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ARTICLE

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Yield and quality of intercropped wheat in jujube- and walnut-based agroforestry systems in southern Xinjiang Province, China

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Abstract

Agroforestry is widely practiced in China and has the benefit of diversifying agricultural production and enhancing natural resource utilization; however, these systems create competition for light between trees and understory crops. We investigated the effects of shading by jujube (*Zizyphus jujuba* Mill.) and walnut (*Juglans regia* L.) trees on the yield and quality of intercropped wheat (*Triticum aestivum* L.) in agroforestry systems in southern Xinjiang Province, China. In the walnut–wheat intercropping system, mean daily photosynthetically active radiation (PAR) and net photosynthetic rates (Pn) in the understory were reduced by 72.4–79.7% and 45.8–49.6%, respectively, at the grain-filling stage as compared to wheat grown in monoculture. Relative to monoculture wheat, the walnut-based system resulted in significant reductions in the number of florets and spikelets per spike, grain-filling rate, and grain yield and its components in intercropped wheat. In contrast, N and P concentrations, and protein and wet gluten contents of intercropped wheat were significantly increase. In the jujube–wheat intercropping system, mean daily PAR and Pn in the understory were reduced by 23.2–25.5% and 27.2–34.3% at the grain-filling stage compared to monoculture wheat, but grain yield and its components, the number of florets and spikelets, N and P concentrations, and protein and wet gluten contents of wheat did not differ between the two systems. The jujube-based agroforestry system was more sustainable than the walnut-based system in our study region, but competition for light between walnut trees and intercrops may be alleviated by selective felling, pruning, and wider tree spacing.

Abbreviations: LER, land equivalent ratio; PAR, photosynthetically active radiation; Pn, net photosynthetic rates; TPAR, transmitted photosynthetically active radiation

1 | INTRODUCTION

Agroforestry is a land use system in which woody perennials are grown in association with agricultural crops or pastures; this intermingling results in ecological and economic interactions between component crops (Nair, 1985). Intercropping of trees and grain crops has been practiced for thousands of years in China and elsewhere (Inurreta-Aguirre, Lauri, Dupraz, & Gosme, 2018; Zhang et al., 2017), In recent decades, researchers from many fields have become increasingly interested in traditional agroforestry systems because of their potential to increase land productivity, diversify production, and enhance resource utilization (Gao et al., 2013; Hong et al., 2017; Yang et al., 2019; Zou & Sanford, 1990). Qiang, Zhao, Wu, Gao, and Sun (2019) suggested the agroforestry system could increase the soil water content. Trees and crops differ in temporal and spatial patterns of resource acquisition, resources such as light and nutrients may be more fully captured in agroforestry systems than in monocultures (Inurreta-Aguirre et al., 2018). Additionally, when annual monoculture crops are converted into intercropped agroforestry systems, the strategies of frequent disturbance used to control pests and disease are to some extent replaced by internal control processes (Armengot et al., 2020; Schroth, Krauss, Gasparotto, Aguilar, & Vohland, 2000).

Two major interactive processes, niche complementarity and facilitation, can be leveraged to improve resource acquisition among species in agroforestry systems (Fridley, 2002; Loreau et al., 2001). Land equivalent ratio (LER) values are >1 in most agroforestry systems (Wang et al., 2014; Yang et al., 2019; Zhang et al., 2017), indicating complementarities in resource use between trees and crops. However, agroforestry typically results in a reduction in understory crop yields due to competition between perennial trees and annual crops for light, water, nutrients, and/or space (Gao et al., 2013; Inurreta-Aguirre et al., 2018; Yang et al., 2019). Light is a primary limiting factor in agroforestry systems, and strongly influences understory crop growth in intercropping systems (Chirko, Gold, Nguyen, & Jiang, 1996; Fernández, Gyenge, Licata, Schlichter, & Bond, 2008). Kittur, Sudhakara, Kumar, Kunhamu, and Sureshkumar (2016) proposed a linear equation based on the association between rhizome yield and photosynthetically active radiation (PAR) in the understory. Gao et al. (2013) observed a clear, positive linear relationship between distance from apple (*Malus* spp.) tree rows and understory daily mean PAR and net photosynthetic rates (Pn) in intercrops in agroforestry systems. Khybri, Gupta, Ram, and Tomar (1992) found that crop yield was reduced by 39, 33, 25, and 12% at distances of 1, 1–2, 2–3, and 3–5 m from tree rows, respectively, in rice (*Oryza sativa* L.) and wheat grown in rotation as intercrops with three tree species in the outer hills of the western Himalaya. Similar results have been reported in other studies (Pandey, Verma, Dagar, & Srivastava, 2011; Peng, Zhang, Cai, Jiang, & Zhang, 2009). In contrast, Wang et al. (2016) reported that the effects of shading by jujube (*Zizyphus jujuba* Mill.) trees on yields of upland cotton (*Gossypium hirsutum* L.) were offset by increasing plant density as a result of greater bole numbers per unit ground area in Xingjiang Province, China. Kittur et al. (2016) found that appropriate spacing (8 by 8 m and 10 by 10 m) of bamboo [*Dendrocalamus strictus* (Roxb.) Nees] optimized the productivity of turmeric (*Curcuma longa* L.) without compromising bamboo yields. Therefore, it is important to explore the basic mechanisms underlying the effects of fruit trees on understory crop yields in agroforestry systems to develop effective management strategies that can improve intercrop yields and to guide policy decisions.

Core Ideas

- Grain yield and quality did not differ between jujube–wheat intercropping system and monoculture.
- Wheat yield was significantly reduced but grain quality was markedly enhanced in walnut-based agroforestry.
- Jujube-based agroforestry is more sustainable than walnut-based agroforestry in southern Xinjiang.

Xinjiang Province is landlocked and located within the warm temperate continental drought climatic zone characterized by an arid climate, low rainfall, high evaporation, abundant sunshine, and strong diurnal temperature fluctuations. As such, the region is well suited to growing crops and fruit trees. With recent changes to planting systems in pursuit of high-yield and high-efficiency crops, economic trees, particularly fruit trees, have been widely planted in farms in southern Xinjiang Province (Zhang et al., 2017). By 2012, the total area of fruit tree plantations exceeded 1 million ha in the southern Xinjiang Uygur Autonomous Region in northwestern China (Zhang et al., 2017), with more than 80% of fruit trees planted in intercropping systems. These systems have considerable potential to provide food and nutritional security, and to contribute to local economic development. However, as fruit trees have grown, the productivity of fruits and crops in many agroforestry systems (in terms of high yield and high efficiency) has been lower than expected. At the same time, the effects of shading on intercrops {e.g., wheat [*Triticum aestivum* L.], cotton, corn [*Zea mays* L.], soybean [*Glycine max* (L.) Merr.]} have become increasingly detrimental, whereas food production pressure has increased. Grain quality has been increasingly affected as

TABLE 1 Nutrient status of the experimental soil. Jiw: Jujube tree–wheat intercropping system; Wiw: walnut tree–wheat intercropping system

Cropping system	pH	Organic matter	Total N	Total P	Total K	Available N	Olsen-P	NH_4OAc-K
		g kg^{-1}				mg kg^{-1}		
Monoculture wheat	8.75	8.08	0.69	1.21	19.1	67.2	30.3	91.8
Monoculture jujube	8.68	11.0	0.61	0.97	20.1	47.8	32.9	121.9
Monoculture walnut	8.69	10.7	0.78	1.00	20.4	59.3	28.8	103.3
Jiw	8.66	11.1	0.56	0.98	20.5	48.6	32.1	122.4
Wiw	8.62	11.2	0.71	1.05	19.8	58.9	27.2	101.5

shading intensifies (Gao et al., 2013; Wang et al., 2014; Yang et al., 2019), and the widespread planting of fruit trees has led to a reduction in the area of crop planting, resulting in decreased food outputs. This lowered productivity represents a threat to food security, creating an urgent need to optimize facilitative and complementary interactions between the tree and understory components of agroforestry systems.

