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Optimizing Maize Belt Width Enhances Productivity in Wheat/Maize Intercropping Systems

Guodong Chen , Yunlong Zhai, Jianguo Zhou, Yanfang Li, Jiao Lin, Sumei Wan and Quanzhong Wu *

College of Agronomy, Tarim University, Alar 843300, China
* Correspondence: 120210016@taru.edu.cn

Abstract: Wheat/maize intercropping has been widely practiced in northwestern China. It is crucial to optimize the canopy structure and geometric configurations to enhance the performance of the system. This research determined the responses of intercrops to the different canopy structures created by the different wheat/maize intercropping systems. Field experiments were carried out in 2012, 2013, and 2014 at Wuwei, Gansu. Three intercropping patterns—six rows of wheat alternated with two rows of maize (6W2M), six rows of wheat alternated with three rows of maize (6W3M), and six rows of wheat alternated with four rows of maize (6W4M)—were compared with sole wheat and sole maize. The results showed that maize plant heights differed between the inner rows and the border rows, and the difference was greater for the 6W3M system than for the 6W4M system. The three intercropping systems had an average land-use equivalent ratio (LER, calculated based on grain yield) of 1.25, indicating an increase in land-use efficiency by 25% compared to the corresponding sole crops. The shape of maize strips in 6W3M optimized the canopy structure and increased the productivity of wheat and maize. The wheat in 6W3M had significantly more grain yield compared with the sole wheat and the 6W2M due to the maize belt shape, which resulted in the soil evaporation negatively affecting the intercropped wheat grain yield of the 6W3M. Similarly, the maize belt shape facilitated the light penetration and enhanced the reproductive growth by increasing the two cobs per plant rate (TCR) of the maize. The highest TCR of the 6W3M produced a higher maize grain yield than the 6W2M and sole maize in the three growing seasons. The maize belt width in the strip intercropping system had a significant effect on the grain yield of both wheat and maize, which reduced water evaporation, harmonized light distribution, and increased productivity.

Keywords: wheat; maize; intercropping; canopy shape; productivity

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1. Introduction

Intercropping is a cropping system where two or more annual crops are grown in the same field in the same season [1]. Compared with monoculture, intercropping has yielded advantages due to the effective use of radiation, heat, water, and nutrients, leading to increased land productivity [2]. The yield advantage helps farmers to alleviate the pressure of producing sufficient food on limited farmable land [3].

Wheat (*Triticum aestivum* L.) intercropping with maize (*Zea mays* L.) is mostly practiced in Gansu province and Ningxia autonomous region in China [4]. In these areas, the water shortage is a major factor limiting crop yields. Thus, wheat/maize intercropping is adopted to overcome water issues while fully using the growing season of land, heat, and rainfall [5]. In a typical wheat/maize intercropping system, six rows of wheat are alternately grown with two rows of maize or six rows of wheat alternated with four rows of maize, while some farmers use a system where six rows of wheat are alternated with three rows of maize. In those systems, wheat is usually sown in the middle of March, and maize is planted about 20 days after wheat is sown. This type of strip cropping has been shown to increase grain yield by 40 to 70% over the traditional monoculture; thus, it has been considered a sustainable way to secure food and eliminate poverty [6,7].

In intercropping systems, canopy structure and geometric configurations affect the microclimate, especially air circulation and light penetration through the canopy. Adjusting the belt width with a standardized row ratio between the two intercrops has been shown to increase yields in maize/soybean (*Glycine max* L.) intercropping due to the improved light conditions [8]. Rahman et al. [9] reported that in a maize/soybean intercropping, the 20:140 cm and 20:180 cm belt width ratios between soybean and maize had the highest land equivalent ratio (LER), while the 40:120 cm and 40:160 cm planting geometries had the highest WUE. These researchers focused on the effects of planting ratio and plant density on crop yields [10–12] with a specific bandwidth for each set of intercrops. However, Zhu [13] revealed that in the wheat/maize intercropping, intercropped maize was more depressed when it was arranged closer to intercropped wheat. During the early stage of canopy development, the narrowly intercropped maize had a lower R: FR (red: far red ratio) and photosynthetically active radiation (PAR) than sole maize. Wang et al. [14] reported that in the wheat/maize intercropping, the border row wheat intercepted more PAR than the inner row wheat, whilst the border row maize had no advantage in the light absorption compared to inter-row maize because the canopy development was constrained by the competition from the wheat strip. The intercepted PAR of the wheat border rows increased when the maize strip increased from two rows to four rows. The light interception advantage of the wheat/maize intercropping was mainly attributed to improved canopy structure and plant phenotypic plasticity of the border row wheat and was negatively affected by the phenotypic plasticity of border row maize. These results indicate that the variation of the maize row bandwidth in a wheat/maize intercropping affects the maize canopy structure and the sunlight interception, and thus crop yields.

In northwestern China, the most-practiced wheat/maize intercropping was six rows of wheat alternated with two rows of maize, or six rows of wheat alternated with four rows of maize, in which the wheat was sown with modified machine planter, while the maize was hand planted, and both the wheat and maize were hand harvested. Our hypothesis was: (i) optimizing the ratio of maize rows (i.e., two, three, and four rows of maize) to wheat in the wheat/maize intercropping will enhance the canopy function and improve the performance of both intercrops, and (ii) different maize row ratios will affect yield components of crops on the border rows versus in the inner rows. The objectives of this research were to: (i) determine the effect of different wheat/maize patterns on maize canopy shape, and (ii) assess the grain yield of wheat and maize grown under different intercropping patterns in response to canopy structure.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted during the years 2012–2014 at the Oasis Agricultural Experiment Station (37°52′20″ N, 102°50′50″ E; 1776 m a.s.l.) of Gansu Agricultural University in Huangyang town, Wuwei county, China. The area is in the eastern part of the Hexi corridor—a typical continental temperate arid zone, with an average temperature of 7.2 °C, mean annual precipitation of 156 mm [15], which mainly occurs during June–September, and the mean annual evaporation from a free water surface is more than 2400 mm. The frost-free period is 156 days, the annual sunshine duration is 2945 h, and the annual effective temperature is 1209.5 °C. The properties of the soil are presented in Table 1.

Table 1. Basic physical and chemical properties of the top soil (0–20 cm) in 2012.

Sand (%)	Silt (%)	Clay (%)	BD (g/cm3)	OM (g/kg)	TN (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)	pH
27.9	66.2	5.9	1.42	15.81	0.87	105.96	29.12	169.58	7.36

Abbreviations: BD—bulk density; OM—organic matter; TN—total nitrogen; AN—NO_3–N + NH_4–N; AP—available phosphorus; AK—available potassium.

