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Effects of interspecific competition on crop yield and nitrogen utilisation in maize-soybean intercropping system

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Abstract: Intercropping system plays a crucial role in improving crop yield, nitrogen utilisation efficiency (NUE) and economic benefit. The difference in crop yield and interspecific relationship under different bandwidth and row ratio allocation patterns are still unclear. A field experiment was carried out to explore change regularities between crop yield and interspecific relationships under maize soybean intercropping with different bandwidths and row ratios. The results showed that the yield of intercropped crops was lower than that of the sole crop. The nitrogen accumulation (NA), NUE and nitrogen competition ratio was the highest under the intercropping mode with a bandwidth of 2.0 m, which indicated that this mode was more conducive to the N uptake and utilisation in crops. In all intercropping systems, nitrogen equivalent ratio (NER) and land equivalent ratio (LER) were all greater than one, indicating that intercropping systems were conducive to improving land utilisation efficiency and NUE. Under the same bandwidth pattern, expanding the maize soybean row ratio from 2:4 to 3:4 was beneficial to the improvement of LER, NER, NUE, crop group yield. In conclusion, it was preferable in the NA, NUE, crop group yield under the system of bandwidth 2.0 m and row ratio 2:2, which could be a reference for maize soybean intercropping system.

Keywords: *Zea mays* L.; *Glycine max* L.; rowing spacing; biodiversity; nutrient use efficiency

Intercropping is the simultaneous production of multiple crops on the same field. As an ancient cropping system, intercropping has a vast potential for realising sustainable agriculture. Intercropping provides 15–20% of the world's food supply (Lithourgidis et al. 2011) and alleviates the contradiction between population growth and the reduction of arable land (Fowler et al. 2015). Numerous studies have reported multiple benefits of intercropping systems, such as improving crop yield and maximising the utilisation of light, heat and water resources (Luo et al. 2016), reducing pest and disease incidence (Eskandari 2011), improving crop water utilisation efficiency (Yin et al. 2020), improving soil quality and carbon sequestration capacity (Cong et al. 2015), and increasing soil biodiversity (Jensen et al. 2020). Although maize and soybean intercropping has many advantages, but this planting mode has not to replace maize and soybean monoculture in China, because monoculture is more convenient for field management and mechanised harvesting than intercropping. However, with the effective solution of small mechanisation of maize and soybean in Southwest China (Du et al. 2018), intercropping systems of maize and soybean with different bandwidth row ratio will have broad prospects in the future agriculture development, which will provide a superior maize soybean intercropping scheme for developing countries or global countries.

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Nitrogen (N) plays an important role in plant growth, but excessive use of N fertiliser in China leads to environmental problems, such as serious biodiversity loss, lower N utilisation efficiency (NUE), and increased greenhouse gases (GHGs) emission (Hou et al. 2020, Tilman 2020). Intercropping can alleviate existing problems and increase crop yields at a low cost (Tilman et al. 2011) because legumes can fix N_2 and use soil N sources. Intercropping with gramineous crops also improves soil NUE. If maize soybean intercropping was applied globally, the N demand for fossil fertilisers could be reduced by about 26% (Jensen et al. 2020). In the future of agricultural development, it is necessary to optimise the field allocation mode to improve grain yield and NUE instead of only focusing on optimising the N fertiliser application rate (Wang et al. 2014). Therefore, the intercropping system provides a feasible approach to achieve the goal of sustainable agricultural development (Luo et al. 2016). Different maize and soybean row ratios had different effects on crop yield and NUE under intercropping patterns. In Pakistan, two rows of maize and three rows of soybean intercropping systems would improve crop yield and economic benefits by increasing water equivalent ratio and water use efficiency, which is conducive to maintaining field productivity. At the same time, this plant arrangement allows machine operations by smaller-scale equipment specially designed for maize soybean strip-intercropping systems in China (Raza et al. 2021). Under the relay-planting system of maize and soybean, when the row ratio of maize-to-soybean was 2:2, the crop yield and nutrient utilisation efficiency were the highest (Raza et al. 2020). Therefore, the system was widely used in the Southwest of China (Yang et al. 2014). Rowing spacing and intercrop arrangement play a vital role in the planting patterns of intercropping systems, which can influence the microclimate environment of interspecies, particularly the light transmission rate of crop groups (Liu and Song 2012). Different regions have different maize and soybean allocation patterns due to differences in light, heat and water resources. The issue which treatment under different row ratio configuration systems of maize soybean intercropping was conducive to improving the nitrogen equivalent ratio and nitrogen use efficiency is worth further study.

