84	132.84	-0.59%	
2015	August	88.74 ± 3.14	87.72	87.36	-1.55%	124.73 ± 8.73	115.02	120.69	-3.24%	
	September	40.86 ± 3.46	35.49	37.69	-7.74%	31.32 ± 3.58	28.21	29.34	-6.32%	
	Total	495.27 ± 13.96	477.53	489.07	-1.25%	420.89 ± 23.46	399.37	406.16	-3.50%	
	May	97.07 ± 4.24	93.61	94.61	-2.54%	36.76 ± 4.15	35.98	35.98	-2.11%	
	June	127.66 ± 2.99	123.55	123.69	-3.11%	100.78 ± 9.82	94.45	94.45	-6.28%	
2016	July	137.14 ± 4.67	130.23	132.65	-3.27%	124.98 ± 8.03	126.94	126.94	1.56%	
2010	August	95.93 ± 6.54	97.17	97.87	2.02%	121.5 ± 7.78	115.80	119.91	-1.31%	
	September	40.73 ± 6.31	36.89	39.13	-3.93%	35.69 ± 3.76	32.06	33.34	-6.59%	
	Total	498.53 ± 16.75	481.45	487.94	-2.12%	419.71 ± 19.82	405.22	410.62	-2.17%	
	May	109.86 ± 8.27	115.80	117.16	6.65%	35.2 ± 1.75	38.04	38.04	8.06%	
	June	135.41 ± 6.36	122.65	124.80	-7.84%	106.33 ± 12.72	111.24	111.24	4.62%	
2017	July	133.6 ± 6.48	125.67	129.27	-3.24%	127.71 ± 6.09	121.70	121.70	-4.71%	
2017	August	99.62 ± 4.56	100.37	102.11	2.50%	110.56 ± 4.62	109.36	113.27	2.45%	
	September	39.34 ± 2.32	32.08	35.29	-10.31%	34.54 ± 4.27	31.72	32.99	-4.48%	
	Total	517.83 ± 17.56	496.57	508.63	-1.78%	414.34 ± 18.77	412.06	417.24	0.70%	

Table 3. Comparison of simulative and measure evapotranspiration of single crop in each month.

It can be seen from Table 4 that, on the whole, the regression coefficients of single-crop jujube and cotton were close to 1 for the three years, indicating that the simulated values and the observed values were statistically close, $R^2 = 0.871 \sim 0.911$, showing that the model is able to explain the variance of the observed data. The estimated error of the model is small, RMSE = $0.411 \sim 0.494 \text{ mm} \cdot \text{d}^{-1}$; AAE = $0.299 \sim 0.382 \text{ mm} \cdot \text{d}^{-1}$. The relative error is $-3.499 \sim 0.700\%$, and the absolute error is $-14.726 \sim 2.899 \text{ mm}$, indicating that the model does not overestimate or underestimate crop evapotranspiration. The modeling efficiency of all crops is very high (EF ≥ 0.846). Therefore, the simulation accuracy of this model is high, and the simulation results can be used for related subsequent research.



Figure 3. Correction of soil water consumption coefficient p under water deficit.

Table 4. Error statistics of simulated and measured evapotranspiration in single-crop jujube and cotton.

Year	Treatment	b	R ²	EF	RE	AE	RMSE	AAE
icui	incutificati	v	ĸ	LI	%	mm	$mm \cdot d^{-1}$	$mm \cdot d^{-1}$
2016	Z2	0.955	0.894	0.887	-2.123	-10.583	0.411	0.337
(calibration)	M2	0.933	0.911	0.897	-2.166	-9.091	0.463	0.367
2015	Z2	1.016	0.871	0.846	-1.253	-6.205	0.453	0.356
(verification)	M2	0.990	0.906	0.906	-3.499	-14.726	0.494	0.382
2017	Z2	0.933	0.900	0.896	-1.776	-9.196	0.413	0.323
(verification)	M2	0.957	0.908	0.905	0.700	2.899	0.445	0.299

EF: Error factor; RE: Relative error; AE: Absolute error; RMSE: Root mean square error; AEE: Average absolute estimation error

3.1.2. Jujube/Cotton Intercropping

The simulated error statistics of crop evapotranspiration in the 3a intercropping mode are shown in Table 5. It can be seen from Table 5 that the b-numbers of the regression lines for all intercropping setups are close to 1.0, indicating that the predicted evapotranspiration was close to the observed value. The higher R² value (>0.797) indicates that most of the observed variance could be explained by the model (RMSE = $0.383 \sim 0.667 \text{ mm} \cdot \text{d}^{-1}$; AAE = $0.316 \sim 0.540 \text{ mm} \cdot \text{d}^{-1}$). Although the simulation accuracy was lower than that for single crops, the decrease was within the acceptable range. Therefore, the modified dual crop coefficient can effectively simulate the change in total evapotranspiration in a jujube/cotton intercropping setup in the experimental area.

Table 5. Error statistics of simulated and measured evapotranspiration under intercropping mode.

