Canopy Light Distribution Characteristics and Yield of Winter Wheat in a Jujube-Wheat Intercropping System (Postprint)

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Abstract

To address the recent issue of "competition for land and light between forestry and agriculture," this study investigated a jujube||winter wheat intercropping system with a plant spacing of 3 m 4 m in north-south row orientation. Two treatments were established under field conditions: jujube-wheat intercropping (JZ) and winter wheat monoculture control (CK). Based on photosynthetic physiological parameters and canopy light intensity of winter wheat during the 2013-2014 growing season, a measurement transect was established by connecting the planting points of two jujube trees. On this transect, using distances east (E) and west (W) from the jujube trees as references, measurement points were set every 50 cm, establishing seven positions: E50 cm, E100 cm, E150 cm, E200 cm (W200 cm), W150 cm, W100 cm, and W50 cm. During different survey periods, canopy photosynthetically active radiation (PAR) of winter wheat was measured at each position, and yield was investigated at each position at winter wheat maturity. Polynomial regression and definite interval integration methods were employed to calculate the duration and spatiotemporal windows of canopy saturated PAR during the tillering, jointing, heading, flowering, grain filling, and maturity stages of winter wheat, exploring the effects of jujube tree shading on canopy light distribution and yield of intercropped winter wheat in the jujube-wheat intercropping system. The results showed that canopy light intensity and yield in the intercropping system exhibited distinct spatiotemporal distribution characteristics overall, with a certain degree of reduction compared to the monoculture wheat system. The saturated PAR spatiotemporal window of monoculture winter wheat canopy was 56.1% larger than that of the intercropping treatment, while grains per spike, effective spike number, thousand-grain weight, and yield were 14.7%, 15.9%, 33.5%, and 53.0% higher than those of intercropped wheat, respectively. Compared with the monoculture control, the intercropped winter wheat experienced severe losses in canopy PAR spatiotemporal windows throughout the growth period at positions E50~E100 cm, E100~E150 cm, E150~E200 cm, W150~W200 cm, W100~W150 cm, and W50~W100 cm from the jujube trees, reaching 92.5%, 45.7%, 7.0%, 5.4%, 10.9%, and 54.0%, respectively. The loss of canopy PAR spatiotemporal windows led to winter wheat yield reduction, with yield reduction degrees reaching 46.2%, 39.6%, 26.3%, 24.7%, 32.4%, and 37.6% at the above positions, respectively. Therefore, differences in jujube tree shading degree caused varying degrees of yield reduction in intercropped winter wheat, and light quality in the west side of the intercropping alley was better than that in the east side. This requires appropriate pruning of jujube trees after the flowering stage of winter wheat and appropriately increasing the plant spacing of jujube trees on the east side of the alley to avoid excessive growth of new shoots, improve interception of photosynthetically active radiation by winter wheat canopy, and enable the intercropping system to achieve higher yield.

Full Text

Preamble

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Canopy Light Distribution Characteristics and Yield of Winter Wheat in Jujube-Wheat Strip Intercropping System*

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Abstract

In response to recent conflicts between forestry and agriculture over land and light resources, this study investigated a jujube (*Ziziphus jujuba* Mill.) and winter wheat (*Triticum aestivum* L.) strip intercropping system with 3 m × 4 m plant spacing in north-south rows. Field experiments were conducted with two treatments: jujube-winter wheat intercropping (JZ) and monoculture winter wheat (CK). Based on photosynthetic physiological parameters and canopy light intensity of winter wheat during the 2013-2014 growing season, a measurement transect was established between two jujube trees. Measurement points were set at 50 cm intervals from the jujube trees in both east (E) and west (W) directions, designated as E50 cm, E100 cm, E150 cm, E200 cm (W200 cm), W150 cm, W100 cm, and W50 cm. Canopy photosynthetically active radiation (PAR) was measured at each point during different growth stages, and yield was surveyed at each position at maturity. Polynomial regression and fixed-interval integration methods were used to calculate the duration and spatiotemporal windows of canopy-saturating PAR during the tillering, jointing, heading, flowering, filling, and maturity stages of winter wheat. The effects of jujube shading on canopy light distribution and yield of intercropped winter wheat were examined. Results showed that canopy light intensity and yield of intercropped winter wheat exhibited distinct spatiotemporal distribution patterns, with overall attenuation compared to the monoculture system. The saturated PAR spatiotemporal window in monoculture winter wheat was 56.1% larger than in the intercropping treatment, while grain number per spike, effective panicle number, 1000-grain weight, and yield were 14.7%, 15.9%, 33.5%, and 53.0% higher, respectively. Relative to the monoculture control, intercropped winter wheat experienced severe losses in canopy PAR spatiotemporal windows of 92.5%, 45.7%, 7.0%, 5.4%, 10.9%, and 54.0% at positions E50-E100 cm, E100-E150 cm, E150-E200 cm, W150-W200 cm, W100-W150 cm, and W50-W100 cm, respectively. These losses resulted in yield reductions of 46.2%, 39.6%, 26.3%, 24.7%, 32.4%, and 37.6% at the corresponding positions. Thus, differential shading by jujube trees caused varying degrees of yield loss in intercropped winter wheat, with overall better light quality on the west side of the intercropping alley than on the east side. This suggests that appropriate pruning of jujube trees after winter wheat flowering and increased plant spacing on the east side of the alley could prevent excessive growth of new jujube branches, improve canopy PAR interception by winter wheat, and enhance overall system productivity.