Interspecific and intraspecific competition is very important in intercropping systems. Intra- and interspecific competition usually cause that one crop grows well, but another crop is not growing well (Li et al. 2011). Therefore, when the interspecific and intraspecific competition is harmonious, the intercropping productivity will be improved. There are many approaches to optimise crop competition in intercropping systems, such as expanding the maize-to-soybean row ratio, which significantly reduced N accumulation (NA) in the soil and increased the total NA of maize (Zhang et al. 2015). However, there are few studies on inter- and intraspecific competition among crops in different intercropping systems of maize and soybean in China. The aims of this study are (*i*) to discuss the effects of maize-soybean intercropping under different row ratios on crop yield; (*ii*) use interspecific competition index to screen out the harmonious planting patterns of maize soybean interspecific relationship, aiming at providing an important basis for developing countries or global countries to improve the level of agricultural production, optimise the planting patterns and soil ecological environment.

MATERIAL AND METHODS

Field site. The field experiments were conducted in 2018–2019 at the Jiangxi Institute of Red Soil (116°20'E, 28°15'N) by using loam soil with the following properties: pH 5.72, organic carbon content 11.40 mg/kg, available N 102.76 mg/kg, available P 12.80 mg/kg, available K 174.08 mg/kg, total N 1.23 g/kg, total P 0.47 g/kg, total K 23.46 g/kg. The weather conditions (average temperature and monthly rainfall) during the growth stage of the intercrops in 2018 and 2019 are shown in Figure 1.

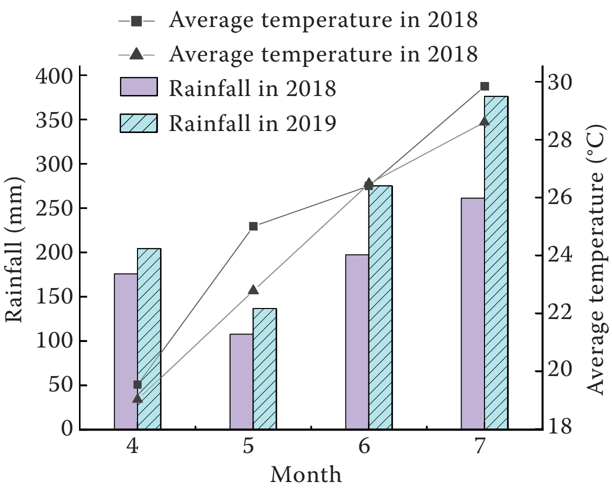

Figure 1. Change of average temperature and rainfall from April to July in 2018–2019

