Journal of Agricultural Science; Vol. 8, No. 4; 2016
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Analysis of Leaf Area Index Dynamic and Grain Yield Components of Intercropped Wheat and Maize under Straw Mulch Combined with Reduced Tillage in Arid Environments

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Received: January 31, 2016 Accepted: February 28, 2016 Online Published: March 15, 2016

doi:10.5539/jas.v8n4p26 URL: http://dx.doi.org/10.5539/jas.v8n4p26

Abstract

Knowledge on effect of yield formation under straw combined with plastic film mulch is important in highlighting the importance of cultivating high-efficient and high-yield crops in the arid environments. In this study, we developed a ‘double-mulching’ system, i.e., plastic film coupled with straw mulch, integrated together with intensified strip intercropping. We determined (i) the responses of leaf area index improvement to the integrated double mulching system, and (ii) Its effects on yield formation process and mechanism of intercropped wheat and maize under the integrated systems. Experiments were carried out in northwest China in 2009 to 2011. Results showed that wheat-maize strip intercropping in combination with plastic film and straw covering on the soil surface (i.e., NTS) increased maize yield by 27 to 42% compared to conventional monoculture maize, and increased wheat yield by 149 to 160% compared to conventional monoculture wheat. The crops on NTS had higher harvest index of maize, an increase of 8.2 to 21.6% than that of conventional monoculture maize. NTS system increased spike number (i.e., SN) by an average of 30.4%, increased kernel number per spike (i.e., KNS) by an average of 10.8%, and increased thousand-kernel weight (i.e., TKW) by an average of 7.0% of intercropped wheat in comparison with conventional monoculture wheat. Similarly, there was an average increase of 5.7% of SN, 23.8% of KNS, and 7.5% of TKW under intercropped maize in comparison with conventional monoculture maize. Moreover, the treatment on NTS had greater leaf area index (i.e., LAI) an average increase of 64.1% than that in conventional monoculture maize. Similarly, LAI had an average increase of 29.3% than conventional monoculture wheat. Path analysis exhibited that straw mulching combined with reduced tillage increased the grain yield of intercropped wheat by improving KNS, and increased the grain yield of intercropped maize by improving SN. We conclude that the intercropping system in combination with plastic film and straw mulching can be an effective system for boosting crop productivity via improving yield components and LAI under limited resources in arid enviroments.

Keywords: intercropping, straw retention, yield conponents, leaf area index, path analysis

1. Introduction

Wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are two main grain crops in China. In recent years, food demand has increased continuously as a result of increase in population, resulting in the generation of gap between food demand and production. Arable land resources are insufficient and reducing year after year, especially in the Northwestern China. Understanding how to produce more food while utilizing the limited arable land resources, it is urgent to meet people’s demand. However, intercropping, an agricultural cropping pattern has been long practiced in many parts of the world (Francis, 1986). It is characterized by making full use of water and nutrient resources to meet the actual needs, achieving agricultural biodiversity, and increasing yield significantly (Li et al., 2001b; Yin et al., 2015). In China, one-third of the cultivated lands is used for intercropping systems and produces about half of the total grain yield (Zhang & Li, 2003). It can be said that intercropping has played a very significant role in ensuring secure food supply and increasing farmers’ income in China and balancing high grain demands and low water availability (Fan et al., 2013; Hu et al., 2015).

Wheat-maize strip intercropping, a prevailing intercropping system has a long history in crop production in northwestern of China, especially in irrigated areas where climatic conditions allow only one cropping season annually (Huang, 1999; Li et al., 2001b). Studies on wheat-maize intercropping mainly focused on irrigation system, irrigation methods, spatial layout (Fan et al., 2013; Yang et al., 2010, 2011). The mechanism of high yield in root partitioning and interspecific relationship (Mu et al., 2013; Yang et al., 2010). Results from these studies that suggested that wheat-maize intercropping had contributed a great in food security and poverty elimination. It also contributed a lot in resolving the conflict between ever constantly increasing food demand and gradually decreasing area of arable land.

Grain yield in wheat and maize is the results of a number of complex morphological and physiological processes affecting each other and occurring at different growth stages during vegetative period (Mohammadi et al., 2014). It was proposed that grain yield is contingent on the number of spikes per unit area, the number of kernels per spike and the average kernel weight (Poehlman & Sleper, 1995), which further depend on condition of soil moisture, temperature, nutrition, light and other resources in a suitable environment. To our knowledge, leaf area index (LAI) is an important agronomic parameter which reflects crop growth and predicts crop yield. Leaf area has great influence on crop yields (Fageria et al., 2006). Differences in leaf area can affect plant spatial distribution and the microenvironment within population (Giunta et al., 2008), which plays a decisive role in the photosynthetic efficiency and light energy distribution of crops (Boedhram et al., 2001; Elings, 2000). A suitable LAI is a major sign of high crop yield, coordinating the relationship between sink and source of crops, and balance the development of each organ in crops. Study on crop leaf area index, for obtaining the level of variation of crop growth and yield, can provide a scientific basis for obtaining high yield by regulating crops physiological characters. At present, some research has been conducted on the spatial variation of LAI and crop grain yield, but limited research has been conducted on the relationship between LAI and grain yields in intercrops. Therefore, the analysis of the relationship between LAI and grain yield in this study, would provide theoretical basis for high yield in intercropping system.

Saving water and emission reduction is the main task of sustainable agriculture. Although intercropping plays a crucial role in balancing high grain demands, its development is restricted by the large water consumption, therefore, it has become an urgent issue to improve water use efficiency through proper cultivation methods and management measures. It is well-known that saving water and conservation tillage are the two main trends in modern agriculture. No-tillage and reduced tillage have become a popular conservation practice in the world (Al-Kaisi & Yin, 2005). Studies have shown that conservation tillage can effectively preserve soil moisture, and increase crop yields significantly in intercropping system (Fan et al., 2013; Hu et al., 2015). Meanwhile, most of studies with reduced tillage and straw mulch are focused more on monoculture crops like maize and wheat, and limited research conducted in intercrops (Fan et al., 2013). Moreover, recent research demonstrates that double mulching with plastic film and straw can increase yield, increase water use efficiency, and decrease carbon emission (Fan et al., 2013; Hu et al., 2015; Yin et al., 2015). However, the effect of double mulching with plastic film and straw on yield and changes on photosynthetic source is rarely reported in wheat-maize intercropping. In this study, we carried out a field experiment to investigate the effects of reduced tillage combined with plastic film and straw mulch on yield for intercrops, to provide new ideas for mechanism of increasing yields in intercrops at the Oasis Irrigation Area.

