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

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 a 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., 2015). The interactions in intercropping systems are still poorly understood and the spatial pattern changes in intercropping systems need further investigation.
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 rainfall 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.

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    | 56  | 153 | 182 | 246 | 228 | 212 | 58  | 57  |
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):
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:

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

(6)

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

(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:

$$CR_m = \left( \frac{LER_{maize}}{LER_{soybean}} \right) \left( \frac{P_{is}}{P_{im}} \right)$$  

(8)

$$CR_s = \left( \frac{LER_{soybean}}{LER_{maize}} \right) \left( \frac{P_{im}}{P_{is}} \right)$$  

(9)

When $CR_m < 1$, a positive benefit was observed, and the crop can be grown in association with another crop. When $CR_m > 1$, 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.
system. AYL is calculated according to the following formula (Banik et al., 2000):

$$AYL = AYL_m + AYL_s$$

$$AYL_m = \left[ \left( \frac{Y_{im}/P_{im}}{Y_m/P_m} \right) - 1 \right]$$

$$AYL_s = \left[ \left( \frac{Y_is/P_is}{Y_s/P_s} \right) - 1 \right]$$

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:

$$MAI = \left( \text{value of combined intercrops} \times (LER - 1) \right) / LER$$

$$IA_m = AYL_m p_m$$

$$IA_s = AYL_s p_s$$

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.
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 $K_s$ (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.

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-biomass} and LER_{total-grain} 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-biomass} (calculated from the biomass of maize and soybean) and LER_{total-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.

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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.

### 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 (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.

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### 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.

| Year | Narrow–wide-row planting patterns | Row spacing (cm) | $K_m$ | $K_s$ |
|------|-----------------------------------|-----------------|-------|-------|
| 2012 | 20:180                            | 20              | 3.81  | 2.31  |
|      | 30:170                            | 30              | 4.53  | 2.42  |
|      | 40:160                            | 40              | 7.81  | 2.35  |
|      | 50:150                            | 50              | 7.41  | 1.69  |
|      | 60:140                            | 60              | 14.54 | 1.45  |
|      | 80:120                            | 80              | 30.52 | 1.05  |
| 2013 | 20:180                            | 20              | 5.15  | 2.5   |
|      | 30:170                            | 30              | 5.74  | 2.3   |
|      | 40:160                            | 40              | 7.52  | 2.67  |
|      | 50:150                            | 50              | 9.56  | 2.16  |
|      | 60:140                            | 60              | 10.52 | 1.93  |
|      | 80:120                            | 80              | 15.4  | 0.98  |

**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.

| Year | Narrow–wide-row planting patterns | Row spacing (cm) | $A_m$ | $A_s$ | CR$_m$ | CR$_s$ | $AYL_m$ | $AYL_s$ | $AYLt$ |
|------|-----------------------------------|-----------------|-------|-------|--------|--------|---------|---------|--------|
| 2012 | 20:180                            | 20              | 0.05  | 0.05  | 0.87   | 1.15   | 0.74    | 0.34    | 1.08   |
|      | 30:170                            | 30              | 0.00  | 0.00  | 1.00   | 1.00   | 0.69    | 0.39    | 1.08   |
|      | 40:160                            | 40              | 0.09  | 0.09  | 1.26   | 0.79   | 0.77    | 0.40    | 1.18   |
|      | 50:150                            | 50              | 0.18  | 0.18  | 1.63   | 0.61   | 0.70    | 0.27    | 0.97   |
|      | 60:140                            | 60              | 0.28  | 0.28  | 2.13   | 0.47   | 0.72    | 0.21    | 0.93   |
|      | 80:120                            | 80              | 0.42  | 0.42  | 3.57   | 0.28   | 0.63    | 0.03    | 0.66   |
| 2013 | 20:180                            | 20              | 0.05  | 0.05  | 0.88   | 1.14   | 0.80    | 0.37    | 1.16   |
|      | 30:170                            | 30              | 0.02  | 0.02  | 1.06   | 0.95   | 0.77    | 0.37    | 1.13   |
|      | 40:160                            | 40              | 0.08  | 0.08  | 1.21   | 0.82   | 0.77    | 0.45    | 1.22   |
|      | 50:150                            | 50              | 0.17  | 0.17  | 1.53   | 0.66   | 0.74    | 0.39    | 1.13   |
|      | 60:140                            | 60              | 0.23  | 0.23  | 1.85   | 0.54   | 0.69    | 0.36    | 1.05   |
|      | 80:120                            | 80              | 0.42  | 0.42  | 3.65   | 0.27   | 0.60    | 0.01    | 0.58   |

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

### 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.

| Year | Narrow–wide–row planting patterns | Row spacing (cm) | MAI | IA |
|------|----------------------------------|-----------------|-----|-----|
|      |                                  | 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≤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≤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.