Keywords: Jujube-wheat intercropping; Winter wheat; Canopy; Photosynthetically active radiation; Spatiotemporal window; Yield

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1.1 Study Area Description

The experiment was conducted in Yuekexianbaizha Township, Yuepuhu County, Kashgar Prefecture, Xinjiang Uygur Autonomous Region (76°23 13.8 E, 38°48 18.5 N) at an elevation of 1,250 m. The site experiences a warm temperate continental arid climate characterized by dry conditions, distinct seasons, low precipitation, and long sunshine hours. Annual precipitation is 51.7 mm, mean annual evaporation is 2,651 mm, and average annual temperature is 11.7 °C (January mean: -6 °C; July mean: 27 °C). The frost-free period is 213 days, with annual effective accumulated temperature $ $10 °C of 4,354 °C. Wind-blown sand and dust weather occurs frequently, concentrated in spring and summer. The study area has 12,947.7 ha of cultivated land, of which 22.3% is used for jujube-wheat intercropping. Soil texture is light, dominated by sandy and sandy loam soils with good permeability. Basic soil physicochemical properties are shown in .

Some basic chemical properties of different soil layers in the experiment field

Soil layer	Organic matter (g • kg^{-1})	Total nitrogen (g • kg^{-1})	Total phosphorus (g • kg^{-1})	Total potassium (g • kg^{-1})	Available nitrogen (mg • kg^{-1})	Available phosphorus (mg • kg^{-1})	Available potassium (mg • kg^{-1})
0–20 cm	26.48$±1.22*Aa*|0.97±0.06*Aa*|0.86±0.06*Aa*|11.15±0.03*Aa*|57.9±4.5*Aa*|17.5±0.3*Aa*|204.6±3.2*Aa*20–4						

Values are means±SD. Different capital and small letters in a column indicate significant difference at 0.01 or 0.05 levels. The same below.

1.2 Experimental Design

The experimental subject was a jujube-wheat intercropping production system. Jujube trees (*Ziziphus jujuba* Mill. 'Huizao'), aged 6 years with moderate vigor, high and stable yield, were used. Mean tree height was 3.66 m, basal diameter 5.70 cm, east-west crown width 2.39 m, and north-south crown width 2.79 m, with plant spacing of 3 m × 4 m in north-south rows. Winter wheat variety 'Xindong 20' , a local main cultivar, was machine-drilled with 15 cm row spacing, with 20 rows intercropped between two jujube rows. Sowing date was late September at 430 kg • ha^{-1}, resulting in 6.9$×10^{6}$ plants • ha^{-1} and a growth period of approximately 238 days. The experiment ran from October 2013 to June 2014, with jujube-wheat intercropping at 50 cm distance. Four irrigations were applied during the co-growth period: March 25 (first), April 12 (second), April 25 (third), and May 20 (final). Plot size was 3 m × 4 m with nine replicates. A split-plot design was employed: tree pairs with consistent growth (crown width, height, basal diameter) were randomly selected, with a measurement transect established between two trees. Three transects formed one experimental group with three replicates. Measurement points were set at 50 cm intervals along the transect based on distance from jujube planting points. The main factor was growth stage with six levels: tillering (mid-March), jointing (mid-April), heading (early May), flowering (mid-May), filling (late May), and maturity (mid-June). The subplot factor was measurement position with seven levels: E50 cm, E100 cm, E150 cm, E200 cm (W200 cm), W150 cm, W100 cm, and W50 cm (E and W denote east and west sides of the wheat belt). Canopy PAR was measured at each position during different growth stages, and yield was surveyed at each position at maturity. The monoculture winter wheat control had identical cultivation methods, survey periods, and positions, with the jujube planting area designated as open space. Both jujube trees and winter wheat were managed according to local high-yield field practices for fertilization and irrigation.