Simple correlation analysis is not able to provide factual cognizance between response and predictor variables, therefore, path analysis is used in the most case and effect associations. This method allows studying complex relationships between traits. It is a statistical tool and organizes the effect and presents the causal relationships between predictor and response variables by path diagram. Therefore, path coefficient technique was performed to divide the correlation coefficients between grain yield and yield components into direct and indirect effects via pathways. Some researchers applied a sequential path analysis to determine the relationship between yield and yield component factors in wheat (Leilah & Al-Khateeb, 2005) and maize (Mohammadi et al., 2003). Therefore, this study was carried out to determine direct and indirect effects of yield components to grain yield in intercropped wheat and maize and to estimate correlations between grain yield and the other studied traits under double mulching combined with straw and plastic film.

With above issues in mind, we integrated ‘double-mulching’ system, i.e., plastic film coupled with straw mulch, integrated with intensified strip intercropping combined with various straw mulching approaches. The objectives were to determine (i) the responses of leaf area index to the integrated double mulching system, and (ii) the effects on yield formation process and mechanism of intercropped wheat and maize under the integrated systems. Our central hypothesis was that there was a great advantage towards increasing photosynthesis source, increase in crop productivity, and improvement in yield components in integrated system. The hypothesis was tested using a 3-year field experiment conducted in an Oasis region of northwest China.

2. Materials and Methods

2.1 Experimental Site

Field experiments were conducted at the Wuwei Experimental Station (37°96′N, 102°64′E) of Gansu Agricultural University, in 2009-2012. The area, located in the eastern part of Hexi Corridor of northwestern China, is in a typical temperate arid zone, with average annual sunshine duration higher than 2945 h, annual mean air temperature 7.2 °C, accumulated air temperature above 10 °C higher than 2985 °C, and the frost-free period 155 days. Mean annual precipitation is below 150 mm, and potential evaporation 2400 mm. Three main river systems—the Shiyang, Black, and Shule rivers, originate from the Qilian Mountain and flow to the desert in the north. These rivers supply water from mountain snowmelt and generate many oases in their respective fluvial plains. The soil at the Research Station is classified as a kind of desert land filled with calcareous particles. This area is a typical oasis agriculture zone, which rely solely on irrigation. The low water availability limits the potential of cropping extension based on the conventional tillage, even though there is plenty of sunshine and sufficient temperature resources for the development of intercropping system. For the three study years, during the wheat growing season (March–July) precipitation was 58.8 mm in 2010, 65.8 mm in 2011, and 40.5 mm in 2012, respectively. During the maize growing season (April–September) precipitation was 94.7 mm in 2010, 179.1 mm in 2011, and 128.5 mm in 2012, respectively.

2.2 Experimental Design

In the study, we integrated two components together in crop intensification with wheat-maize intercropping: (i) plastic film mulch, (ii) various straw mulching approaches, which formed "double mulching" with plastic film and crop straw (both plastic film and straw were used to cover the maize strips). Three approaches implemented for high efficient agronomic measures were: (i) no-till with straw standing (i.e., NTSS), where no-till was combined with 25 to 30 cm height of wheat straw standing in the field after wheat harvest the previous fall; (ii) no-till with straw covering (i.e., NTS), where no-till was combined with wheat straw of 25 to 30 cm high that was chopped and evenly spread on the soil surface at wheat harvest the previous fall; (iii) tillage with straw incorporation (i.e., TIS), where 25 to 30 cm height of wheat straw was incorporated into the soil through tillage at wheat harvest the previous fall. These three straw mulching approaches were applied to the wheat-maize intercropping systems (Table 1), and (iv) conventional tillage (tillage without straw retention as the control), where conventional deep plowing (30 cm deep) was applied to the plot with straw removed off the field for monoculture wheat (i.e., CTW), monoculture maize (i.e., CTM), and wheat-maize intercropping system (i.e., CT), with three replicates in a total of 18 plots. In late October to early November, wheat strips were managed as described above, and maize strips were deep plowed and raked. In the next spring, first, fertilizing, harrowing, smoothing, and compacting at the maize preceded strips were done; then, a wheat crop was planted on the maize-preceded strips by strip rotary tillage wheat seeder; meanwhile, plastic film mulching on the wheat straw surface in the wheat-preceded strips and maize planted on the wheat-preceded strips by dibbler. Wheat strips were rotated with maize strips in alternate years (Table 1); this was done to provide the crops with an "intra-field strip rotation" to avoid potential weakness or problems that may occur with continuous cultivation. Also, the "intra-field strip rotation" may help balance soil nutrients required by the two different crops in the alternate years.

Spring wheat (cv. *Yong-liang* 4, a popularly grown cultivar) was planted on 20 March in 2010, 28 March in 2011, and 19 March in 2012, respectively. Maize (cv. *Wu-ke* 2, a popular-grown hybrid) was planted on 22 April, 17 April, and 20 April, respectively, in the 3 years. Each plot was 48 m^2 (10 m × 4.8 m) with a 0.5 m wide by 0.3 m high ridge built between two neighboring plots to eliminate potential movement of irrigation water. Wheat and maize crops were alternated in sets of 160 cm wide strips. Each wheat strip (80 cm wide) consisted of 6 rows of wheat plants with rows spaced at 12 cm between rows, and maize strip (80 cm wide) had two rows of maize plants with 40 cm row spacing. Planting density was 6,750,000 plants ha^{-1} for monoculture wheat and 82,500 plants ha^{-1} for monoculture maize, 3,750,000 plants ha^{-1} for intercropped wheat and 52,500 plants ha^{-1} for intercropped maize. Urea (46-0-0 of N-P_2O_5-K_2O) and diammonium phosphate (18-46-0 of N-P_2O_5-K_2O) were broadcast and incorporated into the soil at sowing. Monoculture wheat received 225 kg N ha^{-1} and 150 kg P_2O_5 ha^{-1}, while monoculture maize received 450 kg N ha^{-1} and 225 kg P_2O_5 ha^{-1}, respectively. The two intercrops each received the same rate of fertilizers as the monoculture crops on a per hectare basis, i.e., the N and P rates were halved for each intercrop because each species in the intercropping occupied1/2 of the total land areas. All N and P were applied as base fertilizers for wheat, while for maize crops, 30% of N was applied at sowing, 60% top-dressed at jointing, and the remaining 10% top-dressed at grain-filling.

Irrigation was applied to the crops due to low precipitation, according to the recommendation for optimizing crop production in the local areas (Chai et al., 2014b). All plots received 120 mm of irrigation during late fall just before soil freezing, and then various irrigation quotas were applied at the different growth stages the current year. A hydrant pipe system was used for the irrigation, and a flow meter was installed at discharging end of the pipe to record the irrigation volume entering each plot.