Year	Treatment	h	<i>R</i> ²	EF	RE	AE	RMSE	AAE
		U		21	%	mm	mm∙d ^{−1}	$mm \cdot d^{-1}$
	Z2M2	0.975	0.849	0.828	-1.753	-7.695	0.448	0.356
2015	Z1M2	0.885	0.847	0.844	1.504	5.417	0.477	0.399
	Z2M1	1.061	0.797	0.700	4.139	16.678	0.616	0.482
	Z2M2	0.999	0.841	0.805	2.881	13.447	0.472	0.338
2016	Z1M2	0.965	0.852	0.838	0.110	0.424	0.383	0.316
	Z2M1	0.925	0.814	0.795	2.442	10.760	0.476	0.376
	Z2M2	0.944	0.814	0.830	0.433	2.118	0.623	0.424
2017	Z1M2	0.918	0.837	0.830	0.636	2.501	0.538	0.414
	Z2M1	0.803	0.827	0.770	3.997	17.766	0.667	0.540

EF: Error factor; RE: Relative error; AE: Absolute error; RMSE: Root mean square error; AEE: Average absolute estimation error

3.2. Variation of Evapotranspiration in Single-Crop Jujube and Cotton

The measured values of crop evapotranspiration in the 3a single-cropping mode are shown in Figure 4, where the average Z2 + M2 is the weighted average of single-crop jujube and cotton according to planting area. Values followed by different small letters within figure are significantly different at 0.05 level. It can be seen from Figure 4 that the evapotranspiration of a single-crop jujube tree increased exponentially, from 495.27 to 498.52 mm and then to 517.83 mm. Single-crop cotton basically had no changes during the three years, and the overall evapotranspiration was steady at 414.34~420.89 mm. Comparing Z2M2 and average Z2 + M2 in 2015, the two values are similar, with a difference of only 2.19%. Over the course of the study, the difference gradually expanded, and by 2017 the difference reached 7.96%. This shows that the evapotranspiration in the intercropping mode increased significantly compared to the single cropping mode. There are two possible reasons for this situation: (1) due to the planting model, the root development of the two crops improved, and the ability to extract water from soil and shallow groundwater levels improved [36,37]; (2) intercropping enhanced sunlight retention, aerodynamic canopy roughness, and micro advection energy. Intercropping promotes crop physiological development significantly better than single cropping and increases evapotranspiration [38].



Figure 4. Comparison of measured values of crop evapotranspiration in 3a single and intercropping mode.

When the jujube tree irrigation amount was adjusted (Z1M2), the evapotranspiration of intercropping decreased significantly, and the difference between Z1M2 and Z2M2 increased from 78.69 mm to 96.01 mm with time. Similarly, when the cotton irrigation amount was adjusted (Z2M1), the evapotranspiration of intercropping also decreased significantly (26.10~44.67 mm), but the decrease was smaller than that of Z1M2 treatment. This shows that in the intercropping system, the jujube was less adaptable to water deficiency than cotton, and was more susceptible to competition between species, and that the evapotranspiration appeared to decrease. In addition, for the Z1M2 and Z2M1 treatment, due to the interannual changes, it can be seen that the 6-year-old jujube tree was an important node in the intercropping mode. When the age of jujube reached 6 years, if intercropping was still carried out in the next year, the increase in interspecies competition was easily caused by the adjustment of irrigation volume. The growth and development of the fruit tree was obviously weakened.

3.3. Yield of Single-Crop Jujube and Cotton

Figure 5 shows the yield of jujube and cotton crops under single-cropping mode. Values followed by different small letters within figure are significantly different at 0.05 level. The crop yield of the single-crop jujube tree steadily increased with time, reaching 3321.84 kg·ha⁻¹ in 2017, while cotton is

an annual crop, and the output remained at 2624.67~2774.19 kg·ha⁻¹. When intercropping was carried out, the interspecies complementary effect was obvious in 2015, and the crop yield, especially cotton yield, increased by 26.47%. However, as the age of jujube trees increased, the intensity of interspecies competition increased, and jujube and cotton yields declined. As of 2017, jujube production fell by 9.25% and the cotton yield increased by 20.33%.



Figure 5. Yield of jujube and cotton crops under single cropping and intercropping mode.

After adjusting the irrigation amount of jujube trees, the jujube tree output decreased by 10.90% in 2015. During the following two years, the jujube tree output remained basically unchanged. It shows that adjusting the irrigation amount of jujube trees is very unfavorable to the growth and development of jujube trees and causes serious reduction of fruit production. When the cotton irrigation was adjusted, the jujube yield in 2015 decreased by 2.22%. The jujube yield in 2016 was similar to that in 2015, but increased by 10.14% in 2017. This indicates that under the sufficient water support of intercropping jujube trees, when the fruit trees reach 7 years of age, the interspecies competitiveness will be significantly improved, leading to an increased crop yield. As for cotton yield, from Z2M2, Z1M2, and Z2M1 treatments, we can see that the adaptability of cotton to water deficit was significantly higher than that of jujube trees. Under high-intensity interspecies competition conditions, cotton yield was significantly less affected than jujube tree.