### 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, 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 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’. 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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References

Agegnehu, G., Ghizaw, A., & Sinebo, W. (2006). Yield performance and land-use efficiency of barley and faba bean mixed cropping in Ethiopian highlands. European Journal of Agronomy, 25, 202–207. doi:10.1016/j.eja.2006.05.002

Addo-Quaye, A. A., Darkwa, A. A., & Ocloo, G. K. (2011). Yield and productivity of component crops in a maize-soybean intercropping system as affected by time of planting and spatial arrangement. Journal of Agriculture and Biological Sciences, 9, 50–57. Retrieved from http://www.arpnjournals.com/jabs/research_papers/rp_2011/jabs_0911_314.pdf

Banik, P., Sasmal, T., & Ghosal, P. K. (2000). Evaluation of mustard (Brassica compestris Var. Toria) and legume intercropping under 1:1 and 2:1 row-replacement series systems. Journal of Agronomy and Crop Science, 185, 9–14. doi:10.1046/j.1439-037X.2000.00388.x

Borghi, E., Cruciol, C. A. C., Nascente, A. S., Mateus, G. P., Martins, P. O., & Costa, C. (2012). Effects of row spacing and intercrop on maize grain yield and forage production of palisade grass. Crop Pasture Science, 63, 1106–1113. doi:10.1071/CP12344
Dhima, K., Lithourgidis, A., Vasilakoglou, I., & Dordas, C. (2007). Competition indices of common vetch and cereal intercrops in two seeding ratio. *Field Crops Research*, 100, 249–256. doi:10.1016/j.fcr.2006.07.008

Farnham, D. E. (2001). Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agronomy Journal*, 93, 1049–1053. doi:10.2134/agronj2001.9351049x

Franco, M., & Harper, J. L. (1988). Competition and the formation of spatial pattern in spacing gradients: An example using Kochia scoparia. *Journal of Ecology*, 76, 959–974. doi:10.2307/2260626

Ghosh, P. K. (2004). Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. *Field Crops Research*, 88, 227–237. doi:10.1016/j.fcr.2004.01.015

Hauggaard-Nielsen, H., Ambus, P., & Jensen, E. S. (2003). The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutrient Cycling in Agroecosystems*, 65, 289–300. doi:10.1023/A:1022612528161

Knörzer, H., Graeff-Hönninger, S., Guo, B., Wang, P., & Claupein, W. (2009). Rediscovery of intercropping in China: A traditional cropping system for future Chinese agriculture – A review. In E. Lichtfouse (Ed.), *Climate change, intercropping pest control and beneficial microorganisms*. Berlin: Springer Netherlands. Publication, doi:10.1007/978-90-481-2716-0

Li, L., Sun, J., Zhang, F., Li, X., Yang, S., & Rengel, Z. (2001). Wheat/maize or wheat/soybean strip intercropping: I. Yield advantage and interspecific interactions on nutrients. *Field Crops Research*, 71, 123–137. doi:10.1016/S0921-6126(01)00156-3

Li, L., Zhang, F., Li, X., Christie, P., Sun, J., Yang, S., & Tang, C. (2003). Interspecific facilitation of nutrient uptake by intercropped maize and faba bean. *Nutrient Cycling in Agroecosystems*, 65, 61–71. doi:10.1023/A:1021885032241

Lithourgidis, A. S., Vasilakoglou, I. B., & Dhima, K. V. (2006). Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. *Field Crops Research*, 99, 106–113. doi:10.1016/j.fcr.2006.03.008

Lithourgidis, A. S., Vlachostergios, D. N., Dordas, C. A., & Damalas, C. A. (2011). Dry matter yield, nitrogen content, and competition in pea–cereal intercropping systems. *European Journal of Agronomy*, 34, 287–294. doi:10.1016/j.eja.2011.02.007

Liu, T. D., & Song, F. B. (2012). Maize photosynthesis and microclimate within the canopies at grain-filling stage in response to narrow-wide row planting patterns. *Photosynthetica*, 50, 215–222. doi:10.1007/s11099-012-0011-0

Liu, W., Zou, J., Zhang, J., Yang, F., Fan, Y., & Yang, W. (2015). Evaluation of soybean (Glycine max) stem vining in maize-soybean relay strip intercropping system. *Plant Production Science*, 18, 69–75. doi:10.1626/pps.18.69

