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Optimizing Cotton Row Configuration in Jujube–Cotton Intercropping Systems Improves Their Productivity, Net Effects, and Sustainability

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Abstract: The bare row spacing between young jujube trees reduces resource use efficiency. Planting cotton between rows of jujubes can improve the efficiency of light, heat, water, and temperature resources. However, it is not clear how many rows of cotton between the jujube rows would be the most suitable pattern. A field study with different cropping systems was performed to investigate the land equivalent ratio (LER), the competition of cotton to jujube, and the sustainability index. The treatments included (1) monoculture jujube, (2) monoculture cotton, (3) jujube intercropped with two rows of cotton (J/C2), (4) jujube intercropped with four rows of cotton (J/C4), and (5) jujube intercropped with six rows of cotton (J/C6). The results showed that the LER under the J/C2, J/C4, and J/C6 systems were 1.17, 1.30, and 1.28, respectively. The LER and total yield were higher under J/C2 than under the J/C4 and J/C6 treatments. The overyielding rate of cotton was increased, while those of jujube were decreased with increasing rows of cotton. The competition between cotton to jujube was less than 0. The net, complementarity, selection effect, and sustainability index were significantly higher under J/C4 and J/C6 than under J/C2, with J/C4, showing stronger net effects. Both complementarity and selection effects contributed to the intercropping yield advantages. Comprehensively considering yield, economic efficiency, sustainability index, land use efficiency, and net effect, J/C4 is one of the most productive and sustainable planting patterns of jujube–cotton intercropping system in southern Xinjiang, which is the more ideal pattern in arid and semi-arid regions.

Keywords: jujube–cotton intercropping systems; cotton row configuration; productivity; net effects; sustainability



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1. Introduction

Xinjiang province in northwestern China is a typical arid area that is facing several ecological and environmental problems, such as drought climate, water shortage, and water and soil desertification, which greatly limit the sustainable development of agriculture [1,2]. However, the region has abundant light and heat resources, with large diurnal temperature differences [3], and can provide good habitats for crop growth. Jujube (*Zizyphus jujube* Miller) is an economically important fruit tree across the world. China is the world's main producer of jujubes, accounting for a large proportion of the world's total output [4], and Xinjiang's jujube production, in particular, accounts for more than half of China's total output [5]. Recently, the cultivated area of jujubes in Xinjiang is ranked first in the country, and most of it is distributed around the Taklamakan Desert [6]. Therefore, the development of the jujube industry is crucial to the sustainable development of agriculture in Xinjiang.

However, the bare row spacing between jujube trees reduces land use efficiency [7], and it is necessary to further optimize the planting structure to improve resource use efficiency.

Intercropping can increase the utilization efficiency of resources and land, and it is an important means to guarantee food security, diversify cropping systems, and promote sustainable agricultural development [8,9]. In Xinjiang, farmers commonly intercrop jujube with cotton to improve land use patterns [10]. This planting system plays crucial roles in reducing wind erosion, adjusting the agricultural microclimate, improving environmental conditions, and providing economic benefits [11,12]. In recent years, the jujube–cotton intercropping system has been widely used in southern Xinjiang and gradually promoted in northern Xinjiang [13]. However, it is a complex system with high environmental heterogeneity [14]. Jujube and cotton compete with each other for available resources to meet their own growth needs, which appears to have negative implications for system productivity and sustainability [15,16].

The selection and complementarity effects suggest that more diverse mixtures achieve a spatial and temporal ecological niche segregation among species, an interspecific facilitation through habitat improvement or resource enrichment, or a reduced interspecific competition, leading to greater access to finite resources and, thus, increased productivity [17,18]. The adjustment of planting patterns based on the row spacing configuration of cotton is an important field management measure to harmonize microenvironmental strips, such as light, temperature, and moisture [19]. The selection of an appropriate row spacing configuration is an important measure to improve the morphological characteristics of cotton and fully utilize light energy, which will improve the photosynthetic efficiency, effectively reduce the cost of production, and achieve high crop yields [20,21]. Therefore, it is necessary to investigate how to carry out appropriate row spacing configurations of cotton in jujube–cotton intercropping systems, reduce the competition between the two, and promote complementarity, which, in turn, will improve yields and land use efficiency and promote the sustainability of jujube–cotton intercropping systems.

The bare row spacing between jujube trees reduces land use efficiency. Planting cotton between jujube rows can improve resource efficiency. However, how many rows of cotton are the most appropriate pattern to plant between jujubes is still unclear. To explore the appropriate number of rows of cotton to plant to improve the sustainability of jujube plantations, a jujube–cotton intercropping field experiment with three different planting rows of cotton was performed to (i) investigate the effects of row spacing configurations of cotton on crop yield and land equivalent ratio; (ii) clarify the selection and complementarity effects of the jujube–cotton intercropping system; and (iii) assess the sustainability of the system. We hypothesized that moderate row spacing configurations of cotton would improve the productivity, land use efficiency, complementary effects, and sustainability of jujube–cotton intercropping systems.