In our previous study, we observed mean daily shade intensities of 21.3, 54.5, and 80.3% in the understory of jujube-, apricot (*Prunus armeniaca* L.)-, and walnut (*Juglans regia* L.)-based intercropping systems, respectively, compared to monoculture crops (Qiao, Sai, Chen, Xue, & Lei, 2019). However, it is important to understand how tree species affect the growth and development of intercrops. Different fruit trees may have different effects on understory crops by shade, but little information is available about crop performance under different tree species. Here, we explore the influence of different fruit tree species on the growth, yield, and quality of intercropped wheat (cultivar Xindong-20) in jujube (cultivar Junzao) and walnut (cultivar Wen-185) agroforestry systems; jujube and walnut were chosen because of their importance as economic fruit trees and food crops in southern Xinjiang. The objectives of this study were to (a) assess whether shading effects of different fruit trees had a significant influence on the yield and quality of companion wheat, and (b) determine which tree species is more suitable for agroforestry in Xinjiang.

2 | MATERIALS AND METHODS

2.1 | Site description

Field experiments were conducted in 2011 and 2012 in four villages of Zepu County (38°05' N, 77°10' E), Kashi Prefecture, Xinjiang Uygur Autonomous Region, China. Altitude is 1318 m above sea level. Annual mean temperature is 11.6 °C (1961–2008). Cumulative temperatures above 0 °C is 4183 °C. The mean frost-free period is 212 d. Annual precipitation is 54.8 mm, potential evaporation is 2079 mm, and the region has a typical arid climate. The soil at the site is classified as an arenosol in the classification system of the Food and Agriculture Organization (FAO).

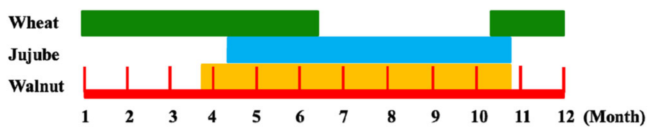

FIGURE 1 Growth stage of wheat, jujube and walnut trees in the field

2.2 | Experimental design

We compared wheat, jujube, and walnut grown as monocultures with wheat intercropped with 9-yr-old jujube trees and 10-yr-old walnut trees. Figure 1 presents the growth stages of wheat, jujube, and walnut trees, and Table 1 lists the local soil chemical properties. Row spacing for wheat was 0.13 m for both monoculture and agroforestry, and rows were oriented north–south. Table 2 provides a basic description of the fruit trees. The wheat strips in jujube and walnut intercropping systems were 3.3 and 6.0 m wide, respectively. Each wheat strip was divided into three equal sections, hereafter referred to as the east-row, inter-row, and west-row positions (Figure 2). Minimum distances between trees and wheat rows were 0.85 m for jujube and 1.0 m for walnut, and intercropped wheat occupied 66.0% of the total area in the jujube-based system and 75.0% in the walnut-based system. The monoculture plots and the intercropping systems were each 0.4 ha in area and had a density of 425 wheat plants m^{-2}.

Wheat for the 2011 season was sown in all plots on 8 Oct. 2010 and harvested on 11 June 2011. Wheat for the 2012 season was sown on 3 Oct. 2011 and harvested on 9 June 2012. Nine replicates were included in the study. All fields were fertilized with urea, triple superphosphate, potassium sulfate, and farmyard manure (N: P_2O_5: K_2O = 0.37%: 0.41%: 0.46%) at rates of 15 × 10^3 kg ha^{-1}

TABLE 2 The basic information of the two fruit trees. DBH: diameter at breast height (cm)

Fruiter	Spacing	Age	DBH	Trunk	Height	Crown width
	m	yr	cm	m		
Jujube	1.5 × 5.0	9	9.4	0.4	2.5	2.4-2.3
Walnut	5.0 × 8.0	10	20.2	1.3	6.6	6.3-6.7

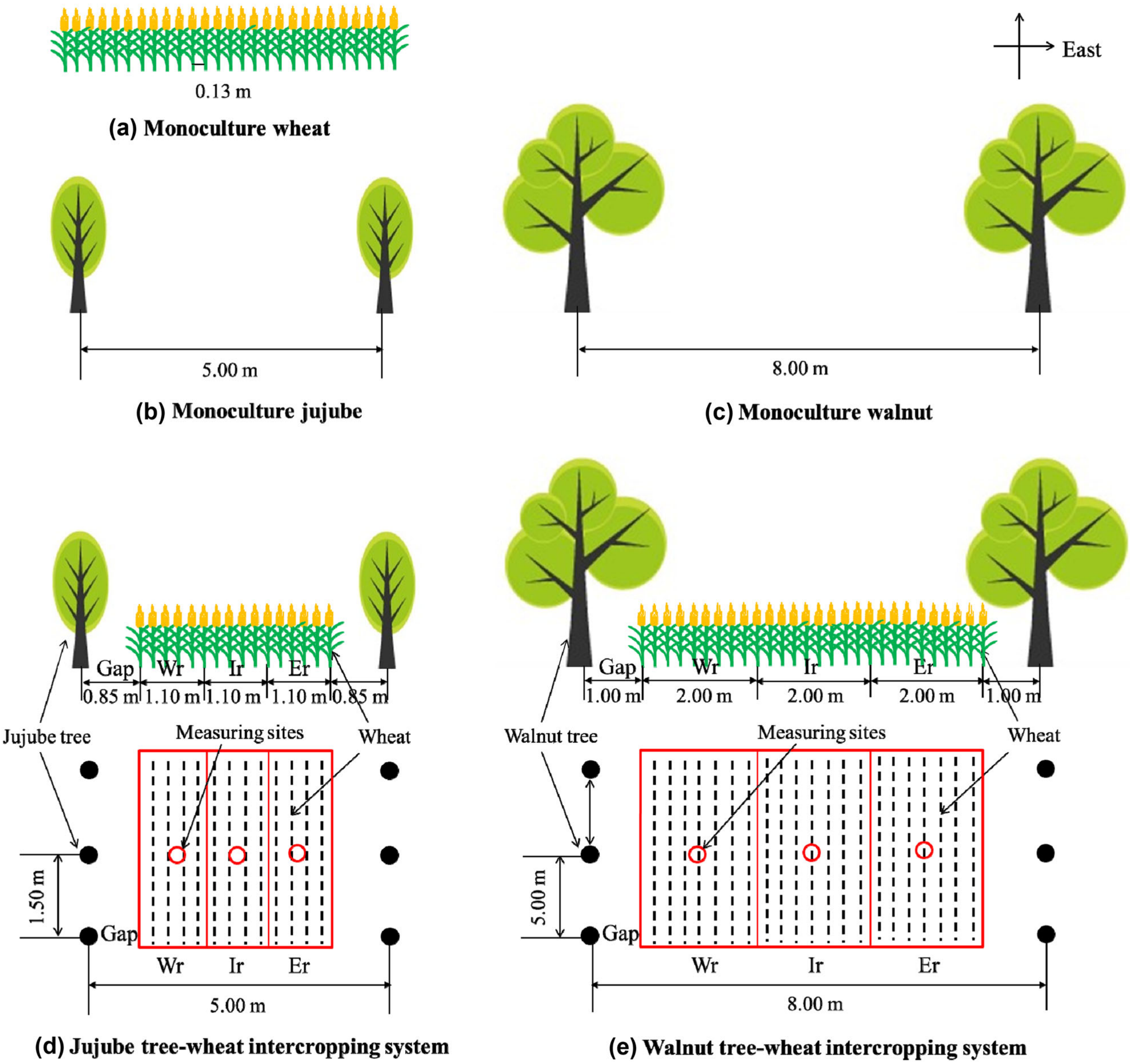

FIGURE 2 Schematic illustration of planting patterns in monoculture configurations and in jujube and walnut tree-wheat based intercropping systems. Er: east-row position; Ir: inter-row position; Wr: west-row position

(farmyard manure), 275 kg ha^{-1} (N), 150 kg ha^{-1} (P_2O_5), and 275 kg ha^{-1} (K). All farmyard manure, P and K fertilizers, and 40% of the N fertilizer were applied homogeneously throughout the fields before wheat was sown; the remaining 60% of the N fertilizer was applied when wheat reached the stem elongation stage. Fertilizer application was identical for monoculture and intercropped systems. Plots were irrigated three times, with irrigation coinciding with the reviving, jointing, and filling stages of wheat growth. Each irrigation application consisted of 900–1000 m^3 ha^{-1} and followed practices recommended by local agronomists.

