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Effects of Maize/Peanut Intercropping on Yield and Nitrogen Uptake and Utilization under Different Nitrogen Application Rates

Yongyong Zhang [1,†], Fengyan Zhao [2,3,4,†], Zhanxiang Sun [2,3,4], Wei Bai [2,3,4,*], Zhe Zhang [2,3,4], Chen Feng [2,3,4] and Qian Cai [2,3,4]

1 College of Land and Environment, Shenyang Agricultural University, Shenyang 110866, China; yongyongzhang@syau.edu.cn
2 Institute of Crop Cultivation and Farming System, Liaoning Academy of Agricultural Sciences, Shenyang 110161, China; zfysyau@163.com (F.Z.); sunzx67@163.com (Z.S.); chick409@126.com (Z.Z.); sandyla570521@126.com (C.F.); caiqian2005@163.com (Q.C.)
3 National Agricultural Experimental Station for Agricultural Environment, Fuxin 123102, China
4 Key Laboratory of Water-Saving Agriculture of Northeast, Ministry of Agriculture and Rural Affairs, Shenyang 110161, China
* Correspondence: libai200008@126.com
† These authors contributed equally to this work.

Abstract: The effects of maize/peanut intercropping on crop yields, peanut nodulation, biological nitrogen (N) fixation in peanuts, crop N uptake, and N use efficiency under different N application rates were studied. A long-term maize/peanut intercropping micro-plot experiment was started in 2015. The experiment included the following three planting patterns: maize sole crop (SM), peanut sole crop (SP), and maize and peanut intercropping (intercropping maize: IM; intercropping peanut: IP). Additionally, three N application rates were tested as follows: 0 kg·ha^{-1} (N0), 150 kg·ha^{-1} (N150), and 300 kg·ha^{-1} (N300). The results indicated that N fertilization significantly increased maize yield. Intercropping increased maize yield while decreasing peanut yield across different N application rates. Both N fertilization and intercropping significantly increased the maize harvest index (HI), whereas intercropping decreased the peanut HI under N300. The number and fresh weight of peanut nodules decreased with the increasing N application rate with reductions ranging from 31.15% to 45.23% and 39.60% to 46.67%, respectively. Intercropping increased the number of peanut nodules by an average of 62.56% under the N0 treatment. Intercropping significantly improved the N absorption capacity of the whole intercropping system, and the contribution of maize was higher than that of peanuts. Maize demonstrated a stronger competitive ability for N uptake compared with peanuts in the intercropping system. Intercropping significantly increased the N use efficiency for both maize and peanuts. However, the N use efficiency of maize increased with N application rates, while that of peanut decreased. Compared with sole crops, intercropping increased the partial factor productivity of maize by 55.2% but decreased that of peanuts by 56.3%. In conclusion, at an N application rate of 150 kg·ha^{-1}, maize/peanut intercropping increased overall crop yield and improved the N absorption and use capacity of maize

Keywords: intercropping; nitrogen fertilizer; yield; nodule; nitrogen use efficiency

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1. Introduction

Excessive use of synthetic nitrogen (N) fertilizers is common in the agricultural production process to obtain high yields [1]. However, excessive N fertilization leads to several ecological and environmental issues globally, such as increased greenhouse gas emissions, eutrophication of water bodies, decreased soil pH, and imbalanced microbial community structure [2,3]. Therefore, it is crucial to improve N fertilizer use efficiency and reduce N input while maintaining crop yields to maintain the health of the agricultural ecosystem.

Cereal and legume intercropping benefits from resource complementarity in terms of light, water, and nutrients through ecological niche differentiation. For instance, maize-peanut intercropping improves resource use efficiency and land productivity (as indicated by a land equivalent ratio (LER) greater than 1), demonstrating significant intercropping advantages [4,5]. Maize can also utilize the N fixed by peanut nodules, reducing the need for N fertilization and alleviating environmental pressure [6–8]. Therefore, studying yield changes and plant N absorption and utilization in maize/peanut intercropping under different N application rates, and clarifying the mechanisms leading to increased yield and improved N use efficiency, is crucial. This research is significant for enhancing maize/peanut intercropping fertilization techniques and promoting the green and sustainable development of agriculture in China.

Research on maize/peanut intercropping primarily focuses on aspects such as crop yield, biological N fixation in peanuts, system light use efficiency, and water use efficiency [9–11]. Previous studies have shown that maize/peanut intercropping enhances the utilization of strong light by maize and weak light by peanuts. Maize/peanut intercropping can also reduce crop disease incidence by increasing agricultural diversity [12], thereby increasing crop biomass accumulation and yield, which ultimately increases land productivity [13,14]. Additionally, maize/peanut intercropping significantly improves system water and nutrient use efficiency through root interactions [11,15]. Liu et al. [16] used a ^{15}N tracing method to study N uptake and use in a maize/peanut intercropping system. Their results indicated that maize competes with peanuts for N within the intercropping system, which decreases the concentration of nitrate in the peanut rhizosphere and enhances the biological N fixation of peanuts, thus increasing the overall N input of the intercropping system. However, biological N fixation is highly sensitive to exogenous N, and both insufficient and excessive N application reduce biological N fixation [17]. Similarly, insufficient or excessive N application is also unfavorable for maize biomass accumulation and yield formation [18]. Therefore, it is important to clarify the optimal N fertilization rates to maximize N use efficiency.

