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Formation of factors influencing cotton yield in jujube–cotton intercropping systems in Xinjiang, China

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Abstract Jujube–cotton intercropping system is a common efficient practice in China, especially in Xinjiang, Northwest China. While setting up two jujube–cotton intercropping systems, we planted two or four rows of cotton between two rows of jujube to study the formation of yield and factors influencing yield of 1-year jujube on intercropping cotton. The results indicated that photosynthetic/physiological characteristics of cotton in different planting patterns were significantly different only from the squaring stage to prophase of the boll opening stage, and the soil plant analyzer development value were not different all the time. Under the influence of jujube shading, the net photosynthetic rate, stomatal conductance, transpiration rate, and yield of cotton in a four-row cotton intercropping pattern (Int-4) and a two-row cotton intercropping pattern (Int-2) were significantly decreased compared with those of one-row cotton (Sole) and the intercellular CO_2 concentration increased. There was no significant difference between Int-2 and Int-4 in above photosynthetic/physiological characteristics. The higher planting density makes the harvested number and boll number of Int-4 superior. Compared to the Int-2, the yield of Int-4 increased significantly by 10.50%, and the economic benefits from high to low were Int-4 > Int-2 > Sole. Therefore, we concluded that an appropriate increase of cotton planting density is beneficial to the high yield of cotton in a jujube–cotton intercropping system, because it is conducive to increasing the income of farmers.

Keywords Jujube–cotton intercropping · Photosynthesis · Yield · Economic benefit

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Introduction

Rapid population growth, resource shortages, and climate change have created three great crises currently facing the world (Pimentel et al. 2018; UN 2019). China is the most populous country in the world with increasingly prominent environmental and resource-related problems, especially in Xinjiang Uyghur Autonomous Region (Xinjiang), which is located in northwestern China (Yuan et al. 2015; Zarei et al. 2020). Xinjiang is facing severe ecological situation of water shortages (Ling et al. 2013), drought climate (He et al. 2020) and soil desertification (Li et al. 2018), which greatly affects the agricultural development. However, Xinjiang is very rich in solar energy resource, the annual duration of sunshine reads

2550–3550 h, the annual irradiation quantity $5.43 \times 10^5 - 6.67 \times 10^5$ J/cm^2 (Lei and Yang 2008). The sufficient light and heat resources have become the advantages of agricultural development in Xinjiang. Therefore, agricultural development requires the careful conservation of resources while ensuring food security and paying attention to the relationship between agriculture and the environment.

Intercropping systems of agroforestry, which combine annual crops with perennial woody plants, are widely used in semi-arid regions to improve land use patterns and to provide the economic benefits of intercropping. Meanwhile, the planting pattern in any agricultural system also plays a crucial role in reducing wind erosion, adjusting the agricultural microclimate, improving environmental conditions, and so on (Zhang et al. 2013; Gao et al. 2014; Wang et al. 2014; Zhang et al. 2018). In Xinjiang Province, the agroforestry-intercropping systems have developed into an important agricultural management mode that is used to improve the income of farmers and includes systems such as jujube-grain intercropping, jujube–cotton intercropping, and other systems (Hong et al. 2017). jujube–cotton intercropping is a relatively complex system with relatively high environmental heterogeneity. It can realize the twin benefits of growing both jujube and cotton, although jujube will directly affect the distribution of light above the canopy of intercropped cotton and changes the photosynthetic characteristics of intercropped cotton. However, effective photosynthesis is still the basis of crop yield formation (Li et al. 2008; Joesting et al. 2009; Peng et al. 2009; Varella et al. 2011). Minimizing resource competition between jujube trees and cottons, while maximizing the use of available light resources, is central to improving yield and overall productivity in agroforestry systems (Zamora et al. 2009). Therefore, knowing how to optimize the allocation of light and heat resources between jujube and cotton crops is the core problem to be solved with the goal of improving the yield of a jujube–cotton intercropping system.

Some studies have shown that the shading of trees in an agroforestry intercropping system results in a decrease of photosynthetically active radiation received by crops, which leads to a reduction in crop yield (Zamora et al. 2007; Feldhake and Belesky 2009). Varying the density of cotton planting in a jujube–cotton intercropping system will affect the canopy structure of cotton, thus affecting the photosynthesis and yield of cotton (Zhang et al. 2014). In recent years, the jujube–cotton intercropping system has become well developed in southern Xinjiang and has been gradually been popularized in northern Xinjiang. However, previous studies have mainly focused on biological research, interspecific relationships, ecological effects, water resources use efficiency, and competition for nutrients (Allen et al. 2004; Wanvestraut et al. 2004; Su and Liu 2005; Bai et al. 2016; Wang et al. 2016; Zhang et al. 2019). Changes in the photosynthetic and agronomic characteristics of cotton in a jujube–cotton intercropping system are still far from being well understood.