2.3 | Harvest and analysis

Wheat and fruits were harvested by hand at maturity. In both 2011 and 2012, 6.5 m^2 (5.0 by 1.3 m) of monoculture wheat was harvested, along with 3.3 m^2 of jujube-based intercropped wheat (3.0 by1.1 m from the east-row, inter-row, and west-row regions), and 5.0 m^2 of walnut-based intercropped wheat (2.5 by 2.0 m from the east-row, inter-row, and west-row positions). Samples were dried to a constant weight on a sunny ground to thresh seeds (when the moisture content of the grain was below 13%) immediately after harvesting. Stalk and grain samples were digested in a mixture of concentrated H_2SO_4 and H_2O_2. Nitrogen concentrations were determined using the micro-Kjeldahl method, and P concentrations using the vanadomolybdophosphoric acid colorimetric method (Fixen & Grove, 1990). We also harvested four jujube and walnut fruits from each replicate, air-dried them to a constant weight, and recorded their dry weight. In 2011, 15 plants from each replicate were selected for calculations of stalk biomass at the overwintering, reviving, jointing, booting, anthesis, filling, and mature stages. Stalk samples were heated at 105 °C for 30 min and then oven-dried for 72 h at 75 °C.

2.4 | Calculation of land equivalent ratio

The land equivalent ratio (LER) is defined as the relative land area with monoculture crops needed to produce the dry biomass or yield of each species achieved in intercropping system (Willey, 1979). The LER is the most widely accepted index for evaluating the effectiveness of all forms of mixed cropping and has been widely used in agroforestry systems as well (Cao, Kimmins, & Wang, 2012; Zhang et al., 2017). Gross yield LER for a fruit tree–wheat intercropping system is the sum of the partial LER values for wheat (LER_W) and fruit (LER_F):

$$\mathrm{LER} = \mathrm{LER_W} + \mathrm{LER_F} \tag{1}$$

$$\mathrm{LER_W} = \mathrm{GY}\text{-}_{\mathrm{IW}} / \mathrm{GY}\text{-}_{\mathrm{SW}} \tag{2}$$

$$\mathrm{LER_F} = \mathrm{GY}\text{-}_{\mathrm{IF}} / \mathrm{GY}\text{-}_{\mathrm{SF}} \tag{3}$$

where $GY\text{-}_{SW}$ and $GY\text{-}_{SF}$ are the gross yields of wheat and fruit in pure monoculture, respectively; and $GY\text{-}_{IW}$ and $GY\text{-}_{IF}$ are the gross yields of wheat and fruit in agroforestry system, respectively. If the LER is greater than 1.0, intercropping is advantageous, and less than 1.0 indicates a disadvantage.

2.5 | Fertile floret and grain-filling measurements

In both 2011 and 2012, we selected 300 spikes from each treatment combination during the flowering period for tagging (50% anthesis). Selected spikes were of similar sizes and had flowered on the same day. To increase the representativeness of the data, 30 spikes from three row positions (east row, inter-row, and west row) were destructively sampled to investigate spikelets and florets. We also destructively sampled 30 spikes from the three row positions at 5-d intervals after 50% anthesis, for a total of up to 45 d. Floret initiation was observed to be more advanced on the sixth or seventh spikelet, so we selected the first grain on the left side of the sixth and seventh spikelet positions, heated them at 105 °C for 30 min, and then oven-dried them for 72 h at 75 °C. Grains were weighed, and grain-filling rates were assessed using an ordinary logistic regression model.

The grain weight (Y; mg) of crop plants are typically a sigmoid function of time, t. We followed Trinder, Brooker, Davidson, and Robinson (2012) to compute the grain-filling progress. The logistic equation is:

$$Y_{t+1} = Y_t \triangle_t \left[1 + (r[1 - (Y_t / Y_{max})])\right] \tag{4}$$

where r is relative growth rate of grain dry weight (d^{-1}) for per capita seed dry weight production; Y_{max} is a maximum value of grain weight) was used to separately fit the data of grain weight by simultaneously adjusting r and Y_{max} to maximize R^2 with the SOLVER in Microsoft Excel 2010.

2.6 | Photosynthetically active radiation measurement

Light penetration was measured using a SunScan Canopy Analysis System (Delta-T Devices, Cambridge, UK), and the measured position was just 10 cm above wheat (values indicate the PAR transmitted by fruit trees and incident over the wheat canopy) and underneath wheat (values indicate the PAR transmitted fruit trees and wheat canopy getting to the ground surface, TPAR) canopy. The 64 light sensors of the SunScan measured individual levels of PAR, which were transmitted to a handheld personal digital assistant (PDA) and expressed as μmol m^{-2} s^{-1}. SunScan readings were taken when the sky was clear to avoid the interference of the clouds at the filling stage of wheat on 28 and 29 May 2011, respectively, for walnut- and jujube tree-based intercropping systems; and correspondingly SunScan readings were taken on 27 and 28 May in 2012. One measurement was performed every 2 h from morning at 0900 h until late afternoon at 1900 h (there is a 2-h time difference from Beijing in Xinjiang). The measurement positions were taken in the central part of each area (east-row, inter-row, and west-row positions). For understory PAR: An average value was calculated from two positions (the 64 light sensors were placed in North−South and East–West orientations) per replicate positioned; for TPAR: the value was only measured from East–West orientation.

$$\text{Mean shade intensity}(\%) = (\text{PAR}_{\text{mono}} - \text{PAR}_{\text{int}})/\text{PAR}_{\text{mono}} \times 100\% \quad (5)$$

PAR_{mono} is the mean daily photosynthetically active radiation of monoculture wheat system; PAR_{int} is the mean daily photosynthetically active radiation of a fruit tree-based intercropping system.

2.7 | Photosynthetic parameters

The Pn of flag leaves was determined with a LI-6400XT Portable Photosynthesis System (LI-COR, Inc.), and the readings were taken when the sky was clear to avoid the interference of the clouds at the filling stage of wheat. The measurements were conducted under a traditional open system and under controlled conditions with a CO_2 concentration of 380 μmol m^{-2} s^{-1}. The PAR was set at 1200 μmol m^{-2} s^{-1}, which was provided by a 6400-2B LED light source. The Pn was measured every 2 h from morning at 0900 h until late afternoon at 1900 h on 28 and 29 May 2011, respectively, for walnut- and jujube tree-based intercropping systems; and correspondingly the Pn was measured on 27 and 28 May 2012.

2.8 | Grain quality analyses

Grain protein content (%) was determined using a near-infrared reflectance analyzer (FOSS-1241, near infra-red reflectance, Sweden) and wet gluten content was determined using the Glutomatic 2200 (Perten Instruments) calibrated based on official AACC methods (AACC International, 2010).

2.9 | Statistical analysis

Two-way ANOVA was used to assess yield, its components, and protein and wet gluten content, using the JMP professional version 9.0 (SAS Institute Inc.). Tree species and position included fixed effects, and a Tukey test was used for pair-wise comparisons. The control treatment was excluded. Treatment effects were deemed significant when $P < .05$. One-way ANOVA was used to assess yield, its components, florets, spikelets, N and P concentrations, and protein and wet gluten content. Significant differences among means were assessed using a Tukey test at a protection level of 5%. Standard error was calculated using nine replicates for yield, its components, florets, and spikelets, and using three replicates for PAR and TPAR (PAR reaching the ground), Pn, N, and P concentrations, and protein and wet gluten content.