Previous studies on maize/peanut intercropping have primarily focused on the effects of different strip widths or planting densities on systematic light and water utilization, yield, and land productivity [9–11,19]. However, there has been relatively little research on the impact of different N application rates on intercropping system yield and N utilization advantages. Based on a maize/peanut intercropping micro-plot experiment, we performed a two-year systematic investigation of the effects of different N application rates on crop yield, biological N fixation of peanuts, and aboveground N absorption. We aimed to elucidate the underlying mechanism for maximizing N use efficiency through maize/peanut intercropping, thereby providing a theoretical basis for optimizing the benefit of maize/peanut intercropping.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at the Liaoning Academy of Agricultural Sciences, Shenyang, China (41°49′ N, 123°33′ E), which started in 2015. The data analyzed in this study were collected during the years 2019 and 2020. The region is characterized by a temperate humid to semi-humid monsoon climate of the northern temperate zone, with an average annual temperature of 7.0–8.1 °C, a frost-free period of 148–180 d, accumulated temperature above 10 °C of 3350 °C, and an average annual evapotranspiration of 1440 mm. The average annual precipitation is 600–800 mm. The bulk density of the soil is 1.38 $g \cdot cm^{-3}$, with 15.2 $g \cdot kg^{-1}$ of organic matter, 0.62 $g \cdot kg^{-1}$ of total N, 78.74 $mg \cdot kg^{-1}$ of available N, 25.4 $mg \cdot kg^{-1}$ of available phosphorus, and 64.3 $mg \cdot kg^{-1}$ of available potassium. The available nutrient content was measured following the method described by Lu [20].

2.2. Experimental Design

This study consisted of three planting patterns and three N application rates. The three patterns included maize sole crop (SM), peanut sole crop (SP), and maize/peanut intercropping (intercropping maize, IM; intercropping peanut, IP). Two rows of maize and two rows of peanuts were planted in each of the intercropping plots. Four rows of maize and four rows of peanuts were planted in the maize sole crop and peanut sole crop plots, respectively (Figure 1). Thus, the intercropping design in this study is a replacement design. The N application rates were 0 kg N·ha^{-1} (N0), 150 kg N·ha^{-1} (N150), and 300 kg N·ha^{-1} (N300). Each treatment was replicated three times. In total, 27 plots were arranged at random, each plot covering an 8 m^2 of area (4 m length × 2 m width). Polypropylene boards with a depth of 1.0 m were used to separate the plots to prevent nutrient, water, and root interactions between plots. In the sole crop plots, the row spacing was 0.5 m, with a sowing density of 6 seeds·m^{-2} for maize and 30 seeds·m^{-2} for peanuts. Accordingly, in the intercropping plots, the sowing density was 3 seeds·m^{-2} for maize and 15 seeds·m^{-2} for peanuts.