Table 1. The detailed description of treatments in 2010, 2011 and 2012

Crop patterns	Treatment abbreviation[a]	Tillage and straw management on wheat	Rotation patterns
			Year 1—year 2—year 3—year 4
Wheat-maize intercropping	NTSS	No-till with 25 to 30 cm straw standing	Wheat—maize—wheat—maize Maize—wheat—maize—wheat
	NTS	No-till with 25 to 30 cm straw covering	Wheat—maize—wheat—maize Maize—wheat—maize—wheat
	TIS	Tillage with 25 to 30 cm straw incorporated	Wheat—maize—wheat—maize Maize—wheat—maize—wheat
	CT	Conventional tillage without straw retention	Wheat—maize—wheat—maize Maize—wheat—maize—wheat
Monoculture	CTW-CTM	Conventional tillage without straw retention Monoculture wheat and maize rotation	Wheat—maize—wheat—maize Maize—wheat—maize—wheat

Note. [a] The experiment in 2009 was to provide various wheat straw management options for the treatments implemented in the following years. Systematic data measurement in 2010-2012.

2.3 Measuring Indices and Methods

2.3.1 Leaf Area Index (LAI)

Label similar plant for growth is consistent at seedling stage of crops in each plot; sampling plants are similar with labeled plants on growth at each stage. We take 20 plants of wheat and 5 plants of maize with "S" type method each plot at an interval of 20 d, the leaf area, leaf length and the greatest leaf width were measured with ruler, and leaf area index of crops are determined by following formula: leaf area = leaf length × the greatest leaf width × 0.75/0.83 (the compensation coefficient of wheat is 0.83, and that of maize is 0.75), and calculate the leaf area index (LAI). Especially, LAI of intercrops groups was determined using the following equation:

$$LAI = LAI_A \times P_A + LAI_B \times P_B \quad (1)$$

Where, LAI_A and LAI_B are LAI of intercrop A and intercrop B, respectively; P_A and P_B are the proportions of intercrop A and intercrop B in whole intercropping system.

2.3.2 Grain Yield, Biomass Yield, and Yield Components

At full maturity, all plots were harvested by hand, and the grains were air-dried, cleaned, and weighed for grain yield. The wheat and maize straw were air-dried, cleaned, and weighed for biomass yield. Spike number (SN), kernel number per spike (KNS), and thousand-kernel weight (TKW) were also determined.

2.3.3 Harvest Index

Harvest index (*HI*) was determined by grain yield (*GY*) per unit area divided by biomass yield (*BY*) per unit area.

$$HI = \frac{GY}{BY} \quad (2)$$

2.4 Statistic Analysis

Data were analyzed using the mixed effect of the SPSS statistical analysis software (SPSS software, 17.0, SPSS Inst. Ltd., USA) with the treatment as the fixed effect and replicate as random effect. Due to significant year by treatment interactions for most of the variables evaluated in the study, the treatment effect was assessed separately for each year. All statistical significance was declared at the probability level of 0.05.

3. Results

3.1 Effect of Integrated Systems on Crop Yields, Harvest Index, and the Component Factors of Grain Yield

3.1.1 Integrated Systems Boosted Crop Yields

Compared to monoculture maize without straw retention, i.e., the control treatment (CTM), wheat and maize intercropping increased yield by 16 to 42%, where as increase in yield was 118 to 160% compared to conventional monoculture wheat. In particular, the intercropping with straw covering on the soil surface (i.e., NTS), the most productive system, increased maize grain yield by 42% in 2010, 27% in 2011, and 38% in 2012, compared to the monoculture maize without straw retention (Table 2). Similarly and more dramatically, the integrated systems increased wheat grain yield by 149% in 2010, 153% in 2011, and 160% in 2012, compared to the conventional monoculture wheat.

Total yields are the sum of the yield of two component crops, wheat and maize, in the intercropping systems (Table 2). The integrated system of wheat and maize intercropping combined with straw retention produced significantly higher grain yields than the intercropping without straw retention treatment (i.e., CT) in each of the 3 years. Averaged across three years, the three straw retention treatments (i.e., NTSS, NTS, TIS) increased yields by 9.2, 12.0, and 5.6%, respectively. In particular, the intercropping with straw covering on the soil surface (i.e., NTS), increased grain yield by 14.3% in 2010, 9.9% in 2011, and 11.9% in 2012, compared to the intercropping without straw retention (i.e., CT control).

A close examination of the component yields of the two intercrops revealed that straw retention affected intercropped maize yield significantly ($P < 0.05$), with none or little effect on intercropped wheat yield. On average, the intercropped maize yields of the three straw retention treatments were 9.8, 16.4, and 5.8% greater than the yield of the control treatment. Overall, intercropped maize yields accounted for about 63.9 to 70.8% of the total yields (Table 2), showing that intercropped maize are the greater contributor to the productivity of the intercropping than the intercropped wheat. Most importantly, among the three straw retention treatments, the system with no tillage coupled with straw covering on the soil surface, achieved the highest grain yield.

Table 2. Grain yield of wheat, maize in intercropping system under different tillage patterns

Treatment[a]	2010			2011			2012		
	Component yield		Total[b]	Component yield		Total[b]	Component yield		Total[b]
	Wheat	Maize		Wheat	Maize		Wheat	Maize	
	kg ha^{-1}								
Intercropping									
NTSS	5,326	10,518	15,844	5,432	10,398	15,829	4,991	10,621	15,611
NTS	5,203	11,101	16,304	5,193	10,972	16,165	4,687	11,377	16,064
TIS	5,355	9,865	15,220	5,199	10,369	15,568	4,772	10,173	14,946
CT	5,155	9,107	14,261	4,899	9,806	14,703	4,505	9,857	14,362
Monoculture									
CTW	6,556	-	6,556	6,383	-	6,383	6,170	-	6,170
CTM	-	11,460	11,460	-	12,706	12,706	-	11,650	11,650
P-value	0.017	0.000	0.000	0.011	0.001	0.000	0.005	0.000	0.000
LSD (0.05)	272	442	474	301	516	428	263	339	460

Note. [a] NTSS, no tillage with straw standing; NTS, no tillage with straw covering; TIS, tillage with straw incorporated in the soil; CT, conventional tillage without straw retention; CTW, conventional tillage without straw retention in monoculture wheat; CTM, conventional tillage in monoculture maize.

[b] Total yields are the sum of the yields produced by the two component crops.

3.1.2 Integrated Systems Increased Harvest Index of Intercropped Wheat and Maize

Harvest index (i.e., HI) of crops can reflect the ability of photoassimilates to transform into grain yield.

Compared to conventional monoculture wheat, i.e., the control treatment (CTW), the three integrated systems decreased HI, but there is no clear trend. However, compared to the monoculture maize without straw retention, the three integrated systems increased HI by 5.5 to 21.6%. In particular, intercropping with straw covering on the soil surface (i.e., NTS), increased maize HI by 15.7% in 2010, 8.2% in 2011, and 21.6% in 2012, respectively (Figure 1).

