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Effect of Maize (*Zeal mays*) and Soybean (*Glycine max*) Intercropping on Yield and Root Development in Xinjiang, China

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Abstract: Intercropping is a breakthrough in land-use optimization. This work aimed to study the effects of intercropping patterns on the growth, yield, root morphological characteristics, and interspecific competition of maize and soybean, as well as provide a reference for the development of intercropping patterns of maize and soybean in Northwest China. Three different cropping patterns were designed: monocropping maize, monocropping soybean, and maize-soybean intercropping. Agronomic traits, intercropping indicators such as land equivalent ratio (LER), aggressivity (A), competition ratio (CR), and actual yield loss (AYL), as well as root morphological characteristics were assessed. The results showed that, compared with monocropping, the intercropping maize plant height increased by 6.07–8.40%, and the intercropping soybean plant height increased by 35.27–38.94%; the root length density (RLD) of intercropping maize was higher than that of monocropping maize, the RLD of intercropping soybean was lower than that of monocropping soybean, in the 0–40 cm soil layer the intercropping increased maize RLD by 1.79–7.44% while the soybean RLD was reduced by 3.06–9.46%; the aggressivity of maize was greater than 0 and the competition ratio was greater than 1, which was the dominant species; the maize/soybean land equivalent ratio was 1.18–1.26, which improved the land utilization rate. Therefore, the effect of increasing yield can be achieved by changing the maize and soybean planting method, which is beneficial to the ecological strategy of sustainable development in the northwest region.

Keywords: interspecific competition; land equivalent ratio; planting pattern; root length density; root morphological characteristics

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1. Introduction

Ensuring food security is the foundation of economic development and social stability [1]. In the face of a growing global population, food security and food sovereignty are seriously threatened [2]. China has the largest population and is also the largest agro-based country in the world [3]. Under the enormous pressure of the increasing population, how to ensure food security is an urgent problem needing to be solved. The global spread of COVID-19 has complicated the international equilibrium of grain production and trade, is disrupting China's food security in the short term, while critical quantitative variables such as grain production and grain consumption per capita have declined. Land-saving technological progress will contribute the most to the arable land area per capita of wheat and other grains in the long run [4]. The volume of China's grain imports has increased, and the number of exports has fallen. Therefore, the yield of staple grain, oil, and protein crops must be enhanced to satisfy food demands for daily dietary energy requirements [5,6].

Intercropping is a widely used agricultural system of cultivating two or more crops simultaneously in one field during the same or part of their growing season [7]. About one third of China's arable land adopts the multi-species model and contributes half of the total output of all crops, which is an important part of China's agricultural heritage [8]. Historically, intercropping has contributed greatly to crop production in Chinese agriculture [9]. Compared with monocropping cropping systems, intercropping can increase the total yield per unit of land area and can greatly promote crop production due to the more efficient use of one or more resources in time and space [10,11]. Intercropping has received increased attention in recent years due to its clear agro-ecological advantages.

Maize (*Zea mays* L.) and soybean (*Glycine max* L. Merill) are important grain and oil crops in China. Intercropping can improve the stability of farmland ecosystems while land production efficiency and has become an increasingly popular planting method [12]. Due to the low economic benefits of soybeans, China's soybean planting area has been declining year by year, and the domestic soybean market mainly relies on imports. In the past 10 years, China's soybean consumption has remained more than 80% dependent on the international market, becoming the world's largest soybean importer country [13]. Due to the limited arable land resources in China, it is impossible to significantly increase the area of arable land for soybean cultivation. Therefore, while the maize planting area continues to increase, the development of the maize/soybean compound planting model can achieve a win-win situation for maize and soybean yields. The No.1 Central Document in 2020 clearly pointed out that it is necessary to stabilize grain production and increase support for the promotion of new agronomics for maize and soybean intercropping [14]. The No. 1 Central Document in 2022 also clearly proposes to promote corn and soybean strip compound planting in Huanghuaihai, northwest and southwest regions [15]. According to the report of the Ministry of Agriculture and Rural Affairs of China, the national soybean and maize belt compound planting area reached 467,000 hm^2 in 2021 and it will be attempted to increase the soybean and maize belt compound planting area by 1,000,000 hm^2 in 2022 [16].

Maize/soybean intercropping has long been widely practiced in China and has played an important role in enhancing crop production and increasing the income of farmers [17,18]. At present, the research on maize/soybean intercropping mode mostly focuses on the research on population yield [19], photosynthetic physiology [20], water use efficiency [21], and nutrient use efficiency [22]. However, there are relatively few studies on the root morphology of the intercropping system under the combination of maize and soybean, especially the response relationship of root morphology under the intercropping condition is still unclear.

The goal of the present study was to simultaneously evaluate root morphology growth characteristics and yield in a maize/soybean intercropping system compared with sole-cropping. At present, there have been few studies on the dynamic changes and interspecific competition of maize and soybean root systems in different growth stages of intercropping, and most of the previous studies on the underground part of crops used destructive sampling. In the experiment, the root canal method was used to sample the crop roots without damage, so that we could more comprehensively understand the law of dynamic changes of the crop root system and further explore the change law of interspecific competition. The purpose of this study was to understand the following.

(i) Which planting mode is advantageous for root growth of crop in this area?
(ii) Which planting mode of intercropping or sole-cropping provide better yield advantages?

We hypothesized that (i) this type of intercropping system would negatively affect the root growth of crops through underground competition. However, we also hypothesized that (ii) this intercropping system would have an overall positive effect on productivity by improving the efficiency of land resource use.

2. Materials and Methods

2.1. Experimental Site

The field experiments were conducted from 2019 to 2020 at the Agricultural Research Station of Shihezi University in Xinjiang Uygur Autonomous Region, China (44°19′ N, 86°03′ E). This area has a temperate continental climate. The mean annual temperature is 8.1 °C, the annual sunshine duration ranges from 2418 to 2732 h, the annual rainfall ranges from 180 to 270 mm, and the annual evaporation ranges from 1000 to 1500 mm. The soil has a sandy loam texture with a pH of 7.6, 13.260 g kg^{-1} organic matter, 0.890 g kg^{-1} total N, 0.023 g kg^{-1} quick-acting phosphorus, 0.259 g kg^{-1} quick-acting potassium, and 0.058 g kg^{-1} alkali nitrogen.

