Field Crops Research 224 (2018) 91–101

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping

Xin Liu[a,b], Tanzeelur Rahman[a], Chun Song[c,d], Feng Yang[a,d], Benying Su[a], Liang Cui[a], Weizhao Bu[a], Wenyu Yang[a,d,*]

[a] College of Agronomy, Sichuan Agricultural University, Chengdu, 611130, China
[b] College of Agronomy, Shandong Agricultural University, Taian, 271018, China
[c] Institute of Ecological and Environmental Sciences, Sichuan Agricultural University, Chengdu, 611130, China
[d] Key Laboratory of Crop Ecophysiology and Farming Systems in the Southwest, Ministry of Agriculture, Chengdu, China

ARTICLE INFO

Keywords:
Intercropping
Land equivalent ratio
Light distribution
Photosynthesis

ABSTRACT

Maize (*Zea mays*)-soybean (*Glycine max*) intercropping is popular in many developing countries because of its high land equivalent ratio (LER). However, very few studies have explored the reason of its high LER, and the relationships between light distribution and the variations in radiation use efficiency (RUE) and LER in different intercropping arrangements. In this study, we conducted field experiments with different row arrangements of intercropping patterns from 2013 to 2015. The three different strip intercropping (SI) row arrangements were 0.2 m, 0.4 m, and 0.7 m (SI1); 0.4 m, 0.4 m, and 0.6 m (SI2); and 0.6 m, 0.4 m, and 0.5 m (SI3) for maize row distance, soybean row distance, distance between maize and soybean rows, respectively. The results showed that, as compared to single row intercropping, the strip intercropping increased the PAR at top of soybean canopy by 1.42 (SI3), 1.67 (SI2) and 1.93 (SI1) times, and increased the PAR at maize leaves close to the ear by 1.02 (SI3), 1.11 (SI2) and 1.12 (SI1) times. Moreover, the increased PAR at crucial positions in SI potentially improved the photosynthetic rate (Pn) for maize leaves close to the ear and radiation use efficiency (RUE) of maize by 1.08 and 1.09 times (averaged by SI1, SI2 and SI3), respectively, and improved the Pn of leaves at top of canopy and intercepted PAR of soybean by 1.75 and 1.36 times (averaged by SI1, SI2 and SI3), respectively. Compared to monoculture, SI also enhanced the RUE of intercropped maize (by 1.18 times) and soybean (by 1.51 times), which compensated for the partial yield loss caused by decreased crop intercepted PAR. Overall, in SI, intercropped maize achieved 90% of the monoculture yield, and intercropped soybean achieved 47% of the monoculture yield. With the expanding gap width for growing soybeans under a fixed bandwidth (2 m), the increasing intercepted PAR of intercropped soybean alleviated the interspecific competition disadvantage of soybean, while the reduction of maize row width decreased the dominant interspecific competition of maize. By adjusting the distances, we suggest that the optimal gap width for growing soybeans is 1.6 m-1.8 m, and the best maize row distance is 0.4 m. The SI2 achieved LER of 1.42, representing the leading level in the world.

1. Introduction

Intercropping has been adopted worldwide since it can improve the radiation use efficiency (RUE) and land use efficiency (Oseni, 2010; Echarte et al., 2011; Mahallati et al., 2014; Yang et al., 2015). However, for maize-soybean intercropping, the LER rarely reaches 1.4 when the crops are grown at their optimal density (Oseni, 2010; Echarte et al., 2011; Lv et al., 2014; Mahallati et al., 2014; Yu et al. 2015), which limits the application of intercropping in practice.