Straw retention had a significant influence on HI of intercropped wheat and maize (Figure 1). The three integrated systems increased the HI of intercropped wheat by 4.0 to 6.0% in 2010, 3.3 to 4.6% in 2011, and 3.9 to 4.3% (except for NTS treatment) in 2012, respectively, compared to the conventional intercropped wheat. Similarly, it increased the HI of intercropped maize by 6.7 to 13.8% in 2010, 12.7 to 15.6% in 2011, and 6.8 to 15.1% in 2012, respectively, compared to the conventional intercropped maize. Effect of straw retention on the improvement of HI in maize was greater than that of wheat in wheat-maize intercropping. Especially, the system with no tillage coupled with straw covering on the soil surface, which achieved the highest HI of intercropped maize, it indicates that the double mulching with straw and plastic film on the soil surface in maize strips was in favor of improving the conversion rate of photoassimilates in maize.

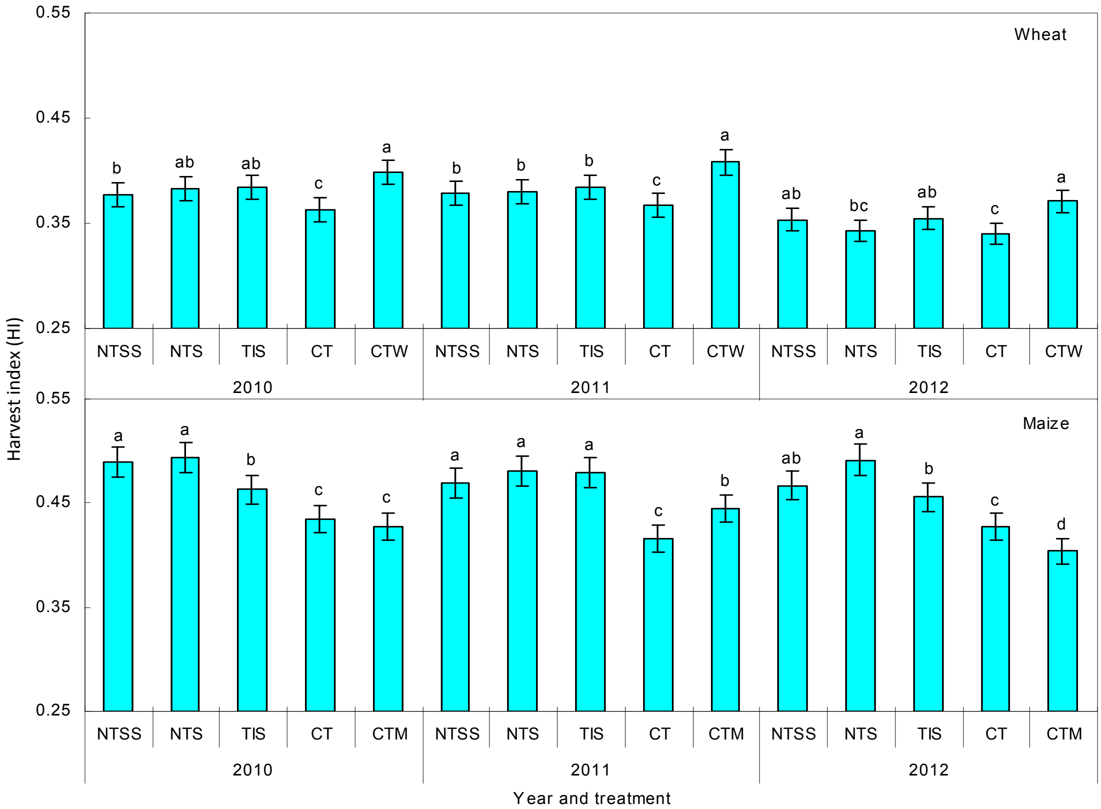

Figure 1. Harvest index (HI) of wheat and maize in monoculture and wheat-maize intercropping under different straw retention approaches. Smaller bars are standard errors ($P \leq 0.05$) among treatments at the given measurement. The treatment names on NTSS, NTS, TIS, CT, CTW, and CTM are the same as those defined in Table 1

3.1.3 Effect of Integrated Systems on the Component Factors of Grain Yield in Wheat and Maize

There is great significance for achieving high yield of crops by exploring the component factors of grain yield. Straw retention had a significant influence on spike number (i.e., SN), kernel number per spike (i.e., KNS), and thousand-kernel weight (i.e., TKW) of intercropped wheat (Table 3). Compared to conventional tillage without straw retention (i.e., the CT treatment), the three integrated systems (i.e., NTSS, NTS, and TIS) increased the SN per square meter of intercropped wheat by 3.1 to 9.5% in 2010, 2.9 to 14.5% in 2011, and 2.8 to 10.2% in 2012, respectively. Treatments NTSS and NTS increased KNS of intercropped wheat (CT) during 2010 and 2011 but not in 2012. During 2010 NTS increased KNS of intercropped wheat more than NTSS, while the reverse was true in 2011. The three integrated systems increased the TKW of intercropped wheat by 3.8 to 10.2% in 2010, 5.4 to 11.8% in 2011, and 2.9 to 10.0% in 2012, respectively. Although NTSS treatment had the greatest effect on yield components of the wheat in the intercropping system, but the difference between NTSS and NTS, were non-significant.

Straw combined with plastic film mulching had a significant increasing effect on SN, KNS, and TKW of intercropped maize. Compared to conventional tillage without straw retention, the three integrated systems increased the SN per square meter of intercropped maize by 2.9 to 12.9% in 2010, 3.2 to 9.3% in 2011, and 1.7 to 10.2% in 2012, respectively. Similarly, it increased KNS by 12.4 to 18.3% in 2010, 11.5 to 19.9% in 2011, and 11.9 to 18.6% in 2012, respectively. TKW was increased by 1.7 to 9.3% in 2010, 1.5 to 6.3% in 2011, and 2.0 to 8.9% in 2012, respectively. Under the integrated systems overall, the treatment, NTS had the highest SN, KNS, and TKW of intercropped maize, which is the foundation of increasing yield in maize.

Under the same land area, compared to conventional monoculture wheat treatment, the intercropped wheat with the three straw retention treatments increased SN by an average of 25.3%, and the intercropped wheat with conventional tillage resulted in average increase of 17.0%, across the three years. The two straw mulching treatments (i.e., NTSS, NTS) increased KNS by an average of 11.9%, and TKW was increased by an average of 10.1%. Similarly, the intercropped maize with the three integrated treatments increased SN by an average of 5.9%, increased KNS by an average of 35.7%, and increased TKW by an average of 5.7% in 2010 and 2012. Especially, the treatment NTS, had resulted in the greatest increase.