3 | RESULTS AND DISCUSSION

3.1 | Land equivalent ratio

Based on gross yields, LER was > 1 for both intercropping systems, with values of 1.43–1.47 for the jujube-based system and 1.22–1.30 for the walnut-based system. The partial LER of wheat was consistently higher in the jujube-based system (0.61–0.67) than in the walnut-based system (0.27–0.33), while the partial LER of fruit was 0.79–0.82 for the jujube-based system and 0.95–0.97 for the walnut-based system (Table 3). In 2011, the grain yield of intercropped wheat on a gross area basis decreased by 33.2% in the jujube system, and by 67.1% in the walnut system, as compared to the monoculture system. Fruit yields in the jujube and walnut systems decreased by 21.1 and 3.2%, respectively.

3.2 | Wheat yield and its components

Grain yield was significantly affected by both tree species and the interaction between species and positions (east row, inter-row and west row), but not by position alone (Table 4). In both study years, the number of spikes, number of grains, 1000-grain weight, and net yield of monoculture and jujube-intercropped wheat were significantly higher than those of walnut-intercropped wheat ($P < .05$) (Table 5). The number of spikes, number of grains, and 1000-grain weight generally did not differ significantly among row positions, with the exception of 1000-grain weight in the inter-row position in the walnut-based system. Spike number, grain number, 1000-grain weight, and yield were strongly and negatively correlated with mean shade intensity in both years ($P < .001$; Figure 3).

3.3 | Florets and spikelets

Fertile spikelets were highly affected by tree species, positions, and the interaction between these two factors (Supplemental Table S1). In both years, monoculture wheat had significantly more total florets and fertile florets than intercropped wheat from either agroforestry systems (Table 6). Wheat grown in the inter-row position in the walnut-based

TABLE 3 Land equivalent ration (LER) and partial LER of wheat (LER_W) and fruit (LER_F) when grown in jujube and walnut-tree based intercropping systems in 2011 and 2012, as calculated for grain and fruit yields on a gross area. Mono: monoculture wheat; Jiw: Jujube–wheat intercropping system; Wiw: walnut–wheat intercropping system

Year	Cropping system	Wheat Monoculture	Wheat Intercropped	LER_W	Fruit Monoculture	Fruit Intercropped	LER_F	LER
		yield, kg ha^{-1}			yield, kg ha^{-1}			
2011	Jiw	8,114	5,422	0.67	12,028	9,491	0.79	1.47
	Wiw	8,114	2,666	0.33	2,901	2,808	0.97	1.30
2012	Jiw	7,506	4,549	0.61	12,319	10,008	0.82	1.43
	Wiw	7,506	1,990	0.27	2,962	2,812	0.95	1.22

TABLE 4 Summary of two-way analysis of variance of the effect of tree species and positions on measured variables

Measurement	Variation	df	2011 *F* value	2011 *P*-value	2012 *F* value	2012 *P*-value
Grain number, grains spike^{-1}	Species	1	28.04	.000	176.0	.000
	Positions	2	0.123	.884	0.447	.642
	Species × Positions	2	0.394	.676	1.146	.327
Spike number, no. m^{-2}	Species	1	99.53	.000	137.0	.000
	Positions	2	0.081	.122	0.256	.775
	Species × Positions	2	1.669	.199	0.870	.425
1000-grain weight, g	Species	1	56.80	.000	324.0	.000
	Positions	2	1.334	.273	0.447	.642
	Species × Positions	2	1.029	.365	5.103	.010
Net yield, kg ha^{-1}	Species	1	481.1	.000	401.9	.000
	Positions	2	1.855	.167	1.110	.338
	Species × Positions	2	7.465	.002	3.524	.037
Protein content, %	Species	1	224.8	.000	69.58	.000
	Positions	2	1.979	.181	0.289	.754
	Species × Positions	2	0.601	.564	0.425	.663
Wet gluten content, %	Species	1	109.5	.000	93.23	.000
	Positions	2	0.776	.482	0.156	.857
	Species × Positions	2	0.282	.759	0.063	.940

system had significantly higher total and fertile florets than plants in the east- and west-row positions, with the exception of fertile florets in 2011. No differences were observed among row positions in the jujube-based system. In both years, the total and fertile spikelets were significantly greater in monoculture and jujube-intercropped wheat than in walnut-intercropped wheat (Table 6). We observed a strong negative correlation between these four parameters and mean shade intensity in both years ($P < .001$; Supplemental Figure S1).

3.4 | Cumulative seed-filling process

The seed-filling process in wheat differed significantly among cropping systems, and was well-described by a logistic regression model ($P < .05$) (Figure 4). The maximum dry weight of seeds (Y_{max}) was strongly affected by tree species. Compared to monoculture wheat, Y_{max} of jujube- and walnut-intercropped wheat was reduced by an average of 10.6 and 23.4% in 2011, and 9.5 and 34.9% in 2012, respectively (Supplemental Table S2).

3.5 | Light interception and Pn variation

Diurnal variations in both PAR and TPAR yielded a single-peaked curve over time in all three cropping systems (Figure 5). Compared to the monoculture system, mean daily PAR in the jujube-based intercropping system was reduced by 30.1% in the east-row, 14.2% in the inter-row, and 33.1% in the west-row positions. Similarly, reductions in the walnut-based system in 2012 were 88.0, 46.6, and 82.7% in the three row positions (Figures 5c, 5d).

TABLE 5 Yield components of wheat in jujube and walnut trees based intercropping systems in 2011 and 2012. Mono: monoculture wheat; Er: east-row position; Ir: inter-row position; Wr: west-row position; Jiw: Jujube tree–wheat intercropping system; Wiw: walnut tree–wheat intercropping system. Across all data, values with the same letter within each column are not significantly different among the treatments ($P < .05$)

Year	Cropping system	Treatment	Grain number	Spike number	1000-grain weight	Net yield
			grains spike^{-1}	no. m^{-2}	g	kg ha^{-1}
2011	Mono	Mono	39.1 ± 2.6a	654 ± 140a	42.1 ± 1.9a	8114 ± 879a
	Jiw	Er	38.1 ± 2.6a	709 ± 118a	36.7 ± 2.6b	8415 ± 582a
		Ir	36.7 ± 3.4a	653 ± 118a	36.8 ± 1.6b	7842 ± 936a
		Wr	37.2 ± 3.0a	714 ± 90a	36.6 ± 2.8b	8388 ± 998a
	Wiw	Er	31.8 ± 4.5b	440 ± 75b	29.8 ± 4.5 cd	3606 ± 878b
		Ir	32.5 ± 4.8b	472 ± 80b	31.7 ± 3.6c	4254 ± 570b
		Wr	31.6 ± 3.5b	427 ± 67b	28.4 ± 3.8d	2805 ± 590c
2012	Mono	Mono	38.8 ± 4.5a	637 ± 89a	37.3 ± 3.1a	7506 ± 695a
	Jiw	Er	37.4 ± 4.8a	633 ± 76a	31.2 ± 1.8b	7372 ± 756a
		Ir	35.5 ± 2.8a	586 ± 116a	30.9 ± 1.3b	6469 ± 858b
		Wr	36.1 ± 3.6a	615 ± 62a	33.1 ± 1.4b	6837 ± 665ab
	Wiw	Er	21.3 ± 5.2b	343 ± 79b	20.8 ± 2.9cd	2592 ± 804c
		Ir	23.1 ± 3.1b	360 ± 57b	22.4 ± 2.4c	3004 ± 952c
		Wr	20.4 ± 4.2b	324 ± 101b	20.0 ± 2.7d	2365 ± 565c

