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Intercropping maize and peanut under semi-arid conditions is a zero-sum game

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ABSTRACT

Context: Maize and peanut have been reported to be compatible species in intercropping with a high land use efficiency. However, little information is available at contemporary higher levels of fertilizer input and the possible importance of root plasticity for water uptake in rain-fed semi-arid condition.
Objective: We aimed to quantify yield, yield components, water uptake, root plasticity and distribution of maize and peanut in dryland agriculture.
Methods: A 3-year field experiment was conducted at two N input levels (N-free, without N fertilizer addition; N-farmer, N fertilizer rates were based on conventional rates used by local famers) in Liaoning province, China.
Results: Maize had an average partial land equivalent ratio (pLER) of 0.73 over three years while peanut had an average pLER of 0.27. The total LER indicates no land use advantage of intercropping. Yields were unresponsive to fertilizer input. The harvest index (HI) of maize was increased by intercropping, from 0.47 to 0.52, whereas the HI of peanut was decreased from 0.39 to 0.32 over all years and N treatments. Intercropping decreased the branch numbers and increased the length of main stem and lateral branches at 1st to 3rd pairs. Roots of maize foraged in the peanut strip while roots of peanut were largely absent from the maize strip. The root length density/aboveground biomass of peanut increased 88 % in intercropping. However, contrary to expectation, total water uptake was not increased by intercrop and was not affected by N application rate.
Conclusions: Under rain-fed semi-arid condition, maize/peanut intercropping does not provide land and water use advantage and the species interaction is a zero-sum game, even though peanut showed high root plasticity (88 %). A key reason for the lack of positive LER response is the reduction of HI. Low plant vigour of intercropped peanut due to water stress and shading and the elevated the branch position and the decreased branch number may be responsible for a low rate of pegging which would then result is lower HI.
Implications: The results provide a testable prediction that the advantage of maize/peanut intercropping may potentially be improved by solving the HI problem of intercropped peanut, such as breeding for more shade tolerant varieties or planting the maize in narrower rows to improve the insolation of peanut. Our study is helpful for field management strategies for maize/peanut intercropping in semi-arid dryland agriculture.

1. Introduction

Rain-fed agriculture is vulnerable to irregular precipitation under global change (Zhang et al., 2019b). Maize and peanut growing under rain-fed condition suffer drought risk while peanuts can negatively affect soil retention due to wind erosion after harvest (Sun et al., 2014;

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Wang et al., 2021b). Intercropping is the practice of cultivating two or more crop species in the same field. Intercropping maize and peanut in narrow strips could reduce wind erosion because maize leaves a stubble in the intercrop that reduces wind speed, thus mitigating soil loss by wind in intercropped peanut strips after harvest (Chen et al., 2010). Moreover, mixing the species would provide an opportunity for complementary water use.

A global meta-analysis by Feng et al. (2021) showed that maize/-peanut intercropping has a land equivalent ratio (LER) of 1.31 (with the first (Q1), median and the third (Q3) quartile of 1.16, 1.28 and 1.39), indicating major land savings are achieved by intercropping. However, most papers summarized in this meta-analysis were from relay intercropping (e.g. in India) and/or under low-input agriculture (e.g. African countries). Therefore, the results of this meta-analysis may be less relevant for simultaneous intercropping of maize and peanut under high input conditions. Recent studies on maize/peanut intercropping with simultaneous sowing of the two species at high fertilizer input in Liaoning, China, resulted in an average LER of only 1.00 ± 0.02, though a higher LER was obtained in dry than wet years (Wang et al., 2020, 2021a). In the maize/peanut intercropping studies mentioned above, light use efficiency (LUE) of intercropped maize was slightly lower than that of sole crop, while LUE of intercropped peanut was higher than sole stand (Wang et al., 2021b, 2021c). It means that intercropping results in more production per unit light compared with sole systems, however there is currently still little information on the belowground related to water and root plasticity in the intercrop. Further work is needed to ascertain whether the maize/peanut intercropping under high fertilizer input conditions and simultaneous sowing takes up more water than the average of the sole crops, and hence obtains a land use advantage (LER $>$ 1).

A land use advantage of mixing maize and peanut is expected because the two species have different water requirement. The species with high water requirement might take up additional water from the peanut strip if peanut does not require all the available water, thus allowing maize to overperform under water limiting conditions while not affecting the performance of peanut. Such water sharing of species growing next to each other requires that the roots are closely intermingled such that species can forage in the strip of a neighboring species in strip intercropping. Conceivably, the roots of the plant species in an intercrop could respond to the presence of the other species and its resource capture. The potential for complementary water uptake in intercrops is affected by root growth, plasticity and distribution. In strip intercrops, complementarity for water capture would require that species forage for water within each other's strip. Otherwise, exchange of water between strips, e.g. through lateral movement of soil water, is not expected to be substantial. But there is no information on the distribution of roots in intercrops of maize and peanut, and it is not known whether the species show plastic responses in root growth in response to intercropping like has been found for above-ground morphological traits in maize-wheat intercropping (Zhu et al., 2015) and maize-soybean intercropping (Li et al., 2020) and for root traits of maize and soybean in maize-soybean intercropping (Zhang et al., 2022a).

Cereal/legume intercropping has the potential to improve land productivity by exploiting species complementarities for nitrogen (N) use (Stomph et al., 2020). Water availability influences N-fixation of root nodules (Sprent, 1971), the N use efficiencies of crops (Haefele et al., 2008) and thus plant growth. Under dry conditions, the processes such as mineralization and immobilization might be impaired (Schomberg et al., 1994), thus the plant growth might be affected. But we do not know if root growth, water capture and yield formation of maize/peanut intercropping are affected by N fertilizer input under dryland conditions.

In this research we address the following questions: (1) What is the LER of a simultaneous maize/peanut intercrop under low and high fertilizer input in dryland agriculture? (2) What is the root distribution in the intercrop and the magnitude of root plasticity under low and high fertilizer inputs? (3) Does the change of root distribution and growth of maize and peanut in the strip intercrop under low and high fertilizer inputs affect the total water capture?

The objectives of this study were therefore: (1) to quantify yield and yield components in maize/peanut simultaneous intercropping under low and regular N input in dryland agriculture; (2) to quantify water uptake, root growth and distribution and explore the ensuing land use efficiency in maize/peanut under these growing conditions.

2. Materials and methods

2.1. Experimental design

A three-year field experiment was carried out at the National Experimental Station for Agricultural Environment at Fuxin (121°65′E, 42°11′N), Liaoning province, China from 2017 to 2019. The soil is a sandy Arenosol (Wang et al., 2021a) with a bulk density of 1.45 g cm^{-3} in the 0–100 cm soil layer, and a total soil nitrogen content of 0.78 g kg^{-1}, an available phosphorus content of 17.4 mg kg^{-1}, and an available potassium content of 69.5 mg kg^{-1} in the 0–20 cm soil layer. The region has a semi-arid climate with hot summers and cold winters, allowing for only one crop annually. From 1980 to 2010, the average annual precipitation was 470 mm.

The experiment was laid out in a randomized complete block design with 3 replicates and permanent plots, allowing cumulative effects of treatments over years to emerge. We compared three cropping systems: single maize and single peanut and an intercrop system with alternating strips of 2 rows of maize and 2 rows of peanut. The strips were planted in the same positions each year (not alternated from year to year). Two levels of N input were compared: (1) N-free, without N application, and (2) N-farmer, based on conventional rates used in Liaoning province, China. The N application rates in N-farmer treatment (farmers' rate) were 240 kg ha^{-1} for single maize, 80 kg ha^{-1} for single peanut, and 160 kg ha^{-1} for the maize/peanut intercrop. N was applied as urea. These N inputs take into account the higher nitrogen demand of maize as compared to peanut, while the intercrop treatment receives per strip the same fertilizer as the sole crops with a total rate per ha of 160 kg ha^{-1} ($240 \times 0.5 + 80 \times 0.5$). All N-fertilized treatments received 80 kg N ha^{-1} as basal fertilizer at sowing, and maize received a top dressing of 160 kg N ha^{-1} when 15 leaf collars were visible. The basal fertilizer also included 120 kg ha^{-1} of P_2O_5 and 100 kg ha^{-1} of K_2O in all treatments. In order to exclude the effect of fertilization on the results, both basal fertilizer and topdressing were carried out using strip application methods in the experiment. For the strip application of basal fertilizer, trenches were excavated to facilitate the concentrated application of fertilizer adjacent to the crop sowing rows. To ensure the crop nutrient requirements without inducing localized high soil solution concentrations, we sow seeds near the fertilizer ditch, so that the seeds are closer to the fertilizer but not in direct contact with it. Regarding the strip application of topdressing, to prevent damage to root system, fertilizers were applied to the soil through the trenches between the plants in a row, maintaining a safe distance from the root system.(Fig. 1)

The maize (*Zea mays* L.) cultivar was Pioneer 335 and the peanut (*Arachis hypogaea* L.) cultivar was Baisha 1016 in all years. The row distance was 50 cm in all cropping systems (Fig. 2). The plant distance in a row was 20 cm for maize in monoculture and intercropping systems. Accordingly, the overall density of maize was 10 plants m^{-2} in the sole crop and 5 plants per m^2 of the whole cropping system in intercropping, respectively. The plant distance in a row was 10 cm in peanut, both in monoculture and intercropping systems. Accordingly, the overall density of peanut was 20 plants m^{-2} in the sole crop and 10 plants m^{-2} in the intercrop. The relative density (density in the intercrop divided by density in monoculture) and land (sowing) use proportions of maize and peanut were 0.5 in the intercrops. Each plot was 7 m long and 6 m wide. Maize and peanut were sown and harvested on the same date (i.e. simultaneous intercropping). Sowing was on 15th May in 2017 and