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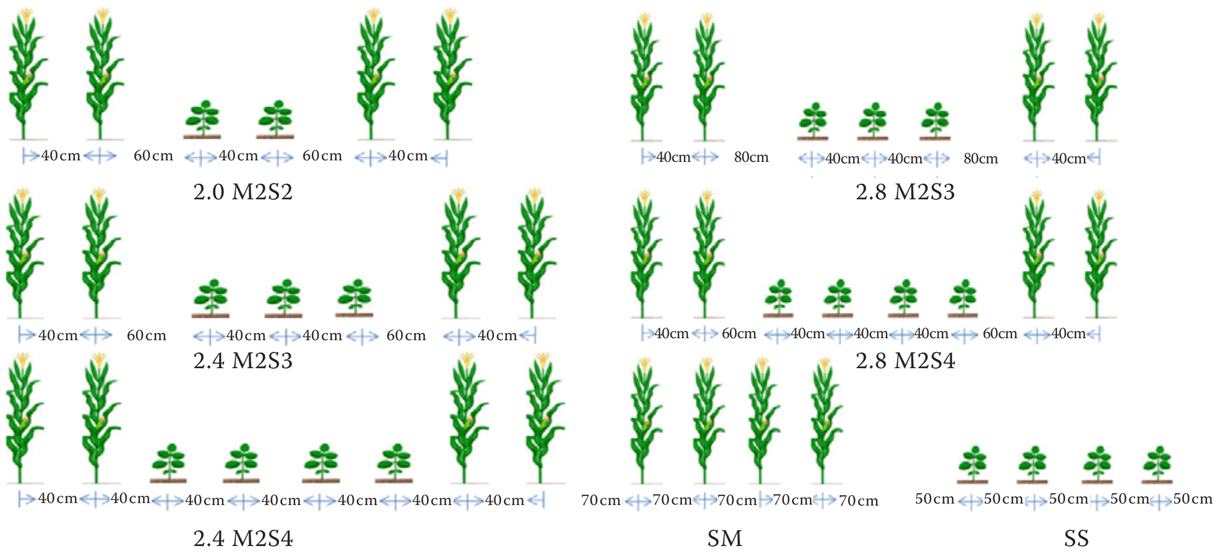

Figure 2. The layout of the seven cropping systems. 2.0 M2S2 – bandwidth 2.0 m (two rows maize with two rows soybean); 2.4 M2S3 – bandwidth 2.4 m (two rows maize with three rows soybean); 2.4 M2S4 – bandwidth 2.4 m (two rows maize with four rows soybean); 2.8 M2S3 – bandwidth 2.8 m (two rows maize with three rows soybean); 2.8 M2S4 – bandwidth 2.8 m (two rows maize with four rows soybean); SM – sole maize (row to row was 70 cm); SS – sole soybean (row to row was 50 cm)

Experiment design. A maize and soybean intercropping system was used in the field experiments. Every experimental block was 5 m long with two strips. The experimental design was laid out using a randomised complete block with 3 replicates. The plant population density was 60 000 and 150 000 per hectare for maize and soybean. This field study consisted of seven different planting pattern arrangements (Figure 2, Table 1).

The Jixiang-1 and Handou-1 maize and soybean cultivars were chosen for this study, respectively. The maize was planted in the 1st week of April in 2018 and 2019 and harvested in the last week of July 2018 and 2019. Soybean was planted in the 1st week of April in 2018 and 2019 and harvested in the 2nd week of July 2018 and 2019. A total of 270 kg/ha of pure N was applied to maize during the whole growth period according to base fertiliser:jointing fertiliser:ear fertiliser = 3:2:5. The base fertiliser for maize was 72 kg pure P/ha, and 90 kg pure K/ha. Soybean base fertiliser was applied 34.5 kg pure N/ha, 72 kg pure P/ha, and 36 kg pure K/ha. Other agro-

Table 1. Field configuration test design of different bandwidth and row ratio

Treatment	Bandwidth (cm)	Row ratio (maize:soybean)	Plant spacing (maize/soybean) (cm)	Maize-soybean row spacing (cm)	Plant population density (maize/soybean)
2.0 M2S2	200	2:2	16.6/6.6	60	60 000/150 000
2.4 M2S3	240	2:3	13.8/8.3	60	60 000/150 000
2.4 M2S4	240	2:4	13.8/11	40	60 000/150 000
2.8 M2S3	280	2:3	11.9/7.1	80	60 000/150 000
2.8 M2S4	280	2:4	11.9/9.5	60	60 000/150 000
SM	–	–	23.8	–	60 000
SS	–	–	13.3	–	150 000

2.0 M2S2 – bandwidth 2.0 m (two rows maize with two rows soybean); 2.4 M2S3 – bandwidth 2.4 m (two rows maize with three rows soybean); 2.4 M2S4 – bandwidth 2.4 m (two rows maize with four rows soybean); 2.8 M2S3 – bandwidth 2.8 m (two rows maize with three rows soybean); 2.8 M2S4 – bandwidth 2.8 m (two rows maize with four rows soybean); SM – sole maize (row to row was 70 cm); SS – sole soybean (row to row was 50 cm)

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nomic measures were used according to crop requirement and famer's practices.