Considering the increasing extensive in jujube trees and cotton for agroforestry systems in northwestern China and jujube–cotton intercropping system is new systems that have received rarely attention in the past (Jose et al. 2004; Zhang et al. 2019). Thus, this study chose jujube–cotton intercropping systems as the test object and it conducted to test the following key questions:

1. What are the differences in photosynthetic characteristics, yield and economic benefits of cotton between the two jujube–cotton intercropping systems with different planting distances?
2. What causes these differences?
3. What are the practical advantages and comprehensive benefits of the three planting patterns?

We hypothesized that (1) the cotton in two jujube–cotton intercropping systems will be adversely affected by different planting distance on photosynthetic characteristics, and the economic benefits may be favorably affected; (2) these problems are related to the shading effect and planting density; (3) the intercropping pattern with suitable density will have better comprehensive benefits and be suitable for local promotion.

Materials and methods

Experimental location

The experiment was conducted in the 15th Unit stationed as part of the 150th Regiment (45° 04′ N, 86° 03′ E) of the 8th Division of the Xinjiang Production and Construction Corps in 2016. This typical arid desert area has a sandy loam soil and a frost-free period of about 170 d. The average annual rainfall is minimal at 189.1–200.3 mm, while annual evaporation is large at 1517.5–1563.8 mm. Temperatures vary widely between day and night. From 2014 to 2019, the average annual temperature was 6.6–7.1 °C, with the highest average temperatures occurring from July to early August at 25.0−26.7 °C and the lowest temperatures occurring in January, averaging between − 17.8 and − 15.2 °C. The planting area of jujube is about 46.7 hm^2.

Experimental design and treatments

The experiment involved 7-year-old winter jujube trees (*Zizyphus jujuba* Mill.) of variety "Zan Huang" with flat stubble every year in mid-March (all parts removed above 10 cm from the ground). "Zan Huang" is the main Chinese jujube cultivar with thin peel, thick flesh, sour and sweet taste and high economic value. This experiment used a random block design and a total of three treatments of which Int-4 and Int-2 involved intercropping of jujube and cotton, while a cotton sole cropping (Sole) was the third treatment. The cell area was 45 m^2 (5 m × 9 m) with three repetitions for each treatment. The layout design of row spacing of the jujube–cotton intercropping systems is shown in Fig. 1. The rows of jujube trees were spaced 2.8 m apart with 1.4 m spacing between individual plants. Drip irrigation under a 1.2-m-wide plastic film was used with planted cotton. Three configurations of cotton planting were employed: (1) four rows of cotton were planted between two rows of jujube trees with cotton row spacing of 0.2 m or 0.4 m (Int-4); the cotton and jujube trees were separated by 1 m; (2) two rows of cotton were planted between the two rows of jujube trees with cotton row spacing of 0.4 m (Int-2); the cotton and jujube trees were separated by 1.2 m; (3) sole cropped cotton was used as a control group with row spacing of 0.3 m and 0.6 m, which was a commonly used row spacing in fields planted in Xinjiang.

The cotton (*Gossypium hirsutum* Linn.) variety used was "XLZ 48," the main cultivar planted in Xinjiang, and drip irrigation technology under mulch was adopted. The cotton was sown on April 25, 2016, with a topping date of July 15, and harvest date of October 10. Before the sowing of cotton, base fertilizer of urea (pure nitrogen content 46%) 260 kg ha^{-1}, diammonium phosphate 130 kg ha^{-1} and potassium sulphate (K_2O 50%) 75 kg ha^{-1} was applied. According to the drip irrigation mode of Xinjiang large-area farmland drip irrigation technology under mulch, the experiment set the irrigation interval as 10 days and sites were irrigated 8 times during the entire growth stages of cotton with 625 m^3 ha^{-1}. Drip irrigation tape with inner diameter of 2.3 cm, drip holes spacing of 30 cm and flow rate of 2.7 L h^{-1} was used. The irrigation amount was controlled by water meter and ball valve, the irrigation time was 10−14 h each time. Following by an application of urea (26 kg ha^{-1}) and diammonium phosphate (13 kg ha^{-1}) with water.

Sampling and measurements

Chlorophyll content in sole and intercropped cotton

In the cotton stages of seedling (06.05), squaring (06.26), flower and boll (07.27), boll opening prophase (08.31) and boll opening anaphase (09.18), five cotton

