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ORIGINAL RESEARCH

Does reduced intraspecific competition of the dominant species in intercrops allow for a higher population density?

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Abstract

Dominant species in intercropping experience less resource competition compared with its monoculture. This reduced competition for resources may allow cultivating the dominant species at an increased density in intercropping to obtain greater yield. However, experimental results are inconclusive when the optimal within row density in the sole crop is not well established. Here, we conducted a two-year experiment to test the hypothesis that optimal within row plant density of dominant species in intercropping would be higher in the intercrop than in the sole crop. We tested three maize densities (3, 4.5, and 6 plants m^{-1}) in both sole maize and two replacement designed intercrops. The row configurations of two intercrops are two rows maize intercropped with four rows peanut (M2P4) and four rows maize intercropped with four rows peanut (M4P4). Peanut was grown at the same plant density of 12 plants m^{-1} row in both sole crop and intercrops. The results indicated that increasing maize density from the optimal density in monoculture is not worthy of promotion to improve yield in intercropping, which denied our hypothesis. The land equivalent ratios (LER) in the dry year (2017) were higher than the wet year (2016). Maize yields per unit area of the whole intercropping system were highest with densities of 4.5 and 6 plants m^{-1} row, with no significant difference between these two densities. Maximum maize yields in sole cropping were obtained with maize densities of 6 plants m^{-1} row. Intercropping provided higher yields at low and intermediate sole crop maize densities, but not at high sole crop maize density. Average land equivalent ratios at 3, 4.5, and 6 plants m^{-1} of maize were 1.09, 1.04, and 0.95 in 2016, and 1.07, 1.10, and 1.02 in 2017. Our results suggest that intercropping performs better at conditions with less resources than adequate resources.

KEYWORDS

density, intraspecific competition, land equivalent ratio, row configuration, yield

1 | INTRODUCTION

Intercropping is the cultivation of multiple crop species in the same field during all or part of their growing period. Due to the yield increase per unit area (Lithourgidis et al., 2011; Stomph et al., 2020) and efficient utilization of natural resources (Li et al., 2003), intercropping is regarded as one of the most prominent systems to dealing with the problem of land shortage. The land equivalent ratio, a measure for land use efficiency of intercropping, ranges globally from 1.22 to 1.32 as shown in meta-analyses (Yu et al., 2015; Martin-Guay et al., 2018; Xu et al., 2020). Intercropping can also improve nutrient cycling and build-up of organic soil carbon and nitrogen (Bedoussac et al., 2015; Cong et al., 2015) and reduce severity of pests, diseases, and weeds (Boudreau, 2013; Liebman & Dyck, 1993; Risch, 1983; Zhang, Dong, et al., 2019; Zhang, Zhang, Sun, et al., 2019). Furthermore, the intercropping practice reduces risk of crop failure (Giller, 2001).

The combination of cereal and legume is the most commonly used intercropping combination (Li et al., 2003). Maize is a major component species used in intercrops worldwide. Peanut ranks second the most important grain legume food only after soybean (Maingi et al., 2001) and is one of the five most important oilseed products. In semi-arid environment, such as Liaoning China, rainfed maize frequently suffers drought during growing season (Cai et al., 2017), and sole peanut causes wind erosion because of loosening surface soil at harvest time (Tan et al., 2015). Therefore, farmers grow maize and peanut as a strip intercrop, normally two rows maize intercropped with four rows peanut. In the intercropping, maize improves iron nutrition of peanut (Zuo et al., 2000). Peanut, on the other hand, improves available nitrogen in the soil of maize, as peanut is able to fix the atmospheric N_2 with rhizobia (Inal & Gunes, 2008). Previous studies on maize and peanut intercropping did not show a significant improvement on yield in semi-arid environment (Wang et al., 2020; Zhang et al., 2020). We hypothesized that increasing the plant density of maize, a major contributor to yield advantage in the intercropping, might enhance the land productivity.

Plant density is an important manage strategy of affecting yield formation in different cropping systems. The yield response to plant density is the comprehensive effects of individual yield components when plant density changes. Increasing plant density, the competition for resources between plants therewith increases. Then, dry matter allocation to leaves, stems, and roots might increase to strengthen the competitive ability for resources (Echarte et al., 2011; Li et al., 2001; Wang et al., 2016; Zhang et al., 2015). Maize yield components decline with increasing plant density due to the increased intraspecific competition (Hashemi et al., 2005). Optimizing plant density becomes a major approach to obtain high yield (Tokatlidis et al., 2011). Maize yield response to plant density is more or less parabolic (Sangoi et al., 2002; Sarlangue et al., 2007), and the optimal plant density depends on genotype, environment and management, such as fertilization, irrigation, and cropping system (Al-Kaisi & Yin, 2003; Amelong et al., 2017; Berzsenyi & Tokatlidis, 2012; Zhang et al., 2017). However, we have little knowledge on density-yield response in intercropping.

In intercropping, both inter- and intraspecific interactions determine the degree of competition and facilitation for light, water, and nutrient resources, and thus contribute to total yields (Vandermeer, 1989). Resource competition not only affects the growth rates and biomass formation, but also the dry matter allocation to different organs (Huang et al., 2018; Violle et al., 2009). In intercropping, the resource uptake and use efficiencies are often higher than in sole cropping, and ultimately improve yield (Li et al., 2003; Mao et al., 2012; Tan et al., 2020). This intercropping advantage occurs when interspecific competition is weaker than intraspecific competition or mutual facilitation between component crops (Hauggaard-Nielsen et al., 2001a, 2001b; Snaydon & Satorre, 1989). The species, which is more competitive, always capture more resources to produce greater biomass and grain yield in intercropping compared with its sole cropping (Wang et al., 2020). The species, which is less competitive, often be suppressed and display a yield reduction under the competition with dominant crops (Zhang et al., 2020). The intraspecific competition might be affected by the interspecific competition when two crops grow together. The density response for intercropped component crops might different with their sole crops, due to the differences in canopy structure and source-sink relationship (Zhang et al., 2020).