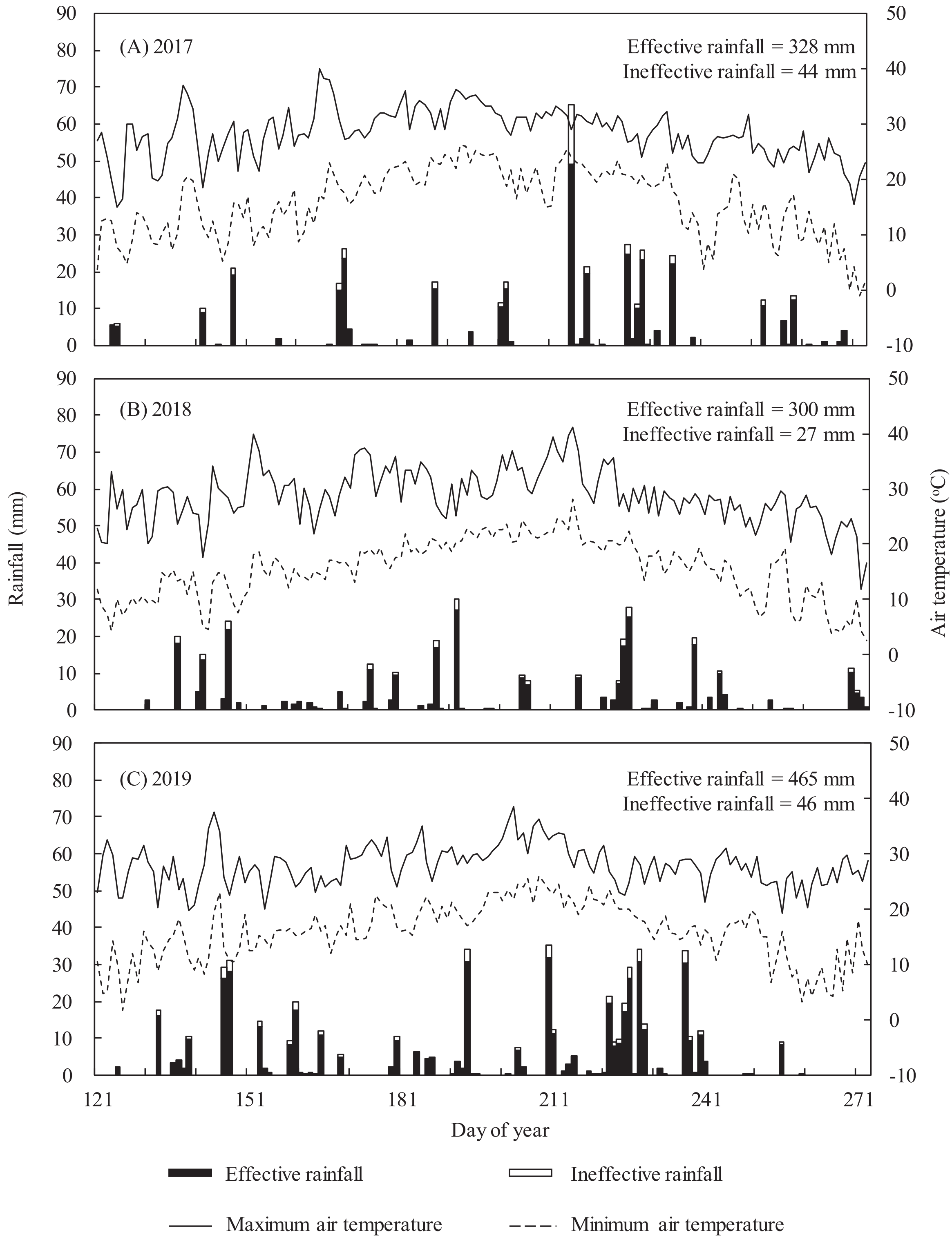

Fig. 1. Daily effective rainfall and maximum and minimum air temperatures during the crop growing season (May to September) in 2017 (A), 2018 (B) and 2019 (C) in Fuxin, Liaoning, China.

2018, and 16th May in 2019, and harvesting was on 26 September in 2017 and on 18 September in 2018 and 2019. The duration of the growing season was thus 134 days in 2017, 126 days in 2018 and 125 days in 2019. Crops were rainfed without any irrigation and weeds were removed manually. The pesticide was applied at the same time with topdressing. Pests and diseases were controlled according to local farmers' practice.

2.2. Yield, yield components, total dry matter and plant morphology

To determine crop yields, sampling was conducted in the central 10 m^2 area (5 m long × 2 m wide) of each plot, which included four rows of maize or peanut in sole systems, and two rows of maize and two rows of peanut in intercropping systems. Seed samples were air-dried to a moisture content of about 14 %. Five plants of maize or peanut in each

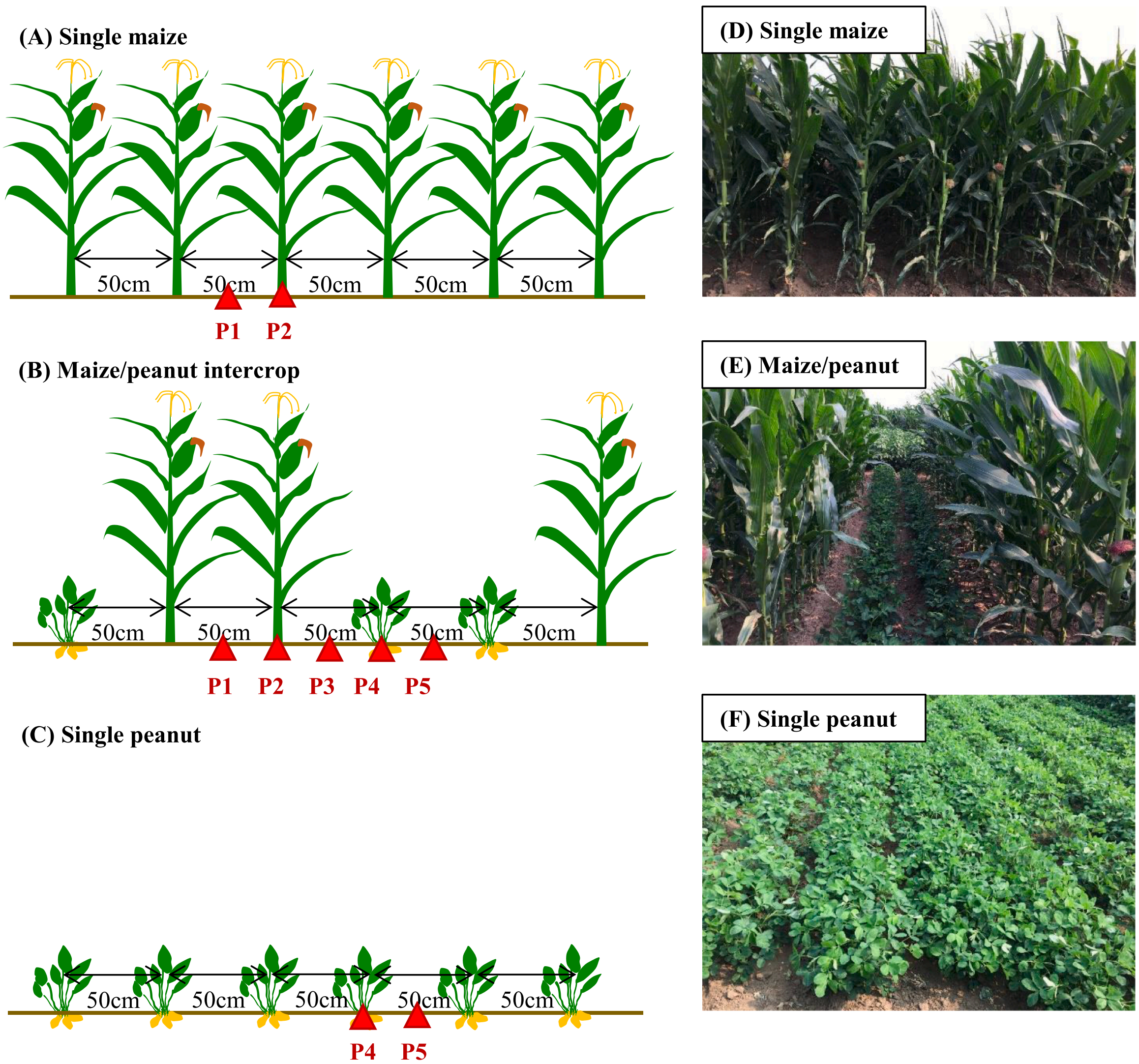

Fig. 2. Field layout of row arrangements of maize and peanut in the intercropping and single crop stands. Photos were taken on 21 August 2018 in Fuxin, Liaoning.

row in the final sampling area were used to quantify yield components. We quantified ear number, grain number per ear and 100-kernel weight of maize, and pod number, seed number per pod and 100-seed weight of peanut. We determined the number of plants over 5 m row length in each plot at harvest to determine actual plant density. Three plants in the sampling area were randomly selected to determine final above-ground dry matter. The samples were oven-dried at 80 °C for 48 hours until the weight remained unchanged. Harvest index (HI) was calculated as grain yield divided by final biomass.

In experimental years, the length of main stem and lateral branch, and total branch number of peanut under N-famer condition were measured. The length of main stem was measured at the seeding stage (V7), flowering and peg forming stage (R1), pod setting stage (R3) and maturity stage (R7) (Boote, 1982) in 2017–2019. Total branch number and branch length were measured at flowering and peg forming stage, and pod setting stage in 2018–2019. The length of main stem was the length from the meristem of the first pair of lateral branches to the parietal internode of the main stem. The length of lateral branches at 1st to 3rd pairs of peanut were the length from the junction of the main stem to the parietal node of the 1st to 3rd pairs lateral branch. The total branch number was the numbers of branches excluding the main stem in the whole peanut.

