INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
19–1721/2020/24–4–799–811
DOI: 10.17957/IJAB/15.1503
https://www.fspublishers.org

Full Length Article

Photosynthetic and Chlorophyll Fluorescence Responses in Maize and Soybean Strip Intercropping System

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Received 08 November 2019; Accepted 02 May 2020; Published 16 August 2020

Abstract

In this study, the photosynthetic mechanisms and superiority of the systematic economic output value of crop yield in a maize–soybean intercropping system was determined. The effects of maize and soybean single cropping, and strip intercropped maize and soybean under four different intercropping ratios of the two crops [maize (M): soybean (S): 2:2, 4:2, 4:4, and 6:6] were compared and analyzed the changes in photosynthetic performance, chlorophyll fluorescence, and yield components. Results showed that strip intercropping effectively improved the light response curve of maize and significantly reduced in soybean which improved the adaptability of functional leaves of maize to strong light. Maize intercropping had more open stomata, higher intercellular CO_2 concentration and higher transpiration rate. Strip intercropping significantly improved the Fv/Fm, qP and Φ PSII value of maize leaves, and each parameter of soybean strip intercropping changed in contrast. The photosynthetic capacity of crops in different strip width was also different under intercropping. The photosynthetic capacity of maize in the strip was gradually reduced with the increase of strip width, while of soybean was gradually restored. Based on these changes in photosynthetic capacity, intercropping significantly increased the yield components of maize, and significantly decreased the yield components of soybean. As a result, the yield in maize strip was significantly higher than in single. However, the compound yield of strip intercropping was all higher than soybean single. In this study, intercropping advantage existed in different strip intercropping treatments and the compound economic output value of crops in each treatment was higher than maize and soybean single, among which maize-soybean 4:2 strip intercropping was the largest compound economic output value and the smallest was soybean single cropping. © 2020 Friends Science Publishers

Key words: Maize; Soybean; Strip intercropping; Photosynthetic characteristics; Chlorophyll fluorescence characteristics; Yield

Introduction

The pursuit of productive, efficient, and green agricultural production approaches guarantees for solving the world's food problems. The yield of traditional crop patterns has been greatly improved in the past decades, but this increase at the cost of sacrificing the productivity of the farmland, is harmful to the ecological environment of the farmland because of fertilizer and pesticides in agricultural production. However, in recent years, the yield of single crop has not increased synchronously with the increase of the amount of fertilizer, and the problems of fertilizer loss, environmental pollution and low fertility have become increasingly prominent. Intercropping, with two crop species cultivated on the same area of land, is a promising way to tackle these issues (Lithourgidis *et al.* 2011; Brooker *et al.* 2015). At present, intercropping is a very important cropping system especially in many developing countries of world (Li *et al.* 2007; Feike *et al.* 2012; Bedoussac *et al.* 2015). Compared with the single cropping system, this model uses the principle of biological diversity, which can make full use of natural resources, improves soil fertility and increase the yield of land (Hauggaard-Nielsen *et al.* 2013), reduces weeds and insect pests (Echarte *et al.* 2011), increase the benefit of farmers, protect the ecological environment (Jensen *et al.* 2015) and achieve sustainable development of agriculture (Echarte *et al.* 2011).

Among different crop systems, the intercropping of a cereal with a legume is considered a preferential system for achieving increased food supply and reduced environmental feedback (Hu *et al.* 2016). At present, the intercropping of maize and soybean is widely practiced in Africa (Oseni 2010), South America (Echarte *et al.* 2011), and Asia (Lv *et al.* 2014), and is associated with a significant enhancement of the land equivalence ratio (Undie *et al.* 2012). Numerous studies have indicated that the yield advantage of intercropping over singles can be attributed to a large extent to a greater efficiency in the capture and utilization of solar radiation. In this regard, it has been found that in the intercropping of maize and soybean, which is characterized by relatively tall and short statures, respectively, can enhance the light capture per unit area by improving soil coverage and reducing the proportion of light penetrating to ground level. In contrast to the respective singles, the light environment of interplanted crops is significantly altered, and amount of light received by the tall stems of maize in the system is significantly increased, whereas light capture by the shorter statured soybean crop is reduced. These changes in light availability inevitably affect the photosynthetic capacity of crops. Liu *et al.* (2017) found that compared with singled soybean, under intercropping, the R:FR ratio at the top of the soybean canopy during the flowering stage is reduced by 17–21% more than the photosynthetically active radiation (PAR). With respect to the soybean growth form, intercropping has been shown to increase of height of plants, the length of the interval, and the leaf area index, whereas the ratio of the leaf decreases (Yang *et al.* 2014). Furthermore, when intercropped with maize, the shading influence of maize reduces the intensity of light, thereby reducing the photosynthetic capacity, owing to significant changes in the photosynthetic rate (Pn), stomatal conductance (Gs), transpiration rate (Tr), and chlorophyll fluorescence parameters (Yang *et al.* 2017). In the maize-soybean relay intercropping system practiced in southwestern China, the yield of maize light energy is significantly higher than in maize single (Liu *et al.* 2018).

The photosynthetic rate of maize leaves has also been shown to be proportional to the distance between rows, and the relationship between the transmittance is logarithmic (Gao *et al.* 2018). Accordingly, the selection of appropriate row spacing and configuration can significantly increase the number of maize ears, and promote the formation of photosynthetic products after flowering, thereby enhancing maize yield. In the relay intercropping system, to balance the production of soybeans, the shading of soybeans by maize can be reduced by increasing the soybean row ratios (Wang *et al.* 2016). Although in a number of respects, maize and soybean intercropping is similar to relay intercropping, there are certain differences. For example, under relay intercropping conditions, soybean is shaded from the seedling period to the end of the early flowering period (Wu *et al.* 2015), whereas in intercropping, the whole life of the soybean was symbiotic with the maize, and the maximum period of birth was the beginning of the early flowering period and the end of the period of maturity.

Northeastern China is the world's main production region for maize and soybean, with a long history of maize–soybean intercropping and considerable production potential. In this regard, maize and soybean single intercropping may serve as a model for effectively boosting regional productivity. In this system, shading by the taller maize crop modifies the light environment experienced by the shorter soybean crop in terms of both light quality and quantity, and these changes are influenced to varying degrees by the intercropping configuration and crop architecture (Tsubo and Walker 2002; Zhang *et al.* 2008; Munz *et al.* 2014). To date, however, few studies have examined light energy utilization mechanisms characterizing the maize and soybean intercropping system in this area or evaluated the system as whole. Therefore, in order to systematically assess the light energy utilization mechanisms, system yield, and economic output value of the crop yield advantage associated with the maize–soybean strip intercropping system in this area, a comparative study examined the performance of maize single cropping, soybean single cropping, and four different maize–soybean strip intercropping ratios in the field to determine changes in the respective light response curves, photosynthetic parameters, chlorophyll fluorescence parameters, yield, and yield components, as well as the different economic benefits associated with each treatment. The findings of this study will provide a theoretical basis and technical reference for further developments in maize and soybean strip intercropping in northeastern China.

Materials and Methods

Experimental design

The experiment was conducted in 2016 and 2017 at the agricultural college experiment base of Jilin agricultural university. The soil was a typical black with an excellent fertility level rich in organic matter content of 26.9 g/kg, alkali-hydrolyzed nitrogen of 120 mg/kg, available phosphorus of 16.5 mg/kg, available potassium of 122 mg/kg, total nitrogen of 1.645 g/kg, total phosphorus of 0.85 g/kg and pH of 6.8. The maize variety xianyu 335, provided by denghai pioneer company and soybean variety jinong 40, provided by department of agriculture, Jilin agricultural university was used. The experiment was designed as a random block, with 3 replicates and 6 treatments, as follows: maize single cropping (strip width 6.5 m, strip length 10 m, 10 rows of maize sown within the strip), soybean single cropping (strip width 6.5 m, strip length 10 m, 10 rows of soybean sown within the strip),–maize-soybean 2:2 intercropping (maize and soybean were seeded with 1.30 m width and 10 m strip length, 2 rows of maize were sown in the maize strip and 2 rows of soybeans were sown in the soybean strip), maize-soybean 4:2 intercropping (maize sowing width was 2.60 m, strip length was 10 m, and maize was sown in 4 rows within the strip; The width of soybean sowing was 1.30 m, and 2 rows of soybeans were sown within the strip, maize-soybean 4:4 intercropping (maize and soybean were planted with 2.60 m width and 10 m strip length, 4 rows of maize were sown in maize belt and 4 rows of soybean were sown in soybean belt) and maize-soybean 6:6 intercropping (maize and soybean were seeded with a width of 3.90 m and a strip length of 10 m, 6 rows of maize were sown in the maize strip and 6 rows of soybeans were sown in the soybean strip).