Studies on maize/soybean intercropping have shown that greater yields in intercropping may be obtained by keeping the overall density of maize in the intercrop the same as in the sole crop (Chen et al., 2019). One way of maintaining overall plant density of maize in the intercrop equal to the sole crop is to increase the number of plants within the maize rows to compensate for the reduction in number of maize rows needed to allow the planting of the companion crop (Yang et al., 2015). A Previous study (Xia et al., 2019) explored the yield response to increasing maize density by shortening plant distance within a maize row in maize/peanut intercropping and showed a positive correlation. However, there are no studies to explore how optimal plant density in intercropping differs with that in sole crops when intercropping is replacement designed. Hence, it remains unclear whether intercropping allows increasing the density of the dominant species in terms of plants per meter row above what is optimal in sole cropping. Here, we tested the hypothesis that optimal within row plant density of maize was higher in intercropping than in the sole maize stand.

2 | MATERIALS AND METHODS

2.1 | Experimental design

A field experiment with permanent plots was conducted in 2016 and 2017 in Fuxin (42°09′02″N, 121°43′48″E), Liaoning, Northeast China. The region has cold dry winters and hot summers, and is classified as Dwa in the Köppen-Geiger classification (Peel et al., 2007). The average annual precipitation from 1965 to 2015 was 531 mm during the growing season (May–September) with a standard deviation of 134 mm. The temperature and rainfall in the experimental years are shown in Figure 1. In 2016 and 2017, the total annual rainfall was 580 and 386 mm, respectively, and the rainfall during the growing season (May–September) was 492 and 351 mm, respectively. The soil is sandy Arenosol (FAO, 2015) with a bulk density of 1.45 g cm^{-3} averaged over 0–100 cm soil layer. The organic matter in the top 20 cm soil layer is 14.4 g kg^{-1}, total nitrogen (N) 0.78 g kg^{-1}, available N 45.2 mg kg^{-1}, available phosphorus 17.4 mg kg^{-1}, and available potassium 69.5 mg kg^{-1}.

The experiment was laid out as a complete randomized block design with 3 replicates. Plot area was 96 m^2 (8 m length × 12 m width). We used the maize hybrid "Zhengdan 958" and the peanut hybrid "BS1016." Both hybrids are commonly used locally. Ten treatments were tested in this study including four cropping systems and 3 plant densities in maize. The four cropping systems were sole maize, sole peanut, intercropping as two rows maize alternated with four rows of peanut (M2P4) and intercropping as four rows maize alternated with four rows of peanut (M4P4).

If interspecific interaction affects the effect of modified maize density in the row, this would be expressed in both maize rows in M2P4 and in the outer maize rows of the maize strip in M4P4. Three maize plant densities in the row were tested, that is, 3 (common practice), 4.5, and 6 plants per meter row length (plants m^{-1}), which were equivalent to 6, 9 and 12 plants m^{-2} in sole maize. These densities were used both in pure stands and intercrops. Peanut plant density (plants per meter row length) was in all treatments 12 plants m^{-1} row. Distance between rows was 50 cm in maize, in peanut and between species strips in intercropping (Figure 2). The species land use proportion was 0.5 for both maize and peanut in M4P4, and 0.33 for maize and 0.67 for peanut in M2P4. The overall plant density in the intercrop (plants per unit intercrop area; plants m^{-2}) is obtained by multiplying plants per meter row length and row length density (m row m^{-2} intercrop area, Table 1).

Both maize and peanut were sown on 21 May in 2016 and 24 May in 2017, and harvested on 30 September in both years. Row orientation was north-south and plots were in fixed locations in both years. Photographs of sole peanut and M2P4 intercropping at seedling and flowering stages are shown in Figure 3. The experiment was rainfed. Fertilizers was applied as farmers' practice in all treatments at sowing: 112 kg ha^{-1} of N, 112 kg ha^{-1} of P_2O_5, and 112 kg ha^{-1} of K_2O.

2.2 | Measurements of yields and yield components

To determine yield of maize and peanut in the intercrops and sole crops, all plants in an 8 m^{-2} (6 m^{-2} for M2P4) final subsampling area in the center of each plot were harvested on 30 September of each year (Zhang et al., 2020). To determine yield, cobs of maize and pods of peanut were air-dried to a grain water content of 14% and threshed by hand.

To determine yield components, all plants of maize and peanut and cobs for maize in the final sampling were counted. To determine pod number per plant, all plants and pods in one-meter row of peanut were counted. Then, ten

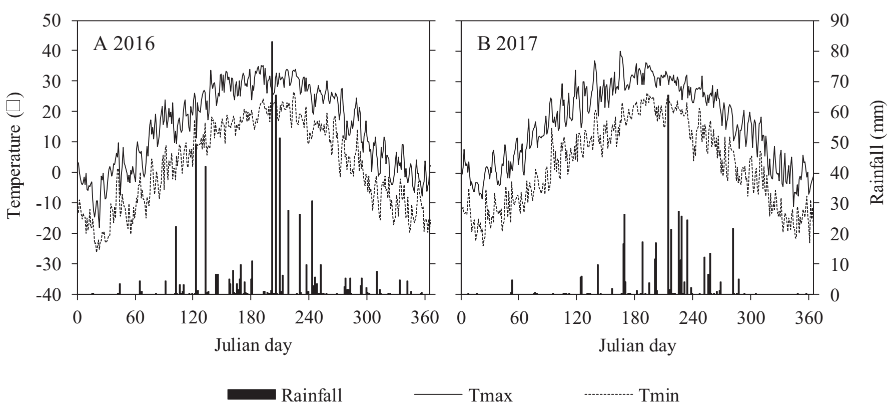

FIGURE 1 Daily maximum (Tmax) and minimum (Tmin) temperatures and rainfall in 2016 (a) and 2017 (b) in Fuxin, Liaoning. The total annual rainfall was 580 mm in 2016 and 386 mm in 2017

A June 25 B August 1

FIGURE 2 Photograph of the experiment with sole peanut in the foreground and M2P4 intercropping in the background. The photograph in Panel a was taken on 25 June 2016, while the photograph in Panel b was taken on 1 August 2016

TABLE 1 Plant densities and related metrics for the sole crops and the two intercrop configurations

	Plants per m row (plants m^{-1})		Row length density (m m^{-2})		Overall plant density (plants m^{-2})		Land use proportion (m^2 m^{-2})	
System	Maize	Peanut	Maize	Peanut	Maize	Peanut	Maize	Peanut
Sole	3.0	12	2.0	2.0	6.0	24	1.0	-
	4.5	12	2.0	2.0	9.0	24	1.0	-
	6.0	12	2.0	2.0	12.0	24	1.0	-
M4P4	3.0	12	1.0	1.0	3.0	12	0.5	0.5
	4.5	12	1.0	1.0	4.5	12	0.5	0.5
	6.0	12	1.0	1.0	6.0	12	0.5	0.5
M2P4	3.0	12	0.67	1.33	2.0	16	0.33	0.67
	4.5	12	0.67	1.33	3.0	16	0.33	0.67
	6.0	12	0.67	1.33	4.0	16	0.33	0.67

Overall plant density is expressed as the number of plants of a species per unit area of the whole intercropping system. The proportion of the land area is the land assigned to a component crop in the intercropping.

cobs and ten pods were selected randomly to count kernel numbers per cob for maize and seed number per pod for peanut. Finally, 100 kernels of maize and seeds of peanut were randomly selected to measure kernel weight. All measurements were done separately for border rows and inner rows of maize and peanut in both M2P4 and M4P4. The border row was the first row adjacent to another species, and the inner rows were the second and third rows (data were averaged).