2.2. Plant Materials and Experimental Design

Field experiments were conducted during the 2019 and 2020 cropping seasons. Maize (*Zea mays*) and soybean (*Glycine max*) were sown on the same days: 28 April 2019, and 30 April 2020. The maize sowing depth was 4 cm, and the soybean sowing depth was 3 cm; a sub-membrane drip irrigation planting method was used. Three treatments (monocropping maize, monocropping soybean, and maize intercropping with soybean) were established. There were a total of 3 plots, 3 repetitions, the test plot was 20 m long, 16 m wide, making a total of 320 m^2. The maize variety was kws3654, and the soybean variety was new soybean No. 1.

In monocropping maize, the row spacing and plant spacing were 60 and 30 cm, respectively, and the planting density was 5.5 × 10^4 plants hm^{-2}, whereas in monocropping soybean, the row and plant spacings were 40 and 30 cm, and the planting density was 8.3 × 10^4 plants hm^{-2}. In maize intercropping with soybean, the row spacing and plant spacing of corn were 60 cm and 30 cm, and the planting density was 2.8 × 10^4 plants hm^{-2}. the row and plant spacing of soybean was 30 cm, and the planting density was 5.5 × 10^4 plants hm^{-2}. The experiment was carried out under field conditions, while irrigation, fertilization, and crop management were carried out according to local methods, based on fully ensuring the needs of crop growth and development.

2.3. Weather Conditions

The weather conditions during the study are shown in Figure 1. The annual precipitation was about 211 mm. The highest monthly value was recorded in May (28 mm on average), whereas the lowest values were recorded in January (9 mm) and February (9 mm). The highest average monthly temperature was recorded in July (32 °C), whereas the lowest was recorded in January (−21 °C).

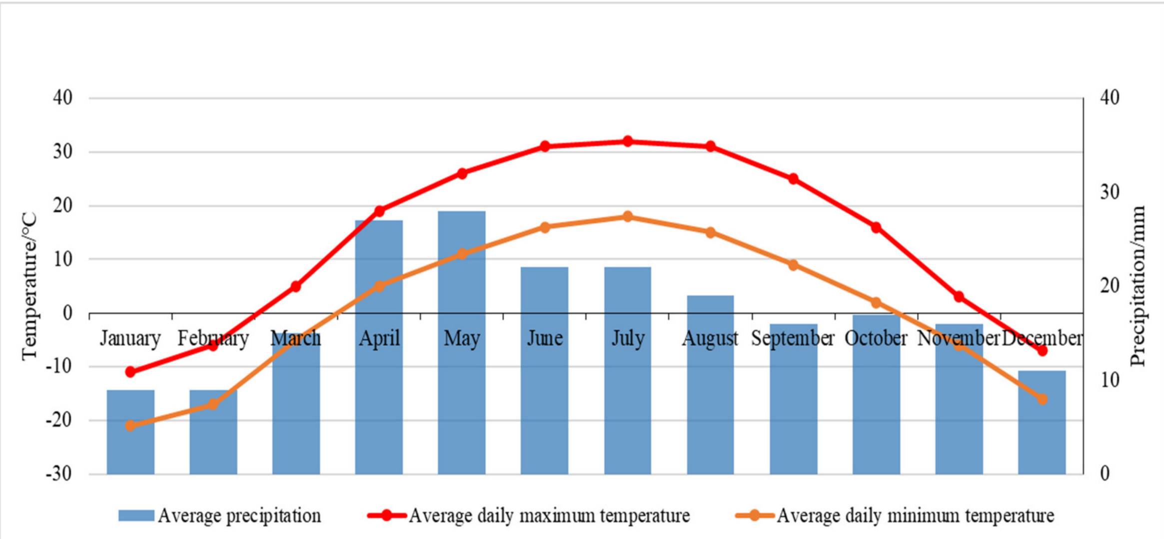

Figure 1. Average monthly precipitation and average temperatures in Shihezi.

2.4. Data Sampling

The data were collected from 19 May 2019 and from 20 May 2020. The sampling time and the corresponding growth period of sampling are shown in Table 1.

Table 1. Sampling time and corresponding crop growth stage.

	2019	2020	Maize	Soybean
I	19 May	20 May	Seedling stage	Seedling stage
II	4 Jun	6 Jun	Jointing stage	Branching stage
III	30 Jun	2 Jul	Large bell mouth stage	Flowering stage
IV	14 Jul	16 Jul	Silking stage	Pod setting stage
V	28 Jul	30 Jul	Grain filling stage	Drumming stage
VI	12 Aug	14 Aug	Maturation stage	Maturation stage

2.5. Plant Height

In each plot, five adjacent plants with similar growth and vigor were selected; the height from the base to the top of the plant was measured, and the average value was calculated.

2.6. Chlorophyll Content (SPAD)

In each plot, five plants with similar growth and vigor were selected, and the SPAD value of the leaves was measured by a hand-held chlorophyll analyzer SPAD-502 (Beijing, China). The 4th leaf was measured at the seedling stage of maize, the 9th leaf was measured at the jointing stage, the three ear leaves were measured after the large bell mouth stage, and the top expanded leaf was measured for soybean. The middle of the leaves was measured at each stage, avoiding the veins, and three points on each leaf were measured and the average value calculated.

2.7. Root Morphological Characteristics

A CI–600 image acquisition instrument (Shanghai, China) was used to capture root images. The embedded angle of the micro-root canal was 45° from the ground, as shown in Figure 2. We collected a soil sample from a depth of 0–20 cm and from a depth of 20–40 cm.

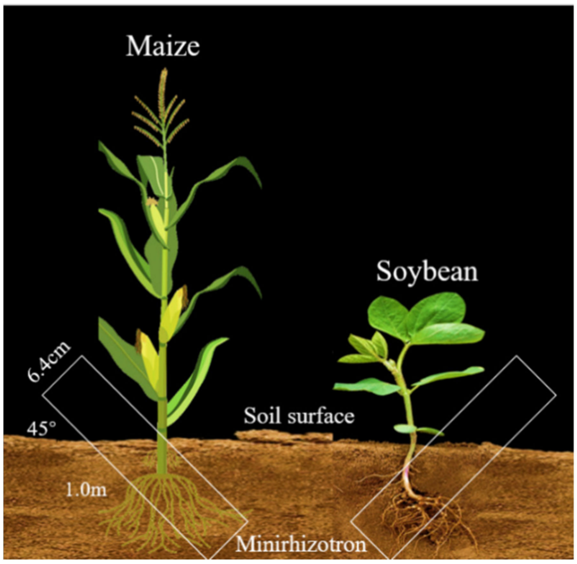

Figure 2. Schematic diagram of micro-root canal layout.