4. Discussion

A lot of research has been done on the estimation of crop water demand in arid areas [39]. Zhao et al. [40] found large errors between measured soil evaporation and simulated soil evaporation when using the dual crop coefficient method. In this paper, it was found that when the daily average evapotranspiration of jujube or cotton was at the peak, most of the measured values were higher than the simulated values. We believe that after heavy rain or irrigation, the soil water content of the surface is basically equal to the soil water holding capacity. Water evaporation rate is only affected by the hydraulic characteristics of soil with energy obtained from the surface [41]. Therefore, the soil evaporation is closely related to the depth of evaporation accumulation in this stage. High-temperature weather can increase the accumulated depth of evaporation Ze, leading to increased evapotranspiration. Ze is selected according to soil properties, which are not related to meteorological factors. This may cause the error in Ze to increase due to extreme weather or other special conditions.

The leaf area index is often used to measure the plant canopy development, and is an important indicator used to describe the physiological development and yield of crops in agriculture [42,43]. It is also one of the indispensable indicators for model simulation [44]. The height of the plant represents the growth and development of the plant, and can be used to measure the physiological development of the

plant. To this end, the dual crop coefficient method simplified the analysis of interspecies competition during intercropping by selecting two representative influencing factors, surface coverage and plant height, to construct a model. The resulting model had good representativeness and applicability in analyzing crop water consumption. This study used the weighted average method on FAO-56, which mainly considered the physiological changes of the plants above ground, but ignored the physiological development of the underground parts of the plant. Related studies have shown that the higher the degree of plant coverage, the better the growth and the more developed the root system [45], but some studies have shown that the external environment also has a great impact on the development of the root system [46], and may even have a lower degree of coverage. Therefore, surface coverage alone cannot describe the development of underground root systems. Some researchers have also found that intercropping can significantly improve the total root system and water absorption capacity of crops [47]. The dual crop coefficient method model uses an approximately linear growth model when simulating root growth, which will cause errors in the simulation of root water absorption and affect the simulation of evapotranspiration.

In some arid areas, due to the lack of water resources, the crop irrigation volume is not able to meet the physiological needs of the crop. Therefore, it is necessary to explore the effect of adjusting the crop irrigation volume on the accuracy of the model simulation. In the jujube/cotton intercropping competition system, research by Li et al. [7] showed that cotton dominates the intercropping system. This study found that when the irrigation amount was adjusted, the effect on cotton yield was significantly lower than that on jujube tree yield. When the model was used for simulation, after adjusting the cotton irrigation amount, the model simulation accuracy decreased. Therefore, we believe that in the intercropping system, reducing the amount of cotton irrigation will cause cotton to plunder the soil moisture from the root zone of jujube trees, increasing the intensity of interspecies competition. The actual degree of water deficiency for cotton was lower than our estimate. The expected water deficit will eventually lead to impaired model simulation accuracy. Regarding regulating the irrigation amount for jujube trees, the competitiveness of jujube trees is significantly lower than that of cotton, leaving the jujube trees with a water deficit while cotton remains unaffected. The model has been corrected for the jujube deficiency, so the simulation accuracy is higher when simulating Z1M2 processing.

5. Conclusions

Estimating evapotranspiration of jujube, cotton, and jujube/cotton intercropping using modified dual crop coefficient method. The simulation error of single-crop jujube and cotton is $R^2 > 0.871$, RMSE = 0.411 ~ 0.494 mm·d⁻¹. The simulation error of intercropping is $R^2 > 0.797$, RMSE = 0.383 ~ 0.667 mm·d⁻¹. This illustrates the model has good applicability to simulate single-crop jujube trees and cotton, and jujube/cotton intercropping. However, compared with single cropping, the accuracy of simulated daily evapotranspiration was decreased from intercropping. In addition, we found adjusting the cotton irrigation amount caused the simulation accuracy to further decrease.

From the perspective of interspecific complementarity and competition, cotton dominates the intercropping system. For jujube trees, the intercropping model showed a negative effect as a whole. After adjusting crop irrigation, both crop evapotranspiration and crop yield decreased by varying degrees. Due to the fact that cotton has a large competitive advantage, it is more tolerant to changes in the external environment than jujube trees, and the difference in crop yields between different intercropping treatments is small. The intercropping jujube trees were significantly different among treatments. Among them, the 6-year-old jujube tree is an important node in the intercropping mode. When the jujube reaches 7 years of age, its interspecies competitiveness is significantly improved. Under water constraints, this increase in competitive intensity is not apparent in terms of yield.

From the perspective of economic benefits, this paper proposes to use 5-year-old jujube trees for intercropping. Due to the fact that the cotton yields increased by 26.47% at this time under the effect of interspecific complementation, the yield of intercropping jujube trees was similar to that of single crops.

As the jujube tree age increases, the increase in cotton production will gradually diminish. The jujube tree will also have a significant reduction in yield due to interspecific competition.

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