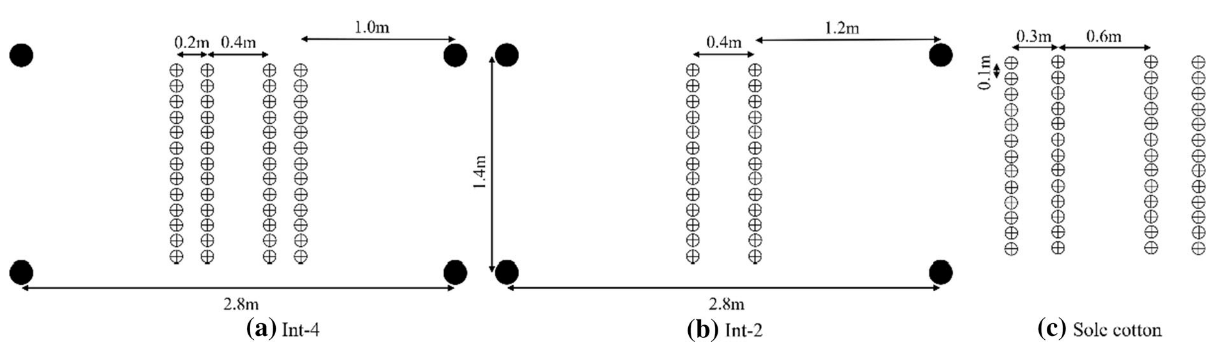

Fig. 1 The planting space in sole cropping and jujube–cotton intercropping systems

plants with good growth were selected in each treatment; a SPAD-502 chlorophyll meter (Minolta Camera Ltd., Osaka, Japan) was used to determine the Soil Plant Analysis Development (SPAD) value of functional cotton leaves (four inverted leaves) with the average of three measurements of each leaf used for analysis.

Photosynthetic characteristics of sole and intercropped cotton

During the four cotton stages listed above, sunny days were selected for weather-related plant measurements. Five cotton plants with good growth were selected for in each treatment; an LI-6400 photosynthesis instrument (Licor, Lincoln, NE, USA) was used to determine the photosynthetic parameters of each cotton functional leaf (inverted four leaves) including net photosynthetic rate (P_n), stomatal conductance (G_s), intercellular CO_2 concentration (C_i), and transpiration rate (T_r). The measurements were generally carried out at 11:00 with the average value of three measurements per leaf used for analysis.

Yield and land equivalent ratio (LER)

In the boll opening stage, harvested plants per ha and bolls per unit area were investigated in each treatment and measurement area; 20 representative cotton plants were selected to determine the single boll weight and lint percentage of cotton. Then cotton fiber yield was calculated. At the same time, fresh jujube fruits were picked and weighed in the two different planting patterns of intercropping, and the output of fresh jujube fruit was calculated.

The Land Equivalent Ratio (LER) is an index that can be used to evaluate the efficiency of environmental resource use and change in yield with intercropping when compared with sole cropping. The LER was obtained using Eq. (2) (Li et al. 2019):

$$LER = \frac{Y_{ic}}{Y_{sc}} + \frac{Y_{ij}}{Y_{sj}} \quad (1)$$

where Y_{ic} and Y_{sc} are the intercropped and sole-cropped cotton yields, respectively, while Y_{ij} and Y_{sj} are the yields of jujube in intercropped and sole-cropped systems, respectively. If LER $>$ 1, this indicates that intercropping is more productive than the sum of the sole crops of the component species.

Economic benefits

The economic benefits corresponding to the output obtained of different planting patterns were calculated based on the current market prices of cotton and jujube (Zhang et al. 2013; Zhang et al. 2017). Monetary advantage index (MAI) is an indicator to describe whether intercropping economy has economic advantages. The MAI was obtained using Eq. (2) (Ghosh 2004)

$$MAI = (YicPc + YijPj) \times \frac{LER - 1}{LER}. \quad (2)$$

Statistical analysis

The cotton leaf area index and yield represent the values of the total leaf area per unit of land area including jujube trees, and the output of jujube trees was also the value of the total leaf area per unit of land area including cotton. Analysis of variance (ANOVA) was conducted using SPSS Version 22.0 for Windows. Among them, least significant difference method was used for multiple comparison analysis. Duncan multiple comparison method was used to analyze the difference significance, and the significance level was set as $\alpha = 0.05$. Different lowercase letters indicate that the difference reached a significance level of 5%. SigmaPlot 12.5 was used for graphing.

Results

SPAD value

As a cotton plant grows, the SPAD value of the inverse fourth leaf of sole cropped and intercropped cotton gradually increased (Fig. 2). The SPAD value peaked in the prophase of the boll opening stage (Sole, 73.4; Int-4, 71.8; Int-2, 72.28), and then began to decline gently, with an average decrease of 5.64%. The SPAD value from high to low was Sole $>$ Int-2 $>$ Int-4 during the entire growth stage. In the cotton flower and boll stage, the SPAD value of the inverse fourth leaf in