The plant spacing of adjacent maize was 19.23 cm and of adjacent soybean was 7.60 cm under single cropping and intercropping condition. Row spacing of maize and soybean all were 0.65 m, and row spacing of adjacent maize and soybean was 0.65 m in strip intercropping. The amount of fertilizer applied to maize was N:230 kg/ha, P_2O_5:120 kg/ha, and K_2O:160 kg/ha. The N amount was 30%, all P_2O_5 and K_2O were applied as the base fertilizer, and the remaining nitrogen fertilizer as top-dressed in the later growth stage of maize. The amount of fertilizer applied to soybean was P_2O_5:60 kg/ha and K_2O:25 kg/ha, all of which were applied as seed fertilizer in one time. Maize and soybean were sown at the same time, the planting date of 2016 was April 28, and in 2017, April 29. After the emergence of seedlings, the seedlings were fixed according to the preset density. In the middle growth period, field management was conducted according to the routine. The harvest dates were September 28, 2016 and September 30, 2017.

Determination of items and methods

Determination of light response curves: At clear, the Li-6400 photosynthetic system (Li-Cor, USA), red and blue light source leaf chamber was selected and open gas was set with CO_2 concentration of 400 μmol mol^{-1}. In 2016, the light response curves were measured at the tasseling stage of maize and the flowering stage of soybean, light quantum density was (photosynthetically available radiation, PAR) to 0, 20, 50, 100, 200, 400, 600, 800, 1 000, 1 200, 1500 and 2 000 μmol m^{-2} s^{-1}. In 2017, the light response curves were measured at filling stage of maize and granulation stag of soybean, light quantum density (PAR) was to 0, 15, 60, 120, 250, 500, 1 000, 1 200, 1 500, 1 800 and 2 000 μmol m^{-2} s^{-1}.

Determination of photosynthetic parameters: The photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), intercellular CO_2 concentration (Ci) were measured from 9:00–11:30 am on a clear, calm day using the Li-6400 photosynthetic system (Li-Cor, United States) during grain filling period of soybean and maize.

Determination of chlorophyll fluorescence parameters: Mini-PAM（Walz，Germany）portable chlorophyll fluorescence apparatus was used to measure dark adaption maximal fluorescence (*Fm*), dark adaption minimal fluorescence (*Fo*), maximal fluorescence under light (*Fm′*) and minimal fluorescence under light (*Fo′*), according to the formula to calculate the maximal quantum yield of PSⅡ(*Fv/Fm*), actual photochemical efficiency of PSⅡ(*ΦPSII*), photochemical quenching (*qP*), non-photochemical quenching (*NPQ*). The formula was as follows: $Fv/Fm=(Fm-Fo)/Fm$；$qP=(Fm'-F)/(Fm'-Fo)$；$\Phi PSII=(Fm'-F)/Fm'$; $NPQ=(Fm-Fm')/Fm'$.

Crop yield, land equivalent ratio and economic output: At mature stage, maize and soybean singles were harvested in the middle 2 rows of plots. Yield of different strip intercropping treatment, was calculated in the maize strip by harvesting all the maize in the maize sowing strip and in the soybean strip by harvesting all the soybean in the soybean sowing strip. After which, the compound yield of strip intercropping was calculated according to the proportion of maize and soybean area by different treatments and the yield in each strip. For each treatment, 10 maize plants and 15 soybean plants were selected to measure the relevant indexes. Land equivalent ratio (*LER*) is used to calculate the land use advantage provided by intercropping (Mao *et al.* 2012), as follows:

$$LER = Y_{im}/Y_{mm} + Y_{is}/Y_{ms}$$

where Y_{im} and Y_{is} are yields of intercropped maize and soybean, and Y_{mm} and Y_{ms} are yields in singled maize and soybean, respectively. These express for each crop species the area of land that would be needed in single cropping to achieve the same yield as one-unit area of intercrop. When the LER is greater than 1, there is a land use advantage of intercropping. The economic output value is calculated according to the output value and the selling price of grain.

Data analysis

All data were processed by Microsoft Excel 2007, and SPSS 13.0 was used for statistics and analysis.

Results

Maize light response curves

Photosynthetic rate: The Pn of maize leaves under both strip intercropping and single cropping initially increased and then decreased with an increase of light intensity, and there were differences between the two systems (Fig. 1). At the tasseling stage, when the PAR level was between 0 to 600 μmol m^{-2} s^{-1}, there was no significant difference in leaf Pn between intercropped and singled maize. When PAR was between 800 to 2000 μmol m^{-2} s^{-1}, the Pn of intercropped maize was significantly higher than maize grown in single, which followed the pattern M2S2 > M4S2 > M. In addition, the maximum Pn of maize under strip intercropping coincided with a PAR value of 1200 μmol m^{-2} s^{-1}, whereas that of maize under single at a PAR of 800 μmol m^{-2} s^{-1}.

At the maize grain filling stage, when the PAR was greater than 1000 μmol m^{-2} s^{-1}, the Pn of intercropping was higher than single cropping. The maximum Pn of intercropped maize coincided with a PAR of 1800 μmol m^{-2} s^{-1}, whereas the maximum Pn of single-cropped maize coincided with a PAR of 1500 μmol m^{-2} s^{-1}. Under high light intensity, Pn of intercropped maize was significantly higher than single-cropped maize. From these results, it can be deduced that strip intercropping enables maize to make more efficient use of the available light resources.

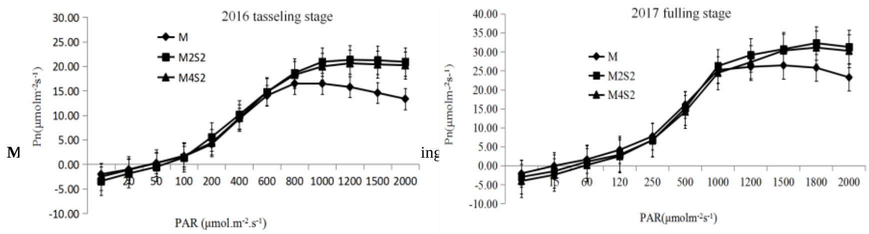

Fig. 1: Changes of Pn of maize leaves with light intensity under strip intercropping and single cropping
M: maize single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

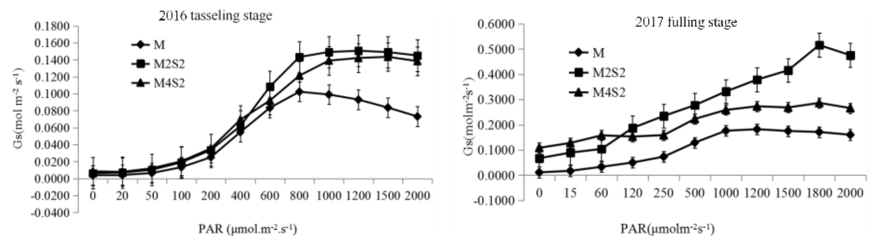

Fig. 2: Changes of Gs of maize leaves with light intensity under strip intercropping and single cropping
M: maize single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

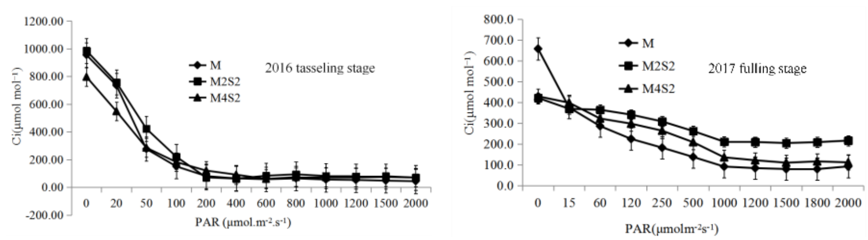

Fig. 3: Changes of Ci of maize leaves with light intensity under strip intercropping and single cropping
M: maize single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

Stomatal conductance

The change of Gs with light intensity was similar to Pn (Fig. 2). At the tasseling stage, when PAR was between 0 to 600 μmol m^{-2} s^{-1}, there was no difference in Gs between intercropped and singled maize. However, when PAR was between 600 μmol m^{-2} s^{-1} to 2000 μmol m^{-2} s^{-1}, the Gs of intercropped maize was significantly higher than maize grown in single, with the trend M2S2 > M4S2 > M. The maximum Gs of singled and intercropped maize coincided with PAR levels of 800 and 1200 μmol m^{-2} s^{-1}, respectively. The Gs of maize leaf at the grain filling stage was overall higher than at the tasseling stage, the curve values increased steadily with an increase in PAR. At a PAR level of 1200 μmol m^{-2} s^{-1}, the maximum Gs value of singled maize was 0.182, whereas at a PAR of 1800 μmol m^{-2} s^{-1}, the maximum Gs values of strip intercropped maize were 0.5158 and 0.2864, respectively. During the grain filling stage, the Gs values of intercropped maize were significantly higher than in single-cropped maize, which was more conducive to gas exchange between internal and external leaf environments.