2.3. Land equivalent ratio

We used land equivalent ratio (LER) to assess land use efficiency (Mead and Willey, 1980).

$$LER = pLER_{maize} + pLER_{peanut} = \frac{I_{maize}}{S_{maize}} + \frac{I_{peanut}}{S_{peanut}} \tag{1}$$

where $pLER_{maize}$ and $pLER_{peanut}$ are the partial *LER*s (i.e. relative yield) of intercropped maize and peanut. I_{maize} and I_{peanut} are grain yields or biomass of intercropped maize and peanut, and S_{maize} and S_{peanut} are grain yields or biomass of sole maize and peanut. *LER* can be interpreted as the relative area of monoculture needed to produce the same quantity of grain or biomass as a unit area of intercrop (Mead and Willey, 1980). If the *LER* is greater than one, intercropping is more land use efficient than sole crops.

2.4. Water use

To quantify water use, soil water content from 0 to 100 cm depth was measured every 10 cm using soil coring. The measurements were made three times each year, i.e. (1) at sowing in each year, (2) at 15 leaf-stage, i.e. shortly before maize tasseling, and during flowering of peanut, and (3) near crop maturity. The second and third measurements were done 64 and 120 days after sowing in 2017; 73 and 119 days after sowing in

2018; and 74 and 128 days after sowing in 2019. The daily water use was calculated from the change in water content in the soil samples during the vegetative stage (from the first to the second measurement) and during the reproductive stage (from the second to the third measurement) (see below).

In the monocultures, soil moisture content was measured at a single position between the rows of maize (P1) or peanut (P5) (Fig. 1). In the intercrop, water content was measured at three positions: between two maize rows (P1), between adjacent maize and peanut rows (P3), and between two peanut rows (P5) (Fig. 2). In the maize/peanut intercrop, the measured values at P1, P3 and P5 were averaged to quantify the average change of soil water contents. The volumetric soil moisture content (m^3 water m^{-3} water) was calculated as the product of gravimetric soil moisture content (g water g^{-1} soil), bulk density (g soil m^{-3} soil) and reciprocal of water density (g water m^{-3} water).

Actual evapotranspiration ET_a, including both soil evaporation and plant transpiration, was quantified using a simplified water balance equation (Mao et al., 2012; Ren et al., 2019).

$$WU = R_e + S_{start} - S_{end} \quad (2)$$

where R_e is the effective rainfall (mm) during the growing season while S_{start} and S_{end} are the soil water content within 0–100 cm root zone (mm) at sowing and harvesting times, respectively. Other terms were not considered because they were negligible. Runoff did not occur due to the flatness of the experimental field and the presence of 15 cm high ridges enclosing each plot. The contribution of capillary rise water was insignificant, as the water table was situated 20 m beneath the root zone (Allen et al., 1998). Deep drainage was negligible because the effective rainfall was used in the equation (Moiwo and Tao, 2015). Effective rainfall (R_e) is the rainfall that is retained in the root zone and is available for evapotranspiration. It omits the precipitation that leaves quickly as deep percolation and was calculated as (Allen et al., 1998; Yang et al., 2021):

$$R_{ei} = \alpha_i \times P_i \quad (3)$$

$$R_e = \sum_{i=1}^{n} R_{ei} \quad (4)$$

where R_{ei} (mm) is the effective rainfall on day i. The P_i (mm) is rainfall amount on day i. The coefficient α_i equals 1.0 when $P_i \leq 5$ mm, 0.9 when 5 mm $< P_i \leq 50$ mm, and 0.75 when $P_i > 50$ mm. R_e (mm) is the total effective rainfall during the growing season. n is the number of days from sowing to harvest.

2.5. Root length density

To collect data on the spatial distribution of roots, soil samples were collected from the 0–100 cm upper layer for each 20 cm depth by using a sharp-edged iron core (1570 cm^3, 10 cm in diameter and 20 cm in height). Root sampling was on the same dates (18th July 2017, 27th July 2018 and 29th July in 2019) as the second measurement of soil water content. Samples were collected within and between the crop rows in sole crops: P1 and P2 for maize, and P4 and P5 for peanut. In intercrops, the samples were collected at 5 locations, P1- P5 (Fig. 2). After washing off the soil, roots of maize and peanut were separated on the basis of color, texture and presence of root nodules. The roots of maize had a smooth surface, white color and a larger diameter while those of peanut were dark brown, relatively thin, and usually with nodules (Li et al., 2006). Then roots of each species were scanned at 600 pixels per mm and root length was analyzed using Win-RHIZO image processing software (Regent Instruments Inc., Canada). Root length density (RLD) for each crop is the ratio of total root length and the sampling volume (cm root cm^{-3} soil). The total root length density RLD_t for a species was the average over all measuring depths.

2.6. Root plasticity

The investment in roots (*IIR*; cm root g^{-1} aboveground dry matter (ADM)) was quantified by dividing the total root length over the 1 m soil profile, RLD_C (cm root m^{-2}) by the aboveground dry matter per m^2, *ADM* (g cm^{-2}) (Zhang et al., 2022a).

$$IIR = \frac{RLD_c}{ADM} = \frac{RLD_t \times \text{Depth}}{ADM} \quad (5)$$

where RLD_t (cm root cm^{-3} soil) is the average *RLD* over the 1 m soil profile and "Depth" is the soil sampling depth (1 m). Root plasticity, defined as the comparative investment in roots over in shoots of a plant in intercrop versus a plant in monoculture (*CIIR*) in this study, was then calculated as:

$$CIIR = \frac{IIR_{int} - IIR_{single}}{IIR_{single}} * 100 \quad (\%) \quad (6)$$

A *CIIR* (%) above zero indicates that the intercropped plants invest a greater proportion of their biomass in roots than plants grown in a pure stand.

2.7. Statistical analysis

Analyses of variance (ANOVA) of yield, yield components, land equivalent ratio and water equivalent ratio were carried out using SPSS 20 (IBM, USA). Mean values were compared using least significant differences (i.e. LSD) at α= 0.05 level.

3. Results

3.1. Weather variability

The total effective rainfall from sowing to harvesting amounted to 328 mm in 2017, 300 mm in 2018 and 465 mm in 2019. The years differed in effective rainfall during early growth in May and June (39 mm in 2017, 66 mm in 2018, and 91 mm 2019) and during kernel formation (July and August): 207 mm in 2017, 155 mm in 2018, and 294 mm in 2019 (Fig. 1). Overall, 2019 was a relatively wet year with an even distribution of rainfall while 2017 and 2018 were dry years with an uneven distribution of rainfall. Thereby 2017 was drier during early growth and 2018 was drier during late growth.

3.2. Yield formation and morphological traits

The yields of maize in monoculture and the intercrops were higher in 2017 (drought during vegetative growth) and 2019 than in 2018 (drought during kernel filling). Average maize yield was 8.07 ± 0.61 t ha^{-1} in the sole crop and 6.13 ± 0.47 t ha^{-1} in maize/peanut across 3 years. Nitrogen fertilization did not affect yield of sole or intercropped maize in 2017 and 2018, but had a large and significant positive effect on yield in 2019 ($P < 0.05$) (Table 1). The yield difference between intercropped and single maize was larger in 2019 than in the other two years. The number of ears per maize plant was not changed by intercropping. On average over all years and N treatments, ears had 45 % ($P < 0.01$) more grains in the intercrop than in sole maize (Fig. 3A,B, supplementary Table 1). The 100-kernel weight was 14 % greater ($P < 0.01$) in maize/peanut than in the sole crop stands in N-free, but there was no significant difference in 100-kernel weight between intercrop and single crop stands in N-farmer (Fig. 3C). The HI was significantly greater in intercropping than in sole crops in 2017 N-farmer and 2019 N-free. There was no significant difference in harvest index (HI) between intercropped and sole maize over all N treatments and years (Fig. 4A,B).

The overall average peanut yield was 2.97 ± 0.13 t ha^{-1} in the sole crop and 0.68 ± 0.03 t ha^{-1} in the intercrop, with no significant

Table 1
Grain yields of maize and peanut (t ha^{-1}) in the intercropping and the monocultures in 2017–2019.

Year	N application rate	Maize (t ha^{-1})		Peanut (t ha^{-1})	
		Monoculture	Intercrop[a]	Monoculture	Intercrop[a]
2017	N-free	9.2 ± 0.2 a	7.8 ± 0.3 a	3.1 ± 0.1 a	0.7 ± 0.1 a
	N-farmer	9.4 ± 0.1 a	8.2 ± 0.1 a	3.7 ± 0.5 a	0.7 ± 0.1 a
2018	N-free	5.3 ± 0.2 a	4.0 ± 0.5 a	2.7 ± 0.1 a	0.6 ± 0.1 a
	N-farmer	5.1 ± 0.5 a	4.1 ± 0.1 a	2.8 ± 0.2 a	0.7 ± 0.1 a
2019	N-free	7.3 ± 0.4 b	4.9 ± 0.6 b	2.5 ± 0.1 a	0.7 ± 0.1 a
	N-farmer	12.1 ± 0.1 a	7.7 ± 0.7 a	3.0 ± 0.2 a	0.7 ± 0.1 a
Mean	N-free	7.3 ± 0.1 b	5.6 ± 0.1 b	2.8 ± 0.2 a	0.7 ± 0.1 a
	N-farmer	8.9 ± 0.1 a	6.7 ± 0.1 a	3.2 ± 0.1 a	0.7 ± 0.1 a
P	Year	0.000		0.046	
	N	0.000		0.066	
	Cropping system	0.000		0.000	
	Year×N	0.000		0.795	
	Year×Cropping system	0.000		0.052	
	Cropping system×N	0.237		0.088	
	Year×N × Cropping system	0.071		0.517	

Same small letter indicates no significant difference between N application rates within same year at the 0.05 level.
[a] Grain yields in the intercrop are homogeneous for total intercropping area.

differences between years and N application rates (Table 1). Pod number per plant was 44 % lower in the intercrop than in the sole crop ($P < 0.01$) and 100-seed weight was on average 7 % lower in the intercrop than the sole crop ($P < 0.01$), on average over years and N application rates (Fig. 3E-H). There was no significant intercropping effect on seed number per pod (Supplementary Table 1). The HI of peanut in the intercrops was 0.32 ± 0.01 across all years and N treatments, 17 % ($P < 0.05$) lower than that in sole crop (0.39 ± 0.02) (Fig. 4C,D).