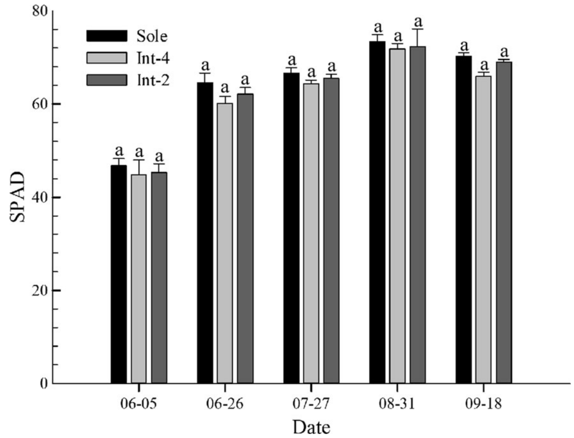

Fig. 2 The dynamic changes of SPAD value of the inverse fourth leaf from top for cotton in intercropping and sole cropping systems

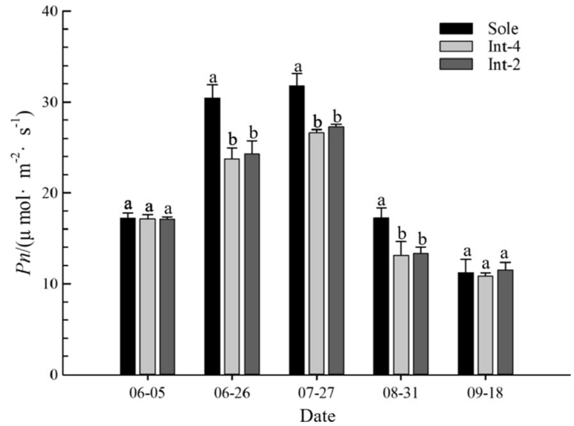

Fig. 3 The dynamic changes of P_n of the inverse fourth leaf from top for cotton in intercropping and sole cropping systems

each planting mode remained at about 65, which is conducive to the photosynthesis of cotton.

During each growth stage, the average SPAD values of Int-4 and Int-2 cotton decreased by 4.45% and 2.23% when compared with Sole, respectively. The average SPAD value of Int-4 cotton decreased by 2.28% when compared with the Int-2 treatment. No significant difference was observed in the SPAD value of the inverse fourth leaf between the various planting patterns.

Net photosynthetic rate (P_n)

In the three planting patterns, the net photosynthetic rate of the inverse fourth leaf of cotton in all treatments showed a single-peak curve that peaked at the flower and boll stage (Sole, 31.77 μmol m^{-2} s^{-1}; Int-4, 26.63 μmol m^{-2} s^{-1}; Int-2, 27.22 μmol m^{-2} s^{-1}; Fig. 3). Throughout the growth stages of cotton, except for anaphase of the boll opening stage, the net photosynthetic rate from high to low was Sole > Int-2 > Int-4. During the entire growth stage, the net photosynthetic rate of the Int-4 planting pattern was 15.51% lower than that of Sole, and the net photosynthetic rate of the Int-2 planting pattern was 11.80% lower than that of Sole. The net photosynthetic rate of Int-4 was 4.21% lower than that of Int-2, however, no significant differences were observed in net photosynthetic rate between Int-4 and Int-2 treatments.

Compared with Sole, no significant difference in the net photosynthetic rate of leaves was observed at the seedling stage and boll opening anaphase stage of intercropping cotton. In the Int-4 and Int-2 intercropping patterns, the net photosynthetic rate of cotton in the squaring stage was reduced by 22.13% and 20.34%, respectively, when compared with sole cropped cotton, and the net photosynthetic rate of cotton in the flower and boll stage was reduced by 16.16% and 14.31%, respectively. Compared to the sole cropped cotton, the net photosynthetic rate in the prophase of the boll opening stage was reduced by 24.14% and 22.84% in the Int-4 and Int-2 systems, respectively. Significant differences were observed between the Sole and the intercropping systems in these three stages.

Stomatal conductance (G_s)

As the growth stage progresses, the stomatal conductance of inverse fourth leaf of cotton showed a single-peak curve, which peaked at the flower and boll stage (Sole, 0.91 mmol m^{-2} s^{-1}; Int-4, 0.62 mmol m^{-2} s^{-1}; Int-2, 0.62 mmol m^{-2} s^{-1}) (Fig. 4). The stomatal conductance of the inverse fourth leaf from high to low was Sole > Int-2 > Int-4 during the entire growth stage of cotton except during the flower and boll stage. Moreover, the stomatal conductance of the Int-4 and Int-2 treatments decreased by 36.12% and 31.68% when compared with that of Sole. The stomatal conductance of Int-4 was reduced by 6.51% compared with Int-2, although the difference was not significant between the two treatments.