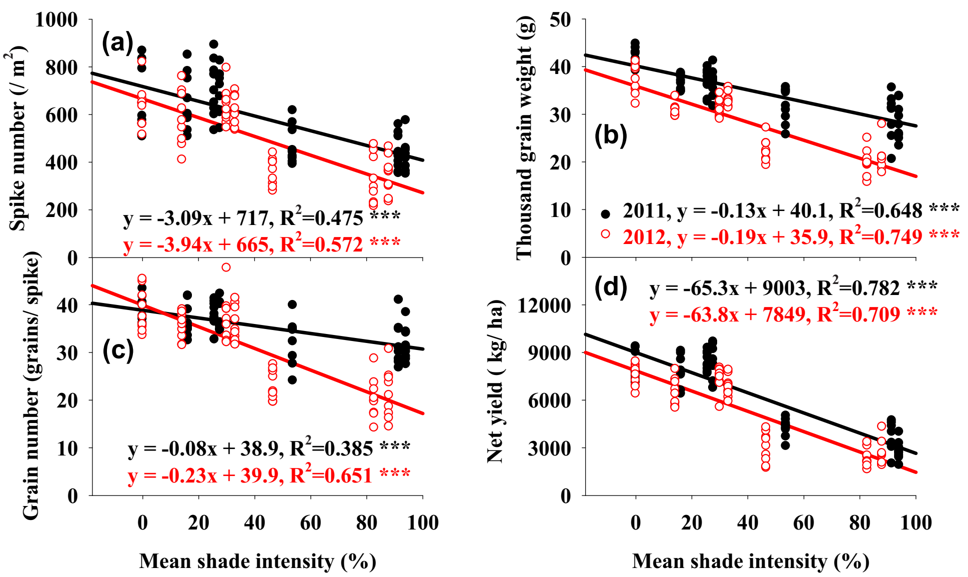

FIGURE 3 Relationship between (a) the spike number, (b) thousand grain weight, (c) grain number, and (d) net yield with mean shade intensity of wheat in 2011 and 2012

The TPAR was significantly lower than PAR, and never exceeded 250 μmol m^{-2} s^{-1} (Figures 5e-5h). Due to the influence of the tree canopy, the east-row and west-row positions in both intercropping systems received lower levels of PAR and TPAR compared to the inter-row position.

Diurnal variations in Pn in the three cropping systems yielded a single-peaked curve over time, and Pn was higher in the monoculture system than in either intercropping system (Figure 6). For example, in the jujube-based intercropping system, the mean Pn of intercropped wheat in 2011 was reduced by 48.3% in the east-row, 24.8% in the inter-row, and 29.6% in the west-row positions as compared to monoculture wheat. Observed reductions in the same three row positions in the walnut intercropping system were 59.7, 33.4, and 55.8%, respectively, in 2011 (Figures 6a,6c). We also observed temporal trends in Pn; wheat in the east-row positions had higher Pn values in

TABLE 6 The florets and spikelets of wheat in jujube and walnut trees based intercropping systems in 2011 and 2012. Fertile florest: its male and female organs were fertile; Fertile spikelet: the spikelet which have fertile florests; Mono: monoculture wheat; Er: east-row position; Ir: inter-row position; Wr: west-row position; Jiw: Jujube tree–wheat intercropping system; Wiw: walnut tree–wheat intercropping system. Across all data, values with the same letter within each column are not significantly different among the treatments ($P < .05$)

Year	Cropping system	Treatment	Total florets	Fertile florets	Total spikelets	Fertile spikelets
			no. spike^{-1}			
2011	Mono	Mono	113.2 ± 6.6a	67.1 ± 6.4a	21.8 ± 0.8a	20.7 ± 0.9a
	Jiw	Er	101.8 ± 9.9b	60.5 ± 5.6b	22.0 ± 1.1a	20.3 ± 0.8a
		Ir	100.3 ± 5.4b	60.6 ± 5.1b	22.2 ± 1.0a	21.0 ± 0.7a
		Wr	99.2 ± 6.9b	59.3 ± 4.4b	21.8 ± 0.6a	20.4 ± 0.5a
	Wiw	Er	78.5 ± 6.5d	45.7 ± 6.7c	20.0 ± 0.8b	16.3 ± 1.7c
		Ir	85.4 ± 6.4c	48.4 ± 5.7c	20.7 ± 0.8b	18.4 ± 1.2b
		Wr	77.5 ± 6.2d	48.2 ± 3.1c	20.6 ± 1.1b	18.1 ± 1.4b
2012	Mono	Mono	111.0 ± 5.7a	66.1 ± 3.1a	21.1 ± 1.5a	20.7 ± 1.3a
	Jiw	Er	98.7 ± 8.5b	59.3 ± 6.8b	21.1 ± 0.7a	19.6 ± 1.1a
		Ir	101.1 ± 4.6b	58.9 ± 3.6b	21.1 ± 0.7a	19.7 ± 0.8a
		Wr	97.4 ± 6.0b	56.4 ± 5.7b	21.0 ± 0.8a	19.7 ± 0.8a
	Wiw	Er	72.9 ± 2.9d	33.1 ± 2.0d	19.7 ± 0.5b	13.6 ± 1.0c
		Ir	83.9 ± 6.7c	43.0 ± 4.9c	20.0 ± 1.3ab	15.6 ± 1.0b
		Wr	75.0 ± 4.3d	36.7 ± 3.9d	19.4 ± 1.0b	14.6 ± 0.8bc

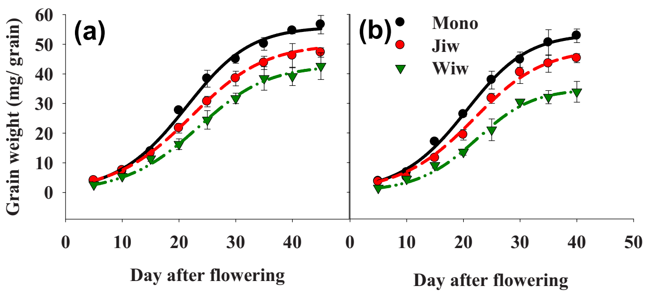

FIGURE 4 Cumulative seed dry weight (mg/grain) by wheat plants in (a) 2011 and (b) 2012. Each symbol represents a single harvest and is the mean values of east-row, inter-row, and west-row positions. Curves are derived from Equation 4 using mean parameter estimates. Mono: monoculture wheat system; Jiw: jujube–wheat intercropping system; Wiw: walnut–wheat intercropping system

the afternoon, whereas wheat in the west-row positions had higher values in the morning.

3.6 | Ntrogen and phosphorus concentrations

Concentrations of N and P in the stalks and grains of intercropped wheat were strongly affected by both tree species and the interaction between species and positions (with the exception of P concentration in grains in 2012), but not by position alone (Supplemental Table S1). In both years, N and P concentrations in the walnut-based intercropping system were significantly higher than those of monoculture and jujube-intercropped wheat (Table 7). For example, N concentrations in stalks of walnut-intercropped wheat increased by 76.5% (east row), 62.8% (inter-row), and 76.3% (west row) in 2011 compared to monoculture wheat, while N concentrations in grains increased by 26.7, 15.4, and 14.7%, respectively, in the same year. Similarly, P concentrations in stalks increased by 66.7, 56.4, and 76.9% in the three row positions, while P concentrations in grains increased by 33.3, 26.6, and 34.8%. In both years, N and P concentrations in stalks and grains were strongly and positively correlated with mean shade intensity ($P < .001$; Supplemental Figure S2).

3.7 | Grain quality

Protein and wet gluten contents were strongly affected by tree species, but not by row position or the interaction between the two (Table 4). In 2011 and 2012, the protein and wet gluten contents of walnut-intercropped wheat were significantly higher than in monoculture and jujube-intercropped wheat (Table 7). Protein and wet gluten contents of wheat did not differ among the three row positions in either intercropping system in 2011 or 2012. Protein and wet gluten contents were strongly and positively correlated with mean shade intensity ($P < .001$) (Figure 7) in both years.