Sampling and measuring. Each experiment plot has two strips of maize and soybean, which were divided into two roughly equal sections. One section was used for analysing the accumulated biomass of maize-soybean patterns at a different stage. In the other section, at the harvest stage of maize and soybean, maize and soybean were harvested using sickle at ground level from all treatments. Then, all the sampled plants were dried for the next 10 days. After that, dried soybean and maize plants were threshed and weighed to measure the sole cropped and intercrop of each plot yield and changed into kg/ha. At the mature stage of maize and soybean, six soybean and three maize plants were harvested successively from all treatment, sampled plants of maize and soybean were oven-dried for 1 h at 105 °C, dried to constant weight at 80 °C, and calculated dry-matter accumulation (kg/ha). The N content in the plant sample of maize and soybean was analysed using the Kjeldahl procedure.

Calculations and statistical analyses. (1) Land equivalent ratio (LER). The LER is defined as the ratio of the area under sole cropping to the area under intercropping needed to give the same yield (Mead et al. 1980). Yim and Yis represent the seed yield of maize and soybean in intercropping, respectively, and Ysm and Yss represent the seed yield of maize and soybean sole, respectively. When LER > 1 means that intercropping system favours the crop growth and yield of intercropping species. LER was determined as:

$$\text{LER} = \text{Yim/Ysm} + \text{Yis/Yss} \quad (1)$$

(2) Nitrogen equivalent ratio (NER). NER was used as a measure of N superiority. Nim and Nis represented NA in maize and soybean, respectively on total intercropping land area, Nsm and Nss are the NA of sole maize and sole soybean, respectively. When NER > 1 indicates an intercropping advantage or indicates an intercropping disadvantage.

$$\text{NER} = \text{Nim/Nsm} + \text{Nis/Nss} \quad (2)$$

(3) Nitrogen accumulation (NA) = weight of dry matter (kg/ha) × N (%)/100

(4) Nitrogen utilisation efficiency (NUE). Y is the yield per unit area, and U is the accumulation of N in crops.

$$\text{NUE} = \text{Y/U} \quad (3)$$

(5) Nitrogen competitive ratio (NCR). It measures the degree of competition between one crop and another in the intercropping system. NCRm represents the competitive ratio of maize to soybean, NCRm and NCRs represent the N uptake in the maize and soybean intercropping system, and Zis and Zim represent the area occupied by maize and soybean in the intercropping system relative to the ratio of sole cropping. When NCRm > 1, the competitiveness of maize in the intercropping system was higher than that of soybean. Otherwise, the competitiveness of maize in the co-growth period of the intercropping system was lower than that of soybean.

$$\text{NCRm} = \text{NCRm/NCRs} \times \text{Zis/Zim} \quad (4)$$

Microsoft Excel 2019 (Microsoft, Redmond, USA) was used for data statistics, and SPSS 20.0 (IBM Corporation, Chicago, USA) was used for the Fisher test. The least significant difference (*LSD*) and Duncan method were used for post-hoc multiple comparisons, difference significance test and interaction analysis. Origin 2018 (OriginLab, Northampton, USA) was used for plotting.