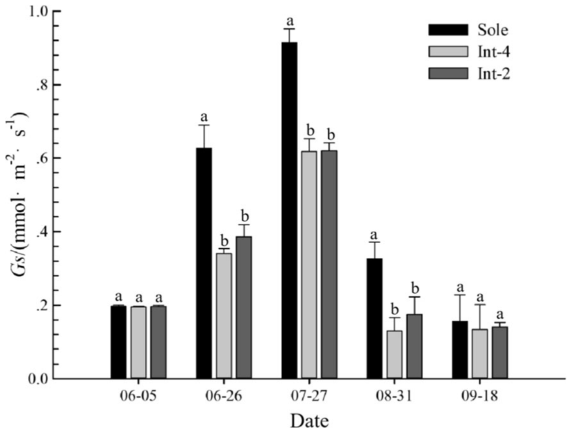

Fig. 4 The dynamic changes of G_s of the inverse fourth leaf from top for cotton in intercropping and sole cropping systems

Compared with the Sole treatment, no significant difference in leaf stomatal conductance was observed during cotton seedling stage. From the squaring stage to prophase of the boll opening stage, the stomatal conductance of single-cropping leaves was significantly higher than that of intercropped cotton leaves, while the stomatal conductance of leaves during the flower and boll stage decreased by 32.19–32.37%.

Intercellular CO_2 concentration (C_i)

In the Sole and jujube–cotton intercropping systems, during the entire cotton growth stage, the intercellular CO_2 concentration in the leaves showed a "V" shape pattern (Fig. 5); in the cotton seedling stage to the flower and boll stage, this concentration decreased, reached the lowest value during the flower and boll stage, and then gradually increased over time. The lowest values of the Sole, Int-4, and Int-2 treatments were 133.82 μmol mol^{-1}, 152.34 μmol mol^{-1}, and 160.17 μmol mol^{-1}, respectively.

Throughout the growth stage of cotton, the intercellular CO_2 concentration of the Int-4 and Int-2 treatments increased by 4.23% and 5.09%, respectively, compared with Sole. In the seedling stage and the anaphase of boll opening stage, the intercellular CO_2 concentration was Sole > Int-2 > Int-4, and in the squaring and early flocking stages from high to low, it was Int-4 > Int-2 > Sole. Significant differences in the intercellular CO_2 concentration were observed between Sole and intercropping in the squaring, early blooming, and late blooming stages, although no significant difference was observed between the two intercropping patterns.

Transpiration rate (T_r)

In the Sole and jujube–cotton intercropping systems, the transpiration rate of the inverse fourth leaf of cotton showed a single-peak curve (Fig. 6). From the seedling to the flower and boll stages, the transpiration rate gradually increased, peaking during the flower and boll stage (Sole, 16.55 mmol m^{-2} s^{-1}; Int-4, 13.43 mmol m^{-2} s^{-1}; Int-2, 13.83 mmol m^{-2} s^{-1}). Later, it decreased during the growth stages, mainly during reproductive growth, which was consistent with the change trend of net photosynthetic rate. The

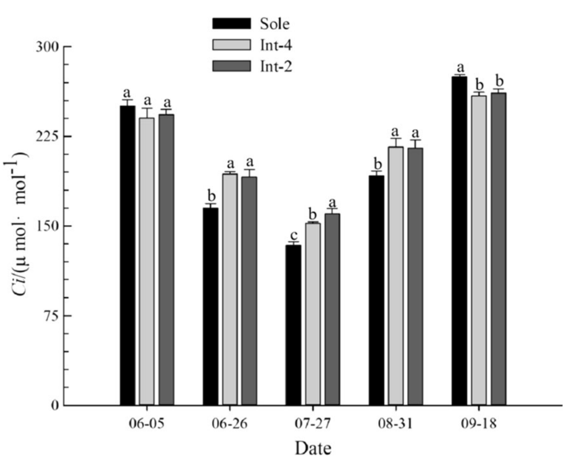

Fig. 5 The dynamic changes of C_i of the inverse fourth leaf from top for cotton in intercropping and sole cropping systems

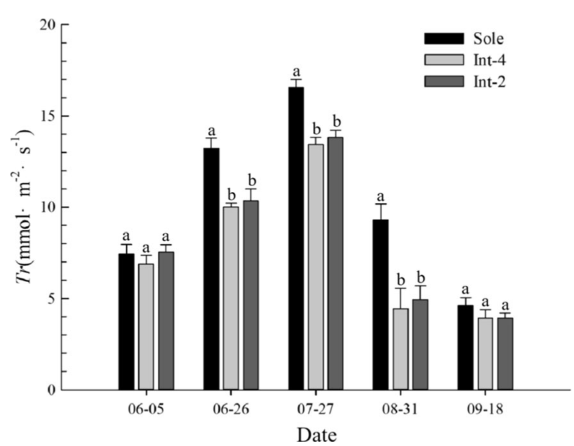

Fig. 6 The dynamic changes of T_r of the inverse fourth leaf from top for cotton in intercropping and sole cropping systems

transpiration rate of the three planting patterns during the entire growth stage from high to low was Sole > Int-2 > Int-4.

The average transpiration rate of cotton in the Int-4 and Int-2 intercropping patterns decreased by 24.33% and 20.65%, respectively, throughout growth when compared to the Sole treatment. Compared with Sole, intercropping had no significant difference in the cotton seedling stage and the anaphase of boll opening stage. The difference between bud stage and early flocking stage was significant between the Sole and intercropping treatments. During the entire period of growth, the transpiration rate of Int-4 cotton decreased by 4.64% compared with Int-2, although the difference was not significant.