1.3.1 Winter Wheat Photosynthetic Physiological Data Collection

Photosynthetic physiological parameters of winter wheat were measured using a Li-6400XT portable photosynthesis system (Li-COR, USA) equipped with an LED artificial light source. During each survey period, flag leaves without disease or pest symptoms were selected from well-managed monoculture winter wheat fields for field measurement. Net photosynthetic rates (Pn) of winter wheat flag leaves were measured under 15 gradients of photosynthetic photon flux density (PPFD) on clear, cloudless mornings between 10:00–12:00, and Pn-PPFD curves were plotted. During measurement, leaf temperature, internal CO_2 concentration in the leaf chamber, and relative humidity were maintained at (32\$±1)°$C, 80\pm1^{\{\text{-}2\}\cdot s}$\{-1\}\$, respectively. Five leaves were measured as replicates each time, and mean values were calculated.

1.3.2 Winter Wheat Canopy PAR Data Collection

Canopy PAR of winter wheat was measured using a linear quantum sensor LI-191 (Li-COR, USA). Starting in March, during each wheat survey period on clear, cloudless days, canopy PAR values were measured at each sampling point from 8:00 to 20:00 using a round-trip observation method, with hourly measurements. Simultaneously, canopy PAR of monoculture winter wheat was measured as the control (CK).

1.3.3 Jujube Tree Mensuration Factor Data Collection in Intercropping System

Mensuration factors of jujube trees in sample plots (basal diameter, crown width, tree height) were measured using diameter tapes, measuring tapes, and hypsometers. Measurement dates coincided with PAR measurement dates, with one measurement per period and 18 replicates per measurement.

1.3.4 Winter Wheat Yield Data Collection

Yield of winter wheat in both intercropping and monoculture systems was measured using the yield component method. At winter wheat maturity, a 0.5 m^2 sampling unit (0.5 m length × 1 m width) was used to harvest winter wheat at each survey position. The same method was applied to harvest winter wheat at corresponding positions in the monoculture control field. After harvest, the number of spikes with \$ \$5 grains per spike was counted in each sampling unit, and 20 plants were randomly selected for determination of grains per spike, 1000-grain weight, and yield. Three replicates were established for both intercropping and monoculture systems, and mean values were calculated.

1.4.1 Minimum and Maximum Spatial Widths Above Saturating Light Intensity

The minimum and maximum spatial widths above saturating light intensity.

1.4.2 PAR Spatiotemporal Window Measurement

A mathematical relationship was established with the maximum photon flux density (PPFD) received by intercropped crop canopy at each measurement point during one day (8:00–20:00) as the dependent variable and measurement time t as the independent variable: $\text{PPFD} = at^2 + bt + c$. This yielded a quadratic equation between PPFD and t for different growth stages of winter wheat. By substituting the LSP values of winter wheat at different growth stages into each equation and solving, the start time (t_1) and end time (t_2) when canopy PAR reached or exceeded the LSP value were obtained for each stage, with $t_2 \geq t_1$.

A PAR distribution map for each transect in the intercropping alley was plotted using real-time PAR values collected at each sampling point. In the map, the spatial length l where PAR received by canopy data collection points reached or exceeded the LSP value was measured at each time point using 6-minute time intervals. Then, a mathematical relationship $l = f(t)$ was established with spatial width l as the dependent variable and time t as the independent variable, followed by a seventh-order polynomial regression to obtain a system of equations.

By substituting any time t ($t_1 < t < t_2$) into the equation $l = f(t)$, the spatial width l where canopy PAR reached or exceeded saturating light intensity at time t on the measured transect could be obtained. Specified interval integration was performed for each equation to obtain the spatiotemporal window (m • h) where PPFD received in the intercropping alley reached above the light saturation point during any time period. The integration interval was set as the period when canopy PAR of winter wheat at different growth stages reached or exceeded saturating light intensity, representing the spatiotemporal window for a specific period.