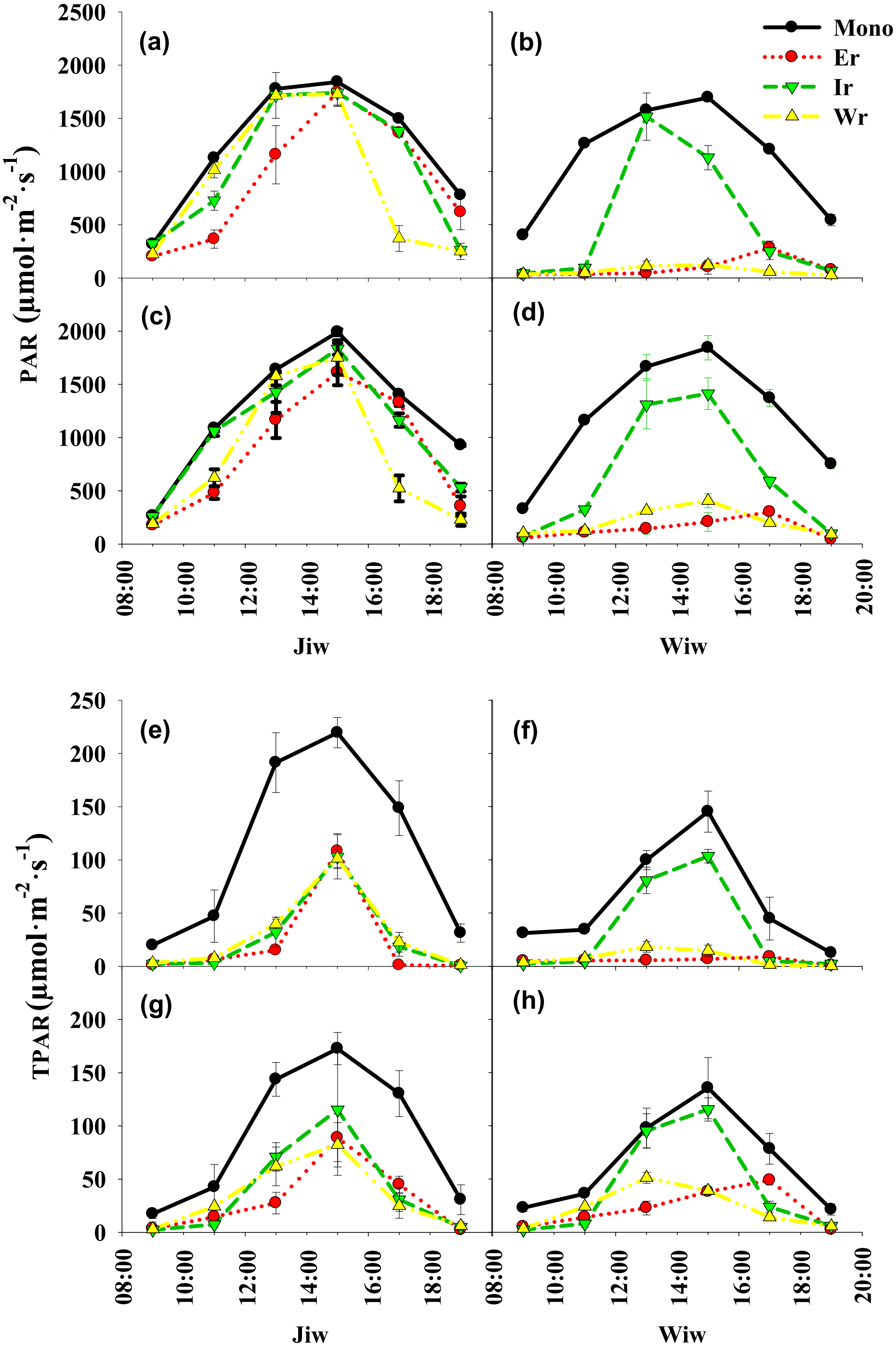

FIGURE 5 The daily change in (a–d) photosynthetically active radiation (PAR) and (e–h) transmitted PAR (TPAR) of wheat in monoculture configuration, jujube and walnut trees based intercropping systems at the filling stage in (a–b, e–f) 2011 and (c–d, g–h) 2012. Mono: monoculture wheat; Er: east-row position; Ir: inter-row position; Wr: west-row position; Jiw: Jujube tree–wheat intercropping system; Wiw: walnut tree–wheat intercropping system

3.8 | Land equivalent ratio values

The LER values of both jujube- and walnut-based agroforestry systems were >1, indicating that the land use advantages of intercropping were significantly greater than those of monocropping; this finding supports the hypothesis that agroforestry systems have greater productivity, and potentially greater sustainability, than comparable monoculture systems (Yang et al., 2019; Zhang et al., 2017). These results agreed with Zhang et al. (2013, 2019)

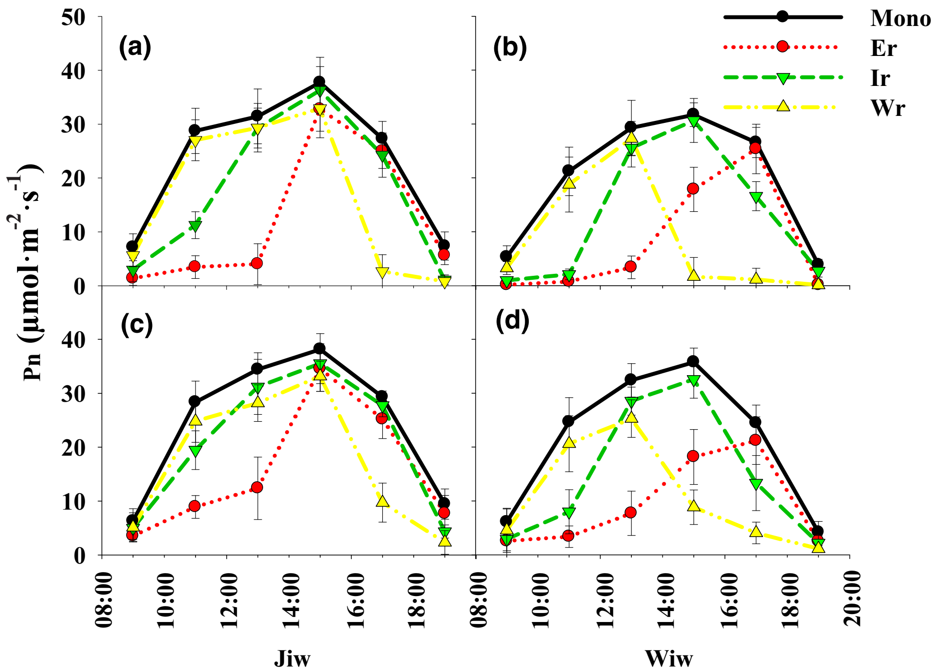

FIGURE 6 The daily change in photosynthesis rate (Pn) of wheat in jujube (a, b) and walnut trees (c, d) based intercropping systems at the filling stage in 2011(a, c) and 2012 (b, d). Mono: monoculture wheat; Er: east-row position; Ir: inter-row position; Wr: west-row position; Jiw: Jujube tree-wheat intercropping system; Wiw: walnut tree-wheat intercropping system.

TABLE 7 The N and P concentrations, and grain quality of wheat in jujube and walnut trees based intercropping systems in 2011 and 2012. Mono: monoculture wheat. Er: east-row position; Ir: inter-row position; Wr: west-row position; Jiw: Jujube tree–wheat intercropping system; Wiw: walnut tree–wheat intercropping system. Across all data, values with the same letter within each column are not significantly different among the treatments ($P < .05$)