2. Materials and Methods

2.1. Study Site

This study was conducted at the Horticultural Experiment Station of Tarim University in Alar City, Xinjiang province (40°32′34″ N, 81°18′07″ E), from 2019 to 2021, at an altitude of 1015 m. The experimental site is located at the upper reaches of the Tarim River and the northwestern edge of the Taklamakan Desert. The average annual solar radiation is 559.4–612.1 kJ cm^{−2}, the sunshine hours are about 2996 h, the average annual temperature is 10.8 °C, the average annual precipitation is 40.1–82.5 mm, and the average annual evaporation is 558.9 mm. The soil type is sandy loam, with a pH of 7.90, organic matter of 11.20 g kg^{−1}, total nitrogen of 1.51 g kg^{−1}, available phosphorus of 58.70 × 10^{−3} g kg^{−1}, and available potassium of 107.34 × 10^{−3} g kg^{−1}.

2.2. Experimental Design

The field experiment followed a randomized complete block design with three replications. The cropping systems comprised two monocropping and three intercropping

systems: (1) monoculture jujube, (2) monoculture cotton, (3) jujube intercropped with two rows of cotton (J/C2), (4) jujube intercropped with four rows of cotton (J/C4), and (5) jujube intercropped with six rows of cotton (J/C6) (Figure 1). The area of the monocropping systems was 120 m², and the area of jujube and cotton planting under the intercropping systems was 40 and 80 m², respectively. The plant spacing of jujube was 1 m, and for cotton, it was 11.5 cm. The test jujube garden was planted with sour jujube in 2012, grafted with gray jujube in 2014, and repaired in 2019. The cotton variety was Xinluzhong No. 82. Both cotton and jujubes were largely harvested around the 20th of October. Except for the cropping systems, all agronomic practices in this study were kept consistent.

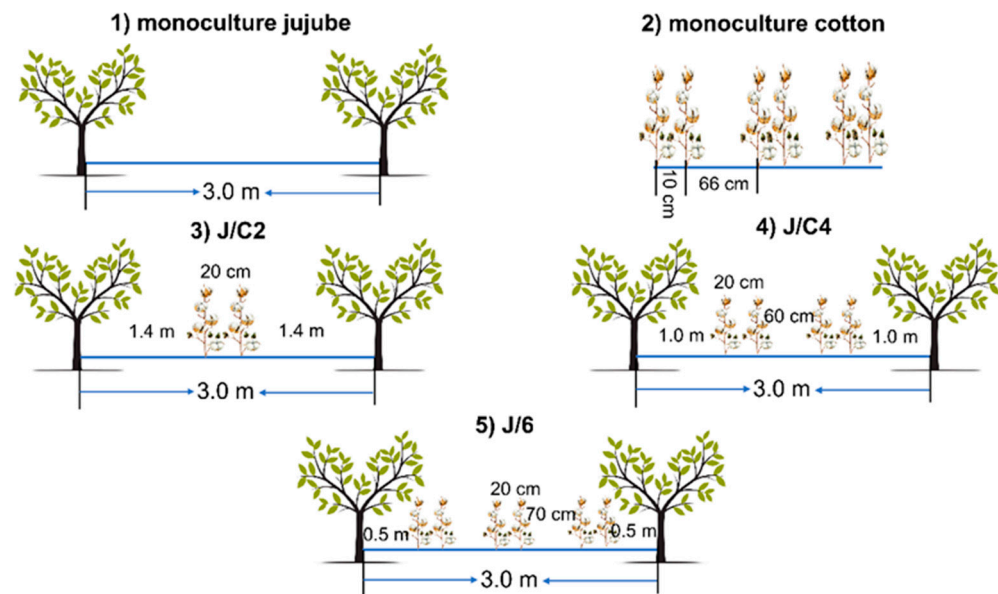


Figure 1. Layout of jujube and cotton cropping patterns and field locations.

2.3. Measurements and Calculations

2.3.1. Yield and Land Equivalent Ratio (LER)

At maturity, all jujube and cotton were manually harvested in each plot, and the grains from each plot were weighted to calculate the yield per hectare (kg ha^{−1}). The LER was used to assess land productivity in each intercropping system and was calculated using the following equation [22]:

$$LER = PLER_j + PLER_c = \frac{Y_{ji}}{Y_{jm}} + \frac{Y_{ci}}{Y_{cm}}$$

where Y_{ji} and Y_{ci} represent the yield of jujube and cotton in the intercropping systems; Y_{jm} and Y_{cm} represent the yield of jujube and cotton in the monocropping systems; and $PLER_j$ and $PLER_c$ represent the partial LER of cotton and jujube, respectively. An LER greater than 1 indicates a land productivity advantage in the intercropping systems.