Intercellular CO_2 concentration

The Ci gradually decreased with the increase of PAR (Fig. 3), contrary to the Pn and Gs. At the tasseling stage, for PAR levels of between 0 and 200 μmol m^{-2} s^{-1}, there were initial rapid decreases in Ci values for both singled and intercropped maize, with values subsequently stabilizing in response to a gradual increase in PAR. Moreover, the Ci values of the leaves under different treatments were similar. During the grain filling period, the leaf Ci values of maize under strip intercropping were all higher than in single cropping, following the trend M2S2 > M4S2 >M. Thus, strip intercropping increased the leaf Ci of maize during the late growth stage, during which could provide sufficient carbon sources for leaf photosynthesis were provided.

Transpiration rate

During the tasseling stage (Fig. 4), in singled maize, there was an initial increase in Tr followed by a decrease in response to an increase in PAR, with the maximum Tr being recorded at a PAR of 1 000 μmol m^{-2} s^{-1}, whereas the Tr of

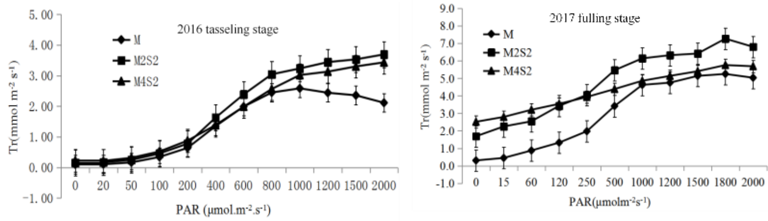

Fig. 4: Changes of Tr of maize leaves with light intensity under strip intercropping and single cropping
M: maize single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

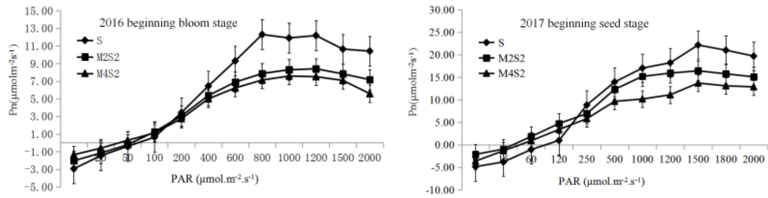

Fig. 5: Changes of Pn of soybean leaves with light intensity under strip intercropping and single cropping
S: soybean single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

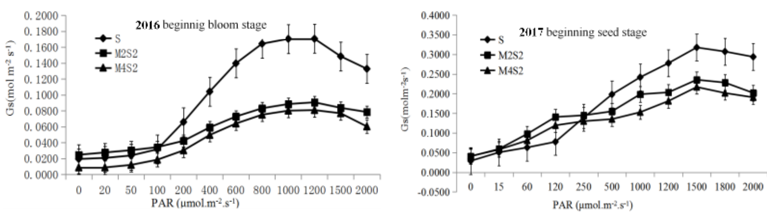

Fig. 6: Changes of Gs of soybean leaves with light intensity under strip intercropping and single cropping
S: soybean single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

intercropped maize increased with an increase in PAR and reached the maximum. At PAR levels greater than 800 μmol m^{-2} s^{-1}, the difference in Tr values observed for singled and intercropped maize gradually increased with an increase in PAR. During the grain filling stage, the Tr of both intercropped and singled maize initially increased and then subsequently decreased with an increase in PAR, with the following maximum Tr values being recorded at a PAR of 1800 μmol m^{-2} s^{-1}, the Tr of intercropped maize increased by 38.45 and 9.69%, respectively. At the same PAR level, the Tr values of intercropped maize were all higher than single-cropped maize.

Soybean light response curves

Photosynthetic rate: With an increase in light intensity, the Pn of soybean under intercropping and single cropping showed an initial increase and subsequent decrease (Fig. 5). However, at the beginning bloom stage, the Pn of singled soybean showed secondary peaks at PAR 800 and 1200 μmol m^{-2} s^{-1}, respectively. In contrast, the Pn of intercropped soybean showed only a single peak at a PAR of 1200 μmol m^{-2} s^{-1}. During the seed filling period, the maximum Pn value for both intercropped and single-cropped soybean was recorded at a PAR of 1500 μmol m^{-2} s^{-1}. Regardless of the soybean growth stage, the Pn of single cropping was higher than intercropping, and the difference gradually increased to a significant extent with a corresponding increase in PAR, showing the trend S > M2S2 > M4S2.

Stomatal conductance

The variation in soybean Gs with increasing PAR showed a pattern similar to Pn (Fig. 6). During the flowering period, the maximum Gs of both intercropped and single-cropped soybean was recorded at a PAR of 1200 μmol m^{-2} s^{-1}, whereas in beginning seed stage, the maximum Gs occurred at a PAR of 1500 μmol m^{-2} s^{-1}. When PAR levels were greater than 500 μmol m^{-2} s^{-1}, the Gs value under single cropping was greater than intercropping, and the difference gradually increased to the level of significance with an increase in PAR following the trend S > M2S2 > M4S2. Strip intercropping reduced the Gs of soybean leaves, thereby reducing the efficiency of gas exchange between the internal and external leaf environments.

Intercellular CO_2 concentration

The Ci of soybean gradually decreased with an increase in PAR (Fig. 7). During the beginning bloom stage at PAR levels of between 0 and 400 μmol m^{-2} s^{-1}, and during the full-bloom stage at PAR levels of between 0 and 1000 μmol m^{-2} s^{-1}, the Ci of both single-cropped and intercropped soybean initially decreased rapidly, but thereafter stabilized and increased slightly with an increase in PAR. In the high PAR range, the Ci of single-cropped soybean was higher than intercropped soybean. Strip intercropping reduced the Ci of soybean in the order S > M2S2 > M4S2.

Transpiration rate

With the exception of two peaks appearing in the Tr curve at the beginning bloom stage of single-cropped soybean, the other Tr curves all showed a pattern characterized by an initial increase and subsequent decrease corresponding with an increase in PAR, with a single maximum peak value (Fig. 8). During the beginning bloom stage, the maximum Tr of intercropped soybean was recorded at a PAR of 1200 μmol m^{-2} s^{-1}, whereas during the beginning seed stage, the maximum Tr of both intercropped and singled soybean occurred at a PAR of 1500 μmol m^{-2} s^{-1}. Furthermore, regardless of the growth stage, at PAR levels greater than 250 μmol m^{-2} s^{-1}, the Tr of single-cropped soybean was higher than intercropping, and, the difference between them gradually increased to a significant extent with an increase in PAR. The Tr of soybean was significantly reduced by intercropping.

Comparison of photosynthesis in functional leaves under strip intercropping and single cropping

Pn, Gs, Ci, and Tr values of maize under intercropping were all greater than in single cropping, with the differences of Pn, Gs, Tr and single cropping reaching the level of significance (Table 1). Moreover, Ci values of the M2S2, M4S4, and M6S6 treatments were significantly different from those of single-cropped maize. Comparison of the different strip intercropping treatments showed that Pn and Tr were shown as M2S2 > M4S4 > M4S2 > M6S6>M, among which, the differences between M2S2 and M4S2, M6S6 reached significant levels; Gs showed the trend M2S2/M4S4 > M4S2 > M6S6>M, with M2S2/M4S4

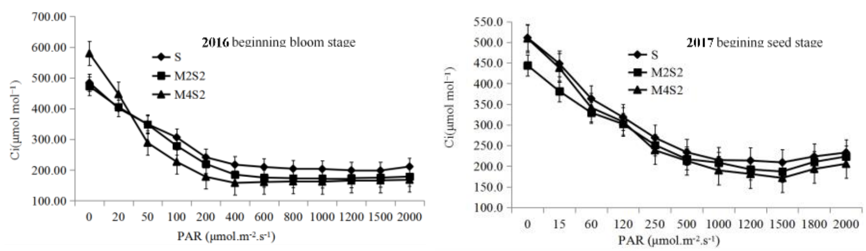

Fig. 7: Changes of Ci of soybean leaves with light intensity under strip intercropping and single cropping
S: soybean single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

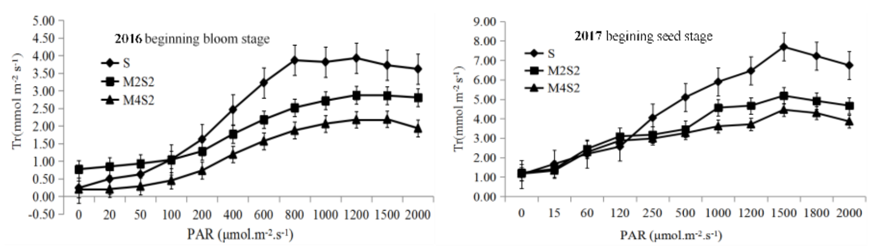

Fig. 8: Changes of Tr of soybean leaves with light intensity under strip intercropping and single cropping
S: soybean single cropping. **M2S2:** maize-soybean 2:2 intercropping. **M4S2**: maize-soybean 4:2 intercropping

