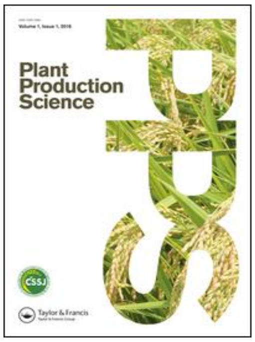

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Effect of narrow-row planting patterns on crop competitive and economic advantage in maize–soybean relay strip intercropping system

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ABSTRACT
Narrow-row planting patterns directly affect crop yield and competition in intercropping systems. A two-year (2012 and 2013) field experiment was conducted to determine the interactive behavior between intercrops in a maize–soybean relay strip intercropping system. Maize plants were planted in different narrow-wide row planting patterns, whereas soybean was planted in wide rows. The total biomass and grain yield of maize increased with increasing maize narrow-row spacing, but the opposite trend was observed for soybean. The aggressivity, competitive ratio, and partial relative crowding advantage values for maize were greater than those for soybean. Moreover, the competitive interaction of the intercrops was affected by the distance between maize and soybean rows. The highest intercrop land equivalent ratio (LER) 1.61 and 1.59 was found in the 40:160 planting pattern (i.e. 40 cm narrow-row spacing and 160 cm wide-row spacing of maize) during 2012 and 2013, respectively. Combined with actual yield loss and LER, the intense intra-specific competition of maize plants reduced the depression for the associated soybeans when the maize narrow-row spacing was less than 30 cm. When the narrow-row spacing was wider than 50 cm, soybean growth was seriously depressed by maize because of the stronger inter-specific competition between maize and soybean. The maximum yield and economic advantage appeared in the 40:160 narrow-wide row planting pattern. Therefore, intercropping advantage may be achieved by changing the row spacing and distance between intercrop rows to coordinate the inter-specific competition between maize and soybean.

Abbreviations: *A*, aggressivity; AYL, actual yield loss; CR, competitive ratio; *K*, relative crowding coefficient; LER, land equivalent ratio; MAI, monetary advantage indices; IA, intercropping advantage indices

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1. Introduction

The increasing global population and decreasing suitable land areas for food production have made high productivity and sustainability of agriculture a global challenge (Tscharntke et al., 2012). In the current scenario of restricted requirements for land, agricultural intensification could be used as a strategy for increasing crop yields (Phalan et al., 2011). Therefore, the multiple cropping index of cropland needs to be increased to develop grain production (Yan et al., 2010; Zhu et al., 2000).

Intercropping plays an important role in the sustainable development of agriculture and food production worldwide (Miyazawa et al., 2014; Rodríguez-Navarro et al., 2010). Compared with the corresponding sole cropping systems, intercropping often has higher yield advantages and land-use efficiency (Mao et al., 2012). However, planting patterns affect the yield potential of intercrops in intercropping systems (Yang et al., 2015).

Intercropping advantage occurs only when each species has adequate time and space to maximize cooperation and minimize competition between them. The individuals interact with their neighbors over restricted distances because of the immobility of plants in intercropping (Stoll & Weiner, 2000). Changing the hierarchies and spatial patterns in plant populations may influence the productivity of the intercropping system (Oseni & Aliyu, 2010). Therefore, assessing the competition of each crop plays key role in the determination of an optimal planting pattern in intercropping systems.

In previous studies, spatial pattern changes were made in terms of row ratios, plant density, and row spacing (Lithourgidis et al., 2006; Undie et al., 2012; Yang et al.,

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Table 1. Monthly mean meteorological data during the growing seasons in 2012 and 2013.

Year	Meteorological data	Month Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
2012	Air temperature (°C)	11	17	21	23	24	25	20	17	11
	Rainfall (mm)	54	80	236	265	365	430	156	116	17
2013	Air temperature (°C)	17	18	21	24	25	26	20	18	12
	Rainfall (mm)	15	96	153	182	464	228	212	58	57

2015). Intercropping systems can produce a higher yield advantage based on a land equivalent ratio (LER) (Zhang et al., 2011). Undie et al. (2012) reported that planting maize and soybean in 2:2 or 1:2 row arrangements can maximize the optimum crop yield in intercropping conditions. These studies have confirmed that the yield advantage is achieved caused by the border row effect, and the competitive behavior of crops is influenced by changing spatial patterns.

Competition is one of the main factors that have significant impact on growth rate and yield of crops used in intercropping compared with monoculture. Several indices such as the relative crowding coefficient (*K*), competitive ratio (CR), aggressivity (*A*), actual yield loss (AYL), and intercropping advantage (IA) indices have been used to quantify the beneficial competitive effects in the different planting patterns (Banik et al., 2000; Yilmaz et al., 2008). These indices facilitate the researchers to describe the competitive behavior in intercropping systems and allow the comparison of results from different studies that had used the same indices (Lithourgidis et al., 2011). However, these indices have never been used to assess the competition in an intercropping system where the distance between two species varied.