Ten plants of each species in the intercrops (if present, separately for border row as well as inner row) and sole crops were randomly selected to determine final aboveground dry matter per plant and per meter row length. The dry matter was used to quantify the relationship between biomass yield (g m^{-1} row) and plant density (plants m^{-1} row).

2.3 | Data analysis

2.3.1 | Land equivalent ratio

Land equivalent ratio (LER) was defined as the relative land area required as sole reference crops to produce the same yield as intercropping, used to evaluate yield and land advantage in intercropping (Rao & Willey, 1980). The LER_j was calculated as the sum of the partial land equivalent ratios for each maize plant density *j* expressed as plants per meter row length (plants m^{-1} row). The $pLER_{m,j}$ and $pLER_{p,j}$ are the partial land equivalent ratios for maize and peanut, respectively, at maize plant density *j* (Connolly et al., 2001; Weigelt & Jolliffe, 2003).

$$LER_j = pLER_{m,j} + pLER_{p,j} = \frac{Y_{m,j}}{M_{m,j}} + \frac{Y_{p,j}}{M_p} \quad (1)$$

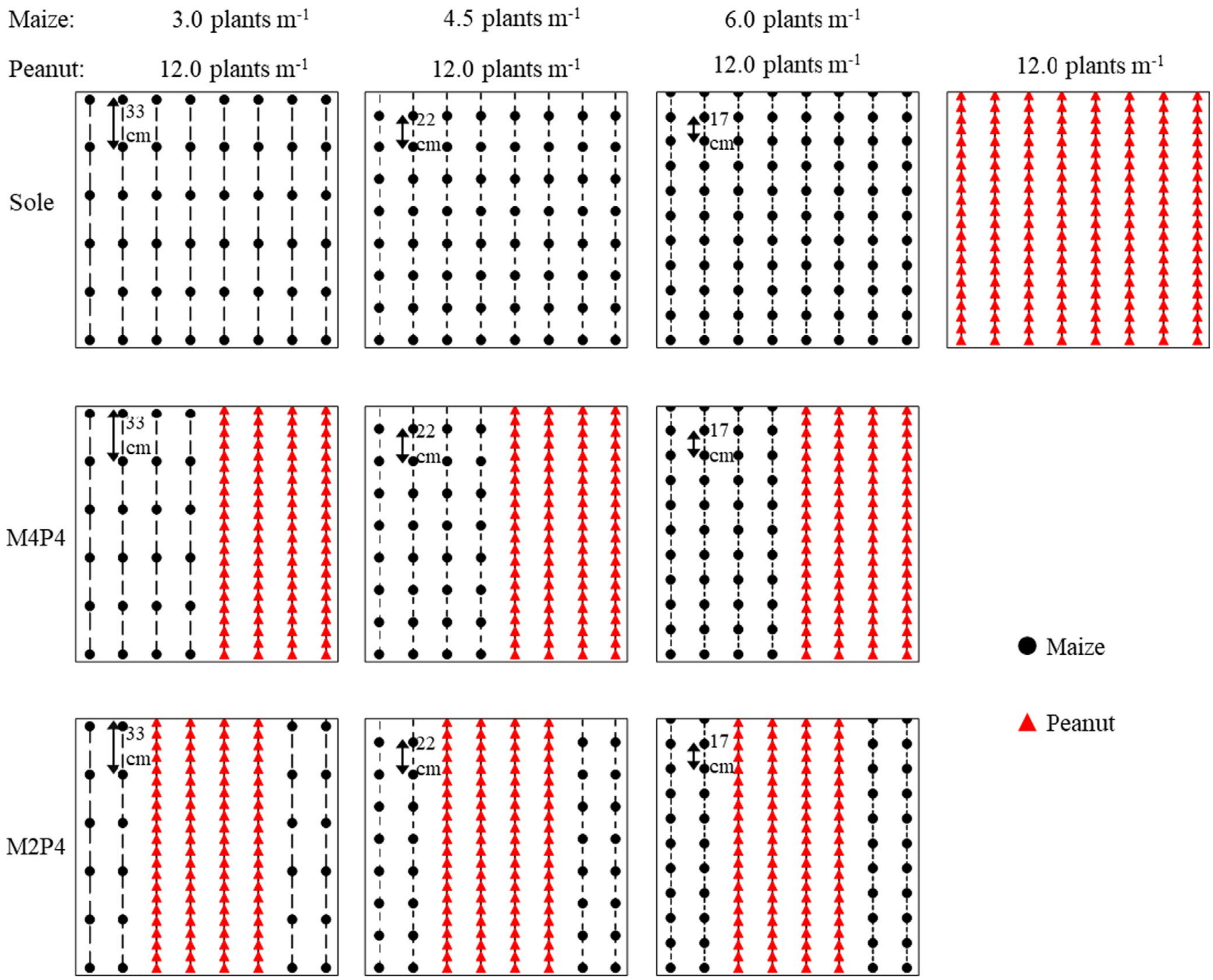

FIGURE 3 Experimental layout. The first row represents sole crops (three for maize at different densities) and one for peanut. The second row of panels represents M4P4 intercropping, with alternating strips of four maize rows and strips of four peanut rows. The third row of panels represents M2P4 intercropping with alternating strips of two maize rows and four peanut rows. All row distances were 50 cm. Maize was grown at three different plant densities in the row: (1) 3 plants/m row (left most panels), (2) 4.5 plants/m row (second column of three panels), (3) 6 plants/m row (third column of three panels). The panel in the far right and first row is for sole peanut. Peanut was grown at 12 plants/m row

where subscript *m* indicates maize, and *p* indicates peanut. $Y_{\mathrm{m,j}}$ and $Y_{\mathrm{p,j}}$ indicate maize and peanut yield in intercropping with maize density of *j*. $M_{\mathrm{m,j}}$ indicates maize yield in sole cropping with maize density of *j*. Sole crop yield of peanut is not affected by maize density; therefore, M_{p} does not have a subscript *j*. $\mathrm{LER_j}$ values greater than one indicate intercropping is more productive and efficient in using resources than sole cropping, and the values smaller than one indicate sole crops have yield advantage over intercropping.