Precipitation in the growing seasons (March to September) of 2012, 2013, and 2014 are shown in Figure 1. In the year 2012, precipitation was lower than the average of 110 cm [15], while in the 2013 and 2014, precipitation observed to be higher than the average.

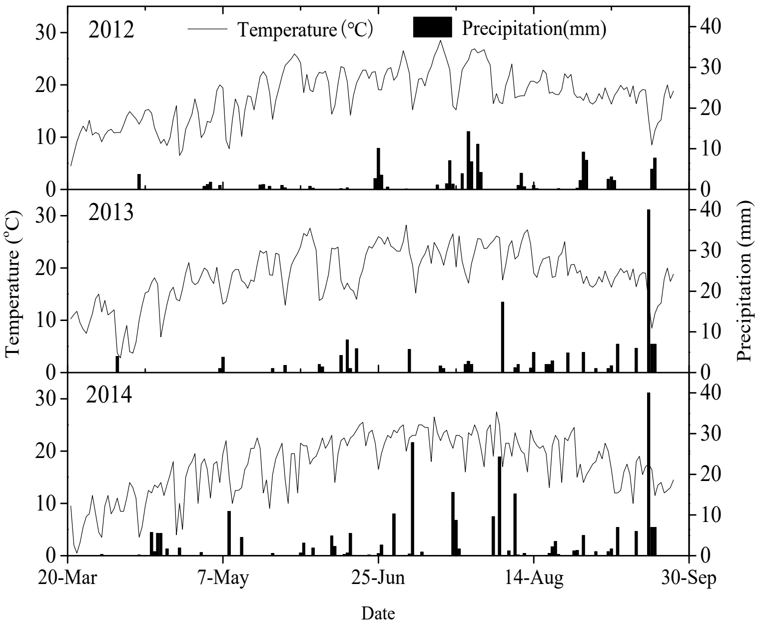

Figure 1. Mean air temperature (°C) and precipitation (mm) from March to September in 2012–2014 at Wuwei Experimental Station, China.

2.2. Experimental Design and Plot Management

The experiment was conducted in a randomized complete block design (RCBD) with three replicates each year. The treatments included: sole wheat (SW), sole maize (SM), three wheat/maize intercropping arrangements of 6 rows of wheat and 2 rows of maize (6W2M), 6 rows of wheat and 3 rows of maize (6W3M), and 6 rows wheat and 4 rows of maize (6W4M).

The SW plot consisted of 36 rows of wheat with a row spacing of 12 cm and 10 m long. The SM plot consisted of 12 rows of maize with row spacing of 40 cm and 10 m long. The 6W2M consisted of three 80 cm wheat belts alternated with 80 cm of two rows of maize belts with a plot length of 10 m. The 6W3M consisted of three 80 cm wheat belts alternated with 110 cm of three rows of maize in a 10 m long plot. The 6W4M consisted of three 80 cm wheat belts alternated with 130 cm of four rows of maize in a 10 m long plot. For the 6W2M, 6W3M, and 6W4M, the wheat row spacing was 12 cm, the maize row spacing was 40, and the distance between the wheat row and maize row was 30 cm (Figure 2). The maize in the sole and intercropping was all mulched with plastic film.

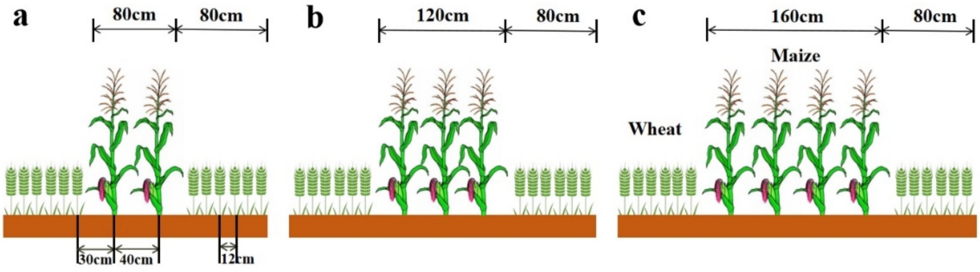

Figure 2. Field layout of wheat/maize intercropping with different row arrangements. (**a**): Six rows of wheat and two rows of maize (6W2M); (**b**): six rows of wheat and three rows of maize (6W3M); (**c**): six rows of wheat and four rows of maize (6W4M).

Before sowing, wheat plots received 225 kg/ha N and 150 kg/ha P_2O_5 as basal fertilizer with urea (46-0-0 of N-P_2O_5-K_2O) and diammonium phosphate (18-46-0 of N-P_2O_5-K_2O). For the maize, 360 kg/ha N (46-0-0 of N-P_2O_5-K_2O) was divided into three portions, with 30% applied as basal fertilizer, 60% applied at the jointing stage, and the remaining 10% applied at the grain filling period. The 225 kg/ha of P_2O_5 (diammonium phosphate, 18-46-0 of N-P_2O_5-K_2O) was applied as basal fertilizer. Five to six times of irrigation was used (Table 2) for the intercrops and the sole crops.

Table 2. Irrigation dates and amounts applied to the wheat and maize in the intercropping systems at Wuwei Station, China, from 2012 to 2014.

Irrigation No.	Irrigation Date			Irrigation Amounts		
	2012	**2013**	**2014**	**Sole Wheat**	**Sole Maize**	**Wheat/Maize**
	———-month–day—— ——			——————-mm——————		
1st	5–5	5–8	5–9	120	120	120
2nd	5–29	5–25	5–28	100	100	100
3rd	6–20	6–25	6–20	100	100	100
4th	7–10	7–26	7–29	100 [b]	100	100
5th	7–31	8–20	8–22	—	80	80
6th	8–26	— [a]	—	—	80	80
Total	—	—	—	420	580	580

[a]: The sixth irrigation in 2013 and 2014 were canceled due to a large amount of rainfall in August. [b]: The fourth irrigation was not applied to sole wheat in 2013 and 2014 due to their early maturity.

The spring wheat cultivar of Yongliang 4 was sowed on 21 March 2012, 24 March 2013, and 22 March 2014, respectively, and was harvested on 23 July 2012, 22 July 2013, and 26 July 2014. The maize cultivar of Xianyu 335 was sowed on 11 April 2011, 6 April 2013, and 8 April 2014, respectively, and was harvested on 29 September 2012, 27 September 2013, and 28 September 2014. The wheat density was 6.75×10^6 plants/ha, and the maize density was 4.5×10^4 plants/ha.