To further explain the HI reduction problem in intercropped peanut, the number and the position of peanut branches, which were important for peg development, were quantified. Compared to sole peanut, maize/peanut intercropping decreased peanut branch number by 12.5 % ($P < 0.05$) in 2018–2019 under N-farmer condition (Fig. 5). Regarding to the position of peanut branches, peanut main stem height was enhanced by intercropping for all growth stages over three years. The main stem height was 13.9 % ($P < 0.01$) higher in the intercrop than the sole crop (Fig. 6). Intercropping also increased the length of lateral branches at 1–3 pairs by 17.8 % ($P < 0.01$) averaged over all years and stages. This increase effect was pronounced in both years, especially at R1 stage (Fig. 7).

3.3. Land equivalent ratio

The land equivalent ratio (LER) for grain yield was 1.07 ± 0.03 in 2017, 1.02 ± 0.04 in 2018, and 0.92 ± 0.05 in 2019 (averages over N treatments). The LER was 1.00 ± 0.03 on average over the three years. The partial LER of maize ($pLER_m$) in the intercrop was on average 0.77 ± 0.03 with a 27 % point difference between pLER and land use proportion. The partial LER of peanut ($pLER_p$) was 0.23 ± 0.01, a 27 % point reduction. The LER was not affected by N input (Table 2). Consistent with the lower HI of intercropped peanut, the $pLER_p$ for biomass (0.28 ± 0.01) was significantly ($P < 0.01$) higher than that for grain yield (0.23 ± 0.01).

3.4. Water use

There were no significant differences between cropping systems in total water uptake during the season (Table 3). However, there were slight differences in water uptake between crop systems in the first and second half of the growing season. The daily water use of sole peanut during vegetative growth in the first half of the growing season, averaged over N levels, was 2.5 mm d^{-1}, versus 2.8 mm d^{-1} in maize/peanut and in sole maize ($P < 0.01$) (Table 4). In the second half of the season, during the reproductive stage, the daily water use of single peanut was 3.3 mm d^{-1} with N-farmer, versus 3.0 mm d^{-1} in the intercrop ($P < 0.05$) and 2.8 mm d^{-1} in sole maize ($P < 0.05$) during the three years (Table 4). Such a difference was not found at zero N input.

3.5. Investment in roots, root plasticity and root distribution

The spatial distribution of roots, measured each year on 9 July, differed between intercropping and single crop stands (Figs. 8, 9). In the intercropped maize strip (P2), the root length density was greater than in the monoculture at all depths, especially in 2019. Intercropped maize roots explored a larger soil volume in N-free than N-farmer, especially in 2019 when more N deficient. In the intercrop, roots of maize were also present in the peanut strip while roots of peanut were scarcely observed in the maize strip. Intercropped maize had greater RLD at all depths when compared to peanut. Regarding peanut, intercropping did not affect the depth of rooting for peanut. In intercropped peanut, there was more and deeper root growth in N-free than in N-farmer (Figs. 8, 9). While intercropped peanut has much greater comparative investment in roots than sole peanut, this did not result in a significant difference in RLD between intercropped and sole peanut, due to the substantially lower biomass per m^2 of intercropped peanut compared to sole peanut.

The investment in roots (IIR) was 82.9 ± 11.0 cm g^{-1} in sole maize and 78.6 ± 6.4 cm g^{-1} in intercropped maize, on average over years and N treatments. The investment in roots was not significantly different between intercropped maize and sole maize (CIIR = 5 %; $P = 0.67$) and was not affected by N input ($P = 0.79$). The IIR was 57.2 ± 4.1 cm g^{-1} in sole peanut and 93.8 ± 10.4 cm g^{-1} in intercropped peanut, an increase of 88 % (CIIR = 88 %; $P < 0.01$) compared to the monoculture (Fig. 10). N input did not affect IIR of peanut ($P = 0.21$).

4. Discussion

4.1. Land equivalent ratio of maize/peanut intercropping

The average LER of 1.0 in our study contrasts with the global meta-analysis average of 1.31 for maize/peanut intercropping (Feng et al., 2021). The pLER of maize in our study is slightly lower than the global level (0.85), while the pLER of peanut is significantly lower than the worldwide average value (0.49). This discrepancy arises because most studies in Feng et al.'s study focused on low-input or relay intercropping systems, whereas our study reflects high-input and simultaneous sowing practices intercropping systems in semi-arid rain-fed agriculture. Under high fertilizer and water-limited conditions, a LER around 1 aligns with recent reports from Liaoning (Wang et al., 2020, 2021a), suggesting that interspecific competition negates complementarity.

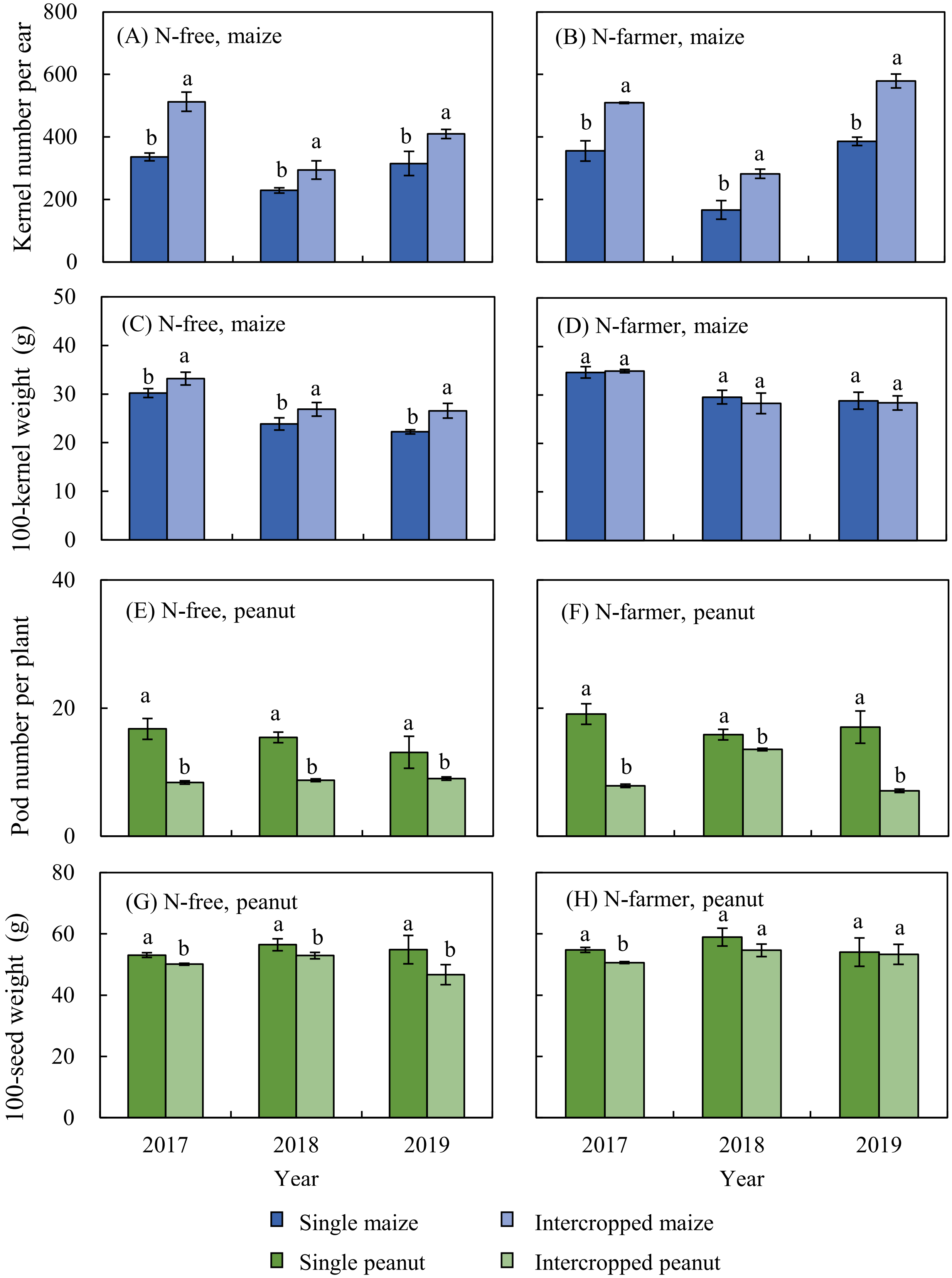

Fig. 3. Yield components of maize and peanut in maize/peanut intercropping and single crop stands in 2017–2019. Same small letters indicate no significant difference between cropping systems within same year at the 0.05 level.