2.8. Root Length Density

The distribution of roots in different soil layers can be indirectly reflected by the root length density, which is given by

$$\text{RLDv} = \frac{\text{RL}}{W \times H \times D} \times \sin 45 \quad (1)$$

where RL is the length of the thin root at the observation interface (mm), W is the width of the image taken by the instrument (cm), H is the length of the image (cm), and D (cm) represents the thickness of the soil layer of the observation interface (D = 0.2, 0.4 m). The RLD of maize and soybean were obtained according to Equation (1).

2.9. Yield and Competition Index

During the harvesting period of soybean and maize, three replicated sampling plots (1 m × 1 m area) were randomly selected from each treatment. The number of maize plants, the number of ears per plant, the number of grains per ear were counted and 1000-seed weighed. The number of soybean plants were counted, all pods per soybean harvested, and 1000-seed per pod and the harvested soybeans after drying at 70 °C were weighed. The theoretical yield of soybean was calculated by the actual yield of the sample plot and plot area.

The land equivalent ratio (LER) is used as an indicator of land productivity for the intensification of the evaluated alternatives [23]. If the value of LER is greater than one, the intercropping system favors the crop growth and yield of the intercropped species; if the LER value is less than one, the intercropping system reduces the growth and yield of the intercropped species. The LER was obtained as follows:

$$\mathrm{LER} = \frac{Y_{mi}}{Y_m} + \frac{Y_{si}}{Y_s} \tag{2}$$

where Y_m and Y_{mi} are the monocropping and intercropping maize yields, respectively. Y_s and Y_{si} are the monocropping and intercropping soybean yields, respectively. LER > 1 signifies that the intensification alternative is more productive than the sum of the sole crops of the component species.

Actual yield loss is the proportionate yield loss or gain of intercrops in comparison to the respective sole crop [24], where:

$$\mathrm{AYL}_m = \frac{Y_{mi}/Z_{mi}}{Y_m/Z_m} - 1,\ \mathrm{AYL}_s = \frac{Y_{si}/Z_{si}}{Y_s/Z_s} - 1,\ \mathrm{AYL} = \mathrm{AYL}_m + \mathrm{AYL}_s \tag{3}$$

Here, Z_m and Z_s represent the proportion of maize and soybean planting in monocropping, respectively, Z_{mi} and Z_{si} represent the planting proportion of maize and soybean in intercropping, respectively, AYL_m and AYL_s represent the actual yield loss of maize and soybean in the intercropping system, respectively, and AYL represents the actual yield losses in intercropping systems. AYL > 0, indicates that the intercropping system has the advantage of intercropping, and AYL < 0, indicates that the intercropping system has no yield advantage.

Aggressivity refers to the degree to which the relative yield increase of a crop in an intercropping system is greater than the yield increase of another crop [25]. The specific calculation of the aggressivity of a crop is as follows:

$$A_m = \frac{Y_{mi}}{Y_m Z_{mi}} - \frac{Y_{si}}{Y_s Z_{\mathrm{si}}},\ A_s = \frac{Y_{si}}{Y_s Z_{si}} - \frac{Y_{mi}}{Y_m Z_{mi}}. \tag{4}$$

Here, A_m and A_s represent the encroachment power of maize and soybean in the intercropping system, respectively. A_m = 0, indicates that the two crops have the same competitiveness; A_m > 0, indicates that the competitiveness of maize is higher than that of soybean; A_s > 0, indicates that the competitiveness of soybean is higher than that of maize.

Competitive ratio is the ability of a crop in an intercropping system to compete relative to another crop [26]. where:

$$CR_m = \frac{E_m}{E_s} \times \frac{Z_{si}}{Z_{mi}},\quad CR_s = \frac{E_s}{E_m} \times \frac{Z_{mi}}{Z_{si}}. \tag{5}$$

Here, CR_m and CR_s represent the competition ratios of maize and soybean in the intercropping system, respectively. CR_m > 1, indicates that maize is more competitive than soybean; CR_s > 1, indicates that soybean is more competitive than maize.

2.10. Data Analysis

An analysis of variance was used to perform data analysis using SPSS 19.0 (SPSS Inc., Chicago, IL, USA). The average values were compared using least significant differences (LSD) at the 0.05 level. Origin 2018 (Northampton, MA, USA) was used to draw the figures.

3. Results

3.1. Plant Height

The plant heights of monocropping and intercropping maize and soybean increased with the advancement of the growth period. In the later stage of crop growth, the crop height tended to be stable, showing an overall "S"-shaped growth curve, with a "slow, fast and slow" growth trend (Figure 3).

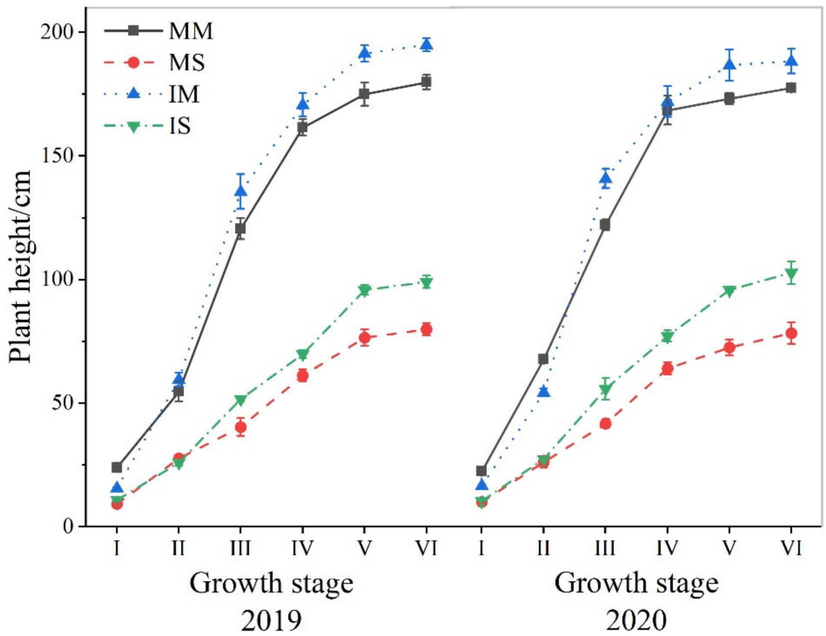

Figure 3. Dynamic changes of plant height of maize and soybean in monoculture and intercropping during 2019 and 2020. Abbreviations: MM—monocropping maize, MS—monocropping soybean, IM—intercropping maize, IS—intercropping soybean. In maize, I–VI mean seedling stage, jointing stage, large bell mouth stage, silking stage, grain filling stage, maturation stage, respectively. In soybean, I–VI mean seedling stage, branching stage, flowering stage, pod setting stage, drumming stage, maturation stage, respectively.