RESULTS AND DISCUSSION

Effects of different intercropping patterns on nitrogen accumulation and nitrogen utilisation efficiency of crops. In this study, both NA and NUE of sole maize were higher than that of intercropping treatments. In intercropping systems, NA and NUE of bandwidth 2.0 m were the better, which showed a significant difference from that of SM treatment. Among the three bandwidth treatments, the NA and NUE of maize were the highest in the 2.0 m, which was beneficial to the N uptake and NUE in two years (Figure 3). The reason may be that the maize-to-maize row spacing (70 cm) of sole maize is wide than that of intercropping maize (40 cm), which is conducive to field ventilation, N uptake, weakening the competition of light, heat, water resources and N between individuals, and increasing the dry matter accumulation of sole maize. The NA of maize under the system of 2.0 m bandwidth and 2:2 row ratio ($B_{2.0}R_{2:2}$) was the highest, which was 3.8% less than that of sole maize (Figure 3A). Compared with other intercropping systems, maize plant spacing is the largest (16.9 cm), while soybean plant spacing is the lowest (6.6 cm). Soybean could fix more N_2 than other intercropping systems, and maize individual shading effect is less than other intercropping maize, so it is more conducive to NA. There was no significant difference in NUE between intercropping

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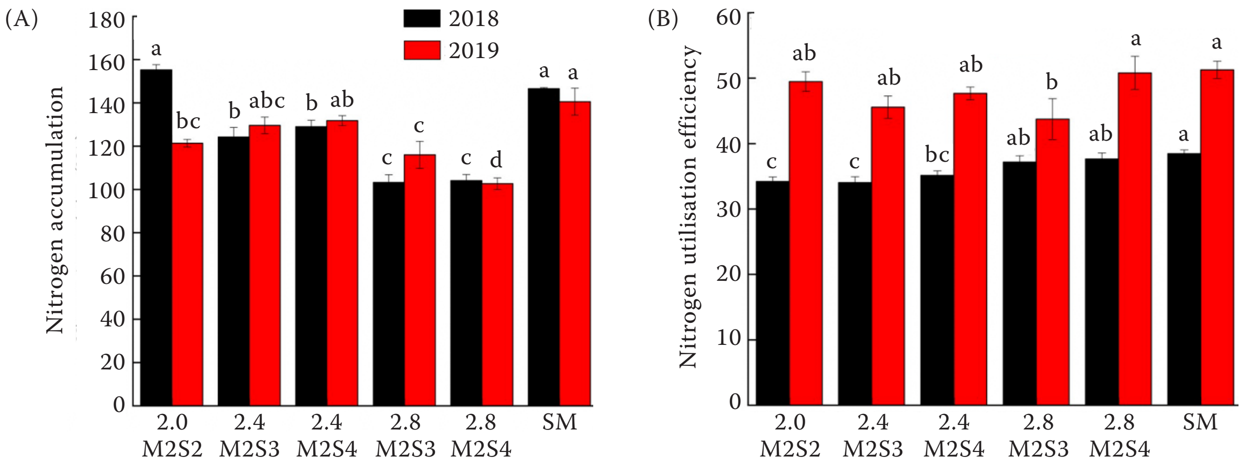

Figure 3. (A) Nitrogen accumulation and (B) nitrogen utilisation efficiency of maize. Different small letters mean significantly different at $P < 0.05$. Same on the below. I mean ± standard error. 2.0 M2S2 – bandwidth 2.0 m (two rows maize with two rows soybean); 2.4 M2S3 – bandwidth 2.4 m (two rows maize with three rows soybean); 2.4 M2S4 – bandwidth 2.4 m (two rows maize with four rows soybean); 2.8 M2S3 – bandwidth 2.8 m (two rows maize with three rows soybean); 2.8 M2S4 – bandwidth 2.8 m (two rows maize with four rows soybean); SM – sole maize (row to row was 70 cm)

with 2.8 m bandwidth and 2:4 row ratio ($B_{2.8}R_{2:4}$) with that of sole maize (Figure 3B), the reason is that the NA under the $B_{2.8}R_{2:4}$ is lower than that of other intercropping treatments in two years, and expanding the bandwidth makes maize planting more conducive to photosynthesis, which is conducive to the improvement of maize yield. Thus, compared with the treatments of 2.8 m bandwidth and 2:3 row ratio ($B_{2.8}R_{2:3}$), maize yield and NUE are increased, results of which are consistent with previous reports (Tan et al. 2020, Raza et al. 2020). Under the mode with a bandwidth of 2.4 m and 2.8 m, the NUE of maize increased by 4.06% and 9.72%, respectively, when a row of soybean was planted (Figure 3). The reason is that the row ratio allocation was increased, and the interspecific distance was reduced. It was possible that the underground maize and soybean root interaction ability was enhanced (Mommer et al. 2016), which was conducive to the N uptake of intercropped maize and improved the NUE of maize.