Maize–soybean intercropping is an important type of cereal–legume intercropping system (Hauggaard-Nielsen et al., 2003). Maize–soybean relay strip intercropping has been widely practiced in Southwest China and other countries (Yang et al., 2014). In this system, two maize rows are alternated by two soybean rows, and also known as a two-by-two staggered arrangement (Yang et al., 2015). The effects of the border rows contribute to the overyield of the intercrops and make possibility of small mechanical operations in strip intercropping systems (Knörzer et al., 2009; Munz et al., 2014). Maize–soybean strip intercropping system increased yield and provided substantially higher land use efficiency (Yang et al., 2015), but each crop's yield was affected by different planting patterns. Our previous studies have identified the soybean response to shading and the most suitable planting pattern in maize–soybean relay strip intercropping (Yang et al., 2014, 2015). However, the competitive behavior between maize and soybean and the economic advantage in a relay strip intercropping system remain still unclear.

The main objectives of this paper were to: (1) analyze the trends of the crop yield and biomass in different narrow–wide-row planting patterns of maize–soybean relay strip intercropping system; (2) estimate the competitive abilities of maize and soybean in different row spacing patterns; and (3) determine which narrow–wide-row planting pattern with the same bandwidth shows promise in achieving higher productivity and economic advantage in maize–soybean relay strip intercropping system.

2. Materials and methods

2.1. Study area

Experiments were conducted from 2012 to 2013 at the experimental farm of Sichuan Agricultural University (29° 59′N, 103° 00′E). Experiments were laid out on a purple clay loam soil. The field climate was subtropical humid. The mean monthly temperature and rain fall were 19.8 °C and 169 mm, respectively, during the growing seasons of the experimentation (Table 1).

2.2. Experimental design and field management

Fields were assigned to different treatments using a single-factorial randomized block design with three replications. The design comprised eight treatments include six different narrow–wide-row planting patterns and monocultures of maize (*Z. Mays* L. cv. 'Chuandan418') and soybean (*G. max* L. cv. 'Nandou12'). The distance between rows was 70 cm both in the maize and soybean monocultures. The intercropping patterns followed the two-by-two staggered arrangement (two maize rows were alternated by two soybean rows). The total width of an adjacent maize and soybean strip was 200 cm in the maize–soybean relay strip intercropping system according to the most suitable bandwidth of previous report (Yang et al., 2015). The following narrow–wide-row planting patterns were used: (i) 20:180, i.e. 20 cm narrow-row spacing and 180 cm wide-row spacing of maize; (ii) 30:170; (iii) 40:160; (iv) 50:150; (v) 60:140; and (vi) 80:120. Soybean was planted in the wide rows of maize at 40 cm row spacing (Figure 1).

Each plot was 5 m long and 6 m wide with three strips. Maize was sown on 1 April and 30 March in 2012 and 2013

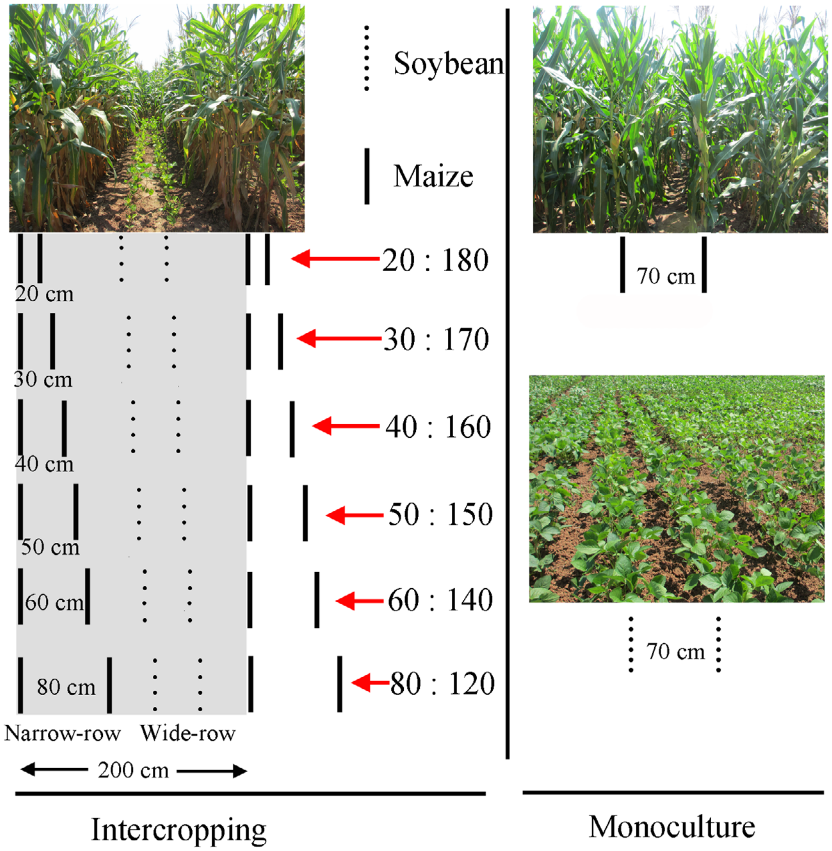

Figure 1. Planting patterns of intercrops in maize–soybean relay strip intercropping. Maize plants were planted in different narrow–wide-row planting patterns on 1 April and 30 March in 2012 and 2013, respectively. Soybean was planted in maize wide rows on 15 June and 16 June in 2012 and 2013, respectively. Intercropped soybean row spacing was 40 cm. The distance between rows was 70 cm both in the maize and soybean monocultures.