The cropping pattern significantly affected the plant height. The height of monocropping and intercropping maize increased rapidly from the seedling stage to the silking stage and increased significantly from the jointing stage to the large bell mouth stage. Compared with monocropping, intercropping significantly increased the height of maize at the large bell mouth stage, grain filling stage, and mature stage. In 2019, the plant height of intercropping maize increased by 12.44%, 9.40%, and 8.40% at the large flare stage, grain filling stage, and mature stage, respectively; in 2020, it increased by 15.32%, 7.82%, and 6.07%, respectively. The 2-year results showed that the intercropping of maize and soybean increased the height of maize by 6.07–8.40%.

The height of monocropping and intercropping soybean increased rapidly from the emergence stage to the pod setting stage and increased significantly from the seedling stage to the branching stage. Compared with monocropping, intercropping significantly increased soybean height at the flowering, drumming, and maturity stages. In 2019, intercropping increased soybean plant height by 28.09%, 25.15%, and 35.27% at flowering, drumming, and mature stages, respectively; in 2020, it increased by 33.60%, 32.15%, and

38.94%, respectively. The 2-year results showed that the intercropping of maize and soybean increased soybean height by 35.27–38.94%.

3.2. SPAD Values

The SPAD values of monocropping and intercropping maize and soybean showed a trend of first increasing and then decreasing gradually with the advancement of the growth period (Figure 4). In 2019, the monocropping and intercropping maize increased rapidly from the seedling stage to the large bell mouth stage and reached a peak in the large bell mouth stage, after which the SPAD value gradually decreased. Intercropping significantly increased the SPAD value of the 2019 maize grain filling stage by 15.35% ($p = 0.01$). In 2020, the monocropping and intercropping maize peaked at the jointing stage and then gradually decreased. Intercropping significantly increased the SPAD value of maize at the jointing stage by 8.50% ($p = 0.045$). In 2019, monocropping and intercropping soybeans reached the peak at the branching stage; intercropping significantly reduced the SPAD value of soybeans at the branching stage by 3.01% ($p = 0.027$). In 2020, the SPAD value of mono-crop soybeans peaked at the branching stage; the SPAD value of intercropped soybeans peaked at the flowering stage. Intercropping significantly decreased the SPAD value of soybean by 15.27% at the branching stage ($p = 0.011$).

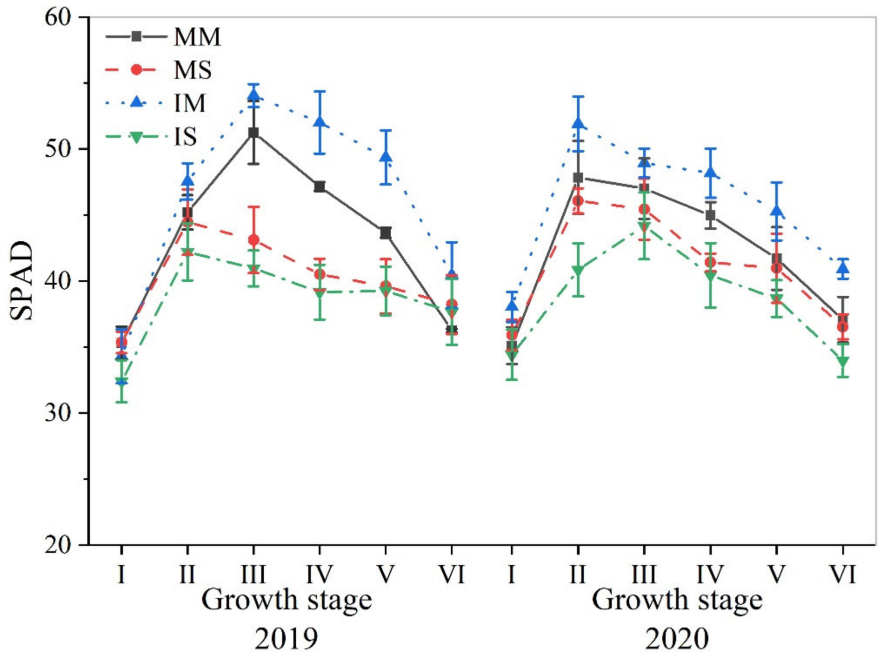

Figure 4. Dynamic changes in the SPAD values of maize and soybean in monoculture and under intercropping during 2019 and 2020. Abbreviations: MM—monocropping maize, MS—monocropping soybean, IM—intercropping maize, IS—intercropping soybean. In maize, I–VI mean seedling stage, jointing stage, large bell mouth stage, silking stage, grain filling stage, maturation stage, respectively. In soybean, I–VI mean seedling stage, branching stage, flowering stage, pod setting stage, drumming stage, maturation stage, respectively.

3.3. Root Morphological Characteristics

The root system is the main organ for crops to absorb nutrients and water, and the interaction between crops is closely related to the spatial distribution of the root parameters. At the same soil depth, the root length, root surface area, and root volume of intercropped maize were higher than those of monocropping maize, and the root length, root surface area, and root volume of monocropping soybean were higher than those of intercropped soybean (Figure 5). Under the mono intercropping mode, the length, volume, and surface area of crop roots in the 0–20 cm soil layer were greater than those in the 20–40 cm soil layer, that is, the root parameters showed a downward trend with the increase in soil depth. The root parameters of maize and soybean were more concentrated in the 0–20 cm soil layer.