2.3.2. Overyielding Rate

The extent to which intercropping increases or decreases yield or biomass compared to monocropping was calculated using the following equation [23]:

$$\text{Overyielding rate} = \frac{Y_i - P \times Y_m}{P \times Y_m} \times 100\%$$

where Y_i and Y_m represent the jujube (or cotton) yield in the intercropping and monocropping systems, respectively. P indicates the land ratio of the crop in the intercropping system; for cotton, it is 2/3; for jujube, it is 1/3.

2.3.3. Competition between Cotton and Jujube

The competition between cotton and jujube for water, nutrients, and other relevant resources in intercropping was calculated using the following equation [24]:

$$A_{cj} = \frac{Y_{ci}}{Y_{cm} \times P_c} - \frac{Y_{ji}}{Y_{jm} \times P_j}$$

where A_{cj} indicates the competition between cotton and jujube in the intercropping system; Y_{ci} and Y_{ji} represent the yield of jujube and cotton in the intercropping system; Y_{cm} and Y_{jm} represent the yield of jujube and cotton in the monocropping system; P_c and P_j indicate the land ratio of cotton and jujube in the intercropping system, respectively: for cotton, it is 2/3; for jujube, it is 1/3. An $A_{cj} > 0$ indicates that cotton is competitively stronger than jujube.

2.3.4. Net Effect (NE), Complementarity Effect (CE), and Selection Effect (SE)

NE, CE, and SE were calculated using the following equations [25]:

$$\begin{aligned} NE &= (Y_{ci} + Y_{ji}) - (Y_{mc} \times P_c + Y_{jm} \times P_j) \\ CE &= \left(\left(\frac{Y_{ci}}{Y_{cm}} + \frac{Y_{ji}}{Y_{jm}} \right) - 1 \right) \times \left(\frac{Y_{cm} + Y_{jm}}{2} \right) \\ SE &= NE - CE \end{aligned}$$

where Y_{ji} and Y_{ci} represent the yield of jujube and cotton in an intercropping system, and Y_{jm} and Y_{cm} represent the yield of jujube and cotton in a monocropping system, respectively. P indicates the land ratio of the crop in the intercropping system: P_c is 2/3; P_j is 1/3.

2.3.5. Sustainability Index

A sustainability index (SI) was created for the intercropping systems based on yield, LER, overyielding rate, competition, net effect, complementarity effect, and selection effect using the following equation [26].

$$\alpha_{xi} = \frac{x_{xj}}{x_{max}} \left(\begin{matrix} i=1,2,3 \\ j=1,2,3,...12 \end{matrix} \right)$$

where α_{xj} is a standard value ($0 < \alpha_{xj} \leq 1$) at the i th treatment and the j th variable. X_{max} is the maximum value for each variable. The sustainability index is also utilized in the following equation:

$$\beta X_{ij} = \frac{1}{\alpha_1 X_{ij}} \times \sqrt{\frac{1}{m} \sum_{i=1}^m (\alpha_1 X_{ij} - \alpha_2 X_{ij})^2} \left(\begin{matrix} i=1,2,3 \\ j=1,2,3,...12 \end{matrix} \right)$$

where βX_{ij} is the coefficient of variation for each parameter and m is the maximum number for i or j .

$$SI = \sum_{j=1}^m \left(\alpha X_{ij} \times \frac{\beta X_{ij}}{\sum_{j=1}^m \beta X_{ij}} \right) \left(\begin{matrix} i=1,2,3 \\ j=1,2,3,...12 \end{matrix} \right)$$

2.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed to evaluate the effects of planting rows of cotton in a jujube–cotton intercropping system using SPSS 22.0 (IBM Chicago, IL, USA). The least significant difference (LSD) test was used to compare the mean treatment values, with $p < 0.05$ considered significant. Linear regression was used to analyze the relationships between the LER and the net, complementarity, and selection effects.

3. Results

3.1. Yield and Land Equivalent Ratio (LER)

In the intercropping systems, the cotton yield increased with an increase in planting rows, while the jujube yield showed an opposite trend (Table 1). The cotton yield under J/C6 and J/C4 increased by 102.2% and 30.3%, whereas the jujube yield decreased by 12.5% and 41.3%, respectively, compared to J/C2. The jujube yield in different years showed a trend of 2021 > 2020 > 2019. However, intercropping produced significantly higher yields than monocropping. The LERs of the three intercropping systems were all greater than 1 (Table 1). Across the three years, the LER under the J/C2, J/C4, and J/C6 systems was 1.17, 1.30, and 1.28, respectively. The LER under the J/C4 and J/C6 systems increased by 11.1% and 9.4%, respectively, compared to the J/C2 system. The partial LER of cotton under the three intercropping systems increased with the number of planting rows of cotton, while that of jujube exhibited a decreasing trend. It is interesting to note that the partial land equivalence ratios of cotton and jujube were both greater than 0.5 under the J/C2 system.