and harvested on 1 August and 28 July in 2012 and 2013, respectively. Soybean was sown on 15 June and 16 June in 2012 and 2013 and harvested on 30 October and 4 November in 2012 and 2013, respectively. Maize and soybean monocultures were used as the control and were planted at the same density as the relay intercrop plots. Maize and soybean plant densities were 6 and 10 plants m^{-2}, respectively. The plant spacing of maize and soybean were 16.7 and 10 cm for all intercropping treatments and 23.8 and 14.3 cm for monoculture, respectively. Basal urea N, calcium superphosphate P, and potassium sulfate K at 135, 40, and 10 kg ha^{-1}, respectively, were applied into the soil prior to maize sowing. Basal N at 75 kg ha^{-1} as urea, P at 40 kg ha^{-1} as calcium superphosphate, and K at 4 kg ha^{-1} as potassium sulfate were applied to soybean before sowing. At the sixth leaf stage (V6) of maize and beginning bloom stage (R1) of soybean, N at 135 and 75 kg ha^{-1} as urea were applied for maize and soybean treatments, respectively.

Given the equal planting row number of two crops and the same density of each crop in the maize–soybean relay strip intercropping systems, row spacing was the only difference in all treatments. According to results of previous studies (Yang et al., 2015), we hypothesized that the center of the space between maize and soybean rows was the dividing line of these two crop areas and can be used for calculating the competitive indices in the intercropping system (Figure 2). Therefore, the proportions of intercropping land that was occupied by maize and soybean in treatments (i), (ii), (iii), (iv), (v), and (vi) were 45%:55%, 47.5%:52.5%, 50%:50%, 52.5%:47.5%, 55%:45%, and 60%:40%, respectively.

2.3. Sampling and measurements

The grain yield and biomass of both maize and soybean were harvested at physiological maturity for 12 m^2 in all three replicates. The samples were oven-dried at 105 °C for 30 min, and then dried at 80 °C until a constant weight was obtained. Yield was analyzed when the grain humidity was approximately 13% (Borghi et al., 2012).

2.4. Land equivalent ratio

LER was used to assess the intercropping advantage (Willey & Rao, 1980). The formula was defined as follows (Mao et al., 2012):

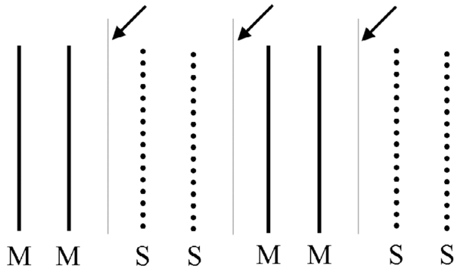

Figure 2. Dividing line of two crop areas for calculating the competitive indices in the maize–soybean relay strip intercropping system. M and S stand for maize row and maize row, respectively. Arrows present the center of the space between maize and soybean rows.

$$\text{LER} = \left(\text{LER}_{\text{maize}} + \text{LER}_{\text{soybean}}\right) \tag{1}$$

$$\text{LER}_{\text{maize}} = \left(\frac{Y_{im}}{Y_m}\right) \tag{2}$$

$$\text{LER}_{\text{maize}} = \left(\frac{Y_{is}}{Y_s}\right) \tag{3}$$

where $\text{LER}_{\text{maize}}$ and $\text{LER}_{\text{soybean}}$ are the partial LER values of maize and soybean, respectively. Y_{im} and Y_{is} are the yields of maize and soybean, respectively, as relay intercrops. Y_m and Y_s are the yields of maize and soybean, respectively, as monoculture crops.

2.5. Competition indices

Several competition indices were used to estimate the advantage of intercropping and the effect of competition between the two species.

2.5.1. Relative crowding coefficient

K measures the relative dominance of one species over the other in a mixture, several scholars gave the following detailed definition of *K* (Ghosh, 2004), which was calculated as follows:

$$K_m = \frac{Y_{im} \times P_{is}}{\left(Y_m - Y_{im}\right) \times P_{im}} \tag{4}$$

$$K_s = \frac{Y_{is} \times P_{im}}{\left(Y_s - Y_{is}\right) \times P_{is}} \tag{5}$$

where P_{im} and P_{is} are the proportional land occupancies of maize and soybean in intercropping, respectively. The dominant species has a higher *K* value and is more competitive in an intercropping system (Zhang et al., 2011).