Table 3. The component factors on grain yield of wheat and maize in monoculture and wheat-maize intercropping under different treatments

Year	Treatment[a]	Wheat			Maize		
		SN (m^{-2})[b]	KNS[b]	TKW (g)[b]	SN (m^{-2})	KNS	TKW (g)
2010	*Intercropping*						
	NTSS	677.2	35.5	46.4	7.5	445.4	338.9
	NTS	700.8	35.9	44.0	7.9	455.3	346.0
	TIS	659.8	34.6	43.7	7.2	432.6	321.8
	CT	640.2	33.8	42.1	7.0	385.0	316.5
	Monoculture						
	CTW	549.3	33.8	41.2	-	-	-
	CTM	-	-	-	7.0	332.8	318.6
	P-value	0.014	0.020	0.008	0.012	0.001	0.009
	LSD (0.05)	9.3	1.7	2.9	0.2	48.1	21.4
2011	*Intercropping*						
	NTSS	782.4	34.0	47.3	7.5	456.6	300.4
	NTS	818.6	32.1	45.0	7.8	476.2	307.8
	TIS	735.6	31.4	44.6	7.4	443.0	293.9
	CT	715.2	29.6	42.3	7.1	397.2	289.4
	Monoculture						
	CTW	558.5	26.1	42.0	-	-	-
	CTM	-	-	-	7.9	513.9	321.1
	P-value	0.014	0.021	0.006	0.010	0.003	0.001
	LSD (0.05)	9.5	2.4	3.2	0.3	54.5	16.0
2012	*Intercropping*						
	NTSS	638.6	36.4	49.3	7.5	454.2	348.8
	NTS	665.4	36.1	46.1	7.8	467.8	355.0
	TIS	621.0	36.3	46.5	7.2	441.1	332.5
	CT	603.8	35.9	44.8	7.1	394.3	325.8
	Monoculture						
	CTW	568.2	35.0	43.1	-	-	-
	CTM	-	-	-	7.4	329.6	329.6
	P-value	0.004	0.045	0.014	0.039	0.002	0.005
	LSD (0.05)	8.1	1.5	4.5	0.2	49.3	18.1

Note. [a] NTSS, no tillage with straw standing; NTS, no tillage with straw covering; TIS, tillage with straw incorporated in the soil; CT, conventional tillage without straw retention; CTW, conventional tillage without straw retention in monoculture wheat; CTM, conventional tillage in monoculture maize.

[b] SN, spike number; KNS, kernel number per spike; TKW, thousand-kernel weight.

3.2 Effect of Integrated Systems on the Leaf Area Index (i.e., LAI) of Wheat and Maize

3.2.1 Integrated Systems on the Leaf Area Index (i.e., LAI) of Wheat

The integrated systems had a significant effect on increasing leaf area index (i.e., LAI) of intercropped wheat (Figure 2). At wheat jointing stage, LAI of intercropped wheat was lower than that of the conventional monoculture wheat treatment (i.e., the control, CTW), but the difference was not significant. However, LAI of the intercropped wheat under the three straw retention treatments were 25.3 to 31.5% at wheat boosting stage, 17.9 to 21.2% at wheat flowering stage, and 29.0 to 35.1% at wheat filling stage, and 39.0 to 50.9% at wheat maturing stage higher than that of the CTW treatment. Also, LAI of the intercropped wheat under conventional tillage without straw retention (i.e., CT) was higher by 30.2, 15.3, 20.5, and 33.1% at the late four growth stage, respectively. Meanwhile, the LAI of wheat was the highest at the flowering stage. During the entire growth period, the three straw retention treatments increased LAI by 25.4 to 27.0%. Conventional tillage without straw retention (i.e., CT) increased LAI by 22.5%, compared with the CTW treatment. The treatment no tillage with straw standing (i.e., NTSS) and straw covering on the soil surface (i.e., NTS) had the highest LAI, responsible for high yield.

3.2.2 Effect of Integrated Systems on the Leaf Area Index (i.e., LAI) of Maize

Integrated treatments increased LAI of intercropped maize significantly compared to the check treatment (conventional tillage without straw retention) in each of the three years (Figure 3). There was no or little effect on LAI between intercropped and monoculture maize before harvest of companion wheat. However, at wheat harvest stage, LAI of intercropped maize in the three integrated treatments was 21.1 to 33.2% greater than that of the conventional monoculture maize treatment (i.e., the control, CTM). Also, intercropped maize under conventional tillage without straw retention (i.e., CT) had 19.2% higher LAI. Moreover, LAI of the intercropped maize under the three integrated treatments were 34.7 to 46.5% at maize filling stage, 50.4 to 68.0% at maize dough stage, and 75.4 to 100.7% at maize full-ripe stage higher than that of the CTM treatment. Also, LAI of the intercropped maize under CT treatment was higher by 28.9, 41.8, and 65.7% at the three determining stage after wheat harvest, respectively. Meanwhile, LAI of maize was the highest at the filling stage. During the entire growth period, the three integrated treatments increased LAI by 29.7 to 44.6%. CT increased LAI by 23.6%, compared with the CTM treatment. No tillage with straw covering on the soil surface (i.e., NTS) had the highest LAI, prolonged the photosynthesis period, which created a larger photosynthetic source to obtain high yield.