2.3. Measurements and Calculations

2.3.1. Grain Yield

The wheat grain yield was determined by harvesting 0.8 m^2 (one meter in length and six rows) in each plot, and all the plants were hand-threshed, the grains were air-dried, and then weighed. In case of maize, in the 6W3M and 6W4M treatments, a 2.6 m^2 (11.7 m in length) area of the border row and the inner row was harvested; for the maize in the 6W2M treatments and sole plots, a 2.6 m^2 (11.7 m in length times two rows) was harvested per plot, and the two cobs rate (TCR) was calculated, then weighed after being air-dried and reported at 14% water content.

2.3.2. Land Equivalent Ratio (LER) and Partial Land Equivalent Ratio (PLER)

LER was used to evaluate the success of intercropping using a concept proposed by Willey and Osiru [15]. The total LER is defined as the total land area required under monoculture to give the yields obtained in the intercropping and is expressed as:

$$\mathrm{LER} = Y_{im}/Y_{sm}+Y_{iw}/Y_{sw} \tag{1}$$

where Y_{im} and Y_{sm} are the yields of intercropped and sole maize, respectively, and Y_{iw} and Y_{sw} are the yields of intercropped and sole wheat, respectively. An LER = 1.0 implies that the two intercropped species make alike demands on the same limiting resources. An LER > 1.0 implies an intercropping advantage or a demonstration that interspecific facilitation (or complementarity) is higher than the interspecific competition so that intercropping results in greater land-use efficiency. An LER < 1.0 implies mutual antagonism in the intercropping system. Thus, an LER less than 1.0 has no intercropping advantage and indicates that interspecific competition is stronger than interspecific facilitation in the intercropping system [16].

$$\mathrm{PLER_m} = \mathrm{Y_{im}}/\mathrm{Y_{sm}}/\mathrm{P_{im}} \tag{2}$$

$$\mathrm{PLER_w} = \mathrm{Y_{iw}}/\mathrm{Y_{sw}}/\mathrm{P_{iw}} \tag{3}$$

where $\mathrm{Y_{im}}$ and $\mathrm{Y_{iw}}$ are the intercropped yield of the maize and wheat, respectively; the $\mathrm{Y_{sm}}$ and $\mathrm{Y_{sw}}$ are the yield of the sole maize and wheat, respectively; and the $\mathrm{P_{im}}$ and $\mathrm{P_{iw}}$ are the land occupying ratio of the intercropped maize and intercropped wheat, respectively.

2.3.3. Maize Plant Height

Maize plant height was measured every 30 days after seedling emergence from the ground vertically to the apex (highest point) during the vegetative stage, and during the reproductive periods, the measurements were taken from the ground to the tip of the panicle at maturity.

2.3.4. Leaf Area Index (LAI)

The LAI of maize were measured after emergence at specific growth stages during the whole growing season. A total of 10 sample plants were selected for each plot, and the leaf length and greatest leaf width were measured with a ruler. The leaf area was determined by following formula: leaf area = leaf length × the greatest leaf width × 0.78.

2.3.5. Soil Water Evaporation

The microlysimeters (MLs) method was adopted to measure soil evaporation in the three wheat/maize intercropping patterns. For the 6W2M and 6W4M treatments, MLs were positioned in the inter-row in the maize strip and the inter-row between the 2nd and 3rd rows. In the 6W3M plots, the MLs were positioned in the central row of the maize strip and were positioned in the inter-row of the 3rd and 4th rows in the wheat strips.

MLs consisted of an inner and outer polyvinyl chloride (PVC) core. The inner core was 14 cm long, an internal diameter of 10 cm, and an external diameter of 10.5 cm. Meanwhile the outer core was 13 cm long, with a diameter of 11 cm. Plastic film was used to cover the base of each inner core to avoid the possibility of water outflow. The outer core was slowly hammered into the field, and the inner core was installed. A portable electronic balance (LP-3102) was used at 8.00 a.m. each day to weigh MLs and determine average daily soil evaporation.

2.4. Data Analysis

The comparisons among different treatments were performed by Duncan's multiple range test (Duncan, 1955). Data on yield, LER, LAI, plant height, and TCR were determined for each plot and analyzed using the analysis of variance (ANOVA) procedure of the SPSS 13.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Grain Yield

Overall, the wheat grain yield decreased and maize grain yield increased with the increase in the number of maize rows for the three growing seasons. However, the total grain yields of the three different planting patterns were not consistent between seasons. In the growing seasons in 2012 and 2013, the grain yields were in the order of 6W4M > 6W2M > 6W3M, but the total yields of the three intercropping systems were lower compared to sole maize. Whereas in 2014, grain yields were in the order of 6W4M > 6W3M > 6W2M, and the total yield of the 6W4M was higher than that of sole maize. The solo wheat had the highest HI harvest index compared with the intercropped wheat with the exception of 2014, and no significant difference was detected between the solo wheat and the 6W2M in 2014. In case of the maize, the 6W3M had the highest HI in the three growing seasons, and the 6W2M had the lowest ones (Table 3).

Table 3. Yield and harvest index of wheat and maize intercropping systems with different patterns.

Years	Treatment	Grain Yield (kg/ha)			Harvest Index	
		Wheat	Maize	Total	Wheat	Maize
2012	SW	6804 a	—	6804 d	0.42 a	—
	SM	—	18,950 a	15,182 ab	—	0.54 b
	6W2M	3697 b	10,713 c	13,885 bc	0.39 b	0.51 c
	6W3M	2807 c	14,445 b	13,788 bc	0.41 a	0.56 a
	6W4M	2237 d	14,983 b	14,012 abc	0.40 a	0.55 ab
2013	SW	8979 a	—	7165 d	0.40 b	—
	SM	—	15,333 b	16,560 a	—	0.55 a
	6W2M	4390 b	14,188 c	15,662 b	0.40 b	0.52 c
	6W3M	3169 c	17,955 a	15,100 bc	0.39 b	0.56 a
	6W4M	2773 d	16,875 a	15,376 bc	0.38 b	0.54 b
2014	SW	7831 a	—	7594 c	0.40 ab	—
	SM	—	15,922 a	15,922 a	—	0.54 a
	6W2M	4783 b	9497 d	14,025 b	0.41 a	0.51 b
	6W3M	4237 b	11,460 c	15,003 b	0.40 ab	0.55 a
	6W4M	3610 c	12,960 b	16,101 a	0.40 ab	0.55 a

Different letter within a column in the same year means the difference between treatments is significant at $p < 0.05$.