2.5.2. Aggressivity

A is often used to indicate the interspecies competition in intercropping systems by relating the yield changes of the two component crops (Agegnehu et al., 2006). This index is derived from the following equation:

$$A_m = \left(\frac{Y_{im}}{Y_m P_{im}}\right) - \left(\frac{Y_{is}}{Y_s P_{is}}\right) \tag{6}$$

$$A_s = \left(\frac{Y_{is}}{Y_s P_{is}}\right) - \left(\frac{Y_{im}}{Y_m P_{im}}\right) \tag{7}$$

When $A_m = 0$, both crops are equally competitive. When A_m is positive, maize is dominant. However, when A_s is positive, soybean is dominant.

2.5.3. Competitive ratio

CR is another way to evaluate the competitive ability of different species in an intercropping system (Willey & Rao, 1980). Compared with *K* and *A*, CR is more advantageous and allows better measurement of the competitive ability of the crops. CR is calculated according to the following formula:

$$\text{CR}_m = \left(\frac{\text{LER}_{\text{maize}}}{\text{LER}_{\text{soybean}}}\right)\left(\frac{P_{is}}{P_{im}}\right) \tag{8}$$

$$\text{CR}_s = \left(\frac{\text{LER}_{\text{soybean}}}{\text{LER}_{\text{maize}}}\right)\left(\frac{P_{im}}{P_{is}}\right) \tag{9}$$

When $\text{CR}_m < 1$, a positive benefit was observed, and the crop can be grown in association with another crop. When $\text{CR}_m > 1$, a negative benefit was present. The reverse is true for CR_s.

2.5.4. Actual yield loss

AYL is based on the yield per plant, which can provide a more precise information regarding competition than other indices between and within the component crops. AYL is also a description of the behaviors of each species in intercropping systems (Banik et al., 2000). AYL is the proportionate yield loss or gain of intercrops compared with the respective sole crops, i.e. the actual sown proportion of the component crops with their sole crops considered. In addition, partial AYL (AYL_m or AYL_s) represents the proportionate yield loss or gain of each species when grown as intercrops, in relation to their yields in the solo cropping

Table 2. Total biomass and grain yield of intercrops in different narrow–wide-row planting patterns of maize–soybean relay strip intercropping.

		Row spacing (cm)		Total biomass ($\times 10^3$ kg ha^{-1})		Grain yield ($\times 10^3$ kg ha^{-1})	
Year	Narrow–wide-row planting patterns	M–M	M–S	Maize	Soybean	Maize	Soybean
2012	20:180	20	70	10.30d	3.50b	5.04c	1.47b
	30:170	30	65	10.40d	3.42b	5.19c	1.45b
	40:160	40	60	10.90cd	3.49b	5.72b	1.40b
	50:150	50	55	11.44c	2.99c	5.75b	1.20c
	60:140	60	50	12.42b	2.74c	6.11a	1.08c
	80:120	80	40	12.87ab	2.21d	6.31a	0.82d
	sole crop	–	–	13.30a	4.70a	6.45a	1.99a
2013	20:180	20	70	10.22d	3.30b	5.10e	1.40b
	30:170	30	65	10.64d	3.26b	5.29de	1.33bc
	40:160	40	60	11.02cd	3.19b	5.57cd	1.35b
	50:150	50	55	11.61c	2.79c	5.77bc	1.23cd
	60:140	60	50	12.60b	2.57c	5.86bc	1.14d
	80:120	80	40	13.36ab	2.07d	6.05ab	0.73e
	sole crop	–	–	13.79a	4.76a	6.31a	1.85a

Notes. M–M indicates the narrow-row spacing of maize. M–S indicates the distance between maize and soybean rows. Different lowercase letters indicate significant differences (LSD, $p < 0.05$).

system. AYL is calculated according to the following formula (Banik et al., 2000):

$$\mathrm{AYL} = \mathrm{AYL}_m + \mathrm{AYL}_s \tag{10}$$

$$\mathrm{AYL}_m = \left[\left(\frac{Y_{im}/P_{im}}{Y_m/P_m}\right) - 1\right] \tag{11}$$

$$\mathrm{AYL}_s = \left[\left(\frac{Y_{is}/P_{is}}{Y_s/P_s}\right) - 1\right] \tag{12}$$

When AYL is positive, an intercropping advantage is indicated. When it is negative, an intercropping system disadvantage is indicated.