Table 1. Effects of different cropping systems on yield of cotton and LER in 2019–2021.

Year	Treatment	Cotton		Jujube		PLER _c	PLER _j	LER
		Inter	Mono	Inter	Mono			
2019	J/C2	2141 ± 324 c	5312	1102 ± 36 a	1678	0.40 c	0.66 a	1.06 b
	J/C4	3498 ± 16 b	5312	1032 ± 40 a	1678	0.66 b	0.62 a	1.28 a
	J/C6	4534 ± 175 a	5312	785 ± 7 b	1678	0.86 a	0.47 b	1.33 a
2020	J/C2	2146 ± 117 c	5269	3927 ± 203 a	4973	0.41 c	0.79 a	1.20 a
	J/C4	3151 ± 97 b	5269	3235 ± 99 b	4973	0.60 b	0.65 b	1.25 a
	J/C6	4247 ± 117 a	5269	1900 ± 103 c	4973	0.81 a	0.38 c	1.19 a
2021	J/C2	2148 ± 213 c	5658	4582 ± 246 a	5275	0.38 c	0.87 a	1.25 b
	J/C4	3339 ± 220 b	5658	4140 ± 134 a	5275	0.59 b	0.79 a	1.38 a
	J/C6	4233 ± 295 a	5658	2956 ± 91 b	5275	0.75 a	0.56 b	1.31 a
Average	2019	3391 ± 365 a	5312	973 ± 51 c	1678	0.64 a	0.58 b	1.22 b
	2020	3181 ± 311 a	5269	3021 ± 306 b	4973	0.61 a	0.61 b	1.21 b
	2021	3240 ± 326 a	5658	3893 ± 257 a	5275	0.57 a	0.74 a	1.31 a
	J/C2	2145 ± 123 c	5413	3203 ± 542 a	3975	0.39 c	0.77 a	1.17 b
	J/C4	3329 ± 97 b	5413	2802 ± 464 b	3975	0.62 b	0.69 b	1.30 a
	J/C6	4338 ± 115 a	5413	1880 ± 316 c	3975	0.80 a	0.47 c	1.28 a
	T	***	—	***	—	**	**	**
	Y	ns	**	***	**	—	**	**
	T × Y	ns	—	***	—	—	**	—

Within a column, mean values ± standard error with different lowercase letters indicate significant differences at $p < 0.05$. J/C2, J/C4, and J/C6 represent jujube intercropped with two, four, and six rows of cotton, respectively. T means intercropping treatments, Y means year, T × Y means the interaction between intercropping treatments and year. ** $p < 0.05$; *** $p < 0.001$; —, $p > 0.05$. PLER_c and PLER_j represent the partial land equivalence ratio of cotton and jujube, respectively.

3.2. Overyielding Rate and Competition

The overyielding rate of cotton under the J/C6 system and that of jujube under the J/C2 system were greater than 0 (Figure 2). The overyielding rate of cotton under the J/C6 system was higher than under the J/C2 and J/C4 systems, and that of jujube under the J/C2 was higher than under the J/C4 and J/C6 systems. The competition between cotton and jujube under the different intercropping systems was almost less than 0 (Figure 3) and was significantly influenced by the planting rows of cotton, exhibiting the trend of J/C6 > J/C4 > J/C2. Compared to J/C2, the competition between cotton and jujube under J/C6 and J/C4 increased by 0.51 and 1.25 in 2019, 0.71 and 1.83 in 2020, and 0.57 and 1.49 in 2021, respectively.