Effects of different intercropping patterns on nitrogen competitive ratio of crops. By averaging

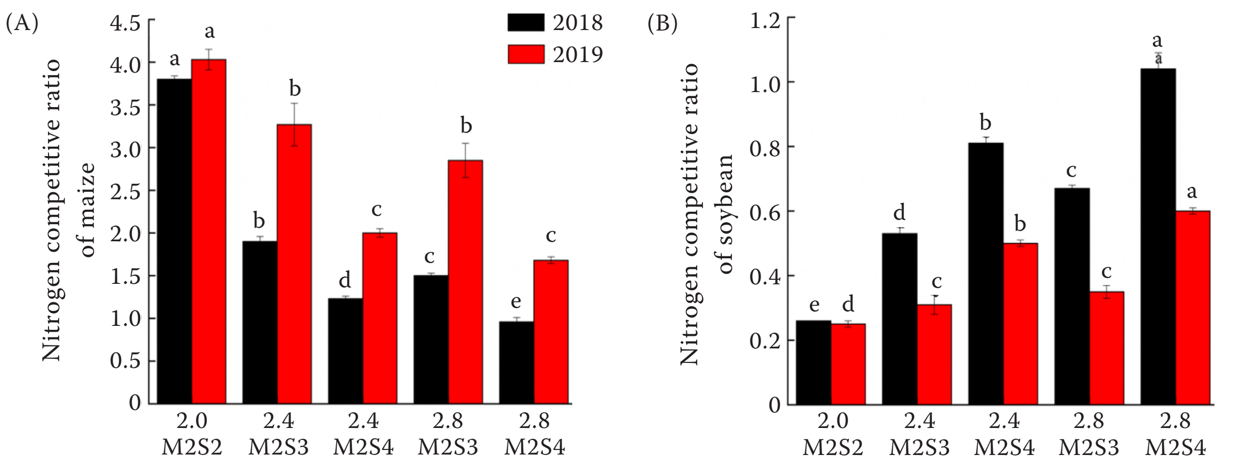

Figure 4. (A) Nitrogen competitive ratio of maize to soybean, and (B) nitrogen competitive ratio of soybean to maize. I mean ± standard error. 2.0 M2S2 – bandwidth 2.0 m (two rows maize with two rows soybean); 2.4 M2S3 – bandwidth 2.4 m (two rows maize with three rows soybean); 2.4 M2S4 – bandwidth 2.4 m (two rows maize with four rows soybean); 2.8 M2S3 – bandwidth 2.8 m (two rows maize with three rows soybean); 2.8 M2S4 – bandwidth 2.8 m (two rows maize with four rows soybean)

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2-year NCR, it was found that NCRm > 1 and NCRm > NCRs. The $B_{2.0}R_{2:2}$ had the highest NCRm and the lowest NCRs among the intercropping systems, indicating that maize under $B_{2.0}R_{2:2}$ system showed advantages in N uptake compared with soybean. When the bandwidth is 2.4 m or 2.8 m, by expanding the maize-to-soybean row ratio from 2:4 to 3:4, the NCRm decreased, and the NCRs increased. The results of this study showed that the NCRm and NCRs were all greater than one and ranged from 1.32 to 3.92 at the harvest stage (Figure 4), indicating that maize had an advantage over soybean in N uptake at the later growth stage and that legumes had a significant compensation effect on gramineous crops (Yang et al. 2018). The reason may be that the root exudates of Gramineae promote the synthesis of leguminous flavonoids, increase the nodulation rate of legumes, enhance the N_2 fixation of leguminous crops, and drive the interspecific promotion effect (Li et al. 2016). Therefore, the potential driving factors for intercropping yield increase are related to maize and the complementarity of species (Li et al. 2020). The results are consistent with those of previous studies (Yang et al. 2013). In our study, with the same bandwidth, expanding the maize-to-soybean row ratio from 2:4 to 3:4, the NCRm decreases and the NCRs increase. The reason may be that due to the decrease of intercropping distance, the N compensation effect of soybean to maize in the intercropping system is strengthened, which weakens the absorption effect of intercropping maize on soil N.