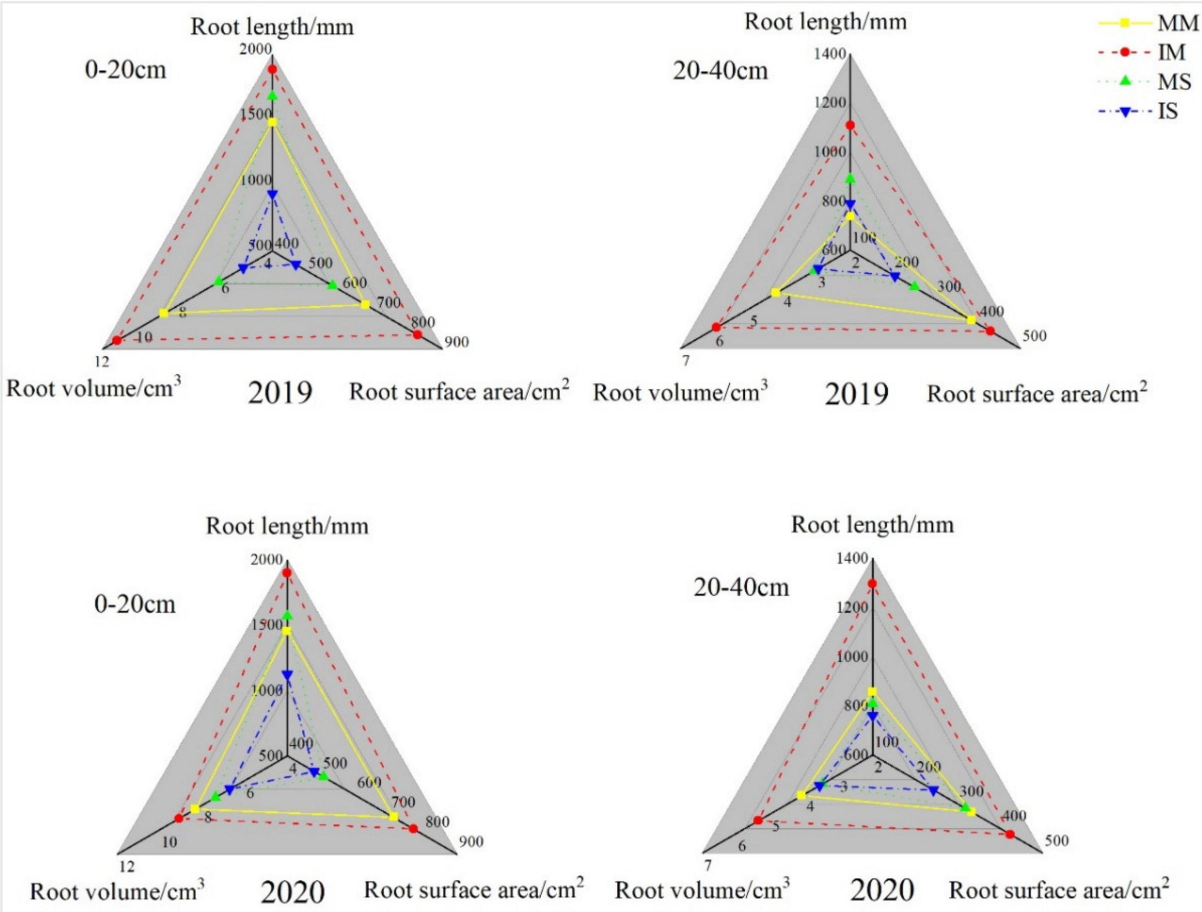

Figure 5. Dynamic changes of root morphological characteristics of maize and soybean in monoculture and intercropping during 2019 and 2020. Abbreviations: MM—monocropping maize, MS—monocropping soybean, IM—intercropping maize, IS—intercropping soybean.

In 2-year, in the 0–20 cm soil layer, compared with monocropping, intercropping increased the root length, root surface area and root volume of maize by 28.79%, 15.48% and 16.67%, respectively; and decreased the root length, root surface area and root volume of soybean by 59.52%, 14.51%, and 15.71%, respectively. In the 20–40 cm soil layer, compared with monocropping, intercropping increased the root length, root surface area and root volume of maize by 50.69%, 19.34%, and 36.66%, respectively; and decreased the root length, root surface area and root volume of soybean by 59.39%, 2.69%, and 4.36%, respectively.

3.4. RLD

With the advancement of the crop growth period, the RLD value showed an increasing trend. At the same soil depth, the RLD value of intercropped maize was higher than that of monocropping maize, and the RLD value of monocropping soybean was higher than that of intercropped soybean. At different soil depths, the RLD value of crops in the 0–20 cm soil layer was higher than that of the 20–40 cm soil layer. That is, with the increase in the soil depth, the RLD value gradually decreased (Figure 6).

In 2019, in the 0–20 cm soil layer, the RLD of intercropping maize was 1.79% higher than that of monocropping, but the RLD of intercropping soybean was 7.61% lower than that of monocropping. The RLD of soybean decreased by 9.46% compared with that under monocropping. In 2020, in the 0–20 cm soil layer, the RLD of intercropping maize was 7.44%

higher than that under monocropping, but the RLD of intercropping soybean was 3.06% lower than that under monocropping. The RLD of soybean decreased by 8.81% compared with that under monocropping.