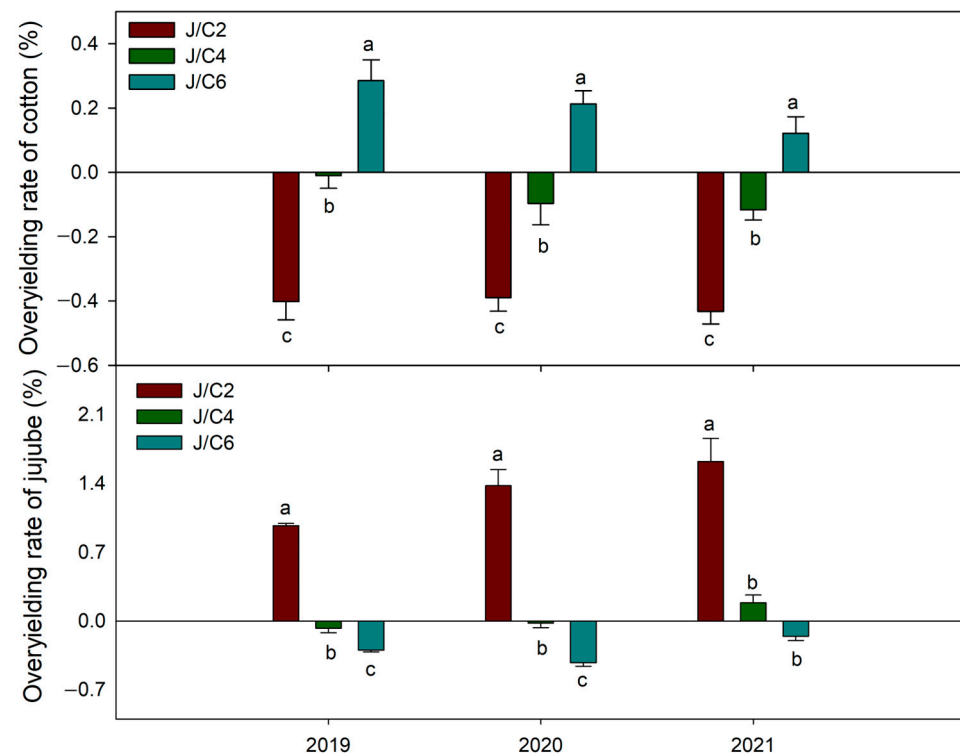


Figure 2. Overyielding rate of cotton and jujube under different intercropping systems. J/C2, J/C4, and J/C6 represent jujube intercropped with two, four, and six rows of cotton, respectively. Bars with different letters indicate significant difference at $p < 0.05$.

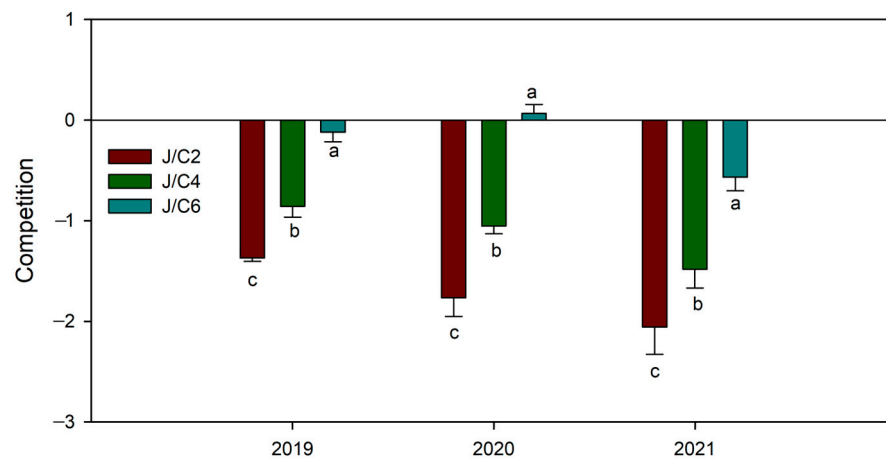


Figure 3. Competition between cotton and jujube under different intercropping systems. J/C2, J/C4, and J/C6 represent jujube intercropped with two, four, and six rows of cotton, respectively. Bars with different letters indicate significant difference at $p < 0.05$.

3.3. Net Effect, Complementarity Effect, and Selection Effect

The net effect increased with an increase in planting rows of cotton in 2019, while it was higher under the J/C4 system than under the J/C2 and J/C6 systems in 2020 and 2021 (Figure 4). Across the years, the net effect under J/C4 and J/C6 increased by 189.0% and 209.8%, respectively, compared to that under J/C2. The change in complementarity effect under the three intercropping systems was similar to the net effect. The complementarity effect in 2019 increased by 493.3% and 724.8% under the J/C6 and J/C4 systems, respectively, compared to the J/C2 system. Compared to J/C2 and J/C6, the complementarity effect under J/C4 increased by 35.0% and 40.5% in 2020 and by 65.5% and 26.8% in 2021, respectively. The selection effect under the J/C4 and J/C6 systems was higher than under

the J/C2 system in all three years. Compared to J/C2, the selection effect under J/C4 and J/C6 increased by 770 and 1316 kg ha⁻¹ in 2019, 101 and 94 kg ha⁻¹ in 2020, and 190 and 198 kg ha⁻¹ in 2021, respectively.