Yield and land equivalent ratio (LER)

The amounts of harvested plants, bolls per unit area, single boll weight, cotton fiber yield, cotton fiber percentage, and yield of fresh jujube in three planting patterns are shown in Table 1. According to the test results, planting patterns significantly affected cotton yield and yield components. Significant differences were observed between intercropping and Sole in harvested plants, bolls per unit area, cotton fiber yield, and fresh jujube yield, whereas single boll weight and lint percentage were not significantly different. In a comparison between the two intercropping patterns (Int-4 and Int-2) and sole intercropping, harvested plants decreased by 41.61% and 47.74%, respectively. The bolls per unit area decreased by 32.70% and 50.64% and cotton fiber yield decreased by 41.61% and 47.74%, respectively.

Compared with Sole, the yield of fresh jujube in Int-4 and Int-2 decreased by 23.36% and 23.84%, respectively. The difference between intercropping and sole cropping was significant. All of yield components from high to low were Int-4 > Int-2 except for single boll weight. No significant differences were observed in lint percentage and fresh jujube yield between the two systems.

The maximum LER was 1.35 for Int-4 and 1.28 for Int-2. The growth rate of the jujube–cotton intercropping system = (LER–1) × 100%. The formula calculated for the growth rate of Int-4 was 35%, while the growth rate of Int-2 was 28%.

Economic benefits

The National Development and Reform Commission of China set the target price of cotton in Xinjiang at around \$2800 US (18,600 RMB) per ton in 2016. The market of jujube in late 2016 was stable around \$3011 US (20,000 RMB) per ton. The total income of Int-4 and Int-2 was around \$7829 US (52,000 RMB) per ha and \$7573 US (50,300 RMB) per ha, respectively (Table 2). However, the total income of the sole cropping systems for cotton and jujube grown separately was only around \$6293 US (41,800 RMB) and \$5616 US (37,300 RMB). The MAI values were positive in two intercropping systems, the higher MAI values were for Int-4 (2068.83) and the lower MAI values were for Int-2 (1655.25).

Correlation between photosynthetic parameters and yield of cotton

Pearson correlation coefficient was obtained by correlation analysis of SPAD value, four photosynthetic parameters (P_n, G_s, C_i, T_r) and cotton fiber yield (Table 3). During the whole growth stages of cotton, the SPAD value, P_n, G_s, T_r were positively correlated

Table 1 The comparison of yield, components and land equivalent ratio of intercropping and sole cropping cotton

Treatment	Harvested plant per ha (10^4 ha^{-1})	Bolls per unit area (10^4 ha^{-1})	Single boll weight (g)	Lint percentage (%)	Cotton fiber yield (kg ha^{-1})	Fresh jujube yield (kg ha^{-1})	LER
Sole	15.18a	93.05a	5.96ab	40.54a	2248.3a	1865.1a	
Intercropping(4)	10.89b	62.62b	5.29b	39.63a	1312.7b	1429.5b	1.35
Intercropping(2)	7.68c	45.93c	6.37a	40.16a	1174.9c	1420.5b	1.28

The same letters in the same column indicated no significant difference at 0.05 level in Duncan's analysis

Table 2 The comparison of economic benefits of intercropping and sole cropping cotton

Treatment	Cotton fiber yield (kg ha^{-1})	Fresh jujube yield (kg ha^{-1})	Cotton price (US$ ton^{-1})	Fresh jujube price (US$ ton^{-1})	Total income (US$ ha^{-1})	MAI
Sole(cotton)	2248.3a	–	2800	–	6293	–
Sole(jujube)	–	1865.1a	–	3011	5616	–
Intercropping(4)	1312.7b	1429.5b	2800	3011	7829	2068.83
Intercropping(2)	1174.9c	1420.5b	2800	3011	7573	1655.25

Table 3 Correlation analysis among the photosynthetic parameters and fiber yield of cotton

Parameter	SPAD	P_n	G_s	C_i	T_r	Yield
SPAD	1					
P_n	0.917	1				
G_s	0.918	0.994**	1			
C_i	− 0.944	− 0.735	− 0.736	1		
T_r	0.928	0.989*	0.986*	− 0.754	1	
Yield	0.802	0.974	0.973	− 0.561	0.967	1

*Significant at 5% ($P < 0.05$)

**Significant at 1% ($P < 0.01$)

with each other, and photosynthetic parameters were positively correlated with yield. The C_i was negatively correlated with SPAD values, P_n, G_s, T_r and yield. In correlation analysis, P_n was highly significantly correlated with G_s (r = 0.994, $P < 0.01$), and T_r was significantly correlated with P_n (r = 0.989, $P < 0.05$) and G_s (r = 0.986, $P < 0.05$). When the correlation coefficient reaches 0.8−1.0, the relationship between independent variable and dependent variable is very strong, and 0.6−0.8 is strong correlation. In all correlation analysis, except C_i had no strong correlation with yield, C_i had strong correlation with P_n, G_s and T_r, the others were extremely strong correlation.