2.5.6. Economic indices

To calculate the economic advantage, Banik et al. (2000) introduced the monetary advantage indices (MAI) to provide any information of the economic advantage and the intercropping IA to give the intercropping advantage of system (Ghosh, 2004). MAI and IA were calculated as follows:

$$\mathrm{MAI} = \frac{(\text{value of combined intercrops}) \times (LER - 1)}{\mathrm{LER}} \tag{13}$$

$$\mathrm{IA}_m = \mathrm{AYL}_m \mathrm{p}_m \tag{14}$$

$$\mathrm{IA}_s = \mathrm{AYL}_s \mathrm{p}_s \tag{15}$$

The value of the combined intercrops was the grain yield (kg ha^{-1}) multiplied by the price per kg (Borghi et al., 2012); and p_m is the commercial value of maize, and p_s is the commercial value of soybean. Crop value based on market prices is €153.27 per ton for maize and €378.35 per ton for soybean. The higher MAI value will mean a more profitable mixed system (Dhima et al., 2007).

2.6. Date analysis

Data were analyzed by one-way ANOVA, following a single-factor randomized block plot design. The significant differences among treatments were analyzed at 5% level of probability. SPSS version 17.0 was used in the statistical analyses.

3. Results

3.1. Biomass and grain productivity

Compared with the intercrops, the mean grain yield and total biomass of maize and soybean were higher in the sole crops (Table 2). The mean data of total biomass and grain yield were 13.55 × 10^3 and 4.73 × 10^3 kg ha^{-1} for sole maize and 6.38 × 10^3 and 1.92 × 10^3 kg ha^{-1} for sole soybean, respectively. With increasing narrow-row spacing, the total biomass and grain yield of the intercropped maize increased, and the maximum mean data, which appeared in the narrow–wide-row planting pattern of 80:120, were 13.12 × 10^3 and 6.18 × 10^3 kg ha^{-1}, respectively. Contradictory results were found in intercropped soybean (2.14 × 10^3 and 0.78 × 10^3 kg ha^{-1} for total biomass and grain yield, respectively). Intercropped soybean showed the maximum total biomass and grain yield in the narrow–wide-row planting pattern of 20:180. A reduction of 3.13% in the mean grain yield of maize under 80:120 planting pattern and a 20.53% loss under 180:20 pattern were observed compared with sole maize. Compared with sole soybean, 59.64 and 25.26% mean grain yield of intercropped soybean depression were noted in the same cases, respectively.