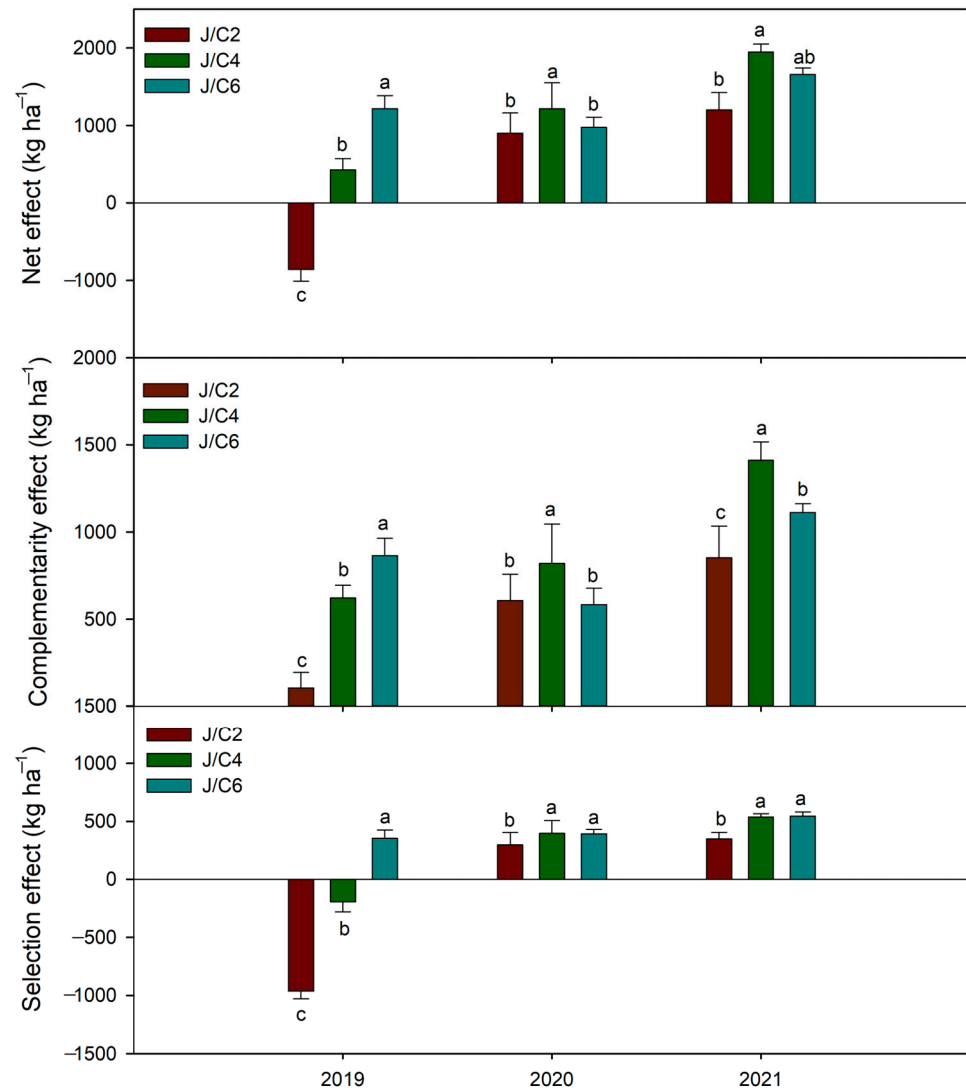


Figure 4. Net effect, complementarity effect, and selection effect under different intercropping systems. J/C2, J/C4, and J/C6 represent jujube intercropped with two, four, and six rows of cotton, respectively. Bars with different letters indicate significant difference at $p < 0.05$.

3.4. Effects of Planting Density and Nitrogen Application on Soil Physical and Chemical Properties

The sustainability index was used to assess the effectiveness or sustainability of the jujube–cotton intercropping systems with different planting rows of cotton (Figure 5). Across all three years, the index was higher under the J/C4 and J/C6 systems than under the J/C2 system, increasing by 44.2% and 47.2%, respectively, compared to the J/C2 system. Therefore, the J/C4 and J/C6 treatments were more sustainable and effective.