Year	Cropping system	Treatment	N concentration		P concentration		Protein content	Wet gluten content
			Stalk	Grain	Stalk	Grain		
			g kg^{-1}				%	
2011	Mono	Mono	5.2 ± 0.6b	18.7 ± 0.9c	0.39 ± 0.04b	3.32 ± 0.39b	12.8 ± 0.4b	28.6 ± 1.0b
	Jiw	Er	5.7 ± 0.5b	18.6 ± 1.1c	0.38 ± 0.03b	3.39 ± 0.27b	12.8 ± 0.6b	29.0 ± 1.1b
		Ir	5.7 ± 0.6b	17.5 ± 1.3c	0.39 ± 0.03b	3.20 ± 0.36b	12.7 ± 0.4b	28.2 ± 0.9b
		Wr	5.6 ± 0.5b	18.2 ± 0.4c	0.40 ± 0.03b	3.54 ± 0.25b	13.0 ± 0.4b	28.2 ± 1.5b
	Wiw	Er	9.2 ± 1.3a	23.7 ± 1.5a	0.65 ± 0.12a	4.42 ± 0.38a	17.5 ± 0.9a	44.1 ± 3.2a
		Ir	8.5 ± 1.5a	21.5 ± 1.6b	0.61 ± 0.13a	4.20 ± 0.20a	17.2 ± 0.2a	40.9 ± 4.5a
		Wr	9.2 ± 0.2a	21.4 ± 0.7b	0.69 ± 0.08a	4.47 ± 0.45a	18.4 ± 1.2a	42.6 ± 3.7a
2012	Mono	Mono	6.1 ± 1.6b	17.9 ± 0.5b	0.32 ± 0.01c	3.54 ± 0.01b	12.7 ± 0.2b	28.2 ± 1.0b
	Jiw	Er	6.5 ± 0.9b	18.3 ± 1.3b	0.35 ± 0.05c	3.49 ± 0.08b	13.4 ± 0.7b	30.9 ± 2.3b
		Ir	6.3 ± 0.6b	17.9 ± 0.9b	0.37 ± 0.01c	3.54 ± 0.22b	13.5 ± 0.4b	29.8 ± 2.2b
		Wr	6.6 ± 1.3b	17.5 ± 0.2b	0.37 ± 0.04c	3.62 ± 0.37b	13.5 ± 0.7b	30.2 ± 2.9b
	Wiw	Er	9.9 ± 0.8a	22.2 ± 1.3a	0.82 ± 0.18a	4.26 ± 0.28a	18.0 ± 1.5a	40.1 ± 2.4a
		Ir	9.8 ± 0.5a	22.4 ± 0.1a	0.94 ± 0.10a	4.12 ± 0.20a	17.1 ± 1.3a	39.9 ± 0.9a
		Wr	9.9 ± 0.7a	21.7 ± 0.4a	0.61 ± 0.03b	4.28 ± 0.13a	17.9 ± 1.4a	39.9 ± 1.5a

who found the LER of jujube tree/wheat intercropping was >1 in Hetian oasis regions in northwestern China. Similar results were also observed in Senegal gum [*Acacia senegal* (L.) Willd.]/sorghum (*Sorghum bicolor* L.) or Senegal gum/sesame (*Sesamum indicum* L.) system in north Kordofan State Sudan (Fadl, 2013), and in willow (*Salix alba* L.)/maize system in the Kashmir valley (Bhat et al., 2019).

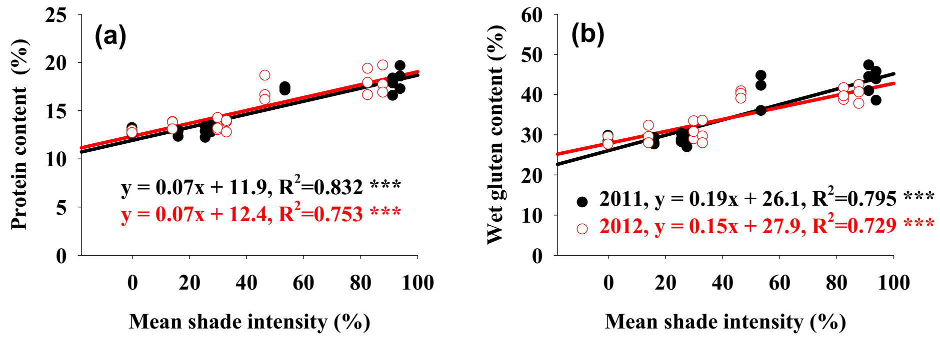

FIGURE 7 Relationships between (a) protein content and (b) wet gluten content with mean shade intensity of wheat in 2011 and 2012

3.9 | Photosynthetically active radiation and photosynthetic rate

In agroforestry systems, the trees are highly dominant over the intercrops due to their taller trunk and large canopy architecture (Yang, Ding, Liu, Li, & Eneji, 2016; Zhang et al., 2019). The PAR transmitted by fruit trees and incident over the wheat canopy directly affects the photosynthetic rate and light product formation (Figures 5, 6 and Supplement Figure S3). This finding is consistent with Yang et al. (2019), who reported that the effects of jujube trees resulted in decreased understory PAR, which inhibited the photosynthesis of the intercropping crop canopy. In the walnut-based agroforestry system, the understory PAR availability significantly decreased, adversely affecting the growth of intercropped wheat, as evidenced by the lower cumulative shoot biomass production (Supplemental Figure S3). It may be that the greater size and larger canopy of walnut trees, which resulted in a critical shade intensity that negatively affected wheat growth and development processes. However, in the jujube-based agroforestry system, the smaller size and lesser canopy of jujube trees alleviated negative effects on the cumulative shoot biomass production of intercropped wheat. It also should be noted that budbreak occurred between 22–25 March for walnut trees and 10–20 April for jujube trees. The effects of intercropped jujube trees on the growth and development of wheat were therefore less pronounced than those of walnut trees during the early growth stage of wheat growth. Additionally, radiation interception by trunks and branches was an important factor in winter, and walnut trees are larger and more branched than jujube trees. The presence of trees thus affected the growth and development of intercrops in a species-specific manner.

We found the east-row and west-row positions received lower levels of PAR and TPAR compared to the inter-row position in both agroforestry systems (Figure 5). This is in agreement with Gillespie et al. (2000), who reported that understory rows received lower PAR than middle rows in a red oak (*Quercus rubra* L.)–maize intercropping system. Similar results have also been reported for red oak/black cherry (*Prunus serotina* Ehrh) and jujube/wheat and jujube/upland cotton agroforestry systems (Bouttier et al., 2014; Wang et al., 2016; Yang et al., 2019). The reduction in understory PAR was not consistent with reductions in Pn throughout the daily measurement period. This may be attributable to strong, rapid changes in PAR throughout the day; Pn was not measured at the same time. Furthermore, lower levels of PAR and Pn in the west-row position in the morning may be offset by greater afternoon sun exposure, and vice versa for plants in the east-row position.

3.10 | Grain yield and components

Competition for light is thought to be a dominant factor constraining understory crop yields in temperate agroforestry systems (Chirko et al., 1996; Dufour, Metay, Talbot, & Dupraz, 2013). Reynolds, Simpson, Thevathasan, and Gordon (2007) observed that maize and soybean yields were reduced by 27 and 21%, respectively, when grown in poplar (*Populus deltoids* × *nigra* DN177)/maize and silver maple (*Acer saccharinum* L.)/soybean agroforestry systems in Canada, and Yang et al. (2016) reported that the mean grain yields of intercropped winter wheat and summer maize were reduced by 35.6 and 35.2% in a 22-yr-old jujube intercropping system, as compared to a monoculture system. Our results demonstrate that the effects of agroforestry on yields of intercropped wheat differ significantly between tree species. In the walnut tree-based agroforestry system, yields of intercropped wheat were significantly reduced compared to monoculture wheat in both study years (Table 5). And furthermore, the walnut trees are highly dominant over the intercrops due to their taller height and larger canopy architecture, which caused a remarkable reduction of net yield in the east-row and/or west-row positions compared to the inter-row position. Similarly, Chirko et al. (1996) reported the low PAR levels resulting from overhead shading significantly reduced yield of intercropped wheat near tree rows, in *Paulownia (Paulownia elongata* S.Y.Hu)/wheat agroforestry system in China. Hence, the present study demonstrated that the significant decrease in understory PAR is not conducive to the light product formation, which caused a reduction in grain yield in walnut tree-based agroforestry system.