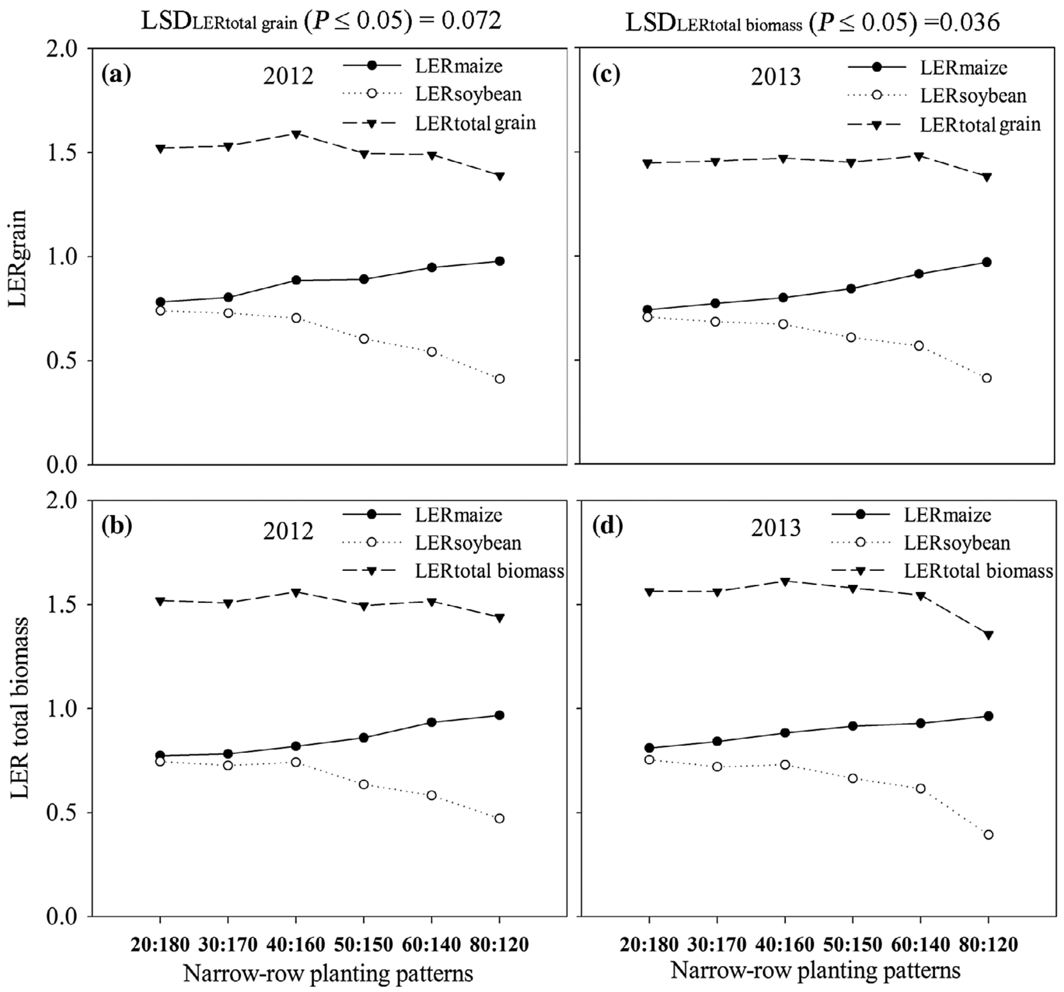

Figure 3. LER of intercropped maize with soybean at different narrow-row planting patterns of the maize–soybean relay strip intercropping in 2012 and 2013. $LER_{total\text{-}grain}$ and $LER_{total\text{-}biomass}$ represent the LER based on the total grain yield and total biomass in different narrow–wide-row planting patterns, respectively. LER_{maize} and $LER_{soybean}$ indicate the partial LER of maize and soybean, respectively.

3.2. Land equivalent ratio

The advantages of the maize–soybean relay strip intercropping system were significant compared with that of the sole cropping system according to $LER_{total\text{-}biomass}$ (calculated from the biomass of maize and soybean) and $LER_{total\text{-}grain}$ (calculated from the grain yield of maize and soybean), the maximum LER was higher than 1.6 (Figure 3). The maximum and minimum values were obtained from 40:160 and 80:120 planting pattern, respectively. The partial LER of maize (LER_{maize}) increased slowly with increasing maize narrow-row spacing (i.e. with decreasing distance between the maize and soybean rows) in the maize–soybean relay strip intercropping system. By contrast, the partial LER of soybean ($LER_{soybean}$) gradually decreased when the maize narrow-row spacing was less than 40 cm, and then steeply decreased with the increasing narrow-row spacing. $LER_{soybean}$ directly affected the changing trends of the total LER in the maize–soybean relay strip intercropping system according to the data from both years.

3.3. Relative crowding coefficient

The partial K values of maize and soybean were shown in Table 3. Referring to the K values of all relay intercropping ratios, K_m was higher than the K_s, thereby indicating that maize was dominant and more competitive than soybean. The K_m value was the greatest (22.96, averaged data of two seasons) under 80:120 pattern among all treatments. However, the lowest partial K (4.77, averaged data of two seasons) of maize was recorded in a narrow–wide-row planting pattern of 20:180. By contrast, the partial K value of soybean was opposite that of maize; the lowest Ks (1.02, averaged data of two seasons) were noted in the 80:120 planting pattern, whereas the highest value (2.41, averaged data of two seasons) was obtained in the 20:180 narrow–wide-row planting pattern.

Table 3. Relative crowding coefficient of maize (K_m) and soybean (K_s) in different narrow–wide-row planting patterns of maize–soybean relay strip intercropping system in 2012 and 2013.

		Row spacing (cm)K values		*K* values	
Year	Narrow–wide-row planting patterns	M–M	M–S	K_m	K_s
2012	20:180	20	70	4.38	2.31
	30:170	30	65	4.53	2.42
	40:160	40	60	7.81	2.35
	50:150	50	55	7.41	1.69
	60:140	60	50	14.54	1.45
	80:120	80	40	30.52	1.05
LSD ($P \leq 0.05$)				3.20	0.19
2013	20:180	20	70	5.15	2.5
	30:170	30	65	5.74	2.3
	40:160	40	60	7.52	2.67
	50:150	50	55	9.56	2.16
	60:140	60	50	10.52	1.93
	80:120	80	40	15.4	0.98
LSD ($P \leq 0.05$)				1.41	0.26

Note. M–M means the narrow-row spacing of maize. M–S means the distance between maize and soybean rows.

Table 4. Aggressivity (*A*), competitive ratio (CR), and actual yield loss (AYL) of intercrops in different narrow–wide-row planting patterns of maize–soybean relay strip intercropping in 2012 and 2013.

		Row spacing (cm)		*A*		CR		AYL		
Year	Narrow–wide-row planting patterns	M–M	M–S	A_m	A_s	CR_m	CR_s	AYL_m	AYL_s	AYL_t
2012	20:180	20	70	−0.05	0.05	0.87	1.15	0.74	0.34	1.08
	30:170	30	65	0.00	0.00	1.00	1.00	0.69	0.39	1.08
	40:160	40	60	0.09	−0.09	1.26	0.79	0.77	0.40	1.18
	50:150	50	55	0.18	−0.18	1.63	0.61	0.70	0.27	0.97
	60:140	60	50	0.28	−0.28	2.13	0.47	0.72	0.21	0.93
	80:120	80	40	0.42	−0.42	3.57	0.28	0.63	0.03	0.66
LSD ($P \leq 0.05$)				0.12	0.059	0.25	0.054	0.040	0.028	0.032
2013	20:180	20	70	−0.05	0.05	0.88	1.14	0.80	0.37	1.16
	30:170	30	65	0.02	−0.02	1.06	0.95	0.77	0.37	1.13
	40:160	40	60	0.08	−0.08	1.21	0.82	0.77	0.45	1.22
	50:150	50	55	0.17	−0.17	1.53	0.66	0.74	0.39	1.13
	60:140	60	50	0.23	−0.23	1.85	0.54	0.69	0.36	1.05
	80:120	80	40	0.42	−0.42	3.65	0.27	0.60	0.01	0.58
LSD ($P \leq 0.05$)				0.08	0.12	0.11	0.036	0.041	0.030	0.025

Note. M–M means the narrow-row spacing of maize. M–S means the distance between maize and soybean rows.