1.5 Data Analysis and Graphing

The winter wheat photosynthetic light response model (light response curve) employed the commonly used non-rectangular hyperbola model:

$$Pn = \frac{\alpha I + P_{\max} - \sqrt{(\alpha I + P_{\max})^2 - 4\theta\alpha I P_{\max}}}{2\theta} - R_d$$

where Pn is net photosynthetic rate ($\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), I is PPFD received by winter wheat leaves $[\text{mol}(\text{CO}_2) \cdot \text{mol}^{-1}]$, P is maximum net photosynthetic rate of winter wheat ($\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), R is dark respiration rate, is convexity of the non-rectangular curve, and α is apparent quantum efficiency [$\mathrm{mol(CO_2)} \cdot \mathrm{mol^{-1}(PPFD)}$]. The light compensation point (LCP) of winter wheat can be obtained from the light response curve. However, due to the non-convergent nature of the non-rectangular hyperbola model, light saturation intensity cannot be calculated directly. Therefore, apparent quantum efficiency (AQE) was obtained through linear regression of net photosynthetic rates and light intensities when PPFD $\leq$ 200 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$. The light saturation point (LSP) was then calculated by solving the equation P = AQE × LSP - R .

Data were processed using Microsoft Excel 2007 and ORIGIN PRO 9.0, and ANOVA was performed using SPSS 18.0.

2.1 Photosynthetic Physiological Parameters of Winter Wheat at Different Growth Stages

Winter wheat exhibits different capacities for utilizing photosynthetically active radiation at different growth stages, though the response trend to PPFD remains consistent. As shown in [Figure 1: see original paper], when PPFD $\leq$ 200 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$, net photosynthetic rate (Pn) of winter wheat increased sharply, nearly linearly, then rose slowly, approaching saturation at 1,400 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$ before leveling off or declining slightly. reveals highly significant differences ($P < 0.01$) in light saturation points among growth stages. The filling stage had the highest LSP (1,428.16 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$), significantly greater than other stages ($P < 0.01$). No significant difference existed between heading and flowering stages, but both differed highly significantly from other stages ($P < 0.01$). The jointing stage LSP differed highly significantly from all other stages ($P < 0.01$). Tillering and maturity stages showed no significant difference, with both having highly significantly lower LSP than other stages ($P < 0.01$). This indicates that winter wheat physiological structure continuously adjusts with growth stage, changing photosynthetic capacity. Light utilization capacity increased during tillering, peaked during filling, then gradually declined.

The highest light compensation point occurred at maturity (86.07 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$), which did not differ significantly from tillering but was highly significantly greater than the other four stages ($P < 0.01$). The tillering LCP was significantly greater than jointing ($P < 0.05$) and highly significantly greater than heading, flowering, and filling stages ($P < 0.01$). No significant differences existed among jointing, heading, filling, and flowering stages. This suggests that the lower limit of light utilization for winter wheat is approximately 60 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$, with an upper limit around 1,400 $\mathrm{mol} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$; normal photosynthesis cannot proceed below or above these thresholds. Winter wheat showed the strongest capacity for utilizing weak light ($ $200\mu mol \cdot m^{\{-2\} \cdot s}${-1}$) during flowering, followed by filling, indicating minimal light requirements and best weak light adaptation when photosynthesis-respiration balance was achieved during flowering and filling.

2.2 Spatial Distribution Characteristics of PAR in Jujube-Wheat Intercropping System

Canopy PAR distribution trends within the intercropping alley were similar across survey periods, showing an overall spatiotemporal pattern of "high in the middle, low on both sides," "high on the west side, low on the east side," and "higher in the afternoon, lower in the morning." Across growth stages, canopy PAR values ranked: filling > flowering > heading > maturity > jointing > tillering. Temporally, canopy PAR peaked at 14:00–16:00; spatially, the highest PAR occurred at E50 cm, M200 cm, and W150 cm positions. This demonstrates uneven spatiotemporal light distribution in the jujube-wheat system, with stronger light in summer than spring, better afternoon than morning light, overall better light quality on the west side than east side, and better light in the middle than on both sides ([Figure 2: see original paper]).