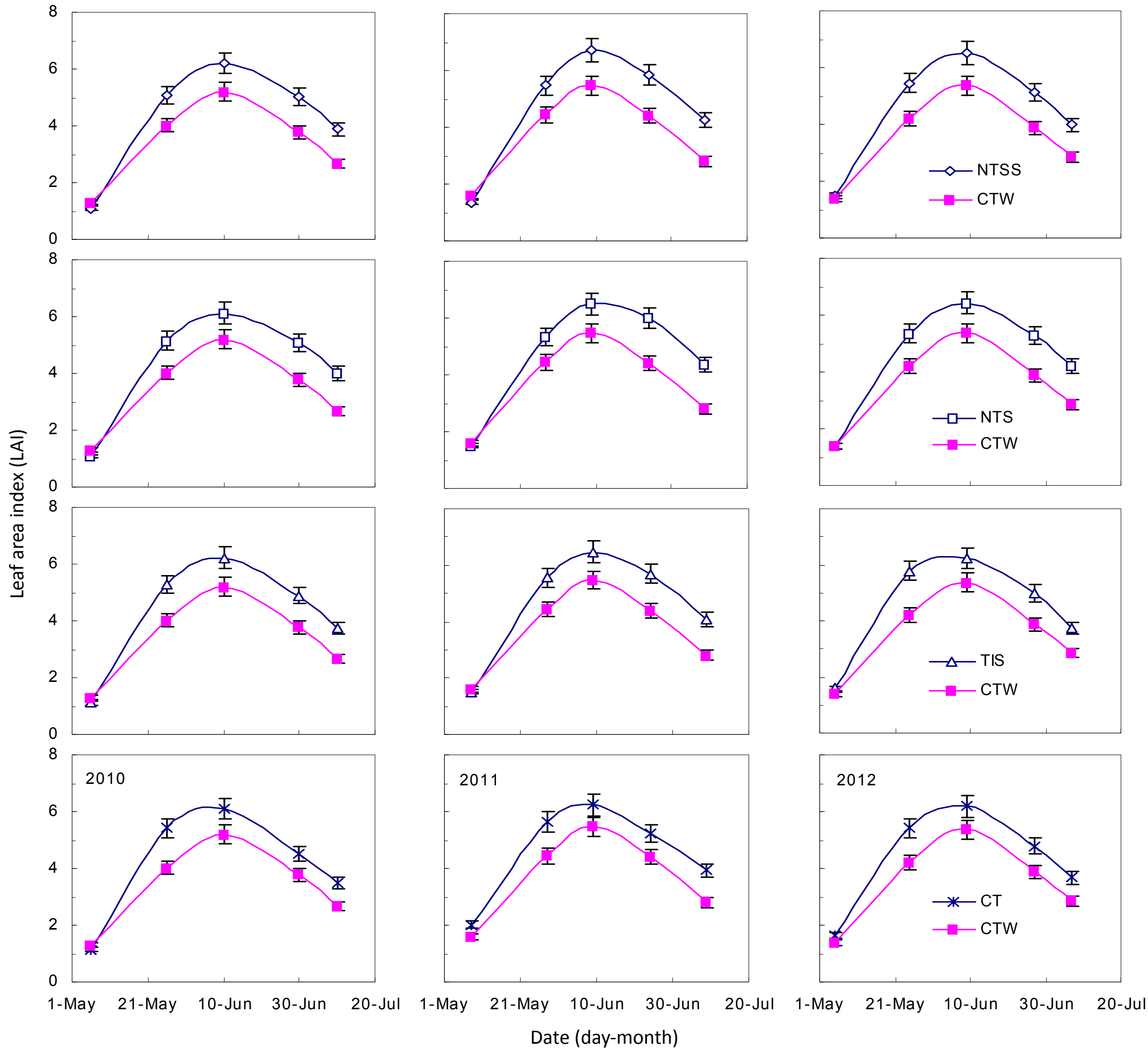

Figure 2. Dynamic on leaf area index (LAI) of wheat in conventional monoculture and wheat-maize intercropping system under different straw retention approaches. Smaller bars are standard errors ($P \leq 0.05$) among treatments at the given measurement. The treatment names on NTSS, NTS, TIS, CT and CTW are the same as those defined in Table 1

3.2.3 Integrated Systems on the Leaf Area Index (I.E., LAI) of Intercropping Groups

The wheat-maize intercropping systems had higher LAI significantly compared to the check treatment (conventional tillage without straw mulch) across the three study years. The three integrated systems significantly increased by an average of 51.7 to 64.1% during the entire growth period, also, conventional tillage without straw retention (i.e., CT) was increased by an average of 45.6%, averaged across the three years, compared with conventional monoculture maize treatment (i.e., the control, CTM). Similarly, the integrated systems increased by an average of 19.6 to 29.3%, CT increased by an average of 14.8%, compared with conventional monoculture wheat treatment (i.e., the control, CTW). During the co-growth period, the three integrated systems were higher LAI by an average of 50.9 to 58.2% than that of CTM treatment; also, CT was 46.6% higher. Especially, the treatment on no tillage with straw covering on the soil surface (i.e., NTS) achieved the highest LAI.

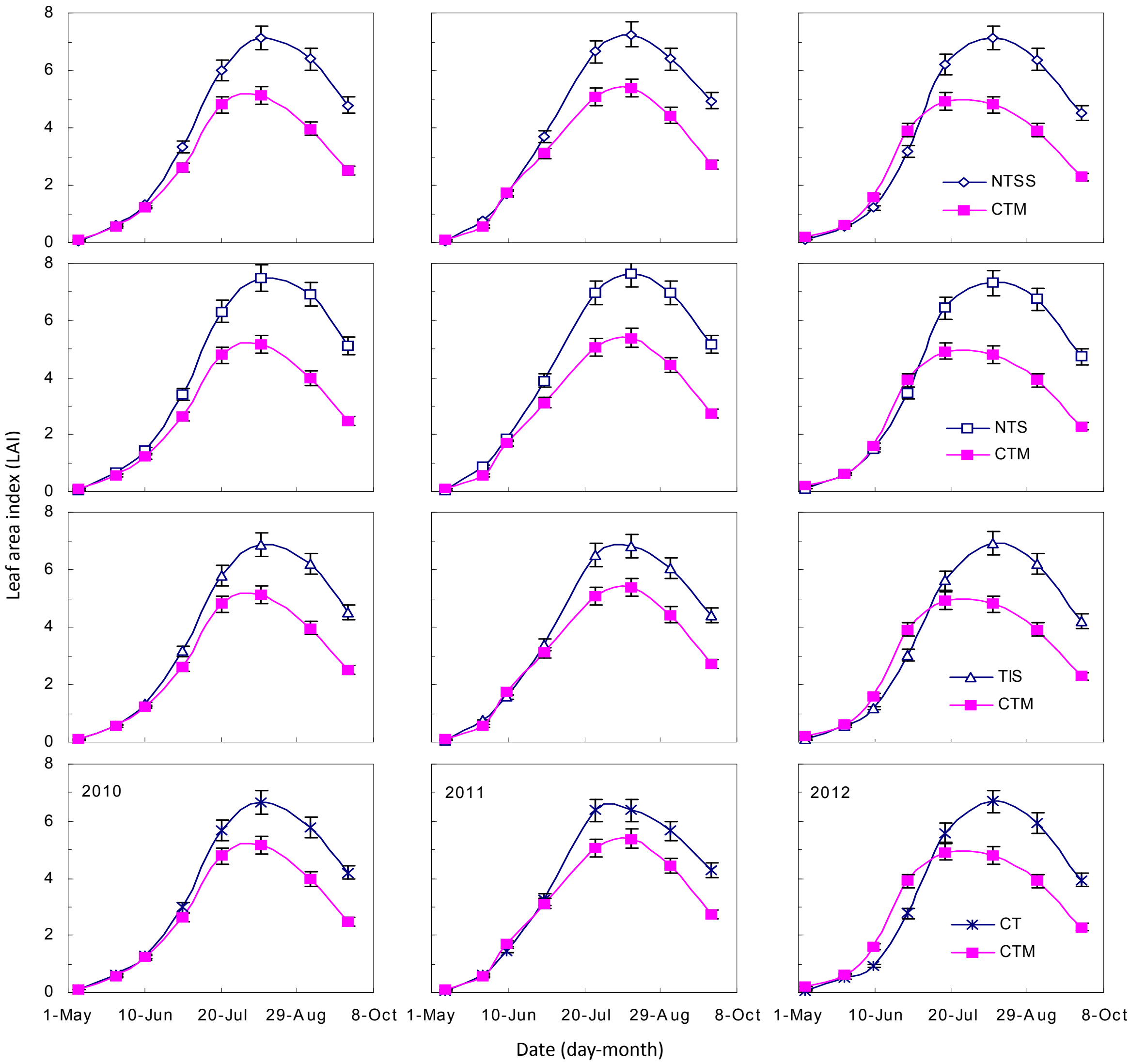

Figure 3. Dynamic on leaf area index (LAI) of maize in conventional monoculture and wheat-maize intercropping system under different straw retention approaches. Smaller bars are standard errors ($P \leq 0.05$) among treatments at the given measurement. The treatment names on NTSS, NTS, TIS, CT and CTM are the same as those defined in Table 1