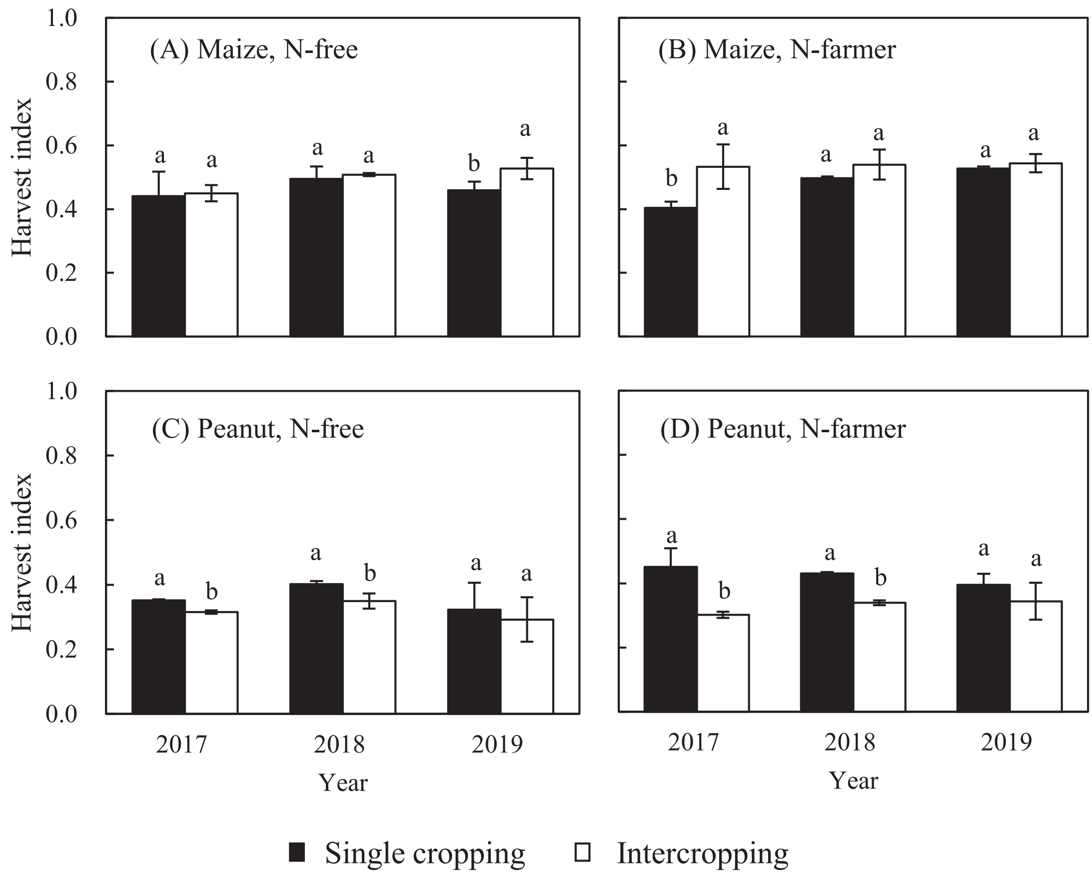

Fig. 4. Harvest index of maize and peanut in single crop stands and intercropping systems in 2017–2019. Same small letters indicate no significant difference between cropping systems within same year for each crop at the 0.05 level.

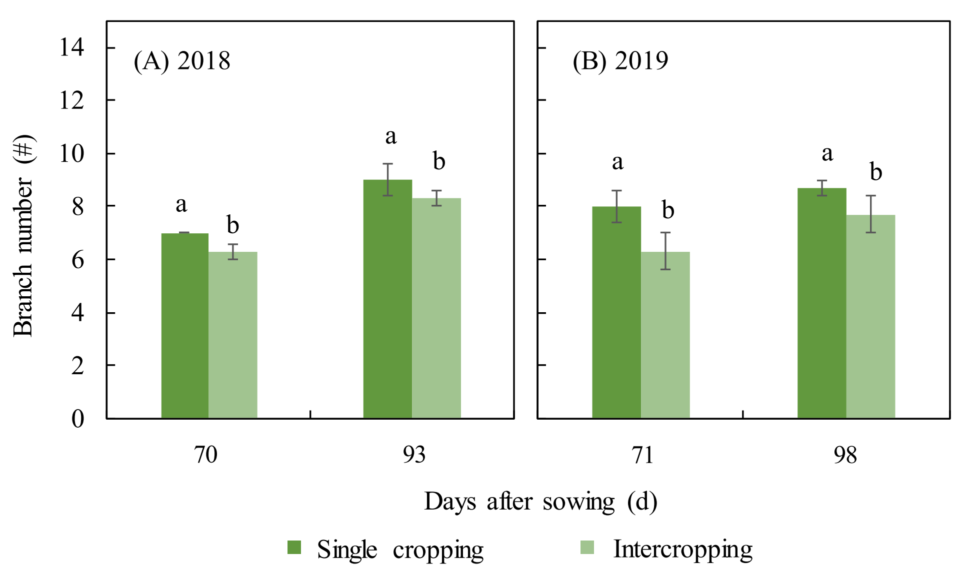

Fig. 5. Branch number of peanut in intercropping and single cropping systems in 2018–2019. Same small letters denote no significant difference between cropping systems for each crop at α= 0.05.

The pLER imbalance in maize and peanut in our study suggests dominance by C4 maize suppresses peanut. The good performance of maize in the intercrop was related to substantial increases (45 %) in kernel number per ear (Fig. 3), consistent with findings in maize/soybean (Zhang et al., 2022a). Kernel formation likely benefited from the better condition of radiation, soil water and nitrogen in intercropped maize (Nemali et al., 2015), especially in the border rows (Stomph et al., 2020). In this study, the large yield advantage of intercropped maize compared with sole maize suggest that maize was foraging in the peanut strip in maize/peanut intercropping systems. Intercropped maize was not only using water from the maize strip but also from the peanut strip. Increased light interception enhances the delivery of photosynthate to

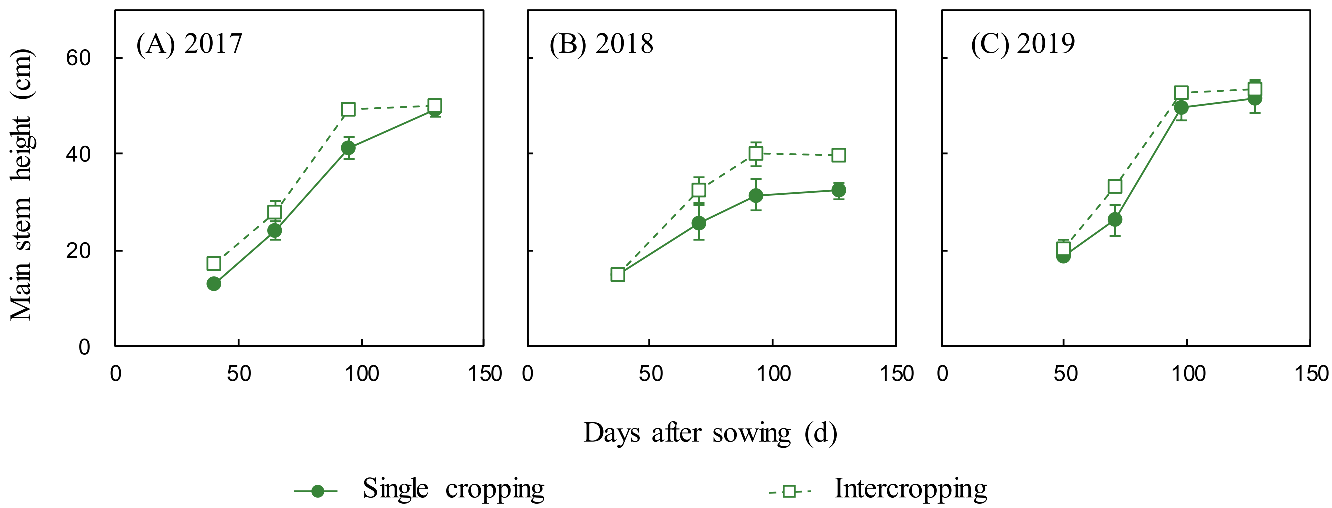

Fig. 6. Main stem height of peanut in intercropping and single cropping systems in 2017–2019.

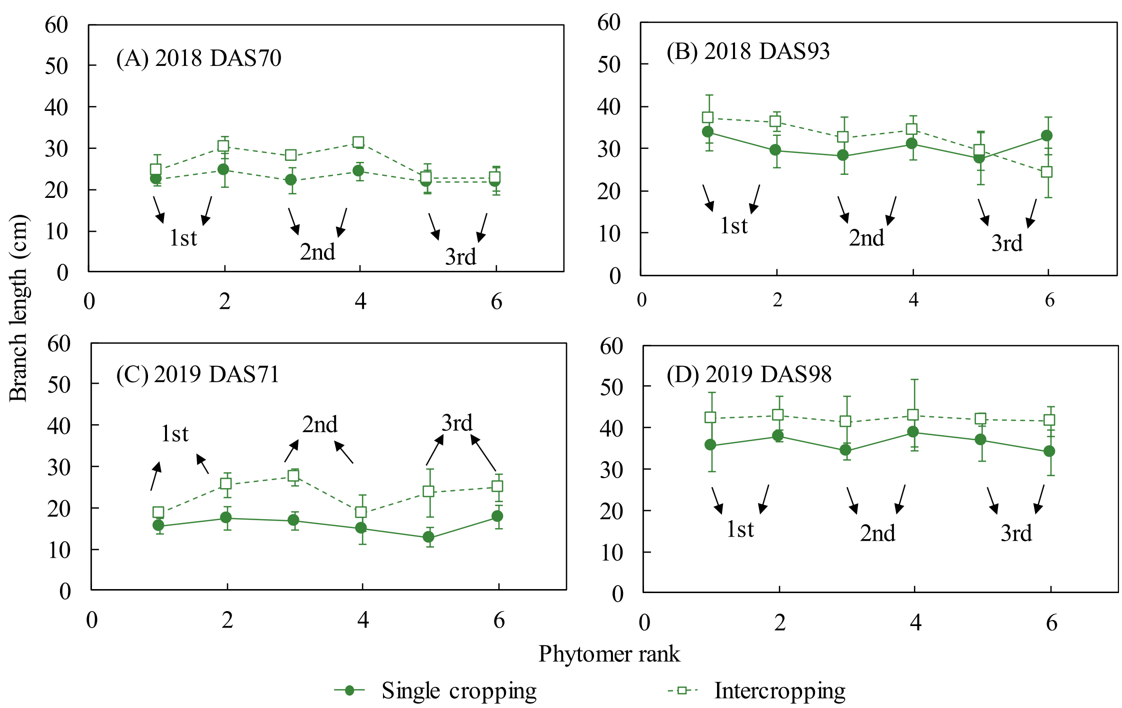

Fig. 7. Length of lateral branches at 1st to 3rd pairs of peanut in intercropping and single cropping systems in 2018–2019. DAS indicates days after sowing.

the young kernels, lessening abortion rates and improving kernel quantity (Zou et al., 2019). The interspecific complementarity could have allowed intercropped maize a high growth rate of shoot dry matter at the crucial stage bracketing silking from our previous study at same environment (Zhang et al., 2020), thus the surplus assimilates generated were able to fill the extra kernels.