2.3.1 Temporal Variation of PAR Spatiotemporal Window

In the jujube-wheat intercropping system, jujube shading intensity varied across winter wheat growth stages. Highly significant differences ($P < 0.01$) existed in the duration of canopy PAR reaching or exceeding LSP among growth stages. The maturity stage had the longest duration (6.8 h), highly significantly greater than other stages ($P < 0.01$), while flowering had the shortest (3.6 h), highly significantly less than other stages ($P < 0.01$). Compared with monoculture (CK), intercropped winter wheat showed the greatest reduction in duration of canopy PAR $\geq$ LSP during flowering and filling stages, both decreasing by 0.7 h (16.3% and 13.7% of CK, respectively). During heading stage, duration was 4.2 h, representing a 0% reduction from CK. This indicates that jujube canopy shading directly affected the start and end times when intercropped winter wheat canopy received saturating light intensity, thereby influencing effective photosynthesis duration. Measured by saturating light duration, these results suggest that jujube shading had the greatest impact on light intensity in the intercropping alley during winter wheat flowering, followed by filling, with minimal impact during heading ().

Time to and above light saturation point (LSP) for photosynthetically active radiation at different growth stages of winter wheat

Treatment	Tillering stage	Jointing stage	Heading stage	Flowering stage	Filling stage	Maturity stage
t_1	t_2	t_1	t_2	t_1	t_2	t_1
JZ	11.4$±0.1*CDe*|17.5±0.0*Bb*|11.6±0.1*Cd*|17.4±0.1*Bb*|12.5±0.1*Ab*|16.7±0.0*Cc*|12.7±0.1*Aa*|16.3±0.1					

JZ, CK represent jujube-wheat intercropping and winter wheat monoculture systems, respectively; t_1, t_2 *mean the start and end times of photosynthetically active radiation above the intercrop light saturation point.*

2.3.2 Spatial Variation of PAR Spatiotemporal Window

Light distribution was spatially uneven, with better light environment on the west side than the east side. Within the intercropping system, light intensity varied among sampling points on the same transect during the same growth stage. After definite integration, saturated light in winter wheat canopy showed an "n" -shaped curve distribution spatially. Highly significant differences ($P < 0.01$) existed in saturated PAR spatiotemporal windows among different spatial positions on the same transect, with the lowest value at E50–E100 cm (highly significantly less than other positions, $P < 0.01$) and the highest value at W150–W200 cm (highly significantly greater than other positions, $P < 0.05$). Saturated PAR spatiotemporal windows at all points on the west side of the alley were significantly greater than those on the east side ($P < 0.01$).

Temporally, significant differences existed in canopy saturated PAR spatiotemporal windows among growth stages. The tillering stage was significantly greater than other stages ($P < 0.01$), with only 18.8% loss relative to CK. The flowering stage was significantly less than other stages ($P < 0.01$), with 54.0% loss relative to CK. No significant difference existed between jointing and maturity stages, with relative losses of 22.5% and 35.3%, respectively. This indicates optimal light conditions during tillering, when tree shading had minimal impact on winter wheat growth and biomass production, while shading was most severe during flowering when light conditions were poorest and unfavorable for winter wheat growth ().

Time and distance (space-time window) of photosynthetically active radiation above light saturation point at different spatial positions and growth stages of winter wheat in jujube-wheat intercropping system (m · h)

Space position	Tillering stage	Jointing stage	Heading stage	Flowering stage	Filling stage	Maturity stage	Sum	Control
E50-E100	0.64±0.12Cd	0.46±0.17Dd	0.00±0.00De	0.00±0.00Ce	0.00±0.00Ee	0.11±0.01Dd	1.21±0.30Gg	14.61
Total	18.00±0.90Cc	17.40±1.02Dd	12.30±0.96Gg	12.60±0.42Ff	15.00±0.66Ee	20.70±1.02Bb	96.00±4.98Aa	61.52±3.66Aa

2.3.3 Effects of Intercropping Shading on Winter Wheat Yield

Yield component data and actual harvest measurements showed that jujube shading significantly reduced grains per spike, effective panicle number, 1000-grain weight, and yield of intercropped winter wheat. The monoculture control had 14.7%, 15.9%, 33.5%, and 53.0% higher grains per spike, effective panicle number, 1000-grain weight, and yield, respectively, than the intercropping treatment. Within the intercropping system, significant spatial differences existed in grains per spike and effective panicle number, with W150-W200 cm showing significantly higher values than other positions ($P < 0.01$ for grains per spike, $P < 0.05$ for effective panicle number). No significant spatial differences were observed for 1000-grain weight and yield, but yield reduction varied markedly among positions: 46.2%, 39.6%, 26.3%, 24.7%, 32.4%, and 37.6% at E50-E100 cm, E100-E150 cm, E150-E200 cm, W150-W200 cm, W100-W150 cm, and W50-W100 cm, respectively. This indicates that differences in shading duration and intensity caused differential organic matter accumulation through photosynthesis, leading to varying yield losses. Reduced photosynthetically active radiation affected normal spike development, decreasing effective panicle number and grains per spike, thereby reducing yield ().