Table 1: Comparison of photosynthetic parameters between strip intercropping and single cropping of maize during grain filling stage

year	Treatments	Pn	Gs	Ci	Tr
		μmol m^{-2} s^{-1}	mol m^{-2} s^{-1}	μmol mol^{-1}	mmol m^{-2} s^{-1}
2016	M	27.26 ± 0.71d	0.2525 ± 0.0285d	107.9 ± 5.03d	5.62 ± 0.18d
	M2S2	36.67 ± 1.47a	0.4648 ± 0.0179b	138.6 ± 11.53b	8.05 ± 0.19a
	M4S2	33.93 ± 1.39b	0.3503 ± 0.0602c	117.9 ± 22.08cd	6.97 ± 0.47bc
	M4S4	34.69 ± 0.56ab	0.6002 ± 0.0384a	172.3 ± 5.07a	7.40 ± 0.23ab
	M6S6	29.66 ± 0.85c	0.3264 ± 0.0406c	129.9 ± 11.22bc	6.66 ± 0.59c
2017	M	23.08 ± 0.91d	0.1539 ± 0.0109d	95.7 ± 5.71d	3.49 ± 0.21d
	M2S2	33.26 ± 0.98a	0.3616 ± 0.0091a	174.5 ± 2.20a	6.85 ± 0.11a
	M4S2	29.13 ± 0.64b	0.1950 ± 0.0039c	101.6 ± 6.18cd	4.57 ± 0.06c
	M4S4	30.42 ± 1.11b	0.2882 ± 0.0034b	151.3 ± 6.38b	6.06 ± 0.23b
	M6S6	25.76 ± 1.09c	0.1809 ± 0.0130c	109.0 ± 3.97c	4.31 ± 0.24c

Values are means ± SD based on triplicate independent determinations and different letters means significant difference by Duncan's multiple comparison test. M: maize single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping; M6S6: maize-soybean 6:6 intercropping values being significantly different from those obtained under M4S2 and M6S6. Ci showed the trend M2S2/M4S4 > M6S6 > M4S2>M, the Ci value recorded for the M2S2 treatment was significantly different from those obtained in treatments M4S2 and M4S4. Intercropping could significantly improve the photosynthetic capacity of maize leaves.

The Pn, Gs and Tr values under single cropping were all greater than intercropping (Table 2), and with the exception of the M6S6 treatment, the differences between the Pn, Gs, and Tr values recorded for single-cropped and intercropped soybean reached the level of significance, in contrast, there were no obvious patterns in the differences of Ci values between treatments. Pn of soybean leaves showed the trend M6S6 > M4S4 > M2S2 > M4S2, among which, the M2S2 value was significantly different from M4S2 and M6S6. Gs showed the trend M6S6 > M4S4/M2S2 > M4S2, among which, the M6S6 value was significantly different from M4S2. Tr showed the trend M6S6 > M4S4 > M2S2/M4S2, among which, the M6S6 and M4S4 values were significantly different from M2S2. It could be seen that variations in the photosynthetic parameters of intercropped soybean showed patterns opposite to maize, intercropping reduced the photosynthetic capacity of soybean leaves.

Chlorophyll fluorescence parameters

Under strip intercropping, the chlorophyll fluorescence parameters *Fv/Fm*, qP, Φ PSII, and NPQ of maize were all higher than in single cropping. The differences between the fluorescence parameters *Fv/Fm*, qP, and NPQ of single-cropped maize and maize under the M4S4 and M6S6 intercropping treatments reached the level of significance. Similarly, the *Fm* and Φ PSII values for single-cropped maize were different from maize under M2S2 and M4S4 intercropping (Table 3). There were differences in the fluorescence parameters of different intercropping treatments, with *Fm* showing the trend M4S4 > M2S2 > M4S2 > M6S6 >M, among which, the M4S4 value was shown to be significantly different from M4S2 and M6S6. The *Fv/Fm* was shown as M4S4 > M6S6 > M2S2 > M4S2 > M, among which, the M4S4 and M6S6 values were significantly different from M2S2 and M4S2. The qP and NPQ were shown as M2S2 > M4S4 > M6S6 > M4S2 > M, among which, the M2S2 value was significantly different from M4S2, M4S4, and M6S6. The ΦPSII values showed the trend M2S4 > M4S4 > M4S2 > M6S6 > M. In general, the chlorophyll fluorescence parameters of maize leaves were enhanced by strip intercropping, thereby implying an enhancement of the photosynthetic capacity of maize.

Table 2: Comparison of photosynthetic parameters between strip intercropping and single cropping of soybean during seed beginning stage

year	Treatments	Pn	Gs	Ci	Tr
		μmol m^{-2} s^{-1}	mol m^{-2} s^{-1}	μmol mol^{-1}	mmol m^{-2} s^{-1}
2016	S	23.46 ± 1.04a	1.6026 ± 0.1101a	254.85 ± 5.24b	11.21 ± 0.83a
	M2S2	18.81 ± 1.35c	1.0284 ± 0.2748bc	267.08 ± 5.95a	9.62 ± 0.79c
	M4S2	16.16 ± 0.34d	0.8667 ± 0.0537c	268.91 ± 5.65a	9.68 ± 0.82c
	M4S4	20.13 ± 0.62bc	0.9779 ± 0.2473bc	254.97 ± 8.59b	10.51 ± 0.17b
	M6S6	21.76 ± 0.93b	1.3692 ± 0.2194ab	259.57 ± 2.67ab	10.97 ± 0.97ab
2017	S	21.53 ± 1.10a	0.9794 ± 0.0755a	240.14 ± 12.84abc	8.33 ± 0.42a
	M2S2	14.85 ± 0.19d	0.6352 ± 0.1119c	221.31 ± 4.04c	6.06 ± 0.20c
	M4S2	12.43 ± 0.63e	0.6133 ± 0.1084c	260.10 ± 3.06a	5.81 ± 0.19c
	M4S4	18.93 ± 0.48c	0.7121 ± 0.1753bc	231.97 ± 24.54bc	7.07 ± 0.53b
	M6S6	19.90 ± 0.74b	0.8981 ± 0.1251ab	251.14 ± 2.11ab	7.64 ± 0.88ab

Values are means ± SD based on triplicate independent determinations and different letters means significant difference by Duncan's multiple comparison test. S: soybean single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping (M4S4); M6S6: maize-soybean 6:6 intercropping

Table 3: Comparison of chlorophyll fluorescence parametertraits between strip intercropping and single cropping of maize during grain filling stage

year	Treatments	Fo	Fm	Fv/Fm	qP	ΦPSII	NPQ
2016	M	415.5 ± 2.50b	2138.3 ± 25.66bc	0.8057 ± 0.0012b	0.3310 ± 0.0167c	0.1662 ± 0.0037c	0.3665 ± 0.0100c
	M2S2	435.0 ± 12.17a	2282.7 ± 68.88a	0.8094 ± 0.0017b	0.4482 ± 0.0351a	0.1912 ± 0.0087a	0.7639 ± 0.0441a
	M4S2	421.0 ± 9.01ab	2178.0 ± 29.05b	0.8067 ± 0.0016b	0.3423 ± 0.0401c	0.1751 ± 0.0026bc	0.4085 ± 0.0272c
	M4S4	425.3 ± 6.03ab	2344.0 ± 57.97a	0.8185 ± 0.0020a	0.3953 ± 0.0288b	0.1799 ± 0.0021ab	0.5435 ± 0.0287b
	M6S6	385.3 ± 10.60c	2082.7 ± 73.66c	0.8149 ± 0.0045a	0.3942 ± 0.0226b	0.1748 ± 0.0077bc	0.5594 ± 0.0420b
2017	M	406.67 ± 8.50c	1800.67 ± 10.50b	0.7742 ± 0.0035c	0.2883 ± 0.0107c	0.1241 ± 0.0031b	0.6554 ± 0.0557d
	M2S2	421.33 ± 9.50a	1892.67 ± 75.61a	0.7773 ± 0.0042c	0.5450 ± 0.0402a	0.1405 ± 0.0049a	1.6735 ± 0.0406a
	M4S2	409.33 ± 13.01bc	1903.67 ± 72.80a	0.7849 ± 0.0017b	0.3585 ± 0.0238b	0.1350 ± 0.0087a	0.9027 ± 0.0776c
	M4S4	416.67 ± 12.34ab	1934.67 ± 65.52a	0.7846 ± 0.0046b	0.4055 ± 0.0217b	0.1379 ± 0.0095a	1.1683 ± 0.1384b
	M6S6	387.00 ± 10.15d	1878.67 ± 64.24ab	0.7940 ± 0.0022a	0.3684 ± 0.0179b	0.1346 ± 0.0053a	0.9694 ± 0.0271c

Fm: dark adaption maximalfluorescence; Fo: dark adaption minimalfluorescence; Fm′: maximalfluorescence under light; Fo′: minimalfluorescence under light, Fv/ Fm: according to the formula to calculate the maximal quantum yield of PSII; ΦPSII: actualphotochemical efficiency of PSII; qP: photochemical quenching; NPQ: non-photochemical quenching. M: maize single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping; M6S6: maize-soybean 6:6 intercropping

In contrast to the patterns of maize, the values of chlorophyll fluorescence parameters *Fv/Fm*, qP, Φ PSII, and NPQ in strip intercropped soybean were generally lower to differing degrees than in single-cropped soybean. The fluorescence parameters *Fv/Fm* and qP of single cropping were significantly different from intercropping, and the Φ PSII and NPQ values recorded for singled soybean were significantly different from M2S2, M4S2, and M4S4 (Table 4). Furthermore, the *Fo* and *Fm* values for soybean under strip intercropping were significantly higher than single cropping, there were differences in the fluorescence parameters of soybean under different strip intercropping treatments, with the values of *Fv/Fm*, qP, Φ PSII, and NPQ for soybean grown in wide strips (M6S6 and M4S4) being greater than in narrow strips (M4S2 and M2S2), whereas the parameters F_0 and *Fm* showed the opposite trend. The fluorescence parameters of most intercropping treatments were significantly different. In summary, intercropping reduced the main fluorescence parameters of soybean leaves and thus reduced the photosynthetic capacity of leaves.