Intercropping maize and peanut was a zero-sum game in this study, in which the advantages of maize were completely offset by the disadvantages of intercropped peanut. On the basis of our findings, we explored the underlying mechanisms in Sections 4.2 to 4.4, focusing on morphological and harvest index (HI) trade-offs, water use and nitrogen limitations, as well as root growth and distribution patterns. These aspects jointly explain why the system failed to achieve a land use advantage in this study.

4.2. Morphological and HI trade-offs and yield penalties

In our study, we found that a key reason for the lack of positive LER response is the reduction of HI. In peanut, pod number was greatly reduced (by 44 %) in the intercrop (Fig. 3). Intercropped peanut intercepts significant less light than peanut in monoculture (Wang et al., 2021c). Peanut develops pegs after flowering that bore into the ground and develop into pods. Pegging may be negatively affected when plants are etiolated by lacking assimilates due to shading in an intercrop (Rylski and Spigelman, 1986). The number and the position of peanut branches are important for peg development and 80–90 % of pegs growing on the first to the third paired lateral branches (Gao et al., 2023). Compared to sole peanut, maize/peanut intercropping decreased peanut branch number by 12.5 %, enhanced peanut main stem height by 13.9 %, and increased the length of lateral branches at 1st to 3rd pairs by 17.8 % (Figs. 5–7). This indicates that the peg numbers decreased by

Table 2
Land equivalent ratios (LER) in maize/peanut intercropping systems under different N application rates in 2017–2019.

Year	N application rate	LER for grain yield			LER for biomass yield		
		$pLER_m$	$pLER_p$	LER	$pLER_m$	$pLER_p$	LER
2017	N-free	0.85 ± 0.04 a	0.22 ± 0.01 a	1.07 ± 0.05 a	0.84 ± 0.16 a	0.24 ± 0.01 a	1.08 ± 0.16 a
	N-farmer	0.87 ± 0.02 a	0.19 ± 0.03 a	1.06 ± 0.04 a	0.70 ± 0.16 a	0.28 ± 0.01 a	0.98 ± 0.16 a
2018	N-free	0.76 ± 0.07 a	0.22 ± 0.03 a	0.98 ± 0.05 a	0.74 ± 0.10 a	0.25 ± 0.02 a	0.99 ± 0.09 a
	N-farmer	0.81 ± 0.07 a	0.25 ± 0.03 a	1.06 ± 0.07 a	0.76 ± 0.07 a	0.32 ± 0.04 a	1.08 ± 0.11 a
2019	N-free	0.68 ± 0.10 a	0.29 ± 0.01 a	0.97 ± 0.09 a	0.60 ± 0.11 a	0.32 ± 0.04 a	0.92 ± 0.11 a
	N-farmer	0.64 ± 0.06 a	0.22 ± 0.03 b	0.86 ± 0.04 b	0.62 ± 0.04 a	0.26 ± 0.01 b	0.88 ± 0.05 a
Mean	N-free	0.76 ± 0.04 a	0.24 ± 0.01 a	1.01 ± 0.04 a	0.73 ± 0.07 a	0.27 ± 0.02 a	1.00 ± 0.07 a
	N-farmer	0.77 ± 0.04 a	0.22 ± 0.02 a	1.00 ± 0.04 a	0.69 ± 0.06 a	0.28 ± 0.01 a	0.98 ± 0.06 a
P	Year	0.028	0.109	0.073	0.370	0.516	0.439
	N	0.819	0.273	0.838	0.733	0.519	0.829
	Year×N	0.724	0.159	0.291	0.764	0.061	0.741
		$pLER_m$ = 0.285	$pLER_p$ = 0.004	LER = 0.814			

Same small letter indicates no significant difference between N application rates within same year at the 0.05 level.

Table 3
Water uptake (mm) of maize and peanut in monoculture and intercropping systems in 2017–2019.

N rate	Cropping system	2017	2018	2019	2017–2019
N-free	Maize (P1)	292.1 ± 12.5 a	299.0 ± 1.2 b	444.4 ± 3.7 a	345.2 ± 5.1 a
	Peanut (P5)	268.4 ± 8.4 a	309.5 ± 2.4 ab	451.3 ± 4.9 a	343.1 ± 3.5 a
	Intercropping system	284.7 ± 13.9 a	315.4 ± 6.8 a	459.3 ± 7.0 a	353.1 ± 1.1 a
N-farmer	Maize (P1)	285.1 ± 10.8 a	311.8 ± 11.7 a	463.0 ± 13.2 a	353.3 ± 6.0 a
	Peanut (P5)	274.0 ± 6.5 a	337.1 ± 3.9 a	462.8 ± 8.7 a	358.0 ± 5.1 a
	Intercropping system	296.8 ± 10.2 a	313.4 ± 7.6 a	458.4 ± 2.6 a	356.2 ± 2.1 a
P	Year= 0.000	Cropping system= 0.517		N = 0.036	
	Year×N = 0.633	Year×Cropping system= 0.062		Cropping system×N = 0.487	
	Year×Cropping system×N = 0.393				

Same small letter indicates no significant difference between cropping system for each N rate at α= 0.05.

Table 4
Daily water uptake (mm d^{-1}) of maize and peanut in monoculture and intercropping systems during the vegetative and reproductive stages in three growing seasons (2017, 2018 and 2019).

N rate	Cropping system	Vegetative stage (mm d^{-1})				Reproductive stage (mm d^{-1})			
		2017	2018	2019	2017–2019	2017	2018	2019	2017–2019
N-free	Maize (P1)	1.8 ± 0.1a	2.5 ± 0.1a	3.6 ± 0.0b	2.6 ± 0.1a	3.2 ± 0.1a	2.5 ± 0.1b	3.3 ± 0.1a	3.0 ± 0.0a
	Peanut (P5)	1.4 ± 0.2a	2.4 ± 0.1a	3.7 ± 0.0b	2.5 ± 0.1b	3.2 ± 0.0a	2.9 ± 0.2a	3.3 ± 0.1a	3.1 ± 0.1a
	Intercropping system	1.5 ± 0.2a	2.5 ± 0.1a	4.2 ± 0.0a	2.7 ± 0.0a	3.3 ± 0.1a	2.9 ± 0.0a	2.1 ± 0.1b	3.0 ± 0.0a
N-farmer	Maize (P1)	1.7 ± 0.1a	2.8 ± 0.1a	4.2 ± 0.1a	2.9 ± 0.1a	3.2 ± 0.1a	2.4 ± 0.2b	2.8 ± 0.1b	2.8 ± 0.1b
	Peanut (P5)	1.5 ± 0.1a	2.5 ± 0.0b	3.8 ± 0.1b	2.6 ± 0.1b	3.2 ± 0.1a	3.4 ± 0.0a	3.4 ± 0.3a	3.3 ± 0.1a
	Intercropping system	1.8 ± 0.2a	2.7 ± 0.1ab	3.9 ± 0.0ab	2.8 ± 0.0a	3.3 ± 0.0a	2.6 ± 0.1b	3.1 ± 0.0a	3.0 ± 0.0b
P		Year= 0.000 Cropping system= 0.001 N = 0.006				Year= 0.000 Cropping system= 0.000 N = 0.687			
		Year×N = 0.577				Year×N = 0.983			
		Year×Cropping system= 0.456				Year×Cropping system= 0.000			
		Cropping system×N = 0.246				Cropping system×N = 0.027			
		Year×N × Cropping system= 0.002				Year×N × Cropping system= 0.002			

Same small letter indicates no significant difference between cropping system for each N rate at α= 0.05.

intercropping, and the position of pegs were elevated by intercropping. A longer distance for pegging into the soil may interfere with penetration into the soil (Wang et al., 2020; Gao et al., 2023). This adverse influence on peg penetration into the soil would negatively affect the formation of pods of intercropped peanut and lower the HI and finally lower pLER for peanut. In our study, LER will enhance around 8 % ($P < 0.01$) if intercropped peanut had same HI as monocropped peanut when the pegging problem of intercropped peanut can be solved. In maize/soybean intercropping under the same growing conditions, intercropping did not change the harvest index. Soybean obtained high root plasticity and had higher land and water productivity in intercropping than in pure stands (Zhang et al., 2022a). Future studies on performance of peanut in intercrops with maize may pay particular attention to pegging.