Discussion

This study revealed the relationship between the difference of cotton photosynthesis and yield formation under the two planting densities pattern (Int-2, Int-4) of agroforestry. In this experiment, SPAD values and photosynthetic parameters (except intercellular CO_2 concentration) of cotton were no significant difference between sole cropping and two intercropping at seedling and boll opening anaphase stage. Within tree-based intercropping systems, there are a number of factors can affect tree shading of adjacent crops including reasonable species selection, plantation design and manual operation (Peng et al. 2009). Cotton is a C_3 plant that is saturated with light at approximately 50% of full sunlight. If tree shading does not reduce light level below the light saturation threshold, then no reduction in photosynthesis should occur (Phillip et al. 2007). As a deciduous tree, jujube should have a temporary shading effect on crops dependent upon leaves emergence and leaves senescence of the tree annual growth cycle. Meanwhile, in terms of manual operation, the upper branches of test jujube trees were pruned with no more than 10 cm in March every year. So the underground part of the jujube trees was perennial, and the upper part regrew annually. When cotton was in seedling stage, jujube tree was in the sprouting of leaf stage, which had small individual and no shade for intercropping cotton. Therefore, jujube had no effect on SPAD values and photosynthetic parameters at seedling and boll opening anaphase stage.

There was no significant difference in SPAD values among the three planting patterns in the other three stages, and showed a Sole > Int-2 > Int-4 trend, indicating that intercropping did not affect SPAD values, which was consistent with Dordas' results (Dordas et al. 2011; Dordas et al.2012) in faba bean (*Vicia faba* L.) -oat and pea-oat mixed intercropping, the results of Li et al. (2020) in wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.), but contrary to the results obtained by Li et al. (2020) in Common vetch (*Vicia sativa* L.) -oat. This is because the field management mode of three treatments in this experiment is consistent with 119.6 kg ha^{-1} of fertilizer nitrogen applied, which is similar to the Dordas' test (80 kg ha^{-1}). Chlorophyll content was closely related to fertilizer conditions (Prost et al. 2007). Even though shading affected chlorophyll synthesis and reduced SPAD values of intercropping, sufficient nitrogen fertilizer could still alleviate the difference of SPAD values (Fan et al. 2006).

Light intensity influences crop photosynthetic rate and yield, and the degree of light reduction would depend upon the extent and duration of shade produced by the trees (Bhatta et al. 2017). From the squaring stage of cotton, the individual of jujube increased gradually and into fruit expansion stage. Thus, the photosynthetic parameters of intercropping and sole cropping were significantly different from this stage. Net photosynthetic rate (P_n) is an important index to evaluate the photosynthesis intensity of plants, which is very important to the growth and development of crops (Zamora et al. 2006; Zhang et al. 2014). From squaring to boll open prophase stage, the results showed Sole > Int-2 > Int-4, which indicated that the shading effect of jujube on cotton directly inhibited P_n of intercropping cotton, and the farther the cotton was from tree, the less shading effect was. Other studies have yielded similar results (Gao et al. 2013; Yang et al. 2017; Liu et al. 2018).

The change trend of G_s and T_r in the whole growth period was consistent with that of P_n, and both were positively correlated with P_n (r = 0.994**, r = 0.989*). The change of C_i was nearly opposite to P_n, which was not only negatively correlated with P_n (i.e., C_i decreased when P_n increased, r=–0.735), but also showed Int-4 > Int-2 > Sole among three patterns. Photosynthesis is determined by stomatal or non-stomatal limitation, and only when C_i and G_s decrease simultaneously, the decline of P_n was mainly caused by stomatal limitation (Farquhar et al. 1982). In this experiment, C_i was negatively correlated with G_s, indicating that non-stomatal factors reduced P_n in jujube cotton intercropping system, which was consistent with Gong et al. (2015). Furthermore, from Sole to Int-4 to Int-2, the density of cotton and the shading effect of jujube on cotton increased gradually, and the light intensity decreased with it.

The lowest P_n was accompanied by a maximal C_i, which was completely consistent with the results of Zhang et al. (2005) and Xu et al. (2015). Therefore, according to previous experiments, we speculated that the non-stomatal factor restricting P_n is the photosynthetic activity of mesophyll cells, that is ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBPCO) (Mächler et al. 1986; Murchie et al. 2002; Wu et al. 2013).