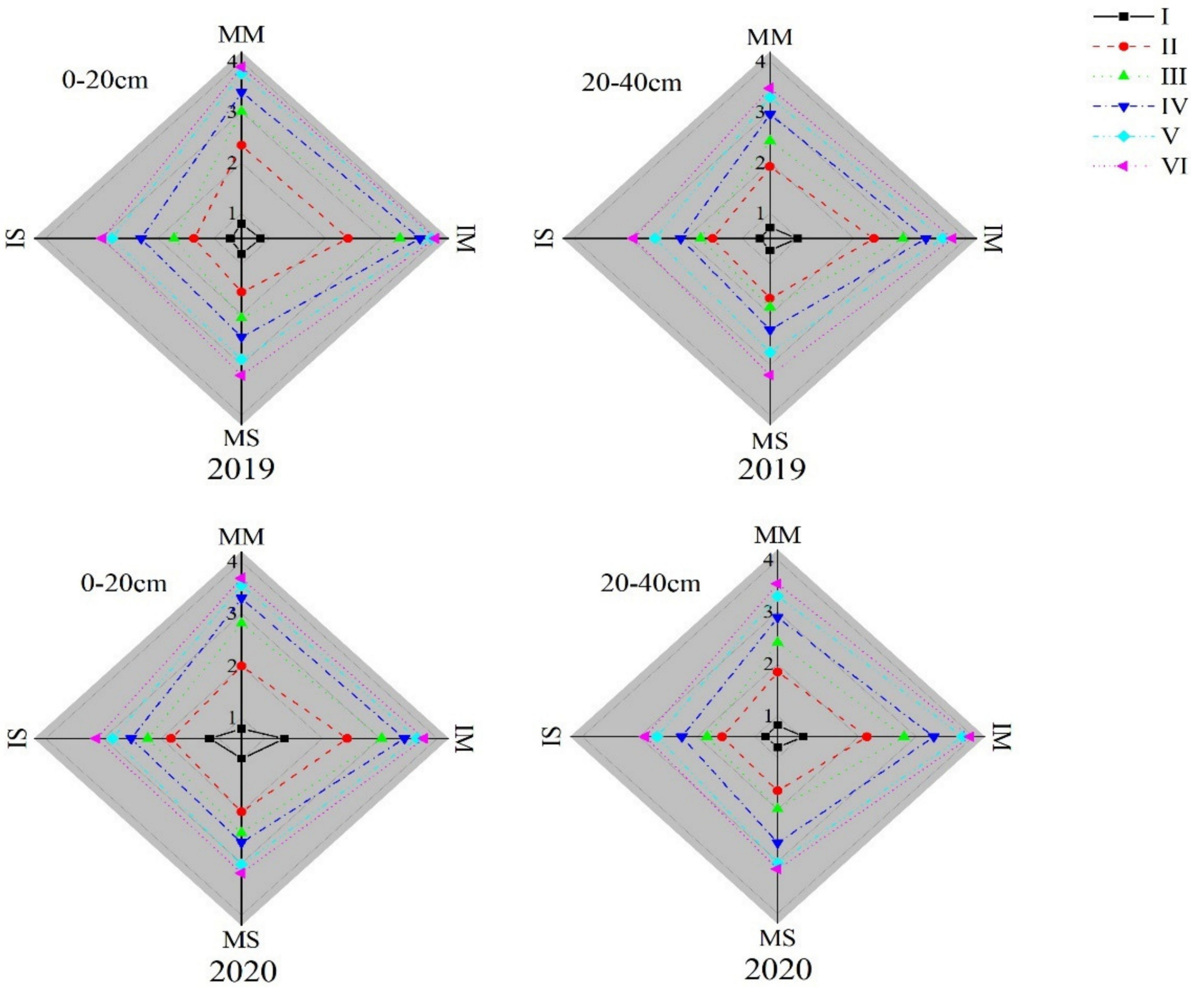

Figure 6. Dynamic changes of RLD of maize and soybean in monoculture and intercropping during 2019 and 2020. Abbreviations: MM—monocropping maize, MS—monocropping soybean, IM—intercropping maize, IS—intercropping soybean. In maize, I–VI mean seedling stage, jointing stage, large bell mouth stage, silking stage, grain filling stage, maturation stage, respectively. In soybean, I–VI mean seedling stage, branching stage, flowering stage, pod setting stage, drumming stage, maturation stage, respectively.

3.5. Correlation

Correlation analysis showed that root morphology, root length density, and soil depth were negatively correlated (Table 2). In monocropping maize treatments, root length, root surface area, and root volume were significantly negatively correlated with soil depth. In intercropping maize, root surface area was significantly negatively correlated with soil depth, and root length was significantly negatively correlated with soil depth. In monocropping soybean, root length was significantly negatively correlated with soil depth, and root surface area, root volume, and root length density were significantly negatively correlated. In intercropping soybean treatment, root surface area was significantly negatively correlated with soil depth, and root length density was significantly negatively correlated with soil depth.

Table 2. Correlation analysis between soil depth and root morphological characteristics in monocropping maize and soybean and maize/soybean.

	Index	RL	RSA	RV	RLD	SD
MM	RL	1				
	RSA	0.966 *	1			
	RV	0.986 *	0.976 *	1		
	RLD	0.899	0.813	0.921	1	
	SD	−0.992 **	−0.991 **	−0.993 **	−0.875	1
IM	RL	1				
	RSA	0.973 *	1			
	RV	0.904	0.972 *	1		
	RLD	0.979 *	0.916	0.842	1	
	SD	−0.982 *	−0.994 **	−0.942	−0.924	1
MS	RL	1				
	RSA	0.964 *	1			
	RV	0.954 *	0.935 *	1		
	RLD	0.979 *	0.889	0.928	1	
	SD	−0.992 **	−0.966 *	−0.984 *	−0.966 *	1
IS	RL	1				
	RSA	0.887	1			
	RV	0.964 *	0.956 *	1		
	RLD	0.981 *	0.939	0.961 *	1	
	SD	−0.887	−0.994 **	−937	−0.951 *	1

Note: * means $p < 0.05$ significant level, ** means $p < 0.01$ extremely significant level. Abbreviations: MM—monocropping maize, MS—monocropping soybean, IM—intercropping maize, IS—intercropping soybean, RL—root length, RSA—root surface area, RV—root volume, RLD—root length density, SD—soil depth.

3.6. Yield Composition

Compared with monocropping, the yield of intercropping maize was higher (Table 3). The number of grains per panicle and the 1000-grain weight were significantly higher than those in the monocrop planting mode, but the difference in the number of panicles was not significant. In 2019, compared with monocropping maize, the number of ears, kernels per ear and the 1000-grain weight of intercropping maize increased by 30.66%, 4.30%, and 7.67%, respectively. In 2020, compared with monocropping maize, the corresponding values of intercropped maize increased by 34.35%, 8.06%, and 6.96%, respectively. In 2-year, intercropping increased maize yield by 49.39–58.10%.

Table 3. Monocropping and intercropping maize yield and yield components in 2019 and 2020.

Treatment		Number of Spikes per Plant (Piece)	Ear Grain Numbers (Grain)	1000-Seed Weight (g)	Yield ($kg \cdot hm^{-2}$)
2019	Monocropping Maize	1.37 ± 0.03 a	318.00 ± 7.79 a	405.48 ± 5.07 a	9715.83 a
	Intercropping Maize	1.79 ± 0.17 a	331.67 ± 10.34 b	436.58 ± 8.35 b	7257.40 b
2020	Monocropping Maize	1.31 ± 0.09 a	294.33 ± 6.93 a	407.32 ± 4.77 a	8637.82 a
	Intercropping Maize	1.76 ± 0.28 a	318.04 ± 7.55 b	435.66 ± 7.63 b	6828.10 b

Note: Means followed by different letters are significantly different at 0.05 levels.