3.2. Land-Use Equivalent Ratio (LER) and Partial Land-Use Equivalent Ratio (PLER)

The grain yield LER ranged from 1.11 to 1.28 for the different wheat/maize planting patterns in the three growing seasons. The value greater than 1.0 showed the yield advantages of the wheat/maize intercrops over the sole crops (Table 4). However, the LERs of the grain yield were inconsistent over the three years; they were in the order of 6W3M > 6W4M > 6W2M in 2012; 6W2M > 6W4M = 6W3M in 2013; and 6W4M > 6W3M > 6W2M in 2014.

Table 4. The LER and PLER of the different intercropping pattern.

Year	Treatment	PW	PM	LER
2012	6W2M	1.12 a	1.13 b	1.11 b
	6W3M	0.98 b	1.27 a	1.17 a
	6W4M	0.99 b	1.19 b	1.12 b
2013	6W2M	0.98 a	1.23 b	1.28 a
	6W3M	0.88 b	1.30 a	1.16 b
	6W4M	0.93 ab	1.10 c	1.16 b
2014	6W2M	1.14 b	1.07 b	1.21 b
	6W3M	1.35 a	1.17 a	1.26 a
	6W4M	1.38 a	1.13 a	1.27 a

Different letter within a column in the same year means the difference between treatments is significant at $p < 0.05$.

The PLER of the intercropped wheat ranged from 0.80 to 1.38, and the PLER of the intercropped maize was from 1.07 to 1.30, averaged over the three growing seasons. The wheat PLER of the different wheat/maize intercropping was greater than 1.0 in 2014; however, it was less than 1.0 in 2012 and 2013, except for the 6W2M in 2012. Across the three growing seasons, the PLER of the 6W2M was the highest in 2012 and 2013, and the 6W4M was the highest in 2014. The maize PLER of the three different wheat/maize intercropping was higher than 1.0, and the 6W3M had the highest PLER in the three growing seasons.

3.3. Yield Component of Intercropped Wheat and Maize

The grain yield components of the intercropped wheat and maize are listed in Tables 4 and 5. The grain number per head of the SW was significantly lower than those of the wheat in the three wheat/maize intercropping patterns, except for 2013 when the SW had a higher grain number per head than the wheat in the 6W2M pattern ($p < 0.05$).

The grain number per head responded to the planting patterns differently between the years; in 2012, the wheat in the 6W3M and 6W2M had more grains per head than the wheat in the 6W4M; in 2013, the wheat in the 6W3M had more grains per head than the wheat in the 6W2M and 6W4M; and in 2014, no significant differences were found between the three planting patterns (Table 4).

Table 5. The grain yield components of the intercropped wheat and maize in 6W2M, 6W3M, and 6W4M.

Year	Treatment	Wheat			Maize		
		Grain Number /Spike	Heads /m^2	1000 Grain Weight (g)	Yield per Plant (g/plant)	Kernel Number (/Plant)	1000 Kernel Weight (g)
2012	6W2M	39.04 a	9.48 a	39.72 b	394.92 ab	659.13 b	567.35 a
	6W3M	40.06 a	0.47 b	39.36 b	427.74 a	800.41 a	556.67 a
	6W4M	36.89 b	9.71 a	37.99 c	410.51 a	754.27 a	571.62 a
	SW	32.64 c	83.23 a	41.73 a	359.72 b	596.67 c	549.39 a
2013	6W2M	33.99 c	91.17 a	37.78 c	444.91 c	1056.52 a	421.13 b
	6W3M	38.17 a	71.20 c	38.87 b	449.73 a	911.53 a	493.28 a
	6W4M	35.79 b	82.05 b	37.77 c	366.80 b	737.91 b	497.04 a
	SW	34.53 c	74.15 c	46.76 a	357.13 b	757.32 b	471.42 a
2014	6W2M	48.66 a	113.33 b	34.15 c	346.92 b	792.19 a	488.38 b
	6W3M	48.65 a	128.67 a	38.67 b	447.43 a	840.21 a	518.72 a
	6W4M	49.16 a	137.01 a	36.81 b	392.90 b	731.06 ab	503.21 a
	SW	23.62 b	97.67 c	45.23 a	247.42 c	540.18 c	487.68 b

Different letter within a column in the same year means the difference between treatments is significant at $p < 0.05$.

As it listed in 2012 and 2013, the ear density of the 6W2M, 6W3M, and 6W4M followed the order of 6W2M > 6W4M > SW > 6W3M. However, it changed in 2014, with the order of 6W4M > 6W3M > 6W2M; the 6W4M and 6W3M were significantly higher than the 6W2M for the three wheat/maize planting patterns, and the 6W4M, 6W3M and 6W2M were significantly higher than the SW. The 1000-grain weight of the sole wheat was significantly higher than those of the wheat in the three intercropping patterns in the three growing seasons. Among the three intercropping patterns, the 6W3M was significantly higher than the 6W2M and 6W4M in 2013, and the 6W3M was slightly lower than the 6W2M and 6W4M in 2012 and 2014, respectively; however, no significant difference was detected.

The kernel number per plant of maize in the 6W3M was highest in 2012 and 2014, while in 2013 the maize of the 6W2M had the highest kernel number per plant. The 1000-kernel weight of the intercropped maize was higher than that of sole maize, except for the 6W2M in 2013. In 2013 and 2014, the 1000-kernel weight of maize in 6W3M was greater compared to 6W2M and 6W4M, while in 2012 the maize in 6W2M had the highest kernel weight.

3.4. Maize Plant Height Concerning Intercropping Pattern

The plant height of the different wheat/maize planting patterns is shown in Figure 3. The maize growth patterns in the co-growth period were different in the three growing seasons, on 23 June 2012, 24 June 2013, and 22 June 2014. For instance, corresponding to the V7, the highest maize height obtained in the solo maize and the 6W2M was the lowest in the three growing seasons and followed the order of: solo> 6W3M inner > 6W4M inner > 6W4M border > 6W3M inner > 6W2M in 2012 and 2014; solo> 6W4M inner > 6W3M inner > 6W4M border > 6W3M inner > 6W2M in 2013. With the development of the intercropped maize, the height difference between the border row and the inner row(s) increased.