Mutual shading significantly affects plant productivity because light plays an important role in photosynthesis and yield (Gillespie et al. 2000; Zamora et al. 2008; Yang et al. 2017). Jujube was the stronger crop in the jujube–cotton intercropping systems, which had a certain advantage in resource competition. Therefore, in this experiment, the yield of jujube in intercropping is less than that of in sole cropping, and may be mainly affected by underground competition (Zhang et al. 2017; Zhang et al. 2019). Cotton in jujube–cotton intercropping system is a weak crop. The results of correlation analysis showed that P_n and yield had a strong correlation (r = 0.974), so the P_n of intercropping was lower than that of sole cropping, the yield of intercropping was also significantly lower than that of sole cropping. The yield of cotton population is formed by the four elements of harvested plant, boll number, single boll weight, and lint percentage (Song et al. 2015). The single boll weight and lint percentage are greatly affected by the genetic characteristics of the varieties itself, these are also significant differences among the varieties (Gapare et al. 2017; Ulloa et al. 2019). The number of harvested plant and boll number is related to the density and growth conditions of crops. Therefore, even though there was no significant difference in P_n between Int-4 and Int-2 in this experiment, based on the larger planting density of Int-4, with the increase of planting plants in Int-4, the number of harvested plants and boll number increased simultaneously, which compensated for the adverse effect of shading on cotton yield from yield components (Wang et al.

2016). However, some studies have also proved that yield does not always decrease with the increase of planting density, too high or too low will cause yield reduction (Zhang et al. 2014; Khan et al. 2017; Song et al. 2020). Therefore, the appropriate and reasonable planting density should be selected under the condition of intercropping and shading. Martin-Guay et al. (2018) reviewed 939 intercrop observations from 41 countries covering a broad range of climatic conditions with an average LER of 1.30 (median LER of 1.28). In this experiment, the LER of Int-4 (1.35) was large than the average of previous investigation, and the LER of Int-2 (1.28) was equal to the media, showing that jujube–cotton intercropping increased system productivity and had yield advantage (Li et al. 2019; Glaze-Corcoran et al. 2020).

The economic benefits of Int-4 and Int-2 were about 19.62% and 16.90% higher than those of Sole cotton and were about 28.27% and 25.84% higher than those of jujube sole cropping, respectively. The experiment shows that the development of a jujube–cotton intercropping mode in Xinjiang has advantages in economic benefits and increases the types of crops harvested per unit area, which can more effectively respond to the changes of market prices and, at the same time, can improve and protect the income of farmers. The higher the MAI index value the more profitable is the cropping system (Dhima et al. 2007). The MAI of Int-4 was greater than that of Int-2, indicating that Int-4 has greater economic advantages.

The above results answer our three questions and conform to the previous hypothesis. In intercropping systems, shading limited the light intensity and reduced the photosynthetic rate of crops. Reasonable planting density can not only make up for the influence of shading on yield, but also gain advantages in land use efficiency and economy. We suggest several specific recommendations to reduce light competition in fruit tree-crop intercropping systems: (1) selecting crop varieties with strong shade tolerance that are more suitable for agroforestry systems. (2) controlling the crown width of fruit trees reasonably by conducting regular pruning, enlarge the transmittance of light, and reduce the effect of shade from fruit trees on crops during production. (3) in cotton production, we can choose varieties with better lint percentage and single boll weight, at same time, we can use cultivation management technology to increase the number of harvested plants and boll number per plant. This experiment only investigated the influence of jujube shade affect on the photosynthesis and yield of intercropping cotton, but ignored the photosynthetic performance of jujube. As a result, this study can be used for understanding limitations of cotton photosynthesis in jujube tree-based intercropping systems, but it cannot be used to evaluate the overall performance of intercropping systems.

Conclusions

jujube–cotton intercropping system is an effective approach for land use, which is widely adopted by farmers in Southern Xinjiang, Northwest China. In the intercropping system, the jujube trees were restricted by pruning and growth at seedling and boll opening anaphase stages, which had no effect on cotton. With the gradual growth of jujube trees, the shading effect of jujube on cotton was more and more obvious from the beginning of squaring stage. The results showed that the light intensity decreased and the photosynthetic activity of mesophyll decreased under shading. The P_n, G_s and T_r of intercropping cotton were significantly lower than those of sole cropping cotton at the same stage, and C_i was significantly higher than that of sole cropping cotton at the same stage. There was no difference among the three planting patterns because of the same nitrogen rate and sufficient nitrogen fertilizer to alleviate the difference of SPAD value. Although the P_n of Int-4 is less than that of Int-2, higher planting density can increase the harvested plant and boll number in terms of yield components. So that the yield of Int-4 is greater than Int-2, land use efficiency and economic benefits of Int-4 are also greater than Int-2 and Sole, which improves farmers' income.

On the whole, the development of jujube cotton intercropping system is a better choice for agriculture and forestry in Xinjiang. We should choose the suitable planting density (e.g., Int-4 treatment in this experiment) and combine with reasonable management technology (e.g., sufficient water and fertilizer, timely construction of branches), so as to ensure the stable yield and maximize the economic benefits for farmers.

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