The yield of intercropped soybeans was lower than that of monocropping soybeans (Table 4). The number of pods per plant and the 1000-grain weight of intercropped soybeans were significantly lower than those of monocropping soybeans, and the difference in the number of seeds per pod between the intercropping and monocropping treatments was not significant. The number of pods per plant, the number of grains per pod, and the 1000-grain weight of intercropping soybeans in 2019 were all lower than those under monocropping, by 27.80%, 4.56%, and 4.91%, respectively. In 2020, the number of pods per intercropped soybean plant, the number of grains per pod, and the 1000-grain weight decreased by 22.32%, 5.69%, and 3.41%, respectively, compared with monocropping. In 2-year, intercropping reduced soybean yield by 29.24–34.48%.

Table 4. Monocropping and intercropping soybean yield and yield components in 2019 and 2020.

	Treatment	Pods per Plant (Piece)	Seeds per Plant (Grain)	1000-Seed Weight (g)	Yield ($kg \cdot hm^{-2}$)
2019	Monocropping Soybean	32.66 ± 9.32 a	2.85 ± 0.08 a	232.59 ± 3.70 a	1796.93 b
	Intercropping Soybean	23.58 ± 5.79 b	2.72 ± 0.03 a	221.16 ± 8.71 b	780.16 a
2020	Monocropping Soybean	31.58 ± 8.80 a	2.81 ± 0.06 a	238.35 ± 3.44 a	1755.543 b
	Intercropping Soybean	24.03 ± 6.03 b	2.65 ± 0.05 a	230.23 ± 5.99 b	823.13 a

Note: Means followed by different letters are significantly different at 0.05 levels.

3.7. Land Equivalent Ratio and Actual Yield Loss

The LER is used as an indicator to measure the yield advantage, and the LER is calculated from the monocropping and intercropping yields [14]. The land equivalent ratio of the intercropping system was 1.18–1.26, i.e., the monocropping needs to increase the land area by 18–26% to achieve the same yield as the intercropping, showing the obvious intercropping advantage. The actual yield loss of maize in the intercropping system was greater than 0, and the actual yield loss of soybean was less than 0, Y > 0, indicating that the maize/soybean intercropping system has intercropping advantages (Table 4).

3.8. Aggressivity and Competitive Ratio

Aggressivity measures the intercrop competition using the simple difference between the extents to which crops a and b vary from their respective expected yields. This study showed that $A_m > 0$, indicates that the competitiveness of maize is higher than that of soybean, and maize as the dominant species. $CR_m > 1$, compared with soybean, maize had a higher competition ratio in the intercropping system, suggesting that maize was more competitive than soybean in the intercropping system (Table 5).

Table 5. Yield and competition index.

	LER	AYL	A_m	CR_m	CR_s
2019	1.181	0.149	+0.839	3.441	0.291
2020	1.259	0.289	+0.873	3.372	0.297

Abbreviations: LER—land L equivalent ratio, AYL—actual yield loss, A_m—aggressivity of maize, CR_m—competitive ratio of maize, CR_s—competitive ratio of soybean.

4. Discussion

4.1. Agronomic Traits of Crops

Plant height is one of the basic indicators used in morphological observations and reflects the growth and development of crops and the rate and robustness of plant growth [27]. In the maize–soybean intercropping system, the shading by the taller maize crop modifies the light environment experienced by the lower soybean crop in terms of both light quantity (PAR—photosynthetically active radiation) and quality (R:FR ratio). These changes are affected by the intercropping configuration and crop architecture and cause changes in both plant height and growth of the soybean crop [28]. This study showed that intercropping increased the plant height of maize and soybean. Intercropped maize is a high-level crop that was less affected by soybean in the later growth stage, and the competition for light, water, and nutrients was greater than that of soybean. With the advancement of the growth period, the degree of shading of maize increased, and the plants underwent a series of shading reactions to adapt to shading stress, resulting in the preferential supply of soybean photosynthates to stem elongation, thereby increasing plant height. Liu, et al. [28] also found that the internode length, plant height, and specific leaf area of intercropped soybean increased due to the reduction of the R: FR ratio of photosynthetically active radiation at the top of the intercropping soybean canopy.

The absorption and utilization of light energy by plants directly affect the growth and development of crops, and the most direct effect of light on crops is photosynthesis. There is a significant positive correlation between the crop SPAD value and the photosynthetic capacity [29]. The increase or decrease of SPAD value affects the content of chlorophyll, and the color of leaves will also change accordingly. The change of leaf color can basically reflect the nitrogen nutritional status of the plant and the nutritional status of nitrogen is also reflected in the change of SPAD value [30]. In intercropped maize and soybean, soybean can supply part of the required nitrogen for maize through its own nitrogen fixation function, improve the efficiency of maize's absorption and utilization of nitrogen, and further increase the chlorophyll content of plant leaves [31]. This study found that the SPAD value of intercropping maize was significantly different from that of monocropping maize, and the SPAD value of intercropping maize was stronger than that of monocropping maize. The SPAD value of intercropped soybean was higher than that of monoculture soybean. Compared with monocropping, intercropping of maize and soybean can maintain a higher level of SPAD, can effectively promote photosynthesis, and is conducive to increasing yield in the later period.

4.2. Root Morphological Characteristics

The yield advantages of intercropping systems are due to both above- and below-ground interactions between the intercropped species [32]. The root system is the main organ for the absorption, transmission, storage, and utilization of underground resources such as water and nutrients in an intercropping compound system. Root systems are key areas of crop resource competition and compensation in intercropping systems and are important contributors to yield formation [33]. Li, et al. [34] and Shinano, et al. [35] showed that root morphologies affect intercrop competition in intercropping systems. The intercropping of broad bean and maize changed the root morphology of crops and increased the effective space for crop water and nutrient absorption [36]. Ren, et al. [37] showed that the intercropping of soybeans expanded the ecological niche of the maize root system in the horizontal and vertical directions, and the root length density and root surface area were positively correlated with nitrogen absorption while promoting the vitality of the maize root system. In legume and Gramineae intercropping, legumes promote Gramineae nitrogen absorption through rhizobia nitrogen fixation and nitrogen transfer, thereby increasing the root growth of Gramineae crops [38]. The results showed that compared with the single cropping mode, the root parameters were improved in the intercropping mode, indicating that the intercropping mode effectively improved the root morphology. Among them, the root length and root surface area increased most obviously, which may be due to the relatively low planting density of the intercropping mode, which gave the root system more growth space and promoted the extension of the root system. Among them, the root length and root volume increased significantly in shallow soil. After the intercropping of maize and soybean, the root morphology of maize (shallow root system) and soybean root system (deep root system) were induced to change, giving full play to the complementarity of the root space niche.