2.3.2 | Maize biomass response to density

A range of mathematical models have been used to formulate relationships between yield or biomass and plant density in field crops (Bleasdale & Nelder, 1960; Shinozaki & Kira, 1956). Here, we use a model proposed by Watkinson (1980).

$$B = \frac{W_{\mathrm{m}} \times \mathrm{PD}}{(1 + a \times \mathrm{PD})^{b}} \tag{2}$$

where B is the aboveground dry matter per meter row length (g m^{-1}), PD is the maize plant density expressed as plants per meter row length (plants m^{-1}). W_{m} is the potential aboveground dry matter per plant in the absence of competition (g plant^{-1}). The parameter a expresses the strength of intraspecific competition (m plant^{-1}) and can be interpreted as the ecological neighborhood of an individual plant in intercropping and sole cropping, which is the row length that an individual plant requires to achieve W_{m} at a given row spacing (Li et al., 2016;

TABLE 2 Yields of maize and peanut in the intercropping and sole cropping in response to maize density in 2016 and 2017 in Fuxin, Liaoning, China

		Plants per meter row (plants m^{-1})		Overall yield (t ha^{-1})			
Year	**System**	**Maize**	**Peanut**	**Maize**	**Δ (%)**	**Peanut**	**Δ (%)**
2016	Sole	3.0	12	9.93 b	—	2.72	—
		4.5		12.12 a	22.1		—
		6.0		12.55 a	26.4		—
	SE			0.50	—	0.13	—
	M4P4	3.0	12	7.06 b	—	1.09 a	—
		4.5	12	8.36 a	18.4	0.96 a	−11.9
		6.0	12	7.56 ab	7.1	0.89 a	−18.3
	SE			0.25	—	0.06	—
	M2P4	3.0	12	4.72 b	—	1.63 a	—
		4.5	12	7.36 a	55.9	1.14 b	−30.0
		6.0	12	7.23 a	53.2	1.02 b	−37.4
	SE			0.47	—	0.11	—
2017	Sole	3.0	12	7.61 b	—	3.58	—
		4.5		9.08 a	19.3		—
		6.0		8.41 ab	10.5		—
	SE			0.26	—	0.21	—
	M4P4	3.0	12	5.92 b	—	1.18 a	—
		4.5	12	7.47 a	26.2	1.01 a	−4.5
		6.0	12	6.67 ab	12.7	0.94 a	−5.8
	SE			0.31	—	0.08	—
	M2P4	3.0	12	4.50 b	—	1.56 a	—
		4.5	12	6.14 a	36.4	1.49 a	−14.4
		6.0	12	4.76 b	5.7	1.47 a	−20.3
	SE			0.28	—	0.11	—

Same small letters indicate no significant difference at $a = 0.05$ level.

Yields are expressed per unit area of the whole system. Δ is the percentage of yield increase at 4.5 and 6.0 plants per meter row length compared with 3.0 plants per meter row length within the same system.

Yahuza, 2011). The value of $1/a$ can be envisaged as the density of plants at which mutual interference between individuals (intraspecific competition) becomes appreciable for the plant growth. Parameter b is a dimensionless scaling parameter that determines the shape of the curve. When b equals 1.0, the function represents a Monod relationship with an asymptotic aboveground biomass at high densities in a crowded population. When b is greater than 1.0, increasing plant density higher than optimal density leads to lower biomass, reflecting a less efficient use of resources (Watkinson, 1980).

2.3.3 | Statistical analysis

An ANOVA analysis of yield was conducted using the data in 2 years, where year, maize density, and treatment were the fixed factors, and replicate was a random factor. For the biomass-density relationship, the model was fitted using data of each plot. Parameters were estimated by the method of maximum likelihood using the function mle2 in the package bbmle in R (Bolker, 2007). Means of yields, LERs, and fitting parameters for each system treatment in each year were analyzed using multiple comparison by Tukey Contrasts at $\alpha = 0.05$ level in R (version 3.5.0).

3 | RESULTS

3.1 | Crop yields

Maize yields were lowest at the lowest tested density of 3 plants m^{-1} row in both the intercrops and the pure stand. Increasing plant density to 4.5 plants m^{-1} row increased average maize yields per unit (inter) crop area in the 2 years by

20.9% in the sole crop, by 22.0% in the M4P4 configuration, and by 46.4% in the M2P4 configuration (Table 2). Further increasing density from 4.5 to 6.0 plants m^{-1} row did not result in a further yield increase in any of the treatments (Table 2). Peanut yield in intercropping decreased with increasing maize plant density across 2 years.

Maize grain yield per m row was much greater in border rows than in inner rows in both years and in both intercropping systems (M2P4 and M4P4), while peanut yield was greater in inner rows than in border rows (Figure 4). The highest grain yield of border row maize was found at a density of 4.5 plants per m row, though the same yield as at 4.5 plants per m row was achieved at 6 plants per m row in M2P4 in 2017 (Figure 4a,b). Yield effects of density change in the sole maize and in inner rows of the intercrop were not significantly different. Peanut yield was substantially reduced in rows that bordered on maize, but there was no consistent response between years and intercrop configurations of peanut yield to the density of maize (Figure 4c,d).

3.2 | Yield components

Cob number per plant and number of kernels per cob were higher in border rows in intercrops than in sole maize or inner rows in the intercrop (Figure 5a,b). Density responses in border rows in the intercrop differed between configurations and years. In 2016, the number of cobs per plant was high (around 1.4 per plant) at all densities in M2P4, but it decreased with density in M4P4, from 1.6 cobs per plant at 3 plants per m row to 1.2 cobs per m row at 6 plants per m row. In 2017, however, the number of cobs per plant was slightly above one per plant (around 1.1) at all densities and in both configurations, because of drought during seedling stage. The number of cobs per plant did not respond to configuration or density in inner rows, with around 1.1 cob per plant in 2016 and around one cob per plant in 2017. Kernel number per cob was higher in border rows than in inner rows or sole maize, and it decreased with density in the sole crop and in the inner rows in the intercropping, but in border rows, it was similar at 3 and 4.5 plants m^{-1} row and only dropped when density was increased to 6 plants m^{-1} row. 100-kernel weight was higher in wet 2016 than in dry 2017, while the difference between plant densities and configuration was not significant in 2016. 100-kernel weight in 2017 tended to be higher in border rows than in inner rows or sole maize especially at a maize density of 4.5 plants m^{-1} row, and tended to decrease with plant density (Figure 5e,f).