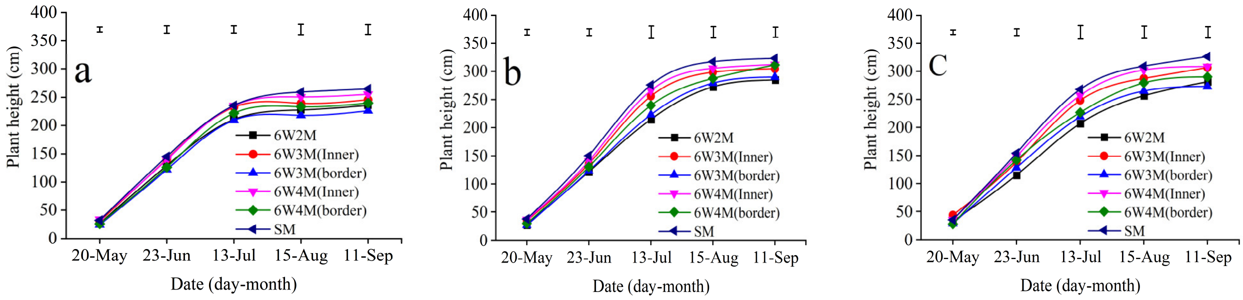

Figure 3. Plant height of maize in intercrops and monoculture in 2012 (**a**), 2013 (**b**), and 2014 (**c**). Vertical bars represent significantly different at $p < 0.05$.

During the V7 period, the maize height in 2014 was significantly lower than those in 2012 and 2013. In 2013, the SM was significantly higher than the others ($p < 0.05$), and the intercropped maize was higher in 2013 compared with 2012 except for the 6W2M. During the V9 period, all the intercropped maize was higher in both 2012 and 2013 than those in 2014, and 2013 was higher than 2012, except for 6W2M.

In the three growing seasons, the plant height of the sole maize was the highest, and the 6W2M was the shortest. For the 6W3M and 6W4M, the difference between the inner row(s) and the border rows of the 6W3M is larger than that of 6W4M in the three growing seasons. In the co-growth period of the wheat and maize, for the three wheat/maize planting patterns, the maize height was higher in 2012 and 2013 than in 2014, the maize plant height of the 6W3M and 6W4M was higher in 2012 than in 2013, and the plant height of 6W2M was higher in 2013 than in 2012; however, no significant difference was detected between 2012 and 2013.

4. Discussion

Intercropping patterns can affect crop growth [16], water-use efficiency (WUE), and evapotranspiration (ETc) [17,18], while the geometric characteristics of crop canopy, such as canopy shape, can affect leaf area index (LAI) and radiation interception [19,20]. In the present study, we used different ratios between intercropped wheat and intercropped maize and found that the width of the maize strips (i.e., the number of maize rows) in the wheat/maize intercropping systems affected maize canopy shape and plant growth, thus affecting the grain yield, LER, and PLER. The magnitude of the effect varied between the study years.

4.1. The Upper Canopy Shape of the Intercropped Maize and LAI of Maize

The canopy shape of wheat/maize intercropping differed with different wheat-to-maize row ratios. During the early co-growth stages, the intercropped maize was suppressed by the shading of the earlier-planted wheat. The shading affected the red: far-red ratio (R:FR) and delayed the leaf appearance of the intercropped maize, with fewer leaves per plant. The suppressed maize plants increased blade and sheath lengths at the low rank and small sizes at the high rank, and the closer the maize to the wheat, the stronger the effect was with the lower PAR [19]. Ma et al. [21] reported that in the wheat/maize intercropping, the border row maize was depressed by both the wheat rows and the inner maize rows, whereas the inner maize rows were little affected by the wheat rows.

In the present study, the inner row maize plants in the 6W3M pattern were 31.3 cm taller than the border row maize at wheat harvest and 25.8 cm taller at maize maturity (R6), averaged over the three growing seasons. Similarly, the inner row maize plants in the 6W4M pattern were 25.3 cm and 17.6 cm taller than the border row maize at wheat harvest and maize maturity, respectively. The maize height of the inner two rows of 6W4M was the same, the two border rows were shorter, and the inner row of 6W3M was much higher than the two border rows, whilst the two rows of the 6W2M were the same. Therefore, for the 6W2M, the top canopy was straight, while for the 6W4M, the middle of the canopy was straight, then tilted down, and for the 6W3M, it appeared from the middle of the canopy. The different number of rows of maize led to the different shapes of an upper canopy in the wheat/maize intercropping. The maize strips in the 6W2M, 6W3M, and 6W4M patterns appeared in the shape of "trapezoid", "triangle", and "square" (Figure 4), which was probably due to the competition for available resources between the two intercrops. In the 6W2M pattern, the two maize rows were bordered by wheat both on the left and right side, leading to severe depression in the maize grown in both rows. In contrast, the border rows of maize in the 6W3M and the 6W4M pattern were suppressed by adjacent wheat on one side and by the sister maize on the other side, and the inner row of maize was sided by sister maize on both sides. We found that in the 6W2M, 6W3M, and 6W4M systems, the inner rows of maize in the 6W4M were the tallest, indicating that the inner rows of maize in the 6W4M were the least depressed, which was consistent with results reported by Ma [21]. The maize rows in the 6W2M system were suppressed the most among the three intercropping systems. The larger differences in maize plant height between the inner rows and the border rows in the 6W3M system compared to the 6W4M system suggest that the canopy shape of intercropping will affect plant growth, likely due to the quality and quantity of sunlight that penetrates the canopy.

Figure 4. The intercropped maize canopy shape of 6W2M (**a**), 6W3M (**b**), and 6W4M (**c**).

The LAI of maize provided information of the cover of the surface earth and the shading of the maize on wheat in the later co-growth period (Figure 5). The results showed the 6W4M had the highest LAI, followed by the 6W3M and 6W2M.

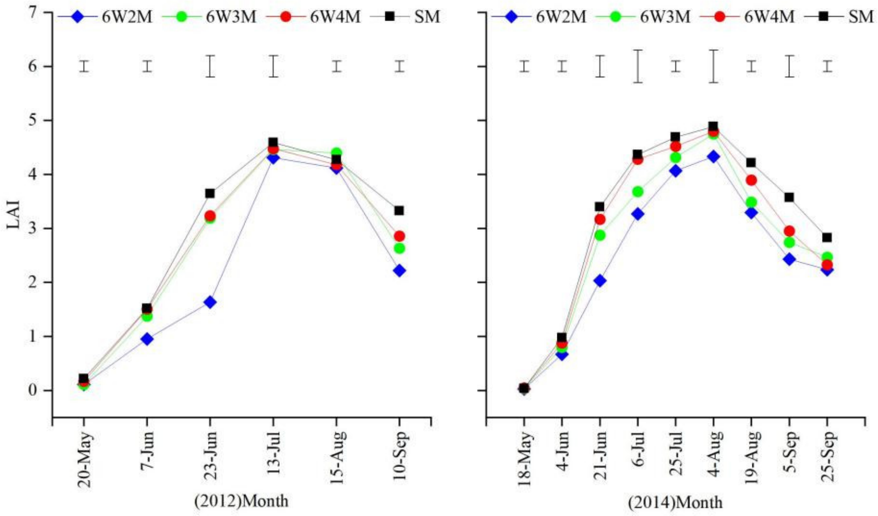

Figure 5. The leaf area index (LAI) of the solo maize and intercropped maize of 6W2M, 6W3M, and 6W4M in 2012 and 2014. Vertical bars represent significantly different at $p < 0.05$.