Mahmoudi, R., Jamshidi, K., & Pouryousef, M. (2013). Evaluation of grain yield of maize (Zea mays L.) and soybean (Glycine max L.) in strip intercropping. *International Journal of Agronomy & Plant Production*, 4, 2388–2392. Retrieved from http://www.academia.edu

Mao, L., Zhang, L., Li, W., Werf, W., Sun, J., Spiertz, H., & Li, L. (2012). Yield advantage and water saving in maize/pea intercrop. *Field Crops Research*, 138, 11–20. doi:10.1016/j.fcr.2012.09.019

Mead, R., & Willey, R. W. (1980). The Concept of a ‘Land Equivalent Ratio’ and advantages in yields from intercropping. *Experimental Agriculture*, 16, 217–228. doi:10.1017/S0014479700010978

Miyazawa, K., Takeda, M., & Murakami, T. (2014). Dual and triple intercropping: Potential benefits for annual green manure production. *Plant Production Science*, 2, 194–201. doi:10.1626/pps.17.194

Munz, S., Feike, T., Chen, Q., Claupein, W., & Graeff-Hönninger, S. (2014). Understanding interactions between cropping pattern, maize cultivar and local environment in strip-intercropping system. *Agricultural and Forest Meteorology*, 195–196, 152–164. doi:10.1016/j.agrformet.2014.05.009

Oseni, T. O., & Aliyu, I. G. (2010). Effect of row arrangements on sorghum-cowpea intercrops in the semi arid savannah of Nigeria. *International Journal of Agriculture and Biology*, 12, 137–140.

Phalan, B., Onial, M., Balmford, A., & Green, R. E. (2011). Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. *Science*, 333, 1289–1291. doi:10.1126/science.1208742

Rodriguez-Navarro, D. N., Oliver, I., & Contreras, M. (2010). Soybean interactions with soil microbes, agronomical and molecular aspects. *Agronomy of Sustainable Development*, 31, 173–190. doi:10.1051/agr/2010023

Stoll, P., & Weiner, J. (2000). A neighborhood view of interactions among individual plants. In U. Dieckmann, R. Law, & A. J. Metz (eds.), *The geometry of ecological interactions: Simplifying spatial complexity* (pp. 11–17). Cambridge: Cambridge University Press.

Tschernke, T., Clough, Y., Wanger, T., Jackson, L., Motzke, I., Perfecto, I., … Whitbread, A. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation*, 151, 53–59. doi:10.1016/j.biocon.2012.01.068

Undie, U. L., Uwah, D. F., & Attie, E. (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. *Journal of Agriculture and Science*, 4, 37–50. doi:10.5539/jas.v4n4p37

Wang, Z., Zhao, X., Wu, P., He, J., Chen, X., Gao, Y., & Cao, X. (2015). Radiation interception and utilization by wheat/maize strip intercropping systems. *Agricultural and Forest Meteorology*, 204, 58–66. doi:10.1016/j.agrformet.2015.02.004

Willey, R. W., & Rao, M. R. (1980). A competitive ratio for quantifying competition between intercrops. *Experimental Agriculture*, 16, 117–125. doi:10.1017/j.fcr.2006.07.008

Yan, Y., Gong, W., Yang, W., Wan, Y., Chen, X., Chen, Z., & Wang, L. (2010). Seed treatment with uniconazole powder improves soybean seedling growth under shading by corn in relay strip intercropping system. *Plant Production Science*, 13, 367–374. doi:10.1626/pps.13.367

Yang, F., Huang, S., Gao, R., Liu, W., Yong, T., Wang, X., … Yang, W. (2014). Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red: Far-red ratio. *Field Crops Research*, 155, 245–253. doi:10.1016/j.fcr.2013.08.011

Yang, F., Wang, X., Liao, D., Lu, F., Gao, R., Liu, W., … Yang, W. (2015). Yield response to different planting geometries in maize-soybean relay strip intercropping systems. *Agronomy Journal*, 107, 296–304. doi:10.2134/ajronj14.0263

Yilmaz, S., Atak, M., & Erayman, M. (2008). Identification of advantages of maize-legume intercropping over solitary cropping through competition indices in the East Mediterranean Region. *Turkish Journal of Agriculture and Forestry*, 32, 111–119. Retrieved from http://www.dergipark.ulakbim.gov.tr
Zhang, G., Yang, Z., & Dong, S. (2011). Interspecific competitiveness affects the total biomass yield in an alfalfa and corn intercropping system. *Field Crops Research, 124*, 66–73. doi:10.1016/j.fcr.2011.06.006

Zhu, Y., Chen, H., Fan, J., Wang, Y., Li, Y., Chen, J., … Mundt, C. (2000). Genetic diversity and disease control in rice. *Nature, 406*, 718–722. doi:10.1038/35021046