Yield components

Strip intercropping optimized the components of maize yield (Table 5). Compared with single cropping, intercropping had the effect of increased the length of the female ear and reduced the length of the bald tip. Moreover, the line grain number, ear weight, ear grain weight and hundred-grain weight of maize all significantly increased under intercropping. The difference in ear thickness between the M4S4 and M2S2 treatments and single treatment reached a significant level. There were differences in yield components under different strip intercropping treatments, among which, the ear length, line grain number, ear thickness, ear weight, ear grain weight and hundred-grain weight of maize under the M2S2 treatment were all higher than other intercropping treatments, with the differences between M2S2 and M4S2 and M6S6 reaching the level of significance. Overall, the aforementioned yield indices, from high to low, showed the trend M2S2 > M4S4 > M4S2 > M6S6 > M. Strip intercropping increased the value of these yield components of maize, which was beneficial to yield formation and thus increased the yield per maize plant. Moreover, the values of maize yield components in the corresponding strip tended to increase with a narrowing of the maize strip width.

Strip intercropping also altered the yield components of soybean (Table 6), with strip intercropping having the effect of reducing the number of nodes, pods, grains, and grain weight per plant compared with single cropping, but increasing the hundred-grain weight and plant height. To varying extents, the differences in number of pods, grains, grain weight per plant and plant height between intercropping and single cropping all reached levels of significances. The hundred-grain weight of the M2S2 and M4S2 treatments was significantly different from single cropping. Based on a comparison of the yield components of soybean under the different strip intercropping treatments, it was concluded that with a widening of the sowing strip of soybean, the numbers of nodes, pods, and grains per plant, and the weight of grains per plant increased, whereas the weight of hundred-grains and the height of plants decreased. The differences of the values of yield components per plant between M2S2/M4S2 and M4S4/M6S6 reached a significant level. In general, the numbers of pods, grains and grain weight per plant from high to low followed the trend S > M6S6 > M4S4 > M2S2 > M4S2, whereas the hundred-grain weight showed the pattern M2S2 > M4S2 > M6S6 > M4S4 > S.

Yield, economic output, and LER comparison

The yield of maize strips under intercropping was significantly higher than in maize single cropping, whereas the yield of soybean strips under intercropping was significantly lower than in soybean single cropping (Table 7). The average yield of maize strips followed the trend M2S2 > M4S4 > M4S2 > M6S6 > M, and when compared with the single treatment, the yield increased by 69.2, 54.5, 64.8 and 47.4%, respectively. The average yield of soybean strips declined in the order S > M6S6 > M4S4 > M2S2 > M4S2, and when compared with the single treatment, the yield decreased by 9.8, 19.6, 44.6 and 49.0%, respectively.

A comparison of the compound yield of crops under intercropping and single cropping (Table 7) revealed that the compound yield obtained under strip intercropping was higher than soybean single cropping; only the compound yield of M4S2 was higher than maize single cropping. The compound yield of crops under different treatments from high to low followed the trend M4S2 > M > M4S4 > M6S6 > M2S2 > S, and with the exception of M2S2 and M4S4, the compound yield of other treatments all reached the level of significance. A comparison of LER values revealed that the LER of all the strip intercropping treatments was greater than 1.000. All treatments showed the advantages associated with intercropping to a certain extent, among which, the LER value of the M4S4 treatment was the highest, with a 2-year average of 1.226. The LER of the different intercropping treatments was shown as M4S4 > M4S2 > M6S6 > M2S2.

The economic output value of maize strips under strip intercropping was higher than in maize single cropping, whereas in contrast, the economic output value of soybean strips under strip intercropping was lower than soybean single cropping, the overall economic output value of maize was higher than soybean (Table 8). Moreover, for both maize and soybean, there were significant differences between the economic output value of strips under intercropping and single cropping. Due to the price of maize and soybeans, there were differences between the patterns of crop compound economic output value and compound yield, with the former being higher in strip intercropping

Table 4: Comparison of chlorophyll fluorescence parameter traits between strip intercropping and single cropping of soybean during seed beginning stage

year	Treatments	Fo	Fm	Fv/Fm	qP	ΦPSII	NPQ
2016	S	229.00 ± 8.89c	1265.33 ± 22.81bc	0.8190 ± 0.0053a	0.6711 ± 0.0470a	0.1843 ± 0.0099a	2.1505 ± 0.1736a
	M2S2	268.67 ± 7.37b	1346.00 ± 42.58b	0.8004 ± 0.0033c	0.4046 ± 0.0231c	0.1291 ± 0.0040c	1.8038 ± 0.0728b
	M4S2	288.67 ± 8.14a	1512.67 ± 38.84a	0.8092 ± 0.0008b	0.3558 ± 0.0431c	0.0916 ± 0.0082d	1.1723 ± 0.1291c
	M4S4	258.33 ± 16.17b	1307.33 ± 33.53b	0.8025 ± 0.0074c	0.5096 ± 0.0648b	0.1568 ± 0.0154b	1.8010 ± 0.1682b
	M6S6	229.33 ± 21.96c	1218.33 ± 94.68c	0.8119 ± 0.0043b	0.5269 ± 0.0820b	0.1592 ± 0.0201b	2.0873 ± 0.0895a
2017	S	198.67 ± 5.69d	1190.0 ± 31.0c	0.8380 ± 0.0016a	0.8599 ± 0.0818a	0.1600 ± 0.0086a	2.1928 ± 0.1488a
	M2S2	240.67 ± 5.69b	1429.0 ± 50.48b	0.8315 ± 0.0021b	0.4465 ± 0.0230bc	0.1367 ± 0.0107bc	1.6101 ± 0.0829b
	M4S2	322.33 ± 6.11a	1926.0 ± 29.02a	0.8326 ± 0.0011b	0.3901 ± 0.0154c	0.1292 ± 0.0108c	1.4016 ± 0.0895c
	M4S4	222.33 ± 8.02c	1340.0 ± 41.0b	0.8341 ± 0.0010b	0.4075 ± 0.0034c	0.1410 ± 0.0137ab	1.6045 ± 0.0394b
	M6S6	204.33 ± 9.50d	1221.7 ± 78.02c	0.8326 ± 0.0012b	0.5191 ± 0.1035b	0.1493 ± 0.0027abc	1.6855 ± 0.0820b

Fm: dark adaption maximal fluorescence; Fo: dark adaption minimal fluorescence; Fm′: maximal fluorescence under light; Fo′: minimal fluorescence under light, Fv/Fm: according to the formula to calculate the maximal quantum yield of PSII; ΦPSII: actual photochemical efficiency of PSII; qP: photochemical quenching; NPQ: non-photochemical quenching. S: soybean single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping, M4S4: maize-soybean 4:4 intercropping; M6S6: maize-soybean 6:6 intercropping