Effects of different intercropping patterns on nitrogen equivalent ratio and land equivalent ratio of crops. The results showed that intercropping maize with different bandwidth modes showed obvious advantages over sole maize, with LER ranging from 1.35–1.59 and NER ranging from 1.51–1.72 (Figure 5), indicating that intercropping maize yield and NA is nearly 1.35–1.59 and 1.51–1.72 times compared with sole maize. The results were consistent with previous research results (Yang et al. 2013). In our study, with the same bandwidth, expanding the maize-to-soybean row ratio from 2:4 to 3:4, both LER and NER are all increased. The reason is that the spatial pattern of crops is improved, and the interspecific distance is reduced, but land-use efficiency and NUE are all increased. When maize and soybean rows were 60 cm, the bandwidth was expanded from 2.0 m to 2.8 m, the LER and NER both decreased. The reason was that with the increase of the row ratio and bandwidth, the yield of intercropping maize decreased, leading to a decrease in the pLER (partial land equivalent ratios of the two intercropped species) of maize.

Effects of different intercropping patterns on crop yield. It can be seen from the data in the table that there are differences in crop yield under years and treatments, which indicates that different bandwidth row ratio configurations could improve the field productivity by changing the field layout. The yield of maize and soybean sole was higher than that of intercropping maize and soybean. This is not consistent with the results of Yang et al. (2018). Maybe the planting environment and experimental design of this experiment are different from those of Yang et al. (2018). The results of the two-factor variance

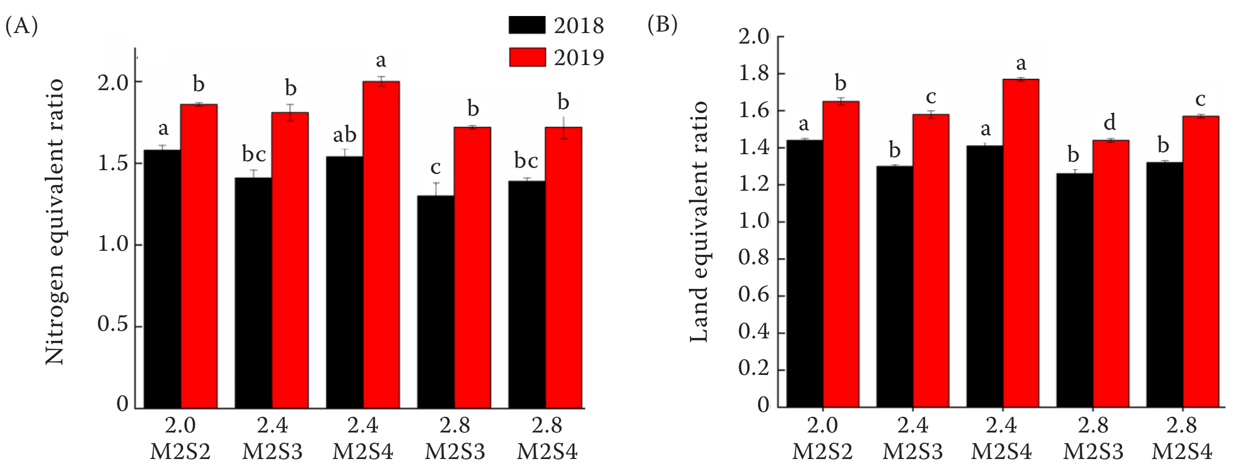

Figure 5. (A) Nitrogen equivalent ratio, and (B) land equivalent ratio. I mean ± standard error. 2.0 M2S2 – bandwidth 2.0 m (two rows maize with two rows soybean); 2.4 M2S3 – bandwidth 2.4 m (two rows maize with three rows soybean); 2.4 M2S4 – bandwidth 2.4 m (two rows maize with four rows soybean); 2.8 M2S3 – bandwidth 2.8 m (two rows maize with three rows soybean); 2.8 M2S4 – bandwidth 2.8 m (two rows maize with four rows soybean)