4.2. The Canopy Shape Affects the Light Distribution and the Soil Surface Evaporation

In the wheat/maize strip intercropping, during the co-growth period of the wheat and maize, the maize border rows were more depressed compared with the inner rows, with a lower plant height and leaf area index (LAI) than the inner row maize. Wang et al. [14] showed that in the systems where the six rows of wheat alternated with two rows of maize (I62), and twelve rows of wheat alternated with four rows of maize (I124), the border row maize was more severely suppressed than the inner row maize, and more light was captured for the I62 system than for the I124 system. It was the shape of the maize strip rather than the height that determined light capturing. This suggested that it is rather the maize strip shape than the maize plant height that determined the light capturing.

In our study, the light interception of the 6W2M was higher than those of the 6W3M and 6W4M; due to the intercropped maize shape, more light would penetrate the canopy of the 6W3M, which suggested the 6W4M could capture more light than the 6W3M. In the present study, we did not perform a direct measurement of sunlight distribution, but we measured soil surface evaporation as an indicator of light penetration through the canopy to the ground (Table 6). More light reaching the ground would induce more water loss through evaporation, which can reflect light distribution in the low part of the canopy. Soil surface evaporation of the three wheat/maize intercropping patterns was in the order of 6W3M > 6W4M > 6W2M in both co-growth stages and after the wheat harvesting periods, and in both the wheat belt and maize belt. The soil surface evaporation was associated with the net radiation, humidity, air temperature, and wind speed due to the shading by the variation of the LAI [22].

Table 6. The soil evaporation of wheat and maize strips in wheat/maize intercropping systems with different row arrangements (mm).

		6W2M		**6W3M**		**6W4M**	
Years	**Growth Stage**	**Wheat Strip**	**Maize Strip**	**Wheat Strip**	**Maize Strip**	**Wheat Strip**	**Maize Strip**
2013	Wheat jointing	32.9	23.74	40.18	28.86	36.85	26.48
	Wheat anthesis	11.5	7.51	14.87	9.65	14.18	9.19
	Wheat grain filling	9.6	6.96	11.84	8.57	10.63	7.67
	Wheat mature	5.91	4.42	7.12	5.28	6.15	4.55
	Total	59.91	42.63	74.01	52.36	67.81	47.89
	Maize grain filling	2.7	2.04	3.24	2.4	3	2.25
	Maize mature	5.65	4.65	7.9	6.49	7.15	5.87
		8.35	6.69	11.14	8.89	10.15	8.12
	Total	68.27	49.32	85.15	61.25	77.97	56
2014	Wheat jointing	30.24	21.47	33.98	24.21	32.48	23.13
	Wheat anthesis	12.58	9.01	13.13	9.5	12.44	8.99
	Wheat grain filling	7.89	5.62	8.9	6.34	8.43	5.98
	Wheat mature	16.35	11.31	17.17	11.8	15.75	10.87
		67.06	47.41	73.18	51.85	69.1	48.97
	Maize grain filling	4.03	3.3	4.05	3.31	3.75	3.06
	Maize harvesting	7.71	6.38	8.27	6.84	7.66	6.34
		11.74	9.68	12.32	10.15	11.41	9.4
	Total	78.8	57.09	85.5	62	80.51	58.37

Morris et al. [23] found that intercropping decreased soil evaporation since the intercrop combination usually had a plant density exceeding that of either sole crop, and this was true in wheat/maize intercropping [24]. In contrast, Miao et al. [25] and Ai et al. [26] reported that intercropping systems increased soil evaporation because of a sparse vegetation cover.

In the 6W2M, 6W3M, and 6W4M intercropping, the maize border rows were depressed with delayed leaf emergence, fewer leaves, and lower LAI [27], and the inner row(s) were little suppressed; the LAI appeared in the order of 6W4M > 6W3M > 6W2M (data not shown). Soil evaporation was highest for the 6W3M system and smallest for the 6W2M system, suggesting that it was the canopy shape contributing to the large differences in soil evaporation. The variation in canopy shape due to the difference in geometrics probably altered net radiation, air temperature, humidity, and wind speed. The canopy shape of the 6W3M system allowed more light to penetrate through the canopy and reach the ground, which increased the soil surface temperature and decreased humidity and, thus, increased soil surface evaporation.

Intercropping can enhance light capture through a combination of tall and short crop species, as such a combination can improve soil coverage and reduce the light reaching the ground. Intercropping short- and long-duration species, such as sorghum (*Sorghum bicolor* L.) with pigeon pea (*Cajanus cajan* L.) [28], winter wheat with cotton (*Gossypium hirsutum* L.) [29], and wheat with maize [30], has been shown to enhance light capture over time by lengthening the period of soil coverage.

In the current study, for the 6W2M, 6W3M, and 6W4M wheat/maize intercropping patterns, the border row maize plants were shorter, and for the 6W3M and 6W4M, the inner row maize was taller with the strip shape of "trapezoid", "triangle", and "square", for the three shapes. Combined with Wang's research [14], it strongly suggested that the 6W3M and 6W4M systems can facilitate light penetration into the canopy more efficiently than the 6W2M system. Furthermore, the maize plants in the 6W3M and 6W4M systems had smaller leaves in the upper of the canopy than those in 6W2M, enabling light to penetrate and reach the middle to lower layers of the canopy straightforwardly.

4.3. Yield Components Concerning Canopy Shape

In wheat/maize intercropping systems, wheat has a competitive edge over maize [14], and the competitive ability increases with fewer maize rows. Water stress during the jointing stage adversely affected the reproductive growth in wheat [31]. In the three wheat/maize intercropping patterns, the spike density of wheat decreased with the increase in soil evaporation, with the 6W3M system having the lowest spike density in 2012 and 2013. However, in 2014, the wheat in the 6W4M and 6W2M produced significantly more spikes than the wheat in the 6W2M system and sole wheat, due to more rainfall during the wheat and maize co-growth period (Figure 1).