Table 5: Comparison of yield components between strip intercropping and single cropping of maize

year	Treat ments	Panicle length (cm)	Bare tip Length (cm)	Ear row number (row)	Grains per row (grain)	Ear diameter (cm)	Weight per ear (g)	Grain weight per panicle (g)	100-grain weight (g)
2016	M	17.30 ± 0.91c	1.45 ± 0.70a	16.00 ± 0.94a	35.90 ± 2.00c	4.74 ± 0.06c	203.01 ± 9.27d	177.40 ± 7.33d	33.78 ± 0.61d
	M2S2	21.80 ± 0.23a	0.50 ± 0.21b	16.20 ± 1.48a	44.00 ± 1.87a	5.49 ± 0.21a	330.00 ± 6.02a	289.33 ± 2.62a	42.61 ± 0.48a
	M4S2	19.55 ± 0.46b	0.71 ± 0.37b	16.67 ± 1.33a	40.20 ± 1.93b	4.92 ± 0.07bc	282.50 ± 10.08c	251.65 ± 8.93c	39.29 ± 1.16bc
	M4S4	21.50 ± 1.11a	0.71 ± 0.36b	16.20 ± 1.14a	43.80 ± 1.18a	5.05 ± 0.11b	314.02 ± 17.6b	275.02 ± 12.16b	41.33 ± 1.27ab
	M6S6	19.55 ± 0.61b	0.97 ± 0.53ab	16.00 ± 0.00a	39.80 ± 1.66b	4.72 ± 0.05bc	274.00 ± 12.11c	242.91 ± 9.51c	38.77 ± 1.73c
2017	M	15.95 ± 1.02c	1.12 ± 0.47a	16.00 ± 1.33a	32.40 ± 1.67c	4.71 ± 0.13c	190.00 ± 9.51d	167.00 ± 8.06d	34.63 ± 0.70d
	M2S2	21.65 ± 0.83a	0.80 ± 0.36ab	16.67 ± 1.33a	44.40 ± 2.00a	5.25 ± 0.20a	324.03 ± 5.03a	285.68 ± 3.61a	41.94 ± 0.77a
	M4S2	18.95 ± 0.62b	0.45 ± 0.23b	16.20 ± 1.14a	38.70 ± 1.67b	4.82 ± 0.15bc	268.23 ± 9.93c	238.52 ± 9.28c	37.51 ± 1.28bc
	M4S4	19.80 ± 0.92ab	0.85 ± 0.44ab	16.40 ± 1.26a	39.80 ± 1.67b	4.96 ± 0.12ab	287.00 ± 15.78b	255.00 ± 11.94b	39.33 ± 1.03ab
	M6S6	18.84 ± 0.78b	0.92 ± 0.35a	16.00 ± 1.73a	37.80 ± 2.00b	4.79 ± 0.11bc	257.01 ± 10.63c	229.40 ± 9.17c	36.79 ± 1.43c

Values are means ± SD based on triplicate independent determinations and different letters means significant difference by Duncan's multiple comparison test. M: maize single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping; M6S6: maize-soybean 6:6 intercropping

Table 6: Comparison of yield components between strip intercropping and single cropping of soybean

Year	Treatment	Plant height (cm)	Node numbers (node)	Pod number per plant	Seeds per plant (g)	Seed weight per plant (g)	100-grain weight (g)
2016	S	91.36 ± 2.01d	14.95 ± 0.08a	48.00 ± 1.23a	80.01 ± 6.08a	14.66 ± 0.59a	17.60 ± 0.36c
	M2S2	104.00 ± 3.43b	14.00 ± 0.34ab	30.40 ± 3.00c	57.00 ± 6.68d	11.00 ± 1.62c	21.11 ± 0.15a
	M4S2	112.18 ± 1.97a	13.27 ± 0.36b	29.18 ± 3.30c	51.73 ± 4.75d	9.88 ± 1.13c	19.91 ± 0.34b
	M4S4	100.20 ± 5.91bc	14.20 ± 0.03ab	40.60 ± 4.06b	69.40 ± 8.86c	12.19 ± 1.03b	17.75 ± 0.35c
	M6S6	97.50 ± 2.71c	14.65 ± 0.23a	43.75 ± 2.43b	75.25 ± 5.43b	13.24 ± 0.43b	17.66 ± 0.23c
2017	S	92.33 ± 2.32d	14.83 ± 0.07a	47.67 ± 2.00a	78.67 ± 8.51a	14.42 ± 0.64a	17.07 ± 0.58c
	M2S2	108.80 ± 3.28b	14.50 ± 0.36ab	26.00 ± 2.33c	46.00 ± 5.11d	8.67 ± 1.03d	21.31 ± 0.17a
	M4S2	114.17 ± 2.77a	13.80 ± 0.31b	24.40 ± 3.38c	39.00 ± 6.31d	8.26 ± 1.20d	20.37 ± 0.32b
	M4S4	105.60 ± 3.14bc	14.20 ± 0.03ab	33.00 ± 3.90b	56.20 ± 5.76c	10.62 ± 0.97c	18.03 ± 0.46c
	M6S6	101.17 ± 2.53c	14.33 ± 0.21ab	39.67 ± 3.00b	61.67 ± 6.93b	12.61 ± 0.81b	17.33 ± 0.56c

Values are means ± SD based on triplicate independent determinations and different letters means significant difference by Duncan's multiple comparison test. S: soybean single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping; M6S6: maize-soybean 6:6 intercropping

than in either maize or soybean single cropping. Under the M4S2 treatment, the compound economic output value was the largest, the S output value was the smallest, and it showed the overall trend M4S2 > M4S4 > M6S6 > M2S2 > M > S. Compared with maize and soybean single cropping, the economic output value under intercropping increased by 4.4–15.2% and 46.4–61.5%, respectively.

Discussion

Light is one of the most important environmental factors influencing crop growth and development, with different light environments showing differing regulatory effects on crop growth, morphogenesis, photosynthesis, and metabolism (Oseni 2010; Chapagain *et al.* 2018). In the spring sowing area of northern China, during the mid- to late stages of crop growth under strip intercropping between maize and soybean, the light resources obtained by the tall-stemmed maize would increase significantly; however, due to the shading effect of maize, the light resources obtained by the shorter-growing soybean would decrease significantly. Accordingly, the changes in light resources would inevitably have a pronounced effect on the photosynthetic capacity of these two crops (Yang *et al.* 2014). In this regard, it has previously been demonstrated that when maize and peanut are intercropped, the light response curves of the daily average light intensity, light transmittance and Pn of maize are significantly higher than

Table 7: Comparison of yield and LER between strip intercropping and single cropping of maize and soybean

Year	Treatments	Yield of maize seeding strip (kg.ha^{-1})	Yield of soybean seeding strip (kg ha^{-1})	Maize and soybean composite yield (kg ha^{-1})			LER
				maize	soybean	compound yield	
2016	S	--	2948.5a	--	2948.5a	2948.5e	1.000c
	M	11578.5e	--	11578.5ab	--	11578.5b	1.000c
	M2S2	19208.3a	1684.6d	9604.1c	842.3c	10446.4c	1.115b
	M4S2	17485.2c	1572.2d	11656.8a	524.1d	12180.9a	1.184ab
	M4S4	18746.3b	2393.4c	9373.2c	1196.7b	10569.9c	1.215a
	M6S6	16827.6d	2685.1b	8413.8d	1342.6b	9756.3d	1.182ab
2017	S	--	2764.6a	--	2764.6a	2764.6e	1.000c
	M	10680.9e	--	10680.9b	--	10680.9b	1.000c
	M2S2	18432.8a	1482.9d	9216.4c	741.5d	9957.8c	1.131b
	M4S2	16883.7c	1343.6d	11255.8a	447.9e	11703.7a	1.216a
	M4S4	17919.0a	2198.6c	8959.5c	1099.3c	10058.8c	1.236a
	M6S6	15970.8d	2469.7b	7985.4d	1234.9b	9220.2d	1.194ab

Values are means ± SD based on triplicate independent determinations and different letters means significant difference by Duncan's multiple comparison test. S: soybean single cropping; M: maize single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping ; M6S6: maize-soybean 6:6 intercropping

Table 8: Comparison of economic output value between strip intercropping and single cropping of maize and soybean

Year	Treatment	Economic output value in maize strip ($.ha^{-1})	Economic output value in soybean strip ($.ha^{-1})	Maize and soybean composite economic output ($.ha^{-1})		
				maize	soybean	composite output
2016	S	--	1598.0a	--	1598.0a	1598.0e
	M	2091.8d	--	2091.8a	--	2091.8d
	M2S2	3470.2a	913.0d	1735.1b	456.5d	2191.6cd
	M4S2	3158.9c	852.1e	2105.9a	284.0e	2389.9a
	M4S4	3386.7a	1297.2c	1693.4b	648.6c	2341.9ab
	M6S6	3040.1b	1455.3b	1520.0c	727.6b	2247.7bc
2017	S	--	1474.1a	--	1474.1a	1474.1d
	M	2214.7d	--	2214.7b	--	2214.7c
	M2S2	3822.1a	790.7d	1911.0c	395.3d	2306.4c
	M4S2	3500.9b	716.4e	2333.9 a	238.8e	2572.7a
	M4S4	3715.5a	1172.3c	1857.8c	586.1c	2443.9b
	M6S6	3311.6c	1316.8b	1655.8d	658.4b	2314.2c

In 2016, the price of maize is 0.1807$. kg^{-1}. In 2017, the price of maize is 0.2074 $.kg^{-1}. The price of soybeans for two years is 0.5465 $.kg^{-1}.
Values are means ± SD based on triplicate independent determinations and different letters means significant difference by Duncan's multiple comparison test. S: soybean single cropping; M: maize single cropping; M2S2: maize-soybean 2:2 intercropping; M4S2: maize-soybean 4:2 intercropping; M4S4: maize-soybean 4:4 intercropping; M6S6: maize-soybean 6:6 intercropping

in single cropping of maize (Jiao *et al.* 2015). In this study, similar conclusions were obtained under the intercropping model of maize and soybean, the values of light response curves of Pn, Gs, Tr and Ci of maize under intercropping were significantly higher than those in single cropping in the high light intensity range, while those in the low light intensity range were similar. At the same time, the light intensity of maize under intercropping was higher than single cropping when the Pn and other indexes reached the maximum. It could be further concluded that stripe intercropping enhanced the response mechanism of maize leaves to bright light, causing maize to utilize light energy more efficiently. Contrary to maize, the light response curve values of photosynthetic indexes of soybean under intercropping were all smaller than single cropping, especially in the range of medium and high light intensity.