3.3 Analysis of Mechanism of Grain Yield Formation by the Integrated Systems

Path coefficient technique was performed to divide the correlation coefficients between grain yield and yield components into direct and indirect effects via pathways. There was significantly positive correlation among grain yield, spike number (i.e., SN), kernel number per spike (i.e., KNS), thousand-kernel weight (i.e., TKW), and averaged leaf area index (i.e., LAI) of intercropped wheat and maize. Table 4 exhibited that SN, KNS, TKW, and LAI exerted positive direct effect on grain yield under different straw retention methods, where sequential importance was KNS, TKW, LAI, and SN. The result of indirect effects indicated that LAI had the highest and positive indirect effects on grain yield which could be justified via KNS.

Similarly, Table 4 exhibited that SN, KNS, TKW, and LAI exerted positive direct effect on grain yield under different straw retention ways, where sequential importance was SN, KNS, LAI, and TKW, in 2010 and 2011, and SN, KNS, TKW, LAI in 2012. Indirect effects indicated that KNS had the highest and positive indirect effects on grain yield which could be justified via SN.

Overall, the integrated systems increased the grain yield of intercropped wheat by improving kernel number per spike (i.e., KNS), and increased the grain yield of intercropped maize by improving spike number (i.e., SN).

Table 4. Correlation coefficient and path coefficient between grain yield and yield components, averaged LAI of intercropped wheat and maize, respectively

Year	Crop	Index	Correlation coefficient	Direct path coefficient	Indirect path coefficient			
					SN	KNS	TKW	LAI
2010	Wheat	SN	0.630* a	0.024	-	0.073	0.418	0.115
		KNS	0.799** b	0.532	0.098	-	0.005	0.164
		TKW	0.769**	0.337	0.039	0.004	-	0.389
		LAI	0.647*	0.240	0.011	0.253	0.143	-
	Maize	SN	0.962**	0.681	-	0.253	0.022	0.006
		KNS	0.901**	0.263	0.595	-	0.012	0.031
		TKW	0.894**	0.022	0.611	0.224	-	0.037
		LAI	0.836**	0.026	0.590	0.197	0.023	-
2011	Wheat	SN	0.680*	0.004	-	0.069	0.447	0.160
		KNS	0.953**	0.605	0.111	-	0.003	0.235
		TKW	0.786*	0.330	0.024	0.002	-	0.430
		LAI	0.619*	0.166	0.002	0.404	0.048	-
	Maize	SN	0.978**	0.780	-	0.163	0.007	0.028
		KNS	0.945**	0.171	0.742	-	0.007	0.025
		TKW	0.843**	0.009	0.669	0.131	-	0.033
		LAI	0.788**	0.035	0.622	0.123	0.008	-
2012	Wheat	SN	0.638*	0.044	-	0.080	0.409	0.105
		KNS	0.652*	0.461	0.052	-	0.004	0.135
		TKW	0.786**	0.339	0.041	0.005	-	0.401
		LAI	0.699*	0.226	0.016	0.289	0.168	-
	Maize	SN	0.946**	0.658	-	0.247	0.034	0.006
		KNS	0.884**	0.298	0.547	-	0.033	0.006
		TKW	0.905**	0.037	0.601	0.261	-	0.006
		LAI	0.897**	0.007	0.588	0.268	0.034	-

Note. [a] *, [b] ** indicate correlation is significant at the 0.05 and 0.01 probability level, respectively. SN, KNS, TKW and LAI indicate spike number, kernel number per spike, thousand-kernel weight and leaf area index, respectively.

4. Discussion

For the cereal crops, coordinated development among the yield components is the foundation for achieving higher yield. Cropping patterns have a significant influence on crops production; especially, intercropping is one of the most common practices used in sustainable agricultural system which has an important role in increasing the productivity and stability of yield in order to improve resource utilization and environmental factors (Qin et al., 2013). In the present study, intercropping increased yield components of wheat and maize. Since intercropped wheat had a strong competition relative to the accompanying maize, for use of light, heat, water, nutrition (Li et al., 2001b), during wheat and maize co-growth period, intercropped wheat obtained greater spike number (i.e., SN), kernel number per spike (i.e., KNS), and thousand-kernel weight (i.e., TKW), and had higher grain yield in comparison with monoculture treatment under the same area. Although, the intercropped maize was at a disadvantage with lower growth rate compared to the intercropped wheat, however, after accompanying wheat harvest, the relative growth rate of intercropped maize increased substantially in comparison to monoculture maize, which allowed intercropped maize a chance to compensate partly or fully due to the expansion of absorption space for light, heat and gas resources on the ground coupled with the expansion of absorption scope for water and nutrients underground play a major role in compensation (Li et al., 2001a). Thus intercropped maize had greater SN, KNS, and TKW, and had higher grain yield in comparison with monoculture treatment under the same area. The results showed that favorable interspecific competition and compensation effect is beneficial to improve yield components and crop grain yield.

Tillage patterns, and cover materials influence soil temperature and moisture, thus affecting crop production (Ramakrishna et al., 2006; Yin et al., 2016). For instance, straw mulching has many advantageous effects when compared with no mulching. It moderates the influence of environmental factors on soil by increasing soil temperature and controlling diurnal and seasonal fluctuations in soil temperature (Li et al., 2013; Novak et al., 2000), therefore, straw mulching can increase crops yield components in comparison with no-straw mulch. This response may be explained by findings of (Alami-Milani et al., 2013) who reported that yield and its components increase under straw residue mulch. Moreover, it has been observed that straw mulching increased soil microbe quantity probably because straw mulching buffered the extreme fluctuations in soil moisture and temperature (Ghosh et al., 2006; Tu et al., 2006) or it also improved crop root growth and increased the type and amount of root exudates, thus providing more carbon sources and energy for soil microorganisms (Zhang et al., 2015). To our knowledge, plastic film mulch can increase temperature and moisture in the upper layers of soil (Li et al., 1999), and increase crop yield due to increased in crop yield components (Liu et al., 2014). This can be attributed to the fact that plastic film mulch could help to increase crop chlorophyll content and improve the photosynthetic rate (Yang et al., 2006). Since temperature and water are important factors that directly affect plant growth, either as resources or as resource regulators, selecting mulching materials is an effective method of manipulating crop growing environment to increase yield and improve product quality by ameliorating soil temperature, conserving soil moisture, reducing soil erosion improving soil structure, and enhancing organic matter content (Aikins et al., 2012).