In peanut, we considered as yield components the number of pods per plant, the number of seeds per pod, and the seed weight. Peanut plants in inner rows had more pods than those in rows bordering on maize, and pod number was higher when the maize strip consisted of only two rows of maize than when it consisted of four rows. Pod number per plant tended to decrease with maize density in 2016, the year in which the maize grew vigorously, but in 2017, there was no consistent effect of maize density in the different configurations and row positions. Seed number per pod was decreased in border rows compared to the sole crop in 2016, but not in 2017 (Figure 6c,d). Maize density showed no significant effects on seed number per pod. The 100-seed weight was substantially lowered in border rows compared to inner rows of intercropped peanut in 2017, but not in 2016, and intercropping did not significantly affect 100-seed weight in inner rows in either year.

3.3 | Yield–density relationships

The relationship between maize biomass and maize plant density in the three treatments (sole maize, M2P4, and M4P4) was well characterized by Equation 2. The R^2 for all treatments and years were greater than 0.83, and the percentages of root mean square error (RMSE) over observed mean were smaller than 4.7% (Figure 7, Table 3). Fitted single plant weight in the absence of competition (W_m) was similar in the three treatments, indicating that data of the pure stand and the intercrop treatments yielded the same estimated plant weight of a competition free maize plant (around 800 g $plant^{-1}$). But there was a difference between 2 years that the W_m in 2016 was higher than 2017, which may be explained by the higher rainfall in 2016. The parameter b was not significantly greater than one in the sole crop, while it was all above one in the intercrops. Based on the fitted parameters from the biomass–density relationship, the plant density for intraspecific competition occurrence in sole maize was 3.1 plants per meter row ($1/a$), while in intercropping this only occurred at or above 8.5 plants m^{-1} because intercropped maize can use the space designated for peanut in the intercropping. There was no difference between the two intercropping, M4P4 and M2P4.

3.4 | Land equivalent ratio

Land equivalent ratios (LER) were calculated for intercrops by reference to the sole maize crop with the same number of plants per m row. The LERs, thus calculated, were mostly above 1, but not by much, indicating that intercrops had only a small yield advantage compared to sole crops with a comparable maize density (Table 4). The value of LER showed the highest at low maize plant density of 3 plants per meter row, which was 0.9% and 9.2% higher than density of 4.5 and 6 plants per meter row. Contrary to yield, the LER for two intercrops in dry 2017 was higher than in wet 2016, indicating the intercropping obtained higher yield stability than sole stands. On average over all treatments and years, the lowest LER was obtained at the highest maize density, indicating that compared to sole maize at a high density (6 plants m^{-1}), intercropping with a high maize density provided no yield advantage, whereas at a low maize density (3 plants m^{-1}), intercropping provided a consistent yield advantage.

The partial land equivalent ratio of maize ranged from 0.47 to 0.67 in M2P4 and from 0.60–0.89 in M4P4, higher than the respective land use proportions of 0.33 and 0.5. Under the shading of maize at the whole growing season, peanut yield was negatively affected in intercropping. The partial land equivalent ratio of peanut was 0.38 to 0.60 in M2P4 and 0.27 to 0.40 in M4P4, lower than the land use proportion of 0.67 and 0.5. The $pLER_p$ decreased with increasing maize density.

4 | DISCUSSION

Results of this study indicated that the optimal maize density was 4.5 plants m^{-1} row in both sole maize and two intercrop configurations. The results did not support the assumption that intercropping expected a higher optimal plant density than sole stands. The biomass-density relationship confirmed that optimal plant density for total biomass in intercropping would be even lower than in sole maize.

In maize/peanut intercropping, the yield increase of the maize compared to the sole crop goes at the expense of the yield of peanut (Wang et al., 2017; Zhang & Li, 2003). Larger plants may capture a disproportionate share of resources, particularly light, but also belowground resources,