Liu *et al.* (2018) and Gou *et al.* (2018) previously found that the photosynthetic capacity of maize differed according to crop row spacing, with the values of Pn, Tr, and yield per plant of maize in widely spaced rows being significantly higher than those in narrow row spacing. In this study similar conclusions were obtained, the Pn, Gs and Tr values of maize under intercropping were all higher than in single cropping. Moreover, with an increase in strip width, the photosynthetic capacity of single maize plants in the strips gradually decreased and became comparable to maize single cropping, whereas when the width of the maize strip was fixed, the photosynthetic parameters increased with an increase in the width of the adjacent soybean strip. The higher photosynthetic capacity of strip intercropped maize compared with that of maize grown as a single can be attributed to the fact that a larger amount of light is received by the maize strip due to the shorter stature of the adjacent soybean canopy, thereby increasing light intensity at the middle and lower layers of the maize plants, and thus enhancing photosynthetic capacity. Furthermore, when soybean is interplanted with maize, it has been observed that the photosynthetic capacity of soybean leaves decreases (Wang *et al.* 2007), whereas the chlorophyll content, apparent quantum efficiency, and CO_2 compensation point increases, and the light compensation point and light saturation point reduces (Li *et al.* 2010). In this study, the

Pn, Gs, and Tr values of soybean under intercropping were all significantly lower than single cropping, the main reason for the decrease of photosynthetic capacity of intercropping soybean was the effect of shading by maize. The values for the photosynthetic indices of soybean grown in wide strips were generally higher than in narrow strips, by increasing the width of soybean, the photosynthetic capacity of a single soybean plant within strip gradually recovered to single cropping.

Photosynthesis is clearly a vital process with respect to determining crop yield, and chlorophyll fluorescence is considered to be a relevant parameter for examining the relationship between crop photosynthesis and the environment, and to represent "intrinsic" characteristics of plants. Differences in the light environment would predictably promote changes in the photosynthetic electron transfer performance of crops (Paweł *et al.* 2019), which are accurately reflected by chlorophyll fluorescence parameters (Yanjun *et al.* 2018). In this regard, Xu *et al.* (2012) have demonstrated that after 6 days of shading, the functional leaf PSII maximum quantum yield of wheat was significantly lower than that of the control treatment, whereas in contrast, the PSII actual quantum yield was significantly higher than that of the control. Under conditions of weak light stress, significant reductions have been observed in the PEPCase, RuBP Case activity, and *Fv/Fm* values of maize leaves (Jia *et al.* 2007; Zhang *et al.* 2007), whereas increases have been observed in the maximum fluorescence of chlorophyll and grana thickness (Li *et al.* 2010; Du *et al.* 2011). Furthermore, Zheng *et al.* (2013) have observed that the maximum potential relative transfer rate, actual photochemical efficiency, and photochemical quenching coefficient of soybean leaves are significantly reduced in response to a decrease in solar radiation in the environment. In this study, the values of the chlorophyll fluorescence parameters *Fv/Fm*, qP, Φ PSII, and NPQ of maize under intercropping were all significantly higher than single cropping. Conversely, the aforementioned chlorophyll fluorescence parameters recorded in intercropped soybean were lower than single-cropped soybean to differing degrees. Consequently, the photosynthetic reaction center of intercropped soybean plants is assumed to dissipate larger amounts of energy in the form of fluorescence, and there is a corresponding reduction in the electron transfer through PSII. There were differences in chlorophyll fluorescence parameter values between different maize–soybean strip intercropping treatments, with the values for soybean plants grown in wide strips generally being higher than narrow strips, and the opposite being true for maize. A decrease in the maize sowing bandwidth and an increase in the soybean sowing bandwidth caused, the main fluorescence parameters of both crops to increase gradually. This rule can be used to adjust the ratio of bandwidth of maize and soybean reasonably in production, and make full use of the advantage of light energy of the system

Crop yield can be considered a measure of the accumulation of photosynthetic products, and developing high-yield, high-efficiency agriculture by improving the utilization of light energy and photosynthetic efficiency during the period of yield formation are prominent goals in the agricultural sector worldwide. In this regard, rational intercropping represents a promising approach for making efficient use of light, temperature, water, fertilizer and other field resources, and enhancing grain yield per unit area by exploiting edge advantage (Yu *et al.* 2019). Maize and soybean, as major cultivated crops, have assumed an important position in many intercropping and rotation systems (Seran and Brintha 2010), and previous studies have shown the significant yield advantages for maize when grown in multiple cropping systems such as maize–wheat (Wang *et al.* 2017), maize–potato (Fan *et al.* 2016) and maize–peanut (Awal *et al.* 2006). In this study, under maize–soybean intercropping system, the yield obtained for intercropped maize strip was significantly higher than that obtained for single-cropped maize, whereas the yield of intercropped soybean was significantly lower than singled soybean The compound yield obtained under strip intercropping was higher than in soybean single cropping, and the compound yield obtained in the M4S2 treatment was higher than single-cropped maize. The increased yield of intercropped maize could be attributed to increases in line grain number, ear width, grain weight per ear, and hundred-grain weight, whereas corresponding reductions in intercropped soybean yield could be ascribed to decreases in the numbers of pods, grains and grain weight per plant, which corresponds the research results of Yang *et al.* (2017).

With respect to the crop compound planting model, the yield advantages gained from intercropping among different crops can be accurately measured in terms of the LER (Willey and Rao 1980). In this study, all the strip intercropping treatments showed an intercropping advantage, among which the M4S4 treatment had the highest LER value, with a 2-year average of 1.226. The LER was found to decrease in the following order: M4S4 > M4S2 > M6S6 > M2S2. Intercropping can increase the system economic output, while also increasing the compound crop yield (Qian *et al.* 2018). Under strip intercropping, the economic output value of maize strips was significantly higher than single-cropped maize, whereas the opposite was true for soybean, and in general, the economic output value of maize was higher than soybean. The crop compound economic output value under strip intercropping was higher than maize and soybean single cropping; the compound economic output value was the largest and the S output value was the smallest under the M4S2 treatment. Compared with single cropping, strip intercropping could improve the economic output of local crops.

Conclusion

(1) The photosynthetic capacity of maize was enhanced by strip intercropping, whereas that of soybean was significantly reduced. (2) The key reason for the increase

in photosynthetic capacity of maize was the significant increase in chlorophyll fluorescence parameters Fv/Fm, qP, and Φ PSII, whereas soybean showed an opposite change. (3) In the strip intercropping mode, the yield of the maize bands was significantly higher than maize single cropping, whereas the yield of soybean band was significantly lower than soybean single cropping. (4) The different strip intercropping treatments evaluated in this study displayed an intercropping advantage, with the compound economic output value being higher than maize and soybean single cropping, among which the compound economic output value and S output value recorded for the M4S2 treatment was the highest and the smallest. (5) In the intercropping compound population, with the increase of soybean bandwidth and the decrease of corn bandwidth, the photosynthetic physiological characteristics of maize were gradually enhanced, while soybeans gradually returned to single cropping level. Strip intercropping of maize and soybean in the main grain-producing areas of northeast China is an effective way to improve the utilization efficiency of light energy in this area, which is of great significance to increase both crop yield and increase crop efficiency. In the actual production, we can make full use of the advantage of intercropping by reasonably adjusting the bandwidth of soybean and maize.

Acknowledgments

This research was supported by Project of Education Department in Jilin (No. JJKH20190934KJ), by China national key research and development plan (No.2017YFD0300607), by the innovation and entrepreneurship project for college students of jilin agricultural university (No.201810193022).