The relay intercropping of maize and soybean is the main planting pattern in southwest China and has been studied extensively (Gong et al., 2015; Yang et al., 2015; Rahman et al., 2016; Du et al., 2018). The main recent improvements are as follows: first, narrow the distance between maize rows in order to increase the distance between maize and soybean rows; second, ensure the same plant densities for maize and soybean in intercrops as in sole crops (with optimal density) by using a smaller plant distance within each row in intercropping, which compensates for the reduced row number. In the recent five years, this approach has been practiced in several Provinces of China, such as Sichuan, Shandong, Guizhou, Henan, Ningxia, etc (Du et al., 2018). High crop yields in each Province were used for comparison to calculate LER, e.g., 9000 kg ha^{-1} for maize and 3000 kg ha^{-1} for soybean in

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* Corresponding author.
E-mail address: mssiyangwy@sicau.edu.cn (W. Yang).

https://doi.org/10.1016/j.fcr.2018.05.010
Received 19 July 2017; Received in revised form 11 May 2018; Accepted 11 May 2018

Shandong province. This approach achieved LER of more than 1.8 in relay strip intercropping, and more than 1.4 in strip intercropping, which are much higher than the averaged values of LER (1.18 for intercropping; up to 1.39 for relay intercropping) summarized by 3313 publications (Yu et al., 2015). In this study, we aim to investigate the underlying causes of achieving this high LER, which can promote its application and further improvement to increase crop yield.

The intercepted photosynthetic active radiation (PAR) and RUE in relay intercropping has been reported (Zhang et al., 2008; Gou et al., 2017b; Liu et al., 2017b). The PAR assimilation mainly includes two steps: the interception of PAR by leaf area of the intercrops and the assimilation of the intercepted PAR by intercrops to produce dry matter. The intercepted PAR can be calculated by models (Wang et al., 2015; Liu et al., 2017b). The HHLA model and ERCRT model were used to calculate the intercepted PAR of single row intercropping and strip intercropping, respectively (Liu et al., 2017b). The intercepted PAR in a strip intercropping system representing the sum of intercropped maize and soybean was about 1.1 times of that in monoculture. The RUE for strip intercropped maize and soybean were about 1.2 and 1.5 times of those in monoculture (Liu et al., 2017b), respectively. However, the reasons for high RUE in strip intercropping need further investigation.

The dynamic changes of PAR at top of soybean canopy in maize-soybean intercropping has been described in our previous study (Liu et al., 2017a). Compared to single row intercropping, strip intercropping increased the PAR at top of soybean canopy (Liu et al., 2017a). Also, strip intercropping increased the PAR at maize leaves close to the ear (Gao et al., 2010), which contributed more to the yield compared to other leaves. Few studies have thoroughly described the PAR distribution within canopy in different intercropping systems, including single row intercropping and strip intercropping with different row arrangements. Also, the relationships among PAR distribution, net photosynthetic rate (Pn) of leaves, intercepted PAR and RUE are rarely analyzed. How the spatial distribution of PAR (especially for some key positions within mixed canopy) potentially relate to Pn and RUE for intercropped soybean and maize remains to be answered.

The row arrangement of intercropping can alter the light distribution, leading to changes in intercepted PAR (Liu et al., 2017b). The intercepted PAR of intercrops differs in different arrangements, causing changes of interspecific competitive relationship. Moreover, the change of light distribution leads to variations of crop yield and LER in different cropping systems. However, how the competitive relationships change with the alterations in row arrangements and light distribution in strip intercropping has not been clearly explained.

Taken together, considering the effects of PAR distribution and leaf photosynthesis, our study has three aims: (i) to investigate the causes for high RUE and LER in strip intercropping considering the PAR distribution; (ii) to hypothesize how the PAR distribution affects intercepted PAR and RUE; (iii) to find the optimal intercropping arrangement resulting in the highest LER.

2. Materials and methods

2.1. Sites description

Field experiments were conducted from 2013 to 2015 at an experimental station in the Crop Breeding Farm (115°25′05″E, 35°15′09″N), located in Heze City, Shandong Province, China. It has temperate continental monsoon climate. The annual average air temperature is 14.7 °C, and the frost-free period is 210 days (data from local meteorological bureau). The daily radiation and temperature data during the growing seasons from 2013 to 2015 are shown in Fig. 1. The clayey soil is formed by Yellow River alluvial silt. At the beginning of the study, the pH of surface soil was 7.6; the available N, P and K contents of soil were 101, 34, and 187 mg·kg^{-1}, respectively; and the soil organic matter content was 18.26 g·kg^{-1}. Enough irrigation was provided to each arrangement by surface irrigation system.