In the jujube tree-based agroforestry system, grain yields did not differ from those of monoculture wheat (Table 5), nor did yields differ significantly among the three row positions. This result was unexpected, as many other studies have reported significant reductions in yield components in row positions closer to trees (Dong, Fu, Liu, & Liu, 2014; Yang et al., 2016), primarily as a result of reductions in global incident radiation (Bouttier et al., 2014) and daily dynamics of radiation (Ding & Su, 2010). Perhaps it is because jujube trees are shorter than walnut trees and have smaller canopies, resulting in higher light transmittance. Additionally, compensation effects (i.e., morphological or physiological changes) may have occurred in the wheat, facilitating better performance in the border plots (east-row and west-row positions) than in the inter-row position. In conclusion, the grain yield of intercropped wheat was significantly affected by both tree species and the distance to the tree rows.

The number of grains per spike is determined by the number of spikelets and the number of florets per spikelet (Mu et al., 2010), and is influenced by understory PAR in agroforestry systems (Gao et al., 2013; Qiao et al., 2019). Our results demonstrate that grain production is strongly influenced by tree species, as mediated by effects on floral initiation (spikelets per spike) and fertility (florets per spikelet; Tables 5 and 6). Indeed, walnut trees significantly decreased the number of grains of wheat compared to monoculture wheat, while jujube trees had less of an effect on the number of grains of wheat. As a result, the understory light regime thus plays a major role in determining grain production by influencing the number of florets and spikelets per spike.

The grain-filling stage is the most important physiological stage in wheat yield formation, and is sensitive to environmental conditions such as light, temperature, and humidity (Nasehzadeh & Ellis, 2017; Wang et al., 2015b). In both agroforestry systems, the grain-filling rates of intercropped wheat were significantly reduced compared to monoculture in the two study years (Figure 4). The grain-filling rate decreased in the order: monoculture wheat > jujube/wheat > walnut/wheat. Reductions in the grain-filling rate resulted in decreased grain weight, and the decrease in grain weight of intercropped wheat are likely attributable to a reduction in photosynthetic assimilates during the grain-filling stage in agroforestry systems. Our results also revealed that maturity in intercropped wheat is delayed by 1–2 d under jujube and 4–5 d under walnut trees. Phenological delays in crop development might partially offset light reductions under the tree canopy by extending the growing period and prolonging grain-filling stage of the crop. The delayed maturity period may also be attributable to differences in relative humidity and temperature under tree canopies; these changes may affect crop phenology in agroforestry systems (Inurreta-Aguirre et al., 2018; Peng, Thevathasan, Gordon, Mohammed, & Gao, 2015). Overall, the understory light regime is a major driver of grain weight through its influence on the seed-filling rate.

Kohli and Saini (2003) found that agroforestry resulted in reduced understory PAR, leading to decreased tillers per land unit area. Similarly, Gill, Singh, and Kaur (2009) reported a declining trend in the number of wheat tillers in a poplar-based agroforestry system. We found that the number of spikes was significantly affected by tree species (Table 5), and that the reduction in spike number in the walnut-based intercropping system was primarily due to substantially reduced tillering of intercropped wheat under low understory PAR (data not shown). In contrast, spike number was not affected by jujube trees. Underground competition is another factor that results in yield reductions in intercropping systems; for example, Zhang et al. (2013) found that root competition decreased wheat yields in a jujube-based agroforestry system. Therefore, the effects of belowground resource competition need to be considered in future studies.

3.11 | Shoot nitrogen and phosphorus uptake, and grain quality

It is important to consider both grain yield and grain quality when evaluating wheat production in agroforestry systems. Lu et al. (1997) reported that protein and wet gluten content were significantly higher in a *Paulownia*–wheat intercropping system than in a control treatment, but the increase did not completely offset reductions in final yields. Kittur et al. (2016) reported declines in oleoresin content and uptake of N, P, and K in understory turmeric as bamboo spacing decreased, presumably due to lower understory PAR. Our results showed that concentrations of N and P, along with protein and wet gluten contents, were significantly affected by tree species. In the walnut-based agroforestry system, N and P concentrations, grain protein, and wet gluten contents of intercropped wheat were significantly increased compared to monoculture wheat in both study years (Table 7), and higher N and P concentrations, grain protein, and wet gluten contents may be associated with smaller grain sizes and lower final yields. However, these parameters were not affected in the jujube-based agroforestry system. Our results suggesting that the understory light regime likely has a major influence on nutrient uptake and grain quality. Wang et al. (2015b) and Qiao, Chen, Lei, Sai, and Xue (2020) also noted that shading by trees during grain development can have a substantial effect on nutrient absorption, yield development, and grain quality in intercropped grains. It is therefore important to minimize radiation competition between trees and crops while maximizing total light energy capture to improve both the quality and yield of fruit and grain, and to enhance overall productivity in agroforestry systems.

High-density planting of fruit trees is very common in Xinjiang, influenced by both traditional attitudes and government policies of "high density, high yield, early benefit" – this is undoubtedly a factor behind the unexpectedly low productivity of intercrops in many agroforestry systems in the region. There are large morphometric differences between jujube and walnut tree species (Table 2), necessitating different approaches to mitigating the adverse influence of shade on understory crops. High planting density (250 ha^{-1}) was applied in the walnut-based agroforestry system. In pursuit of greater profit, farmers are also sometimes reluctant to prune walnut trees, choosing instead to sacrifice the productivity of intercrops. However, as trees age, the influence of tree shade on understory intercrops increases substantially. Additionally, as walnut trees age and canopy volumes increase, the light environment inside the canopy and between tree rows also deteriorates, strongly affecting the yield and quality of walnut crops. For example, dense walnut plantings in Moyu County led to empty shell fruit rates of more than 40% (Wang et al., 2015a). The management of walnut trees has long been a weak link in agroforestry systems, with serious effects for the sustainable development of the walnut industry in Xinjiang. The management of dense plantings has become one of the key issues in walnut production, and specific measures are required to increase the intensity of incident radiation, including appropriate pruning to decrease shading (particularly in older trees) and to increase photosynthate accumulation and grain yield of intercrops. For example, the fruit yield of walnut was substantially improved by selective felling in a 9-yr-old walnut stand (3 by 6 m) (Wang et al., 2015a), while understory PAR in almond tree (*Amygdalus communis* L.) crowns increased by 24.4% following pruning (data not shown). Wider spacing of trees should also be recommended to local farmers to reduce shading. Our results demonstrate that the intensity of shading by walnut trees had significant and negative effects on the growth and yield components of intercrops. Improving yields will require increasing light transmittance to intercropped wheat, which will enhance photosynthesis and thus reduce the adverse effects of walnut trees on the growth and development of wheat. In conclusion, walnut may be a practical component of agroforestry systems if densities are reduced by selective felling and pruning.

The smaller size, slower growth rate, smaller leaves, and lower height of jujube trees alleviated negative effects on the yields of intercropped wheat in the jujube-based system. If high tree densities are necessary, jujube or other small tree species are more suitable than walnut or other large trees with regard to optimizing wheat yields. However, the spacing of jujube trees was 1.5 m by 5 m (planting density = 1333 ha^{-1}), which is not suitable for mechanical operation, and the area sown with wheat occupied only 66% of the total area. Spacing of jujube trees should be increased to increase yields of intercropped grain.

4 | CONCLUSION

The intensity of shading by trees is thought to be the primary factor limiting crop productivity in agroforestry systems. In this study, understory intercropped wheat was substantially affected by tree species. Understory PAR and TPAR were significantly reduced in the walnut-based agroforestry system, resulting in declines in Pn in intercropped wheat; decreased Pn in turn affected the number of florets and spikelets, leading to declines in the number of spikes. Decreased Pn was also associated with declines in grain-filling rates, resulting in decreased 1000-grain weight. Shading by walnut trees significantly decreased grain yield, but enhanced N and P concentrations and protein and wet gluten contents. Although mean daily PAR was reduced by 23.2–25.5% in the understory of the jujube-based agroforestry system, there were no effects on grain yield, its components, florets, spikelets, N and P concentrations, or protein and wet gluten contents. Jujube-based intercropping systems are therefore sustainable in Xinjiang, as jujube trees do not decrease the yield or quality of intercropped wheat. Competition for light between walnut trees and wheat may be alleviated by selective felling and pruning, and increased tree spacing in new walnut-based agroforestry systems will promote optimal results.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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