References

Awal MA, H Koshi, T Ikeda (2006). Radiation interception and use by maize/peanut intercrop canopy. *Agric For Meteorol* 139:74–83

Bedoussac L, E Journet, H Hauggaard-Nielsen, C Naudin, G Corre-Hellou, ES Jensen, L Prieur, E Justes (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agron Sustain Dev* 35:911–935

Brooker RW, AJ Karley, AC Newton, RJ Pakeman, C Schöb, F Pugnaire (2015). Facilitation and sustainable agriculture: A mechanistic approach to reconciling crop production and conservation. *Funct Ecol* 30:98–107

Chapagain T, P Roshan, G Bhawana, G Khem, C Khem, R Laxmi, M Samjhana, BK Bishnu, N Manish (2018). Intercropping of maize, millet, mustard, wheat and ginger increased land productivity and potential economic returns for smallholder terrace farmers in Nepal. *Field Crops Res* 227:91–101

Du CF, CH Li, TX Liu, YL Zhao (2011). Response of anatomical structure and photosynthetic characteristics to low light stress in leaves of different maize genotypes. *Acta Ecol Sin* 31:6633–6640

Echarte L, AD Maggiora, D Cerrudo, VH Gonzalez, P Abbate, A Cerrudo, VO Sadras, P Calvino (2011). Yield response to plant density of maize and sunflower intercropped with soybean. *Field Crops Res* 121:423–429

Fan ZW, TX An, KX Wu, F Zhou, SH Zi, YM Yang, GF Xue, BZ Wu (2016). Effects of intercropping of maize and potato on sloping land on the water balance and surface runoff. *Agric Water Manage* 166:9–16

Feike T, R Doluschitz, Q Chen, S Graeffff-Hönninger, W Claupein (2012). How to overcome the slow death of intercropping in the north China plain. *Sustainability* 4:2550–2565

Gao Y, AW Duan, XQ Qiu, ZG Liu, JS Sun, JP Zhang, HZ Wang (2018). Distribution and use efficiency of photosynthetically active radiation in strip intercropping of maize and soybean. *Agron J* 102:1149–1157

Gou F, MKV Ittersum, C Antoine, Y Zhang, WVD Werf (2018). Intercropping with wheat lowers nutrient uptake and biomass accumulation of maize, but increases photosynthetic rate of the ear leaf. *AoB Plants* 10; Article ply010

Hauggaard-Nielsen H, A Johansen, MS Carter, P Ambus, ES Jensen (2013). Annual maize and perennial grass-clover strip cropping for increased resource use efficiency and productivity using organic farming practice as a model. *Eur J Agron* 47:55–64

Hu FL, YT Gan, Q Chai, FX Feng, C Zhao, AZ Yu, YP Mu, Y Zhang (2016). Boosting system productivity through the improved coordination of interspecific competition in maize/pea strip intercropping. *Field Crops Res* 198:50–60

Jensen ES, L Bedoussac, G Carlsson, E Journet, E Justes, H Hauggaard-Nielsen (2015). Enhancing yields in organic crop production by eco-Functional intensification. *Sustain Agric Res* 4:42–50

Jia SF, ST Dong, KJ Wang, JW Zhang, P Liu (2007). Effects of weak light stress on grain yield and photosynthetic traits of maize. *Chin J Appl Ecol* 18:2456–2461

Jiao Nan-yuan, YH Li, FF Li, HB Hu, YD Mu, YB Zhang, Y Zhang (2015). Photosynthesis and chlorophyll fluorescence characteristics in ear leaves of intercropped maize. *Plant Physiol J* 51:1029–1037

Li L, SM Li, JH Sun, LL Zhou, XG Bao, HG Zhang, FS Zhang (2007). Diversity enhances agricultural productivity *via* rhizosphere phosphorus facilitation on phosphorus-deficient soils. *Proc Natl Acad Sci* 104:11192–11196

Li Z, XY Qin, XG Wang, XT Li, JH Wang, MJ Cao (2010). Effect of intercropping with maize on photosynthesis and chlorophyll fluorescence parameters of soybean. *Soybean Sci* 29:808–811

Lithourgidis AS, CA Dordas, CA Damalas, DN Vlachostergios (2011). Annual intercrops: An alternative pathway for sustainable agriculture. *Aust J Crop Sci* 5:396–410

Liu X, R Tanzeelur, C Song, F Yang, BY Su, L Cui, WZ Bu, WY Yang (2018). Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crops Res* 224:91–101

Liu X, R Tanzeelur, C Song, BY Su, F Yang, TW Yong, YS Wu, CY Zhang, WY Yang (2017). Changes in light environment, morphology, growth and yield of soybean in maize-soybean intercropping systems. *Field Crops Res* 200:38–46

Lv Y, C Francis, P Wu, X Chen, X Zhao (2014). Maize-soybean intercropping interactions above and below ground. *Crop Sci* 54:914–922

Mao LL, LZ Zhang, WQ Li, W Van der Werf, JH Sun, H Spiertz, L Li (2012). Yield advantage and water saving in maize/pea intercrop. *Field Crops Res* 138:11–20

Munz S, S Graeff-Hönninger, JI Lizaso, Q Chen, W Claupein (2014). Modeling light availability for a subordinate crop within a strip intercropping system. *Field Crops Res* 155:77–89

Oseni TO (2010). Evaluation of sorghum-cowpea intercrop productivity in savanna agro-ecology using competition indices. *J Agric Sci* 23:229–234

Paweł Rogowski, WD Wioleta, K Tomasz, D Anna, R Elżbieta (2019). Photosynthesis and organization of maize mesophyll and bundle sheath thylakoids of plants grown in various light intensities. *Environ Exp Bot* 162:72–86

Qian X, HD Zang, HS Xu, YG Hu, CZ Ren, LC Guo, CL Wang, ZH Zeng (2018). Relay strip intercropping of oat with maize, sunflower and mung bean in semi-arid regions of Northeast China: Yield advantages and economic benefits. *Field Crops Res* 223:33–40

Seran TH, I Brintha (2010). Review on maize based intercropping. *J Agron* 9:135–145

Tsubo M, S Walker (2002). A model of radiation interception and use by a maize-bean intercrop canopy. *Agric For Meteorol* 110:203–215

Undie UL, DF Uwah, EE Attoe (2012). Effect of intercropping and crop arrangement on yield and productivity of late season maize/soybean mixtures in the humid environment of south southern Nigeria. *J Agric Sci* 44:37–50

Wang Y, X Zhang, WY Yang, X Sun, BY Su, L Cui (2016). Effect of Shading on Soybean Leaf Photosynthesis and Chlorophyll Fluorescence Characteristics at Different Growth Stages. *Sci Agric Sin* 49:2072–2081

Wang ZK, XN Zhao, PT Wu, Y Gao, Q Yang, YY Shen (2017). Border row effects on light interception in wheat/maize strip intercropping systems. *Field Crops Res* 214:1–13

Wang Z, WY Yang, QL Wu (2007). Effects of shading in maize/soybean relay-cropping system on the photosynthetic characteristics and yield of soybean. *Acta Agron Sin* 33:1502–1507

Willey RW, MR Rao (1980). A competitive ratio for quantifying competition between intercrops. *Exp Agric* 16:17–25

Wu YS, WZ Gong, DP Liao, XL Wu, F Yang, WG Liu, TW Yong, WY Yang (2015). Effects of Shade and Light Recovery on Soybean Cultivars (Lines) and Its Relationship with Yield in Relay Strip Intercropping System. *Acta Agron Sin* 41:1740–1747

Xu CL, YP Yin, RG Cai, P Wang, Y Li, JX Guo, EY Chen, XX Zhai, TN Liu, ZL Wang (2012). Photosynthetic characteristics and antioxidative metabolism of flag leaves in responses to shading during grain filling in winter wheat cultivars with different spike types. *Acta Agron Sin* 38:1295–1306

Yang F, DP Liao, XL Wu, RC Gao, YF Fan, AR Muhammad, XC Wang, TW Yong, WG Liu, L Liu, JB Du, K Shu, WY Yang (2017). Effect of aboveground and belowground interactions on the intercrop yields in maize-soybean relay intercropping systems. *Field Crops Res* 203:16–23

Yang F, S Huang, RC Gao, WG Liu, TW Yong, XC Wang, XL Wu, WY Yang (2014). Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red: Far-red ratio. *Field Crops Res* 155:245–253

Yanjun Y, Z Jinhua, C Linjing, J Aiqing, Z Hongmei, G Pingyi (2018). Effects of fertilizer levels and plant density on chlorophyll contents, its fluorescence and grain yield of *Setaria italica*. *Intl J Agric Biol* 20:737−744

Yu H, H Nico, MJ Zhao, WVD Werf (2019). Intercropping contributes to a higher technical efficiency in smallholder farming: Evidence from a case study in Gaotai County, China. *Agric Syst* 173:317–324

Zhang JW, ST Dong, KJ Wang, CH Hu, P Liu (2007). Effects of shading in field on photosynthetic characteristics in summer corn. *Acta Agron Sin* 33:216–222

Zhang LZ, WVD Werf, L Bastiaans, S Zhang, B Li, JHJ Spiertz (2008). Light interception and utilization in relay intercrops of wheat and cotton. *Field Crops Res* 107:29–42

Zheng YF, KL Gu, RJ Wu, XU Jing-xin, MH Shi, HF Hu (2013). Combination effects of reduced radiation and enhanced O_3 stress on Chlorophyll fluorescence characteristics and yield of soybean. *J Southern Agric* 44:1295–1302