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Table 2. Effects of different intercropping treatments on group yield

Year (Y)	Treatment (T)	Maize yield	Soybean yield	Group yield
			(kg/ha)	
2018	2.0 M2S2	6 029.60 ± 34.12	612.33 ± 11.35	6 641.93 ± 23.02
	2.4 M2S3	4 797.00 ± 52.81	673.20 ± 3.23	5 470.20 ± 53.81
	2.4 M2S4	5 146.50 ± 31.37	743.07 ± 13.67	5 889.57 ± 39.10
	2.8 M2S3	4 355.73 ± 97.25	705.60 ± 11.18	5 061.33 ± 104.56
	2.8 M2S4	4 450.00 ± 50.02	759.53 ± 22.79	5 209.53 ± 28.49
	SM	6 404.80	–	–
	SS	–	1 222.00	–
2019	2.0 M2S2	6 666.67 ± 115.66	672.22 ± 4.49	7 338.89 ± 111.18
	2.4 M2S3	6 545.00 ± 120.19	627.85 ± 7.29	7 177.85 ± 120.74
	2.4 M2S4	6 977.78 ± 124.10	736.40 ± 15.51	7 714.18 ± 111.05
	2.8 M2S3	5 595.24 ± 148.77	611.91 ± 18.90	6 207.14 ± 142.52
	2.8 M2S4	5 780.95 ± 141.50	700.27 ± 9.42	6 481.22 ± 135.41
	SM	7 992.40	–	–
	SS	–	823.10	–
Two-factor variance analysis (*F*)				
Y		451.02**	12.17*	466.92**
T		68.31**	25.18**	72.78**
Y × T		11.18**	9.95**	16.71**

Y × T – interaction; *P < 0.05; **P < 0.01. 2.0 M2S2 – bandwidth 2.0 m (two rows maize with two rows soybean); 2.4 M2S3 – bandwidth 2.4 m (two rows maize with three rows soybean); 2.4 M2S4 – bandwidth 2.4 m (two rows maize with four rows soybean); 2.8 M2S3 – bandwidth 2.8 m (two rows maize with three rows soybean); 2.8 M2S4 – bandwidth 2.8 m (two rows maize with four rows soybean); SS – sole soybean (row to row was 50 cm); SM – sole maize (row to row was 70 cm)

analysis showed that there were great significant differences (P < 0.01) in maize yield, soybean yield, group yield among different treatments (Table 2). There were significant differences (P < 0.05) in soybean yield in different years, and have great significant differences (P < 0.01) among maize yield, crop group yield. The interaction between years and treatments also great significantly affected crop yield (P < 0.01). In this study, the group yield was the highest under the system of $B_{2.0}R_{2:2}$, because the NA and NCRm of maize in 2.0 m bandwidth is the largest, which is conducive to the increase of crop yield and absorption of soil N. With the mode of bandwidth 2.4 m and bandwidth 2.8 m, expanding the maize-to-soybean row ratio from 2:3 to 2:4, the crop group yield is increased, which is consistent with the research results of Tan et al. (2020). It is indicated that the group yield can be improved by reducing the interspecific distance and increasing row ratio configuration under the same bandwidth because the high yield of crops is caused by the underground interaction between the two crops. Intercropping legume crops can significantly improve the maize grain yield and aboveground biomass (Li et al. 2007), which is conducive to the increase of crop yield.

In China, in order to realise mechanised planting and harvesting, a convenient, simple and higher efficient small machinery has been created. However, this kind of machine was only used on a small-scale; it has not been widely applied. The better maize soybean row ratio of this study was 2:2. Combined with smaller-scale equipment, the planting system would provide better theoretical support for the future development of maize soybean intercropping agriculture in developing countries or global countries and would provide a reference scheme for large-scale demonstration planting.

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