4.3. Water use and nitrogen limitations

Effective rainfall was used when calculating the water uptake of sole and intercropping systems in this study. The effectiveness of rainfall can be affected by some factors, such as the rainfall time, intensity and duration, soil texture and structure, canopy cover, crop residue and crop root zone depth, etc (Ali and Mubarak, 2017). For instance, frequent rainfall of more than 50 mm early in the growing season or with a shallow-rooted crop may be lost to deep drainage to a greater extent than calculated. Rainfall exceeding 50 mm may not even have a drainage effect if soil is dry, especially when crops are deep-rooted and rapidly transpiring. At the other extreme, rainfall events less than 2 mm are generally ineffective for crop growth due to rapid evaporation. Regarding the water use and water use efficiency, the total water uptake did not differ between sole and intercropping systems. Intercropping of maize and peanut did not affect water use efficiency at system level in

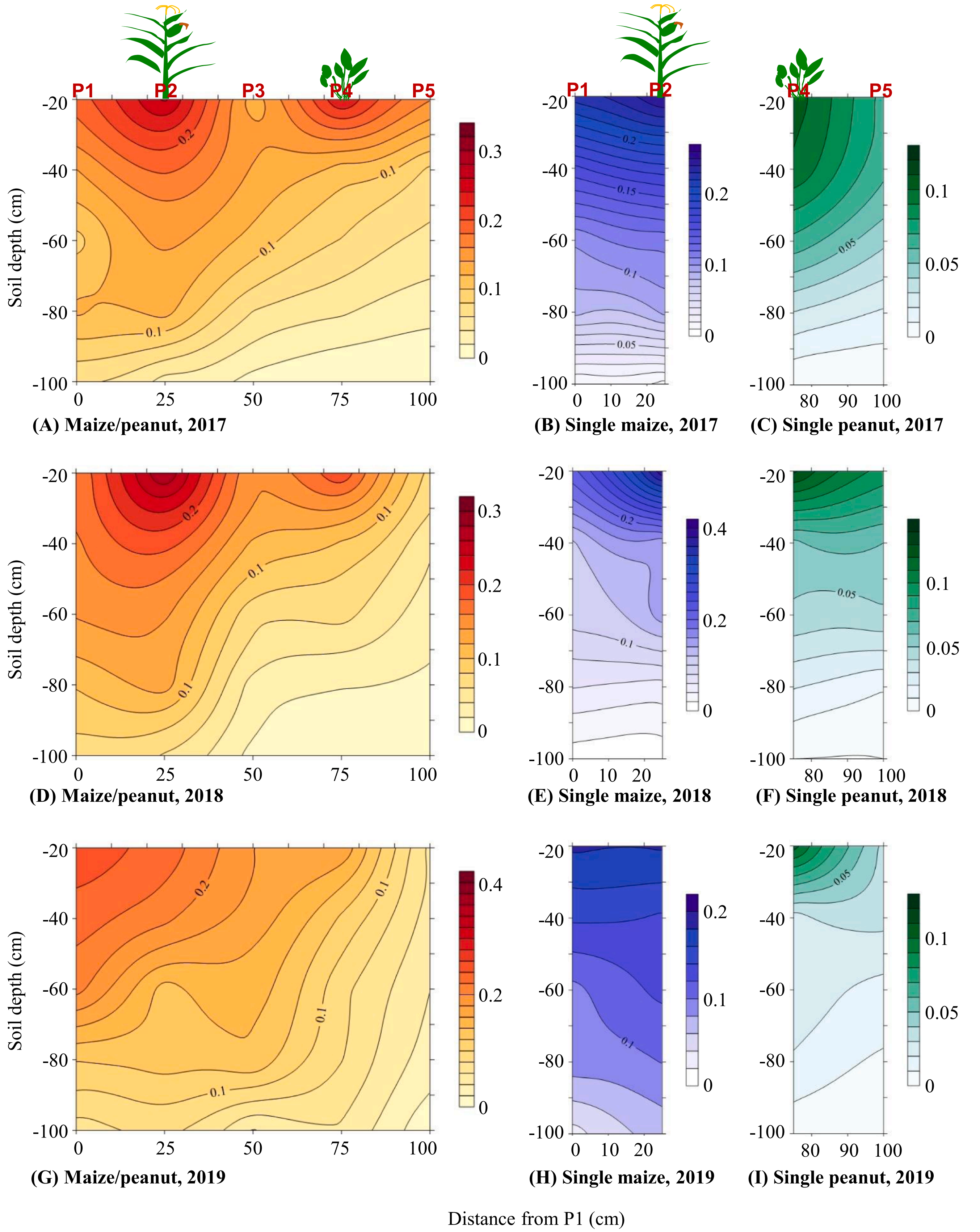

Fig. 8. Distribution of root length densities (cm cm^{-3}) in root zone in maize/peanut intercropping, single maize stands and single peanut stands under N-free condition in 2017–2019. P1 is the middle between two maize rows.

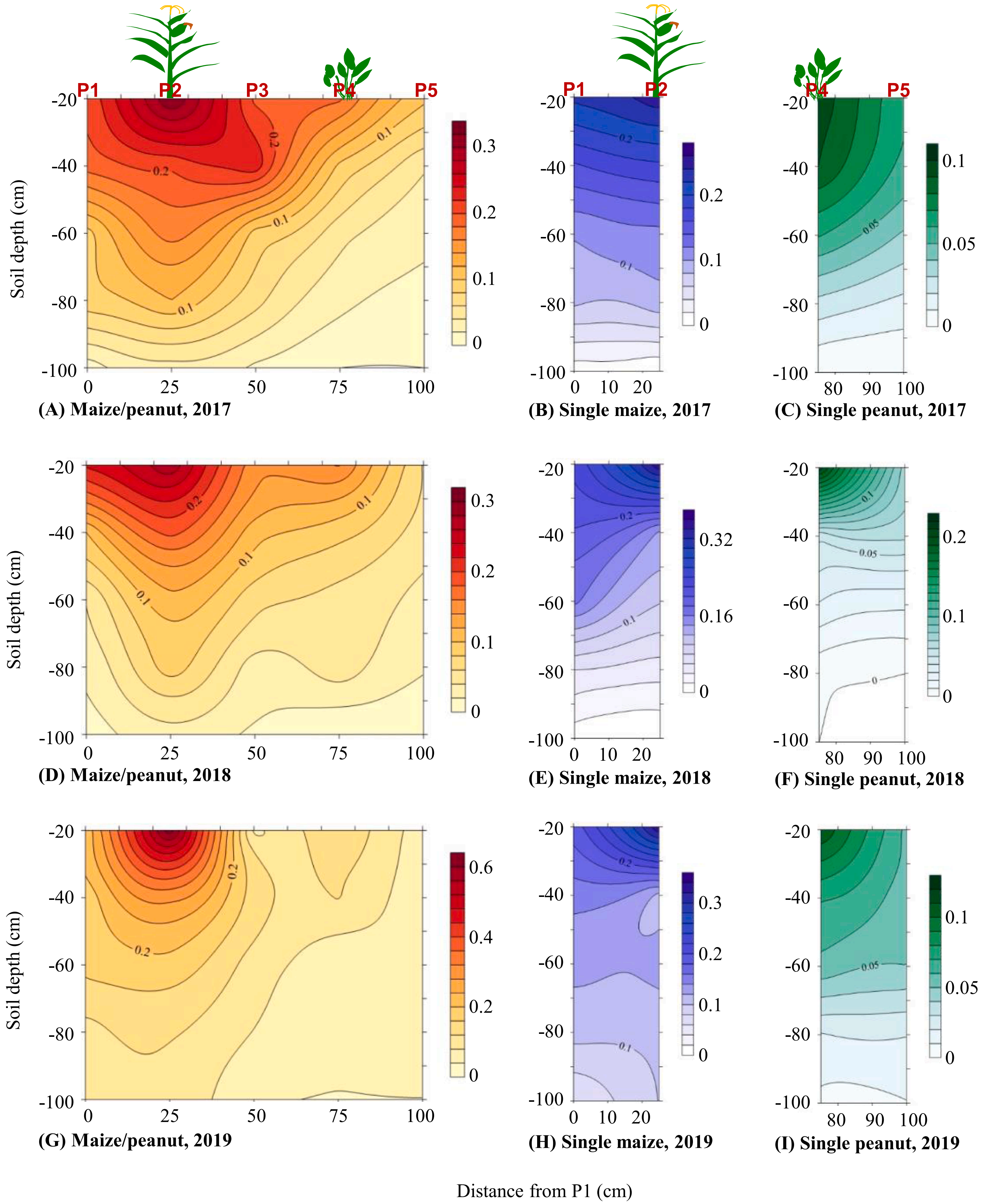

Fig. 9. Distribution of root length densities (cm cm^{-3}) in root zone in maize/peanut intercropping, single maize stands and single peanut stands under N-farmer condition in 2017–2019. P1 is the middle between two maize rows.