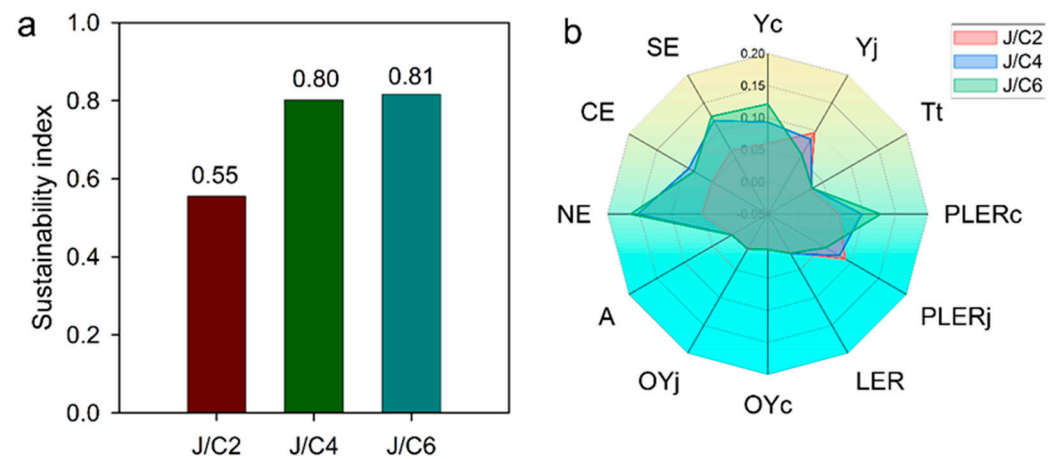


Figure 5. The sustainability index of different intercropping systems (a), and performance of evaluated components for different intercropping systems using radar chart (b). J/C2, J/C4, and J/C6 represent jujube intercropped with two, four, and six rows of cotton, respectively.

3.5. Relationships between LER and Net, Complementarity, and Selection Effects

Linear regression was used to evaluate the relationships between the LER and net, complementarity, and selection effects (Figure 6). The land equivalent ratio was positively correlated with the net effect ($r = 0.82, p < 0.001$), complementarity effect ($r = 0.71, p < 0.001$), and selection effect ($r = 0.94, p < 0.001$).

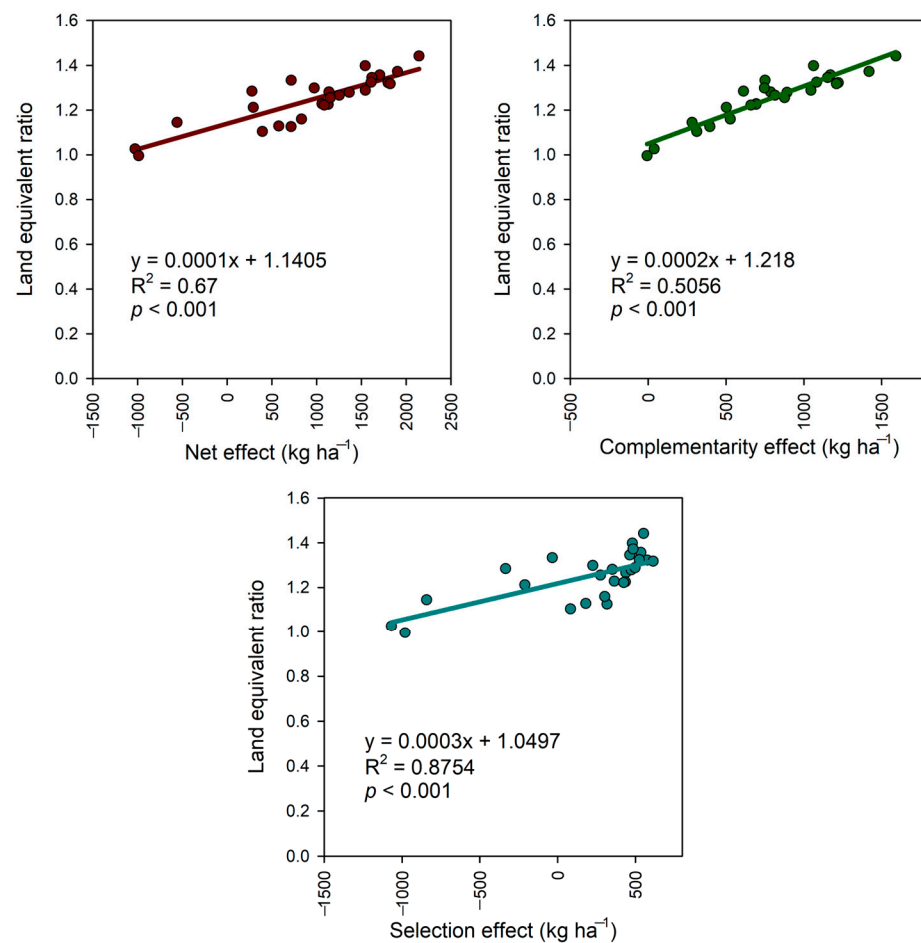


Figure 6. Relationships between land equivalent ratio and net, complementarity, and selection effects.