The thousand-grain weight of wheat in the three wheat/maize intercropping patterns was significantly lower than that of sole wheat; this was due to the shading by the maize after anthesis. Studies have shown that shade reduces grain weight [19] because of decreased photosynthate production [32]. In our study, the wheat of the 6W2M system was the most shaded among the three wheat/maize intercropping patterns, even though the maize in the 6W2M system was shorter compared with 6W3M and 6W4M, which resulted in the lowest grain weight (Table 5).

The grain yield of the intercropped wheat depended on the heads per plant. In the present study, the 6W3M had the fewest number of heads per plant; however, the grain numbers per head and 1000 grain weight were highest among the three intercropping patterns, indicating that less shading enhances wheat grain filling. The yield per plant of the intercropped maize for the 6W3M was the highest among the three growing seasons, due to the highest kernel number per plant (Table 4). A large proportion of maize plants in the 6W3M system had two cubs per plant, due to less shade and more sunlight distribution to the canopy [33].

4.4. Maize Canopy Shape Affected the Rate of the Two-Cob Plant Population

The reproductive growth of the intercropped maize was enhanced and the two-cob plant rate (TCR) increased compared to sole maize (Figure 6). The border row maize in the 6W3M system had the highest TCR averaged over the three growing seasons, followed by the border rows of 6W4M. However, the TCR varied largely between the planting patterns, between the border and inner rows, and among the study years. The TCR depends on the availability of light, CO_2, water, and air circulation [34]. The maize canopy in the 6W3M system captured more light, CO_2, and air circulation, which provided more favorable conditions for the second cob formation, compared with the 6W2M and 6W4M.

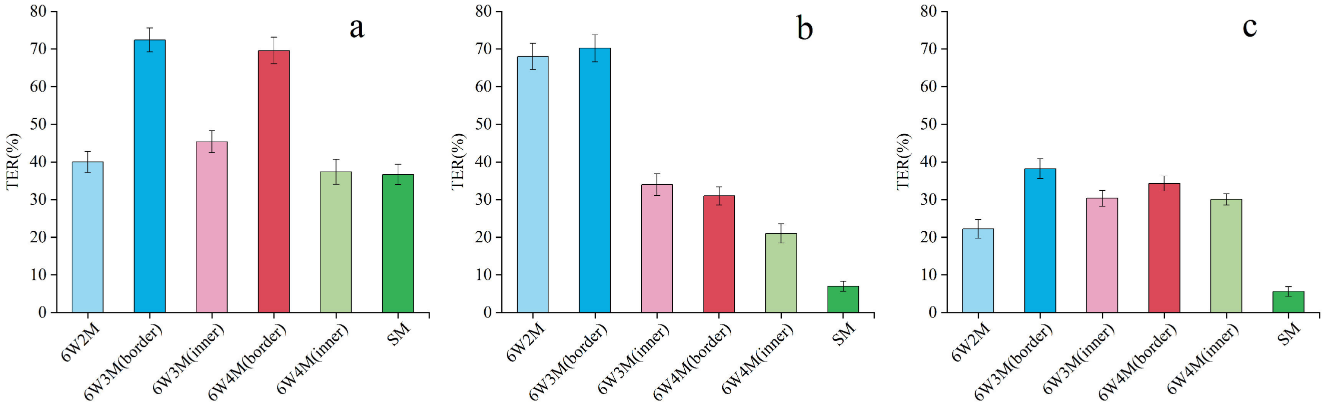

Figure 6. The two cob per plant rates (TCR) of the different wheat/maize intercropping pattern in 2012 (**a**), 2013 (**b**), and 2014 (**c**). Vertical bars represent ± SE.

In intercropping, the plant density of the component crops is typically higher compared to corresponding sole crops. Tetio Kagho and Gardner [35] revealed that with a reduced maize plant density, the cobs per plant increased. In addition, the enhancement of the reproductive growth of the intercropped maize may be due to the depressed vegetative development. Reduction of the redundancy growth of maize can increase grain yield [36]. In our research, the intercropped maize was constrained because of the weaker competition over wheat, which had shorter plant height, fewer leaves, delayed leaf appearance, and lower LAI and biomass. Thapa et al. [37,38] reported that the suppression of the vegetative growth facilitated the reproductive growth in the maize and sorghum.

4.5. Border Row Effects

The yield advantage of intercropping over sole cultivation is partly due to border row effects [27]. The stronger competition of the earlier-sown wheat over the later-sown maize in intercropping resulted in a growing condition more favorable for the border row wheat than for the inner row wheat, contributing to the increased wheat yield [39]. Canopy structure characteristics and plant plasticity of intercropped maize can affect light interception [14], which increases the aboveground and belowground competitiveness of wheat over maize for available nutrients [3]. However, with the development of the intercropped maize, especially at the later co-growth period, the interaction between the wheat and maize would change, and the different wheat/maize intercropping pattern would result in different yield production.

In the present study, the border row (R1, R6) wheat had a significantly higher grain yield than the inner row (R2, R3, and R4) wheat, with the wheat in row 1 (R1) being more productive than the wheat in row 6 (R6) in 2013 and 2014 (Figure 7). However, the magnitude of the border row effect varied with growing seasons. In 2012 and 2013, the grain yield of the border row wheat was in the order of 6W2M > 6W4M > 6W3M. The highest wheat yield in the 6W2M was due to the higher competitive ability of the border row wheat over the intercropped maize. In 2014, however, the border row wheat production of the 6W3M and 6W4M was significantly higher compared to the 6W2M. The 6W3M and 6W4M geometric systems facilitated sunlight penetration to the low range of the canopy, leading to more heads per area.

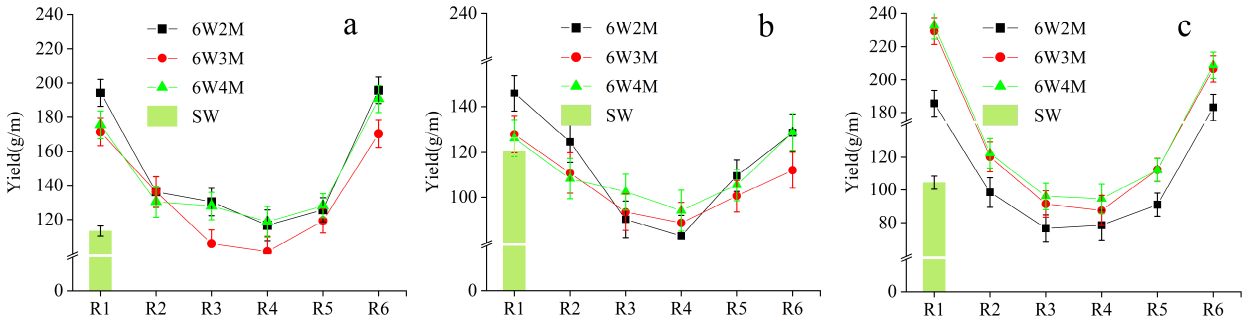

Figure 7. The wheat heads per row and yield per row from row 1 (R1) to row 6 (R6) in 2012 (**a**), 2013 (**b**), and 2014 (**c**). Vertical bars represent ± SE.