The crop growth and final yield of an intercropping system are closely related to the distribution of roots, which determines the uptake and utilization of water and nutrients. The distribution of roots in different soil layers is reflected by the RLD [39]. Root distribution plays an important role in intercropping dominance. Studies of Gao, et al. [40] have shown that the RLD and root surface area density (RSAD) of peanuts in an intercropping system were lower than those of monocropping peanuts, and the RLD and RSAD of intercropped maize were still higher than those of monocropping maize. This study showed that maize and soybean intercropping had a significant effect on RLD compared with monocropping. The RLD of intercropping maize was higher than that of monocropping maize, intercropping promotes root proliferation of maize crops, and maize has intercropping advantages in yield due to the increase of root length density. The RLD of intercropping soybean was lower than that of monocropping soybean, and the distribution of soybean roots was inhibited. This result is inconsistent with the first hypothesis that the corn intercropping soybean system has a positive effect on the root distribution of corn and a negative effect on the root distribution of soybean through underground competition.

4.3. Yield and Land Productivity

Intercropping can optimize the population structure through reasonable crop collocation and appropriate cultivation techniques as well as to give full play to the advantages of the mutual benefits between species to achieve high crop yield and high efficiency [41]. Maize/soybean intercropping has a greater impact on crop yield, but maize and soybean have different performances. The proportion of maize and soybean in intercropping was 1:2, the yield of intercropping maize was equivalent to 49.39–58.10% of the yield of monocropping, and the yield of intercropping soybean was only equivalent to 29.24–34.48% of the yield of monocropping, indicating that intercropping significantly increased the yield of maize, the soybean yield decreased. The nitrogen element supply, fixed by bean plants in the intercropping system, encourages the root system of maize plants to expand their reach therefore it had an impact on raising maize yields [42]. According to Gard and Mckibben [43], an intercropping system has a certain yield reduction effect compared with monocropping. The reduction in seed yield due to intercropping could be the result of interspecific competition and the depressive effect of maize, a C_4 species, on soybean, a C_3 crop. Crops with the C_4 photosynthetic pathway such as maize are known to be dominant when intercropped with C_3 crops such as soybean [44]. Further, the reduction in intercropped soybean could be due to shading by the taller maize plants [45]. In intercropping systems, shorter crops experience shading from taller crops, thus increasing plant height, and decreasing yield [46]. Research has shown that the yield of soybean is inhibited by maize, and the appropriate nitrogen application rate cannot alleviate the inhibitory effect on soybean [47]. It may be that soybean is not sensitive to nitrogen fertilizer, and maize responds quickly to nitrogen fertilizer, resulting in soybean being inhibited by maize, while maize shows yield advantage [48].

Yield advantage is usually assessed and quantified by calculating the land equivalent ratio (LER) in intercropping [49]. In this study, the LER values of corn–soybean intercropping were 1.18–1.26. This means that an additional 18–26% of land area was needed for a monoculture cropping system to produce the equal production as an intercropping system. Hafid et al. [50] stated that the increase in land productivity was caused by choosing the right combination of plants and cropping systems and the existence of a relationship or mutualism symbiosis between plants which were planted in an intercropping way. This symbiosis is closely related to the need for nitrogen for the main plant which was fulfilled from the attached plants through its ability to fix nitrogen from the air. On the other hand, plants that are tolerant to shade can live under stands. The combination of cereal crops and legumes was the best combination. This result supports the second hypothesis that such an intercropping system would have an overall positive impact on productivity by increasing the efficiency of land resource use.

4.4. Interspecific Competition

The competition ratio of maize in the intercropping system was greater than 1, and the aggressivity of maize was greater than 0, indicating that in the symbiotic period of maize and soybean, soybean was at a competitive disadvantage in the intercropping system, and maize was a competitive crop. Previous studies have shown that there is strong interspecific competition among different crops in the intercropping system, and the resource competitiveness of Gramineae crops is higher than that of legumes [51]. According to Banik, et al. [24], the AYL index can give more precise information than the other indices on the inter- and intra-specific competition of the component crops and the behavior of each species involved in the intercropping systems. Quantification of yield loss or gain due to association with other species or the variation of the plant population could not be obtained through partial LERs, whereas partial AYL shows the yield loss or gain by its sign as well as its value. The actual yield loss of maize was greater than 0, indicating that maize has a yield advantage in the intercropping system. The actual reduction of soybean yield is less than 0, indicating that soybean has no yield advantage in the intercropping system, which is consistent with the fact that maize is a competitive crop in the intercropping system, and soybean is a competitive disadvantage crop. The result of interspecific competition was that the actual yield loss of the intercropping system was greater than 0, indicating that the intercropping of maize and soybean had yield advantage because the yield of maize was increased, and the yield of soybean was unchanged or decreased. This is consistent with previous studies on the intercropping of wheat and peas [52], oats and wild peas [26], millet and soybeans [53], which showed that in the legume and Gramineae intercropping system, the yield of grasses increased and the yield of legumes decreased, since the crops in the intercropping system have differences in competitiveness [52]. The intercropping of tall crops (maize) and dwarf crops (soybeans) is caused by the increase of above-ground light interception of maize and the improvement of underground nutrient and water use efficiency [54]. The biological characteristics of soybean are different from those of maize, and it is in a disadvantageous position in the competition for soil water and nutrient absorption and the competition for light interception [55].

5. Conclusions

Maize/soybean intercropping has effects on crop growth, yield, and root morphology. The growth parameters (plant height, relative chlorophyll content) of maize and soybean in intercropping system were better than with monocropping. The yield components of intercropping maize in terms of the number of spikes per plant, ear grain numbers, and 1000-seed weight were higher than those of monocropping, however, in contrast to soybean, monocropping soybean had higher yield parameters than intercropping. The RLD of intercropping maize increased compared to monocropping, indicating greater root growth. The intercropping of maize and soybean has yield advantages; the land equivalent ratio was between 1.18 and 1.26, the aggressivity of maize was between 0.84 and 0.87, and the competition ratio was between 3.37 and 3.44. The reason for improving the yield of the intercropping population is the increase of maize yield and the higher competitiveness of maize for resources than soybean, and maize is the dominant species. Maize and soybean intercropping can improve land use efficiency and crop yield and should be properly promoted to increase maize/soybean productivity.

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