2.2. Experimental design

The field experiments consisted of six arrangements with triplicates, which were randomly organized (Fig. 2). The arrangements included (Table 1) sole soybean (SS, row distance was 0.5 m), sole maize (SM, row distance was 0.7 m), maize-soybean single row intercropping (RI, 1 row of maize intercropped with 1 row of soybean, the distance between maize rows and soybean rows was 0.5 m), and maize-soybean strip intercropping (2 rows of maize intercropped with 2 rows of soybean) with three different row arrangements: SI1, maize row distance was 0.2 m, soybean row distance was 0.4 m, distance between maize row and soybean row was 0.7 m; SI2, maize row distance was 0.4 m, soybean row distance was 0.4 m, distance between maize row and soybean row was 0.6 m; SI3, maize row distance was 0.6 m, soybean row distance was 0.4 m, distance between maize row and soybean row was 0.5 m. Three adjacent bands of maize plus soybean formed a plot. The size of each experimental plot was 6 m by 6 m. The distance between maize plants within each row (MD) was 0.14 m in intercropping, and 0.2 m in monoculture. The distance between soybean plants within each row (SD) was 0.07 m in intercropping, and 0.14 m in monoculture. The maize density was 70,500 plants per hectare (commonly used in production of sole maize) for both intercropping and monoculture. The soybean density was 141,000 plants per hectare (commonly used in production of sole soybean) for both intercropping and monoculture. The row orientation was east-west. The soybean and maize used in the study were local cultivars 'Hedou19' and 'Xundan26', respectively.

The previous crop was winter wheat. The seeds were manually sowed in rows at depths of 0.04 m for soybean and 0.05 m for maize. The organic fertilizer containing 4% organic matter was applied at 30 ton ha^{-1} before sowing. The fertilizer was applied to maize at jointing stage (both intercropped and sole maize) by spreading it in maize rows, with the dosages of 150 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1} and 100 kg K_2O ha^{-1}. No fertilizer was applied to soybean (both intercropped and sole soybean) in order to prevent overly long and thin stems. Both soybean and maize were sown on June 10th–14th from 2013 to 2015, and harvested on September 26th–28th.

2.3. Experimental measurements

Six LI-191SA quantum sensors (LI-COR Inc., Lincoln, NE, USA) with a LI-1400 data logger were used to measure PAR in this study. The radiation profile on a cross section through the canopy was measured using light sensors. The cross section was 2 m wide (cross-row) and up to 2.4 m high (depending on crop height), and measurements were made on a grid with a mesh size of 20 × 20 cm (Fig. 2), resulting in $x \times y$ measurement positions. The measurements at each position were made using six sensors that were mounted on a stick. Measurements by the six sensors were averaged. The stick was mounted in two scaffolds placed in parallel to the crop rows (Fig. 3). The stick with the sensors was moved manually by an observer with approximately 5 s. residence time per position. Data were recorded by a second observer using a logger. The PAR spatial distribution in all arrangements were measured manually from 11:30am to 12:30pm on a sunny day, which was repeated three times between August 15th and 25th (pod filling stage for soybean; grain filling stage for maize) in 2014 and 2015. Based on these data, the PAR intensity at top of soybean canopy (hollow squares), maize outer (hollow circle) and inner (solid circle) leaves close to the ear were calculated (Fig. 2).

The net photosynthetic rate (Pn) was measured on the same day as PAR in 2014 and 2015. Measurements were taken from the third leaf from the top of soybean (upper canopy leaf) and the three leaves close to the ear of maize during 10:30 AM to 11:30 AM with a LI-6400XT (Li-Cor Inc., USA). In strip intercropping, the outer leaves close to the ear (the leaves extended to the gap width for growing soybeans) and inner leaves close to the ear (the leaves within maize rows) of maize were measured separately at positions shown in Fig. 2. The natural light