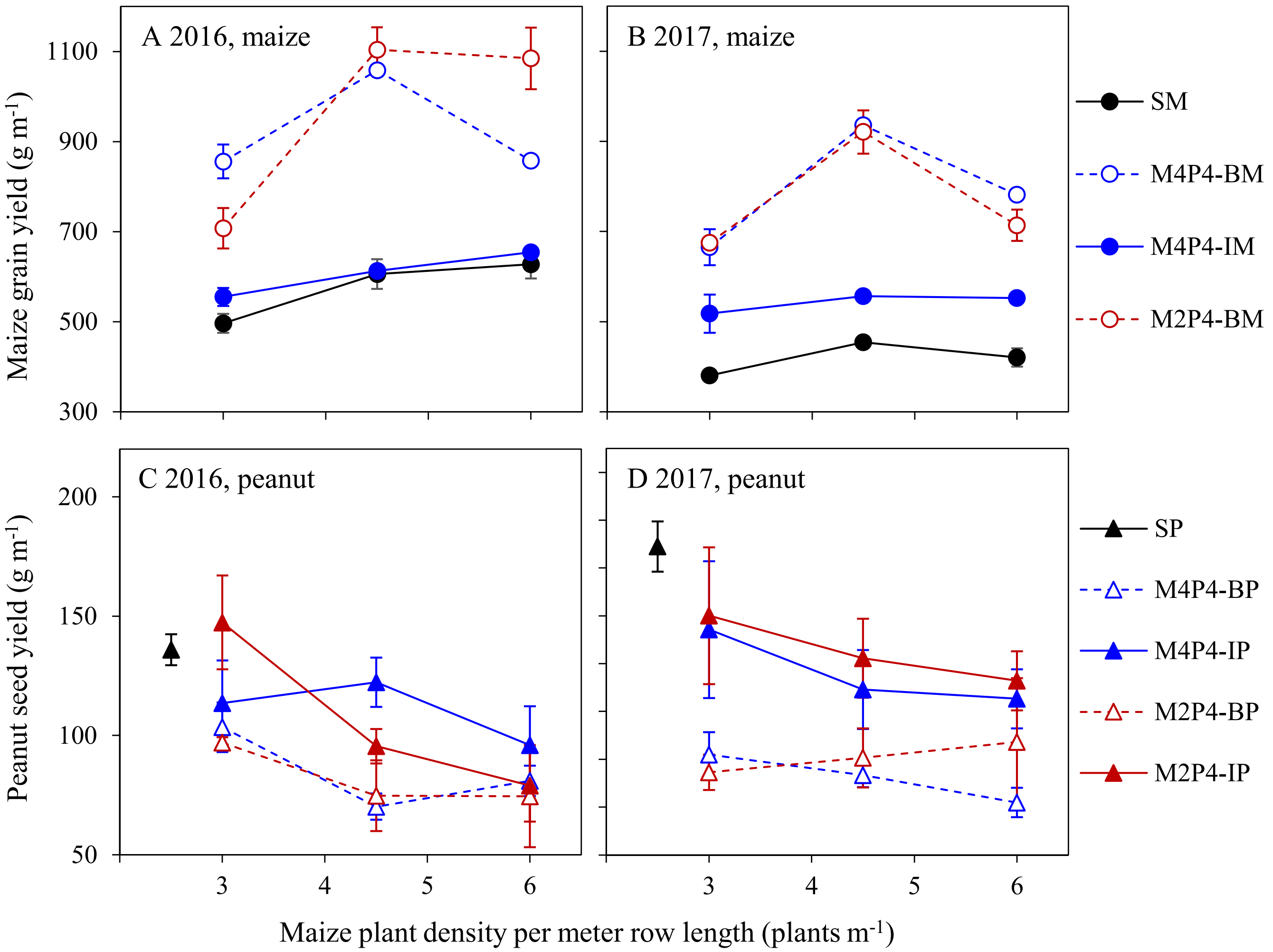

FIGURE 4 Maize yield per meter row length (a, b) and peanut yield per meter row length (c, d) in response to maize density per meter row in different systems in 2016 (a, c) and 2017 (b, d). Yield of sole crops is shown by black symbols. M4P4 represents intercropping of four rows maize with four rows peanut; M2P4 represents intercropping of two rows maize with four rows of peanut. Blue symbols and square symbols denote M4P4, while red lines and triangles denote M2P4. Drawn lines are for sole crops (only for maize) and inner rows in intercrops. Hatched lines represent border rows in intercrops. In the legends, SM represents sole maize; M4P4-BM and M4P4-IM represent border row maize and inner row maize in M4P4 system; M2P4-BM represents border row maize in M2P4 system; SP represents sole peanut; M4P4-BP and M4P4-IP represent border row peanut and inner row peanut in M4P4 system; M2P4-BP and M2P4-IP represent border row peanut and inner row peanut in M2P4 system. Error bars are standard error of the mean

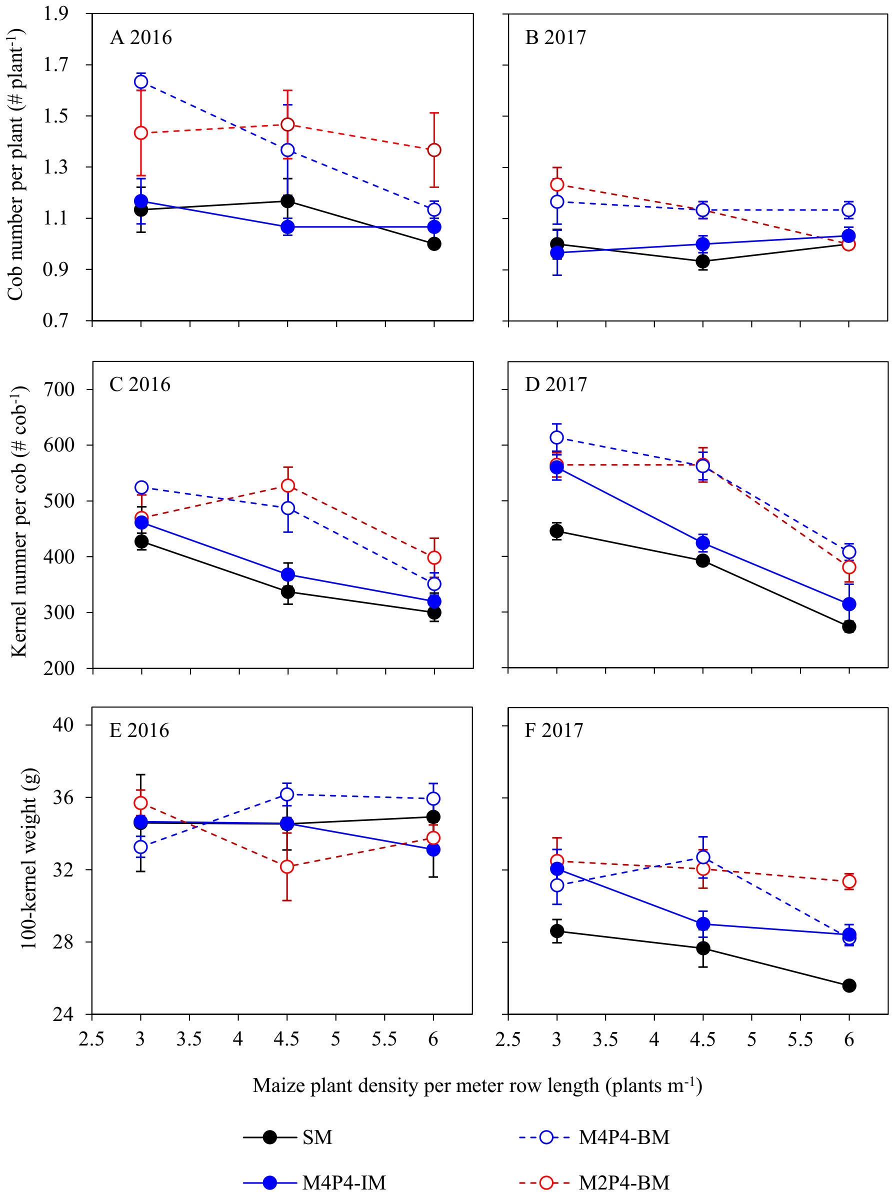

FIGURE 5 Yield components of maize in response to maize density. M4P4 represents intercropping of four rows maize with four rows peanut, M2P4 refers to two rows maize with four rows peanut, and SM is sole maize. BM and IM indicate maize in border rows and inner rows, respectively. Error bars indicate standard error for replicates

resulting in suppression of the growth of the smaller plants (Cannell et al., 1984), a phenomenon called size-asymmetric competition (Weiner, 1990). The parameter *a*, representing the strength of intraspecific competition, was much lower in intercropping than in the sole maize, resulting a bigger plant at border rows in intercropped maize (Li et al., 2013). The intercropping had a nonasymptotic aboveground biomass at high densities as *b* was much greater than 1, which indicated a reduction of resource use efficiencies in the intercropping when the plant was crowded in the strips (Li et al., 2016).