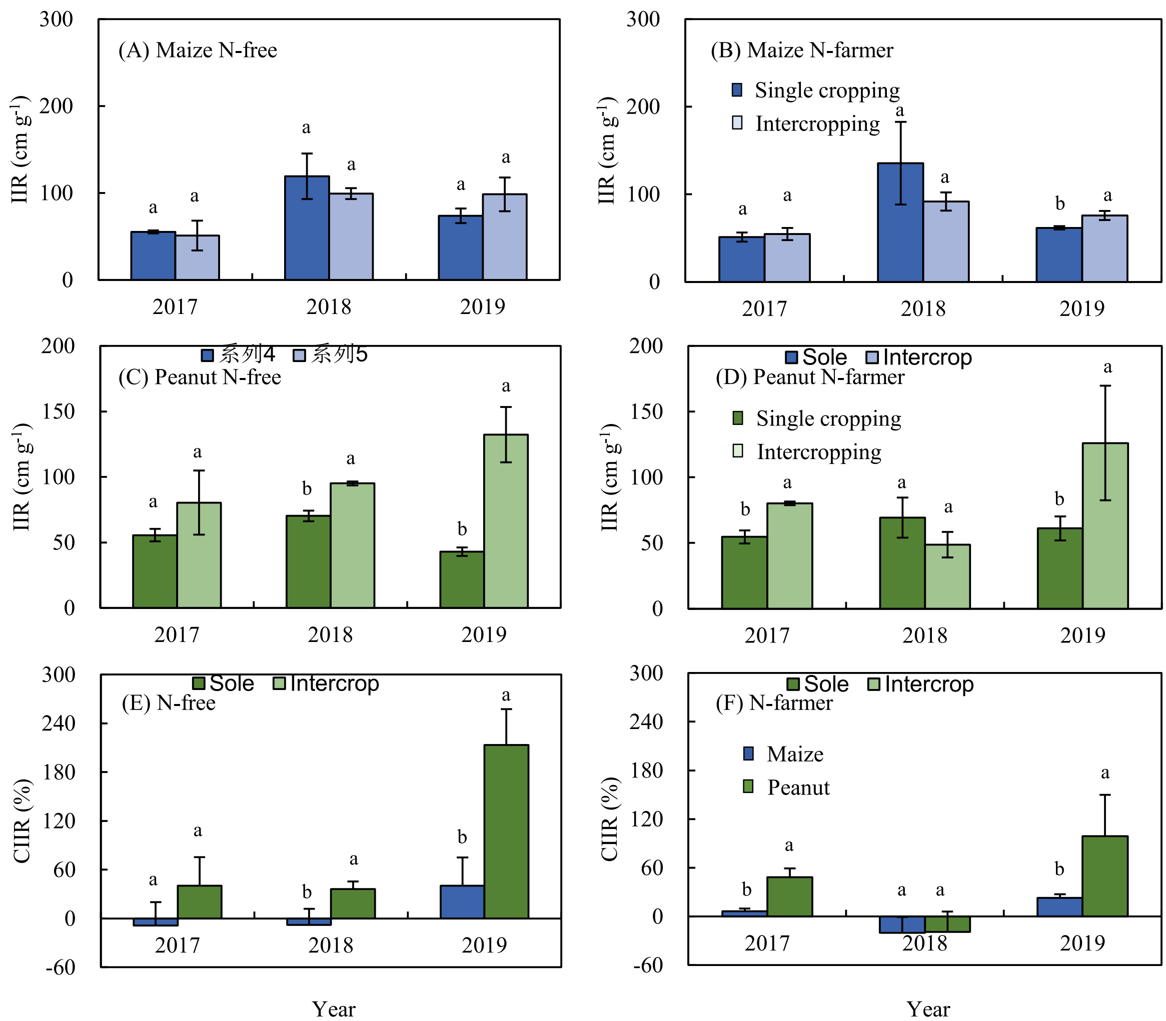

Fig. 10. Investment in roots comparing with in shoots (IIR) and the root plasticity as comparative investment in roots (CIIR, (IIR of intercrop-IIR of single)/IIR of single)) for each crop in 2017–2019. Same small letter denotes no significant difference between cropping systems for each crop and for whole system within same year at the 0.05 level.

this study because total water use was the same and LER was 1.

Though intercropping did not affect total water uptake from the soil, sole maize had slightly greater uptake than sole peanut during the early growth stage, while sole peanut had slightly greater water uptake than sole maize during the late growth stage as shown in our study, indicating the different water requirement and water uptake between maize and peanut in early and late growth stage. This might lead some possibility of temporal complementary water use in maize/peanut intercropping over the season. The temporal complementarity in water use due to differentiation in the development of crop species in intercrops is essential for reducing water stress during key times of yield formation (Bai et al., 2016). Another form of water complementarity is spatial complementarities resulting from differences between species in root distribution. In our study, maize roots extensively colonized the peanut strip (Figs. 8, 9), same with the findings in maize/soybean systems where maize dominates soil exploration (Zhang et al., 2022a). However, unlike soybean, peanut roots showed limited compensatory growth into maize strips, resulting in asymmetric belowground competition. The root segregation rather than intermingling likely constrained the complementarity in water use. Further researches can illuminate the spatial water complementarity by exploring soil water variation dynamics in space and root-water relationships.

In our study, N input did not affect LER, even in 2019 when maize yield was highly responsive to N input and an increase in LER would be expected due to complementary N use. Perhaps due to low soil N supply in the increased volume of soil explored by intercropped maize. N input also did not significantly affect the yield, water use and root growth. This might be due to drought because N uptake requires sufficient soil water (Zhang et al., 2019a). The few study quantified the transpiration for each species in the intercrop separately, such as in maize/wheat intercropping, the water uptake of maize and wheat was separated by measuring sap flow (Ma et al., 2020, 2022). The plant transpiration and water competition between intercropped species might be quantified by directly measuring the sap flow of each plant using heat ratio method (Chen et al., 2022, 2024). After validation of plant transpiration, process-based crop models could help to separate evaporation from soil and transpiration by the plants, and determine crop water competition, as well as explore the effects of CO_2 concentration in intercropping (Zhang et al., 2022a, 2022b).

4.4. Root length density and spatial distribution

For maize, intercropping led to an increase in RLD, particularly in the peanut strip (P2), suggesting that maize roots were able to forage into the peanut strip. This spatial expansion of maize roots in intercropping systems is consistent with findings from other studies on cereal/legume intercropping, where maize roots exhibited plasticity in response to the presence of a neighboring species (Li et al., 2006; Zhang et al., 2022a). The increased RLD of maize in the intercrop, especially under N-free conditions, indicates that maize may have been compensating for limited nitrogen availability by exploring a larger soil volume, which aligns with previous observations in maize/soybean intercropping systems (Zhang et al., 2022a).

For peanut, though the investment in roots (IIR) of peanut increased by 88 % (Fig. 10) in the intercrop compared to sole peanut, consistent with a previous study in maize/soybean intercrops (Zhang et al., 2022a), the overall RLD did not significantly differ between intercropped and sole peanut. This discrepancy was due to the substantially lower biomass of intercropped peanut. The increased root plasticity of peanut in the intercrop suggests that peanut roots were responding to competitive pressure from maize. Perhaps the peanut roots sense competition for water by a different species and increase their root growth in response, but such mechanisms of root sensing are still under discussion (Wang et al., 2021). Other studies showed that legume roots in intercropping systems tend to grow deeper in response to competition to access water and nutrients (Zhang et al., 2022a). However intercropped peanut did not have deeper roots in this study. This might be mainly due to that maize primarily distributes its roots in the upper soil layer. Intercropped peanut may face intense competition from maize roots, especially in the upper soil layer. Although peanuts showed high root plasticity, this plasticity might mainly manifest as increasing root density rather than growth into deeper soil layers.

4.5. Implications for improvement

Some possible ways might play a role in overcoming the HI problem and alleviating the negative effect in intercropped peanut (e.g. shading effect, pegging problem and disadvantages for water competition), such as using ridge-furrow cultivation, higher plant density and adapted genotypes. Cultivation on a ridge facilitates pegging due to the loosened soil (Olayinka et al., 2021). In semi-arid dryland agriculture, the ridge-furrow practice also collects rainfall thus reducing drought risk (Dong et al., 2017). The higher sowing densities of peanut in an intercrop should be chosen such that the above-ground complementarity for light capture is maximized (Wang et al., 2020). Further yield advantage could also be achieved by selecting more suitable genotypes such as shade- and drought- tolerance genotypes of peanut (Yin et al., 2016).

5. Conclusions

Results in this paper show that simultaneous maize/peanut intercropping in dryland agriculture under the semi-arid conditions of western Liaoning has land equivalent ratios around one. Higher land equivalent ratios were obtained in years with less rainfall, suggesting complementary water use between the species plays a role in this system. Intercropped maize benefited greatly from intercropping, with a high partial land equivalent ratio of 0.73, while peanut was disadvantaged, resulting in a partial land equivalent ratio of only 0.27. The high yield of intercropped maize plants was related to increased kernel set and harvest index while the low yield of intercropped peanut plants was related to low pod number per plant and decreased harvest index. Competition for water and in turn for light, with maize as the dominant species, are main drivers for yield in this system. Performance of peanut may be improved by using drought tolerant peanut varieties and breeding of more shade tolerant peanut varieties that have less difficulty in pegging under shading, modifying row configuration with narrower maize rows, allowing better light penetration to the peanut canopy. Then peanut may grow under improved water and light conditions which facilitate pegging.

Author contributions

Sun Z., Zhang L. and Zhang Y. conceived and designed the experiments. Zhang Y., Du G., Feng L., Bai W., Feng C. Dong Z., Yang J., Li C., Yang S., Zhang Z., Cai Q., Zhang D., Zhang X. and Li X. performed the experiments. Zhang Y., Sun Z., Zhang L. and van der Werf W. analyzed the data and wrote the paper.

CRediT authorship contribution statement

Yang Shu: Data curation. **Cai Qian:** Data curation. **Zhang Yue:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Dong Zhi:** Data curation. **Sun Zhanxiang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Zhang Xu:** Data curation. **Feng Chen:** Methodology, Data curation. **Li Xuan:** Data curation. **Du Guijuan:** Methodology, Funding acquisition, Data curation. **van der Werf Wopke:** Writing – review & editing, Methodology, Conceptualization. **Feng Liangshan:** Methodology, Data curation. **Zhang Lizhen:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Bai Wei:** Data curation. **Zhang Zhe:** Data curation. **Zhang Dongsheng:** Methodology, Data curation. **Yang Jie:** Data curation. **Li Chao:** Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109833.

Data availability

Data will be made available on request.

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