3.4. Competition indices

The values of *A*, CR, and AYL in the maize–soybean relay strip intercropping system are shown in Table 4. Based on the *A* and CR values, the intercropping system exhibited different competitive behaviors in different planting patterns. In particular, maize was the dominant species (*A* of maize was positive, and CR was greater than 1) in most of the planting patterns. With the increasing maize narrow-row spacing, the aggressivity of maize (A_m) and soybean (A_s) values were increased and decreased in the intercropping conditions, respectively. The change trends of CR were similar with the value of *A* in the maize–soybean relay strip intercropping system.

All the partial AYL values of intercropped maize (AYL_m) and soybean (AYL_s) in 2012 and 2013 were positive, which revealed a yield advantage compared with sole cropping system (Table 4). The maximum value of the total AYL (AYLt) (+1.20, averaged data of 2 years) and minimum AYLt (+0.62, averaged data of 2 years) of the maize–soybean intercropping system were observed under the narrow–wide-row spacing treatments of 40:160 and 80:120, respectively.

3.5. Economic and intercropping advantage

The MAI values can provide information of the economic advantage of a combined intercropping system. In all the relay intercropping systems, the MAI values were positive, which showed a definite yield advantage compared with sole cropping (Table 5). The MAI values followed a 'low-high-low' trend in different planting patterns. Likewise, the values of combined intercrops confirmed the same trend. The highest MAI values were 522.06 and 518.27 € ha^{-1} for 2012 and 2013, respectively, which were observed in narrow–wide-row planting pattern of 40:160. The minimum MAI value (336.44 € ha^{-1}, averaged data of two seasons) was obtained in the planting pattern of 80:120.

Table 5. Monetary and intercropping advantage indices (MAI and IA) of intercrops in different narrow–wide-row planting patterns of maize–soybean relay strip intercropping.

		Row spacing (cm)		IA			MAI
Year	Narrow–wide-row planting patterns	M–M	M–S	IA_m	IA_s	IA_t	
2012	20:180	20	70	112.87	129.80	242.68	454.59
	30:170	30	65	106.37	146.76	253.13	467.48
	40:160	40	60	118.58	154.00	272.58	522.06
	50:150	50	55	106.99	101.97	208.96	441.82
	60:140	60	50	110.71	77.95	188.66	442.35
	80:120	80	40	96.64	11.41	108.04	358.64
LSD ($P \leq 0.05$)				3.46	7.35	5.26	11.17
2013	20:180	20	70	122.02	142.23	264.25	473.43
	30:170	30	65	117.24	139.75	256.99	470.22
	40:160	40	60	117.32	173.84	291.16	518.27
	50:150	50	55	113.69	151.23	264.92	495.09
	60:140	60	50	105.53	139.75	245.28	468.92
	80:120	80	40	91.65	−5.11	86.54	314.25
LSD ($P \leq 0.05$)				2.31	12.71	4.89	14.77

Note. M–M means the narrow-row spacing of maize. M–S means the distance between maize and soybean row. Crop values are based on market price per ton of maize = €153.27 and soybean = €378.35.

IA, another indicator of the economic feasibility of intercropping systems, can indicate the advantage of intercropping. The IA values of maize–soybean relay strip intercropping systems were positive and followed a trend similar to MAI, indicating the clear advantage of intercropping. The maximum IA (281.87, averaged data of two seasons) was observed in the narrow–wide-row planting pattern of 40:160, whereas the minimum IA (97.29, averaged data of two seasons) was obtained under 80:120 planting pattern.

4. Discussion

Higher grain yield and total biomass of the intercropping treatments relative to corresponding sole crops may be due to the complementary use of the available resources (Li et al., 2001). Light environment directly affects the competition among component crops, and the light interception was affected by the row spacing arrangement (Farnham, 2001). Maize was more competitive than other plants because of its high capacity for intercepting photosynthetically active radiation (Liu & Song, 2012). In this study, when the narrow-row spacing of maize ranged from 80 to 20 cm, the yield of intercropped maize decreased by 25.53–3.13% (Table 2). The yield reduction of the intercropped maize in close row spacing may be attributed to the intra-specificity of intense interplant competition .