It might be questioned whether the intercropping advantage is due to species complementarity or due to density increase. The question is thus whether the LER is high because it is beneficial to increase densities in intercropping beyond replacement or whether the LER is high because density should have, but was not, increased in the reference sole crop. Had we used the maize yield in the sole crop at 3 plants per m row as a reference for intercrops with a higher plant density (which is the common plant density for maize in the study region, Liaoning), we would have found much greater LERs, in the order of 1.2–1.3, because sole crop yields at 4.5 plants per m row were much greater than at 3 plants per m row. Findings of the current study therefore point to the importance of choosing the proper reference sole crop yield when assessing yield advantages of intercropping especially at relative density total in intercrops above one. The relative density total above one could only be obtained from changes in row configurations (e.g., additive design), but not based on

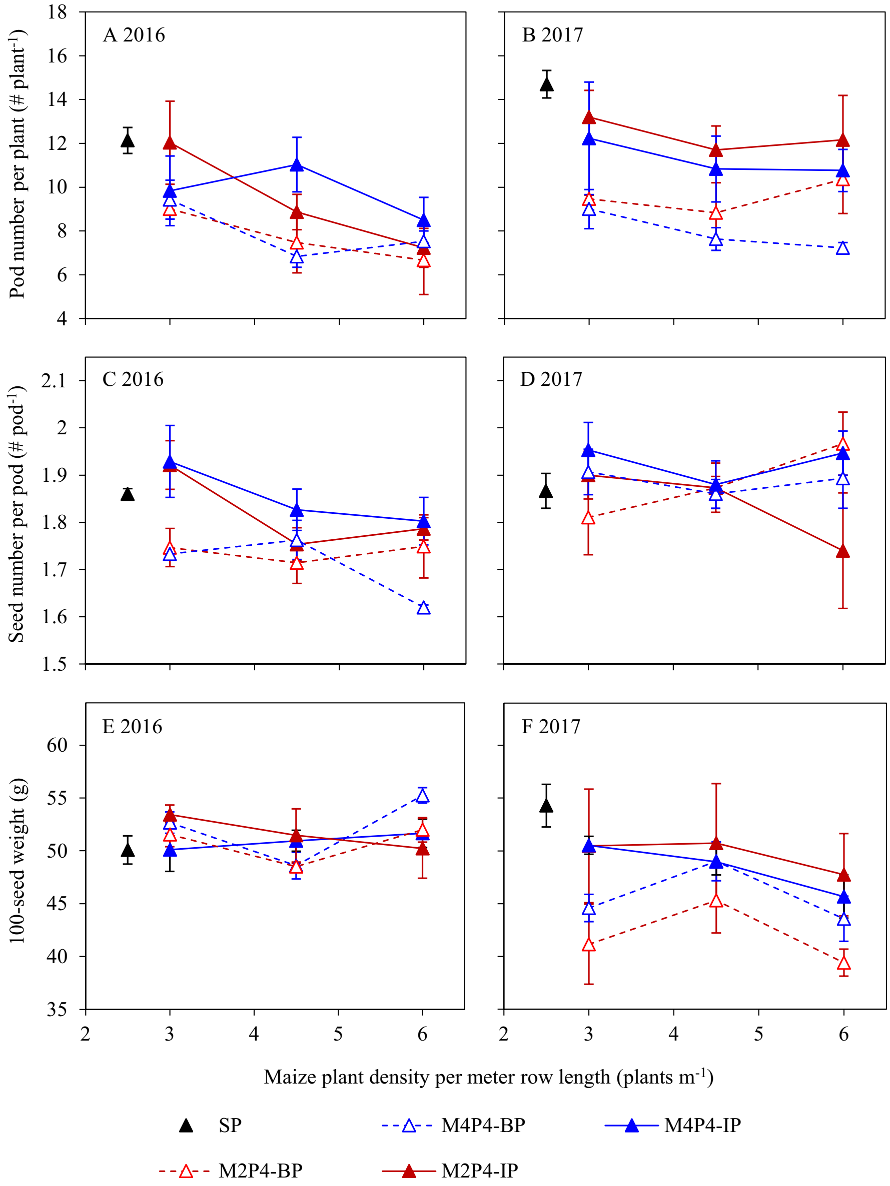

FIGURE 6 Yield components of peanut in response to maize density in 2016 and 2017, showing pod number per plant (a, b), seed number per pod (c, d), and 100-seed weights (e, f). Sole peanut (SP) is denoted by black triangles. M4P4 represents intercropping of 4 rows peanut with four rows maize and M2P4 four rows of peanut with two rows maize. BP indicates the peanut in border rows and IP in inner rows. Error bars indicate standard error of the mean

different plant number per meter row between tested intercropping and monoculture reference.

In the current crop system, the yield advantage as measured by LER was small but consistent, and it was slightly greater under water shortage, when yields were comparatively low. This is understandable as peanut needs less water than maize (Kheira, 2009; Li et al., 2003; Zhao et al., 2010), and a mixed system with one water demanding species (maize) and one less water demanding species (peanut), with some temporal differentiation during the season when the water is needed, is more resilient to drought than a system that consists only of the water demanding species (maize) (Zhang, Zhang, Sun, et al., 2019). Our results that the LER of the intercropping was higher in the dry year than wet year confirmed the intercropping might increase resilience to drought. Moreover, the intercropping system is advantageous because it leaves maize stubble in the field during winter, arranged in strip between peanut strips in which the soil has been disturbed to harvest the peanut pods, and thus reduces the risk of soil erosion particularly from wind. Furthermore, maize in intercropping is more amenable to density increase than maize in pure stands because the plants develop strong stems, resistant to lodging (Zhang, Zhang, Chai, et al., 2019; Zhang, Zhang,