Wheat yield is partly dependent on tillering, and resource competition between tillers determines a tiller's destiny [40]. In wheat/maize intercropping, the border row plants can capture more light [41], nutrients [39], and soil water than the inner rows in most of the co-growth period. Adequate light is critical for young tillers to survive [42,43]. In addition, more tillers in the border rows over the inner rows are attributed to higher red: far red ratio [27], which is responsible for the maintenance of tiller survival [44]. In our study, the head number in the border row wheat was significantly higher (1.9 to 2.4 times) compared to the inner row wheat, largely due to increased tillers in the border row wheat. The R1 wheat had more tillers than the R6 wheat because the R1 in the south captures more light than the north [14]. Zhang et al. [40] reported that in wheat/cotton intercropping, the wheat yield advantage was mainly attributed to the number of border rows; this is consistent with our study.

Our results showed that border row effects in wheat/maize intercropping varied with growing seasons. In 2012 and 2014, the border row wheat in the 6W2M produced the highest yield, whereas in 2013, the highest border yield was obtained for wheat in the 6W4M. The yield variation of the border row wheat was at the expense of the shading of the maize. In 2012, the maize plants in the 6W2M wheat/maize intercropping were 7.6 to 8.0 cm shorter at the V(7) to V(9) periods compared to 2013; this decreased grain weight and grain number per head. This suggests that in the wheat/maize intercropping, the ratio of wheat-to-maize rows in a strip set must be properly designed and that an excessive plant height of the maize could hinder the grain filling of intercropped wheat.

Wheat grain yield in the wheat/maize intercropping was affected by the maize canopy shape [38]. In the present study, the competitive ability of wheat over maize in the 6W2M system was stronger than those in the 6W3M and 6W4M systems. More water and nutrients were absorbed by the wheat in the 6W2M compared with the 6W3M and 6W4M in 2012 and 2013. In 2014, more rainfall occurred during the co-growth period, which alleviated the competition for water between wheat and maize compared with 2012 and 2013. Soil water and nutrients in the maize strip were absorbed by the wheat in the early growth stages when the maize was small; however, the water stress of the maize in 6W3M and 6W4M was alleviated due to higher soil evaporation that was assisted by more light penetration to the lower part of the canopy. Based on our observations and the results, we suggest that in the irrigated areas, the current irrigation schemes with which the wheat and maize belts were irrigated at the same time should be altered by a separate irrigation scheme for the wheat and maize in the intercropping. Previous researchers have also observed that the different intercropping patterns have different water requirements for the intercrops [45]. A separate irrigation scheme for intercropped wheat and intercropped maize should help to improve water-use efficiency for wheat/maize intercropping systems.

4.6. Land Equivalent Ratio (LER) Concerning Canopy Shape

In the three study years, the LER of the three wheat/maize patterns were all greater than 1.0, indicating that intercropping increased land-use efficiency. The partial land equivalent ratio (PLER) of the maize in the 6W3M system was significantly greater than those in the 6W2M and 6W4M systems, as the 6W3M configuration improved light distribution across the canopy, resulting in yield-based PLER.

The high PLER of maize in the 6W3M was achieved at the expense of intercropped wheat in 2012 and 2013, when the wheat PLER was lower than those of wheat in the other two patterns. In 2014, however, the wheat PLER in the 6W3M was higher than that of the 6W2M.

In arid areas, water plays a crucial role in the PLER. In 2012 and 2013, the low wheat PLER was due to low rainfall during the jointing stage that adversely affected reproductive growth. Studies have found that water stress reduces wheat heads per plant [45], and the stress before anthesis reduces grains per head [46]. The scarcity of rainfall during the co-growth periods is the major factor restricting crop yield [47]. In western China, timely irrigation based on crop requirements is not available because the quota and the logistics of irrigation are mostly determined bureaucratically [45]; this practice affected our experimental irrigation regimes. In 2012 and 2013, the wheat in the 6W3M had the fewest heads per plant and a low PLER, largely due to delayed irrigation.

In 2012, the PLER of the intercropped wheat was less than 1.0 in the 6W3M and 6W4M systems, while in 2013 the PLERs of the three wheat/maize intercropping were less than 1.0, suggesting that there was no intercropping advantage; this was mostly due to the great maize plant height during the grain filling of intercropped wheat that shaded the wheat canopy. This indicates that in the wheat/maize intercropping, the grain yield of the wheat can be easily constrained by the shading of the tall maize plants during the late development period. Therefore, adjusting the sowing date of the maize or the spacing between the wheat belt and maize belt will play an important role in optimizing the canopy structure for a productive combination of the intercrops.

In the wheat/maize intercropping, the maize is less water-stressed than the intercropped wheat [48]. The intercropped wheat can spread its roots more widely than the sole wheat and can be extended to the maize belt, while the intercropped maize can extend its roots more deeply than the sole maize [21], which leads to access to soil water in the deeper soil layers. In the present study, the intercropped wheat yield was lower than the sole wheat due to soil water loss triggered by the canopy shape and the upward root distribution, and in comparison, the maize yield was enhanced because of the favorable microclimate environment in the intercropping canopy. These results suggest that appropriate water management, such as irrigation schedules, can help enhance canopy structure and facilitate sunlight penetration for high yields.

5. Conclusions

Due to the border row effects, the different wheat/maize intercropping of the 6W2M, 6W3M, and 6W4M had different maize canopy shapes of "trapezoid", "triangle", and "square", respectively. The canopy shape of the 6W3M and 6W4M can facilitate the light penetration to the lower layer of both the maize and wheat canopy; however, this shape negatively affected the wheat grain yield because of the lower tiller number that resulted from the higher soil evaporation. However, this shape could enhance the intercropped maize grain yield, especially the 6W3M, by increasing the TCR because of the favorable light distribution and CO_2 condition. The wheat/maize intercropping could increase the land-use efficiency with the LER from 1.11 to 1.28 due to the increased maize yield. In this area, the 6W3M intercropping pattern should be adopted; however, the wheat/maize intercropping should be irrigated separately.

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