4. Discussion

4.1. Yield and LER

Cotton and jujube are specialty crops in Xinjiang, and the yields of both are significantly affected by planting patterns and farm management practices in addition to genetic factors [27,28]. An increasing number of studies have recognized crop diversification (jujube–cotton intercropping) as an effective strategy for increasing and maintaining crop productivity [28,29]. In addition, several studies have focused on the effect of the spatial pattern of cultivation on cotton productivity. Zuo et al. (2024) found that optimizing the number of rows of cotton planted increased cotton yield by improving the photosynthetic characteristics of the population [30]. Therefore, this raises the question of how to rationalize the arrangement of cotton planting under the intercropping system. In the present study, it was found that the cotton yield increased with an increase in the number of rows planted, while the jujube yield showed the opposite trend in the jujube–cotton system. The main reason for this result was the competition between cotton and jujube species during the sympatric period [31]. An increase in the number of cotton rows promotes higher rates of increase and yield of cotton, while high cotton yields will inevitably cause more nutrient and water consumption and more competition with jujube trees, thus weakening jujube yields, and the opposite is true. Moreover, although intercropping cotton among jujube trees reduced yields compared to monocropping jujube trees, the intercropping system produced significantly higher yields than monocropping. The LER is an important indicator for intercropping systems, with values greater than 1 indicating intercropping advantages [32]. In this study, we found that the LER under the three intercropping treatments was greater than 1 and showed the trend of $J/C4 > J/C6 > J/C2$, indicating that all of them had intercropping advantages, with $J/C4$ showing stronger intercropping advantages. This was mainly because both the PLER of cotton to jujube and jujube to cotton were greater than 0.5, making the sum of these two much greater than the other two treatments [33]. In conclusion, $J/C4$ is a suitable cropping pattern to improve the yield and LER of intercropping systems.

4.2. Net, Complementarity, and Selection Effects with Crop Productivity

In an intercropping system, there is competition or complementarity between two crops and a combination of both, which together determine the productivity of the system [34]. The net effect was used to assess the difference between the observed and desired yields, with larger values indicating a more pronounced intercropping advantage [25]. In this study, we found that the NE was greater than 0 under both $J/C4$ and $J/C6$, with $J/C4$ displaying a higher NE, indicating a stronger positive effect of intercropping. The net effect is further categorized into complementarity and selection effects [35]. In intercropping systems, selection or complementarity effects are exhibited between crops depending on the length of the crop symbiosis period [36]. Surprisingly, both the complementarity and selection effects were higher for $J/C4$ and $J/C6$ than for $J/C2$ in this study, suggesting that increasing the number of planted rows of cotton in this intercropping system promotes both the selection and complementarity effects for increased yield. This study also found that the LER was positively correlated with the net, complementarity, and selection effects. It further indicated that for a jujube and cotton intercropping system, a reasonable row spacing configuration of cotton could promote the net effect, thus improving the intercropping advantage. The best effect was observed for $J/C4$ in this study.

4.3. Sustainability Index

In intercropping systems, there are complementarity effects and selective competition between the two crops [37]. Therefore, to further clarify whether these effects are positive or negative for intercropping, we synthesized and evaluated this result using a sustainability index [26]. The technique of assessing several factors of crop production practices was recognized as an innovative approach to systematically assess the cropping system's sustainability [38,39]. In this study, we created a sustainable evaluation index through

12 indicators, including crop yield, LER, yield increase, and net effect. We found that J/C4 and J/C6 exhibited higher sustainability indices than J/C2, which suggests that J/C4 and J/C6 increased the net effect and cotton yield while significantly expanding the land equivalent ratio of the intercropping system. In addition, despite a decrease in the yield of intercropped jujube trees, the total yield and the economic efficiency were significantly improved under the J/C4 intercropping system compared to monocropping jujube. Comprehensively considering the sustainability index, land use efficiency, and net effect, J/C4 is one of the most productive and sustainable planting patterns of the jujube–cotton intercropping system in southern Xinjiang, with more ideal patterns in arid and semi-arid regions. However, it is worth noting that this intercropping system begins operation during the sympatric period, when young jujube trees are planted or old jujube trees are just being restored. When jujube trees develop, the shade between them makes it impossible to plant cotton between rows of jujube trees. Therefore, the long-term effects of this intercropping system may need to be further investigated.

5. Conclusions

The systems tested in this study demonstrated a distinct intercropping advantage, showing positive effects. The LER under J/C4 was higher than that under J/C2 and J/C6. Both complementarity and selection effects contributed to the intercropping yield advantages. J/C4 and J/C6 showed higher sustainability indices than J/C2. When comprehensively considering yield, economic efficiency, sustainability index, land use efficiency, and net effect, J/C4 is one of the most productive and sustainable planting patterns of jujube–cotton intercropping systems in southern Xinjiang, with more ideal patterns in arid and semi-arid regions. We recommend to plant four rows of cotton between rows of jujube trees when the jujube trees are young because it improves yields and economic efficiency.

Author Contributions: Conceptualization, G.C.; methodology, P.W.; software, J.W.; validation, G.C.; formal analysis, Z.C.; investigation, T.L. and Y.Z. (Yaru Zhao); resources, S.W.; data curation, Y.Z. (Yaru Zhao); writing—original draft preparation, J.W.; writing—review and editing, G.C. and Z.C.; visualization, S.W.; supervision, G.C.; project administration, S.W.; funding acquisition, Y.Z. (Yunlong Zhai). All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The entire set of raw data presented in this study is available from the corresponding author upon request.

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

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