Maize narrow–wide-row planting patterns also affected the soybean yield in maize–soybean relay strip intercropping system (Table 2). Soybean plants were highly sensitive to shading (Liu et al., 2015; Yang et al., 2014). The higher yield of intercrops at wide-row spacing than at narrow-row spacing is mainly due to obtaining more light interception (Wang et al., 2015). Light interception by lower crop canopy improved because of row arrangements (Addo-Quaye et al., 2011). The distance between maize and soybean rows was wider in different narrow–wide-row planting patterns of intercropping (Table 2); the intercropped soybean accumulated a higher amount of biomass. Thus, high canopy light interception and photosynthesis resulted in high grain yield of soybean (Yang et al., 2014).

The inter-specific competition is defined as the interaction between two species that reduces the fitness of one or both of species (Li et al., 2001). An accurate assessment of the competitive relationship between the component crops can be obtained using the LER. Higher LER indicates yield advantage because of improved land productivity in intercropping (Mead & Willey, 1980). In current study, the mean LERs in intercropping ranged from 1.37 to 1.60 under different patterns (Figure 3). Similar results were reported in the other intercropping systems (Li et al., 2003; Mahmoudi et al., 2013). The partial LER of maize was higher than that of soybean, thereby showing that the maize component contributed more to the total LER of the intercropping system than the soybean component. However, the highest LER (1.60, averaged data of two seasons) was recorded in the narrow–wide-row planting pattern of 40:160 (Figure 3), thereby suggesting that the maximum advantage of intercropping was obtained by coordinating the growth of both crops in the maize–soybean relay strip intercropping system.

The maize *K* values were greater than those for soybean (Table 3). This trend implied that maize was more competitive than soybean. Similar results were found in other species (Zhang et al., 2011). The competitive abilities of intercrops were defined by *A* and CR, respectively (Willey & Rao, 1980). The *A* values of maize (A_m) were always positive, and the CR_m values were greater than 1.0 (Table 4). Therefore, cereal was more competitive than the associated legume, as confirmed by previous reports

(Dhima et al., 2007; Yilmaz et al., 2008). However, the A_m values were negative and the CR_m values were less than 1.0 when the row spacing of maize was less than 30 cm in the maize–soybean relay strip intercropping system. These results indicated that maize was the inferior plant in the said treatment. The intense intra-specific competition of maize plants caused weak competitive ability. Our results were similar with those of Franco and Harper (1988), whose documented that the inter-plant competition may predict a negative correlation in the growth of the neighboring plants. With increasing narrow-row spacing of maize in the maize–soybean relay strip intercropping system, the intra-specific competition of maize decreased. The resulting interaction was mainly inter-specific competition between maize and soybean.

The inter-specific and intra-specific competitions of the component crops can be given by the index of the AYL index (Banik et al., 2000). The partial AYL of maize was greater than that of soybean, which indicated that maize was the dominant crop in the maize–soybean relay strip intercropping system. The highest AYL (+1.12, average of data obtained in 2 years) was observed under the 40:160 narrow–wide-row planting pattern (Table 4). These findings were in agreement with the LER results. Similarly, the advantages of the intercropping systems can be attributed to the better utilization of growth resources by intercrop coordination (Lithourgidis et al., 2011).

The IA values were positive under all planting patterns (Table 5), thereby revealing a definite yield advantage compared with the monoculture system. In addition, the MAI was another economic index that indicated the economic feasibility of using intercropping systems. Higher MAI values were achieved with greater productivity. Furthermore, the IA and MAI values followed a similar trend of 'low-high-low.' In particular, the highest IA and MAI values were recorded in the planting pattern of 40:160, thereby showing that this planting pattern had the highest economic advantage over other planting patterns. Moreover, the LER value and other competition indices conformed to the results of IA and MAI (Ghosh, 2004). The planting pattern of 40:160 had maximum yield advantage. The economic benefits of this planting pattern may be attributed to the sufficiently weak intra-specific competition of maize and the inter-specific competition of maize and soybean in the maize–soybean relay strip intercropping system.

5. Conclusions

Narrow–wide-row planting patterns significantly affected the total biomass and grain yield of intercrops in the maize–soybean relay strip intercropping system. With increasing maize narrow-row spacing, the total biomass and grain yield of maize increased. The opposite trend was observed for soybean.

The partial *K*, *A*, and CR values clearly indicated that the distance between maize and soybean had influenced the competitive ability of intercrops and that maize was the dominant species. When the row spacing of maize was less than 30 cm in the maize–soybean relay strip intercropping system, the maize yield was affected by the intense intra-specific competition. With increasing narrow-row spacing of maize under intercropping conditions, the intra-specific competition of maize got weakened, and the subsequent interaction was mainly inter-specific competition between maize and soybean.

Among all planting patterns, the narrow–wide-row planting pattern of 40:160 was the most profitable and had the highest yield advantage-based LER and economic benefits. Therefore, these advantages of the intercropping systems can be attributed to the improved utilization of growth resources by the intercrop coordinates.

Disclosure statement

No potential conflict of interest was reported by the authors.

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