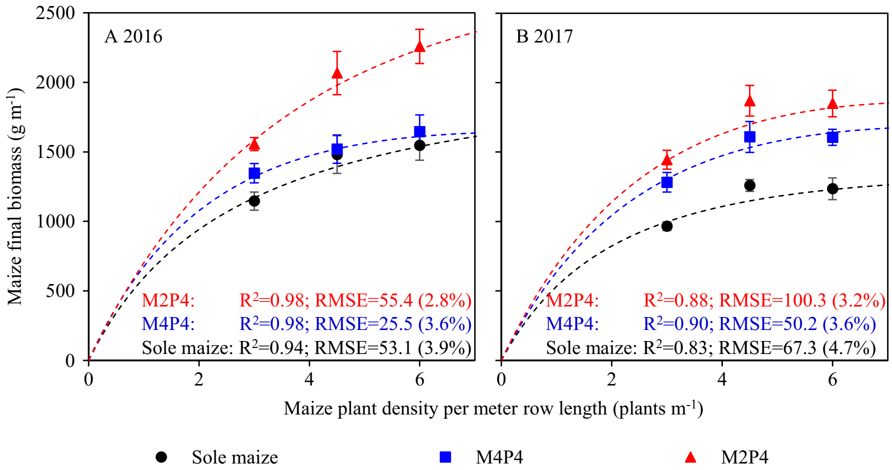

FIGURE 7 The reciprocal relationship between total aboveground biomass of maize and maize density in 2016 (a) and 2017 (b). M4P4 represents the intercropping of four rows maize with four rows peanut; M2P4 represents the intercropping of two rows maize with four rows of peanut. RMSE indicates the root mean square error. The value in the brackets is the percentage of RMSE over observed mean. Error bars indicate standard errors

TABLE 3 Regression parameters of the relationship between maize plant density per meter row (PD) and final maize biomass per meter row, as affected by system

		W_m	a	
Year	**System**	**g plant^{-1}**	**m plant^{-1}**	***b***
2016	Sole maize	803 a	0.344 a	1.02 b
	M4P4	872 a	0.153 b	1.81 a
	M2P4	826 a	0.110 b	1.57 a
	SE	87	0.072	0.32
2017	Sole maize	736 a	0.293 a	1.26 b
	M4P4	792 a	0.124 b	2.13 ab
	M2P4	789 a	0.077 b	2.54 a
	SE	49	0.835	0.77
Mean	Sole maize	770 a	0.319 a	1.14 b
	M4P4	832 a	0.139 b	1.97 a
	M2P4	807 a	0.095 b	2.05 a
	SE	56	0.053	0.49
P	System	0.152	0.000	0.007
	Year	0.028	0.134	0.027
	System ×year	0.754	0.913	0.305

Same small letter indicates no significance at a = 0.05.

The relationship between final biomass per meter row length (g m^{-1}) and maize plant density per meter row is fitted with the equation $B = W_m \times \text{PD} \times (1 + a \times \text{PD})^{-b}$, where B is the biomass production of maize per meter row length (g m^{-1}), W_m is the biomass production of individual maize plant (g plant^{-1}), PD is the plant density in row (plants m^{-1}), a is the ecological neighborhood of maize, and b is a dimensionless scaling factor that determines the shape of the curve. The curve fitting was done for each plot and then did the ANOVA analysis for three replicates.

Sun, et al., 2019). At high plant densities, border row plants in intercropping are expected bigger and stronger than in pure maize stands (Zhang et al., 2020). Therefore, when lodging risk is considered, intercropping offers a better opportunity for density increase.

5 | CONCLUSIONS

Our results showed that the optimal plant density of dominant maize in the intercropping did not higher or even lower than in sole maize, and denied the hypothesis that optimal within row plant density of dominant species in intercropping would be higher in the intercrop than in the sole crop. The optimal plant density in intercropping would differ with the environment, genotype, and other managements (e.g., fertilization and irrigation); therefore, the further quantitative studies in specific locations are necessary. Yield advantages of tested intercropping in this study, as measured by LER, were moderate but inconsistent over years. It highlights that maize/peanut intercropping is practical and useful system to increase land productivity and sustainability. Intercropping yield advantage in dry year was bigger than in wet year, indicating the intercropping would be a practical system to alleviate drought risk especially under the global climate change. The main disadvantage for farming is the shortage of adapted machinery and related additional labor costs. The widen the crop strips, such as four rows maize with four rows peanut or six rows maize with six rows peanut, might also be reasonable configurations when take machinery into account (Wang et al., 2020). It is necessary and important to use optimal plant densities in the pure stand when calculating the LER of intercropping. Under this rule, LER indicates a small but relevant land use advantage. Had we calculated the LER using a reference maize density of 3 plants per m row, common in practice, but suboptimal for yield, we would have obtained comparatively higher LER values, but these

TABLE 4 Land equivalent ratio (LER), partial land equivalent ratio of maize ($pLER_m$), and partial land equivalent ratio of peanut ($pLER_p$) in maize/peanut intercropping in relations to maize density (plants per meter row) in different intercrop configurations

Year	Cropping system	Maize density (plants m^{-1})	$pLER_m$	$pLER_p$	LER
2016	M4P4	3.0	0.71 a	0.40 a	1.11 a
		4.5	0.69 a	0.35 ab	1.04 a
		6.0	0.60 b	0.33 b	0.93 b
		SE	0.03	0.04	0.06
	M2P4	3.0	0.47 b	0.60 a	1.07 a
		4.5	0.61 a	0.42 b	1.03 a
		6.0	0.58 a	0.38 b	0.96 b
		SE	0.03	0.06	0.03
2017	M4P4	3.0	0.77 a	0.33 a	1.10 a
		4.5	0.82 a	0.29 a	1.11 a
		6.0	0.89 a	0.27 a	1.06 a
		SE	0.11	0.07	0.06
	M2P4	3.0	0.59 ab	0.44 a	1.03 b
		4.5	0.67 a	0.42 a	1.09 a
		6.0	0.57 b	0.41 a	0.98 b
		SE	0.06	0.02	0.04
P	Year		0.001	0.001	0.003
	Density		0.005	0.001	0.001
	Row configuration		0.001	0.001	0.012
	Year × Density		0.977	0.010	0.004
	Year × Row configuration		0.030	0.338	0.066
	Density × Row configuration		0.050	0.171	0.449
	Year × Density × Row configuration		0.103	0.202	0.223

Same small letter indicates no significance at $a = 0.05$.

would have given an inflated perspective on the benefits of intercropping.

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