Yield and its components of winter wheat at different spatial positions in jujube-wheat intercropping system

Space position	Grains per spike	Spike number	1000-grain weight (g)	Yield (g · 20 plants^{-1})
JZ	CK	JZ	CK	JZ
E50-E100	25.76$±2.37*Aa*|39.69±3.65*Aa*|724±12*Bb*|874±19*Aa*|18.65±3.16*Aa*|34.69±6.14*Aa*|309±7*Bc*|38			

3 Discussion and Conclusion

Current research divides competition within intercropping systems into aboveground and belowground components, with aboveground competition primarily referring to light competition. Light is a crucial ecological factor and the primary energy source for plant photosynthesis. Light quality directly determines crop yield and quality. In intercropping systems, photosynthetically active radiation intercepted by intercrop canopies directly determines overall system productivity. Shading of low-stature crop canopies by tall plants reduces photosynthetically active radiation interception, consequently decreasing crop yield. International studies on eucalyptus (*Eucalyptus torelliana* F.)-cabbage (*Brassica oleracea* L.) intercropping found that eucalyptus shading reduced cabbage yield. Domestic research on apricot (*Armeniaca vulgaris* Lam.)-wheat intercropping also found that competition for light between apricot and wheat created distinct yield reduction zones in winter wheat near apricot trees, with yield increasing as distance from apricot trees increased and a distinct yield increase zone existing in the alley center.

This study found that winter wheat LSP and LCP varied across growth stages, with physiological activity peaking during filling then gradually declining. Canopy light distribution in the jujube-wheat intercropping system followed certain patterns: temporally, the ranking of canopy saturating light duration across growth stages was maturity > tillering > jointing > filling > heading > flowering; spatially, the ranking of canopy saturated PAR spatiotemporal windows was W150-W200 cm > E150-E200 cm > W100-W150 cm > E100-E150 cm > W50-W100 cm > E50-E100 cm. Within a daily light cycle, canopy saturating light on the same transect showed an "n" -shaped curve distribution. In the jujube-wheat system, the shaded area and shading duration of jujube trees on winter wheat canopy were related to both wheat growth stage and planting position. Shading reduced canopy PAR interception and yield of winter wheat. Winter wheat in the middle position between two jujube rows had significantly higher PAR interception and yield than on both sides, with the west side overall higher than the east. Jujube shading inhibited photosynthetic production, increased sterile spikelets, and significantly reduced grain weight per spike and 1000-grain weight, thereby decreasing yield—results similar to domestic studies on jujube-cotton intercropping.

This study also found that yield reduction was not significant for wheat between two jujube rows, with no yield increase zone, which differs from previous apricot-wheat intercropping studies showing yield spillover effects. This discrepancy may be due to different intercropping environments or different competition mechanisms between jujube-wheat versus apricot-wheat systems, requiring further investigation. This study employed a novel spatiotemporal window measurement method with finer temporal and spatial resolution to examine relationships between canopy light distribution and yield in jujube-wheat intercropping. This method offers high precision but involves complex calculations and high data completeness requirements. Exploring light distribution and yield variation patterns by dividing wheat growth stages can provide scientific basis for managing jujube-wheat intercropping systems. However, this study only examined light effects on yield, without considering other ecological factors such as water, nutrients, and temperature, representing a limitation for future comprehensive analysis.

In summary, canopy light intensity and yield of winter wheat in jujube-wheat intercropping systems exhibited distinct spatiotemporal distribution characteristics with overall attenuation compared to monoculture, in the order: canopy saturated effective radiation > yield > 1000-grain weight > effective panicle number > grains per spike. Jujube shading reduced effective panicle number and grains per spike, thereby decreasing yield. Differential shading caused varying yield losses, with better light quality in the middle than on both sides of the alley and overall better quality on the west side than the east.

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Note: Figure translations are in progress. See original paper for figures.