In spite of the fact that straw mulch and plastic mulch can increase SN, KNS, and TKW of wheat and maize in mono-cropping system, an important question is can we develop an integrated system with straw and plastic film mulch that allows increased crop productivity through increasing yield components? In the present study, the integrated system increased SN, KNS, and TKW of maize, which is derived from the integrated system, which can optimize soil temperature and soil moisture (Yin et al., 2016). Although plastic film mulch can also improve soil temperature and promote crop growth in cooler seasons, and can improve crop production in semi-arid areas (Ramakrishna et al., 2006; Zhou et al., 2009), plastic film mulching throughout the growth season is detrimental to crop yield improvement in some conditions (e.g., extreme high soil temperature), because it accelerates plant senescence during the later growth season (Wang et al., 2009). An added advantage of straw mulching is that it reduces temperature extremes, however, low soil temperature caused by crop residues can delay seedling emergence, especially when soil temperature is low in spring. In some cases, delayed seedling emergence may decreases crop yield (Chen et al., 2011), therefore, the practice of straw and plastic film mulching has also been questioned by farmers for suitability for crop production. In the present study, the integrated system optimized the soil temperature in the wheat and maize strips, and further increased grain yield with increasing of yield components.

There is no doubt that the improvement of grain yields in maize due to stay-green maize was from remobilization of the reserved carbon at pre-silking (He et al., 2005). This is a consequence not only of the longer duration of reproductive growth stage, but also of the larger total leaf areas and delayed leaf senescence, both resulting in longer duration of photosynthesis. Since nutrient uptake depends on the continuous carbohydrate supply from shoot to roots, longer duration of post-silking photosynthesis is beneficial for post-silking nutrient uptake of the plant (Rajcan & Tollenaar, 1999), which in turn increases canopy photosynthesis duration and finally obtained high grain yield (Ciampitti & Vyn, 2011). In wheat-maize intercropping in the present study, straw mulching treatments increased leaf area index of maize under monoculture or intercropping. Most importantly, compared to the conventional monoculture maize without straw retention, the intercropping with straw covering on the soil surface (i.e., NTS treatment) increased LAI of maize by an average of 65.6% after the accompanying wheat harvest, across the three years.

Grain yield of intercropped wheat and maize under straw mulch was greater than that of conventional tillage without straw retention. This might be due to the reason that can prolong crop growth period, delay green leaf functional period, improve the leaf area index, and promote the accumulation and transformation of photosynthetic product, which partly is attributed to more transport of dry matter to grain from leaves, stems and sheaths during the late growth stage, thus obtaining the higher harvest index. This result is consistent with many in intercropping systems, where the harvest index was greater for both species in the intercrops, because the late-maturing crop suppressed the early vegetative growth but early-maturing crop was harvested before the reproductive phase (Rao & Willey, 1983). Also, the harvest index of the species with the weaker competitive ability was much increased and the plant was reduced in size because of competition during the vegetative phase (Baker, 1979). So, effects of straw mulch on harvest index of intercropped crops can be positive. In this study, the positive effect on harvest index resulted in an increasing of grain yield for intercropped wheat and maize.

Wheat-maize intercropping system is long established as major crop production system in northwest China, especially in areas with irrigation and only one cropping season annually due to temperature limitation. Compared to corresponding monoculture crops, yield advantage has been recorded in many intercropping systems (Chai et al., 2014b; Hu et al., 2015; Li et al., 2001b; Yin et al., 2015), but the increased grain yield is typically at the expense of increased water consumption. Little has been reported on how the yield advantage can be captured in areas with annual evaporation more than 20 times precipitation in arid environment. Some studies show that straw mulching can help increase crop establishment and grain yield (Fan et al., 2013; Hu et al., 2015), but little is known about how this technique may be effective in intercropping systems. In the present study, we integrated plastic film together with straw mulching, in alternative systems. The integrated system had a significant influence on increased total yields and the yield of intercropped maize. Moreover, intercropped maize yields accounted for about 63.9 to 70.8% of the total yield in wheat-maize intercropping system, showing that intercropped maize crops are the greater contributor to the productivity of the intercropping than the intercropped wheat. Similar results were repeated by Fan et al., 2013. Most importantly, among the three straw mulching treatments, the system with reduced tillage coupled with straw covering on the soil surface, which achieved the highest grain yield, was most beneficial.

Path coefficient analysis is one of the biometrics techniques which have been exploited to quantify the connections of different yield attributes and also their direct and indirect effects on grain yield using correlation values. According to this procedure, spike number (i.e., SN), kernel number per spike (i.e., KNS), thousand-kernel weight (i.e., TKW), and leaf area index (i.e., LAI) had high positive direct effects on grain yield of intercropped wheat and maize. Results of sequential path analysis showed SN had positive direct effect on grain yield of intercropped wheat via TKW, KNS and TKW had positive direct effect on grain yield of intercropped wheat via LAI as response variable. Similarly, SN had positive direct effect on grain yield of intercropped maize via TKW, KNS and TKW had positive direct effect on grain yield of intercropped maize via SN as response variable. This is especially effective on increasing crop yield in Oasis agricultural regions such as the Hexi Corridor of China where water shortage is the foremost factor threatening agricultural sustainability (Chai et al., 2014a), and adaptation of this type of crop intensification may alleviate the issue while meeting the ever-growing demand for grains (Chai et al., 2014a; Yin et al., 2015).

5. Conclusion

The integrated double mulching system (i.e., plastic film and straw covering on the soil surface) in combination with cropping intensification through two-crop strip intercropping was shown to be effective in increasing leaf area index, crop productivity, and improving yield components for the two intercrops. The improved leaf area index and yield components allowed the higher yield of the two intercrops in wheat and maize intercropping system. In particular, the double mulching system significantly increased the grain yield of intercropped maize and total yields compared to conventional practices, thus obtaining the highest harvest index. Moreover, path coefficient analysis showed that the integrated systems increased the grain yield of intercropped wheat by improving kernel number per spike, and increased the grain yield of intercropped maize by improving spike number. Our results clearly demonstrate that the integrated system (i.e., the wheat-maize intercropping with plastic mulching and straw covering on the soil surface) can play an important role in the development of improved farming systems while meeting the ever-growing demands for grains currently been experienced in the arid and semi-arid environments.

Acknowledgements

We are grateful to the research grants provided by National Natural Science Foundation of China (31360323), the Special Fund for Agro-scientific Research in the Public Interest (201503125-3), and National Key Technology R&D Program (2012BAD14B10). We would also like to thank all staff at Wuwei Experimental Station of Gansu Agricultural University for technical assistance in carrying out the field experiments.

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