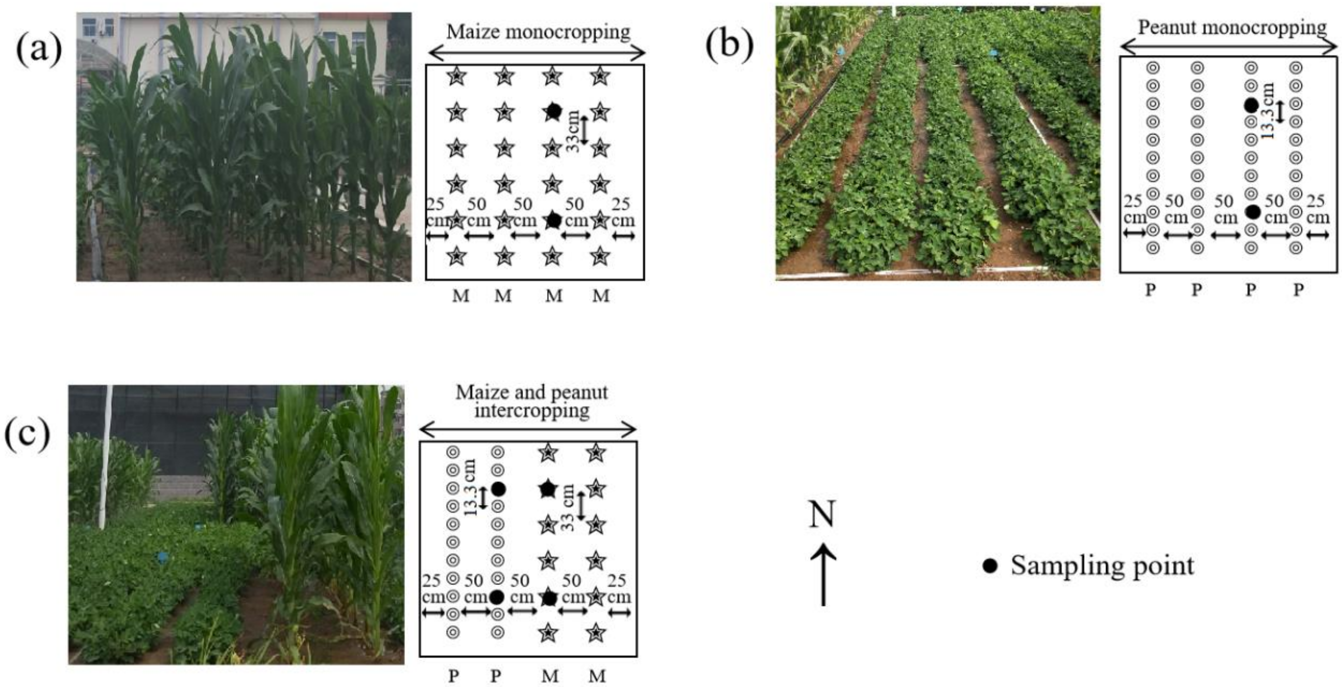

Figure 1. Diagrams of experiment plots and sampling points. Maize sole crop plot (**a**), peanut sole crop plot (**b**), and maize/peanut intercropping plot (**c**). M and ☆, maize; P and ◎, peanut.

The maize variety used in this study was "Zhengdan 958", and the peanut variety was "Baisha 1016". Each plot received 90 kg·ha^{-1} of P_2O_5 and 105 kg·ha^{-1} of K_2O fertilizer. Nitrogen, phosphorus, and potassium fertilizers were applied as urea (containing 46% N), calcium superphosphate (containing 12% P_2O_5), and potassium sulfate (containing 50% K_2O), respectively. Fertilizers were applied in bands at the time of sowing, with no irrigation or additional fertilization applied during the growing season. Sowing occurred in mid-May each year, and the crops were harvested at the end of September.

2.3. Sample Collection and Measurement Methods

2.3.1. Peanut Nodule Characteristics

During the podding stage of peanuts in 2019 and 2020 (75 days after sowing), peanut nodules were collected from both the sole crop and intercropping plots. Ten peanut plants were randomly selected from each plot. The entire peanut plant was carefully dug out using a shovel and placed on sterilized paper. The soil adhering to the roots was gently shaken off, and visible nodules on the roots were collected. The soil was then returned to its original position. The peanut plants were gently washed with tap water, and all the nodules on the peanut roots were stripped for counting and weighing.

2.3.2. Yield Determination

At the maturity stage of the crops (24 September 2019 and 26 September 2020), maize and peanuts were harvested. Plant samples were taken from the inner rows of both the sole crop and intercropping plots (see Figure 1). For maize, a 1.65 m row length (5 plants) was harvested, while for peanuts, a 1 m row length (6 holes) was harvested. These samples were placed in mesh bags and air-dried for yield measurement. The yield components recorded included the number of maize ears per plant, number of grains per ear, thousand-grain weight, peanut weight per hundred grains, number of pods per plant, and number of effective pods.

2.3.3. Plant Nitrogen Content Measurement

The total N content of maize and peanut plants was determined using plant samples collected at the harvest stage. The entire plants were crushed into powder and sieved through a 0.15 mm sieve. The N content was analyzed using an elemental analyzer (Elementar III, Hanau, Germany).

2.4. Calculation Formulas and Statistical Analysis Methods

2.4.1. Relevant Calculation Formulas

The advantage of intercropping is often evaluated using the following indicators:

(1) Harvest index (HI):

$$\mathrm{HI} = \mathrm{Y}/\mathrm{B}$$

where Y represents the yield of maize or peanuts and B represents the aboveground biomass of maize or peanuts.

(2) The relative increase rate of peanut nodule number and fresh weight were calculated as follows [21]:

$$\text{Relative increase rate (\%)} = (N_{ip} - N_{sp}) \times 100/\mathrm{N}_{sp}$$

where N_{sp} and N_{ip} represent the number of nodules or nodule weights of sole-cropped and intercropped peanuts, respectively.

(3) The nitrogen equivalent ratio (*NER*) was calculated as follows [22]:

$$NER = NER_m + NER_p = (NU_{im}/NU_{sm}) + (NU_{ip}/NU_{sp})$$

where NER_m and NER_p represent the N uptake equivalent ratio of intercropped maize and peanuts, respectively, and NU_{sm}, NU_{im}, NU_{sp}, and NU_{ip} represent the N uptake of sole-cropped maize, intercropped maize, sole-cropped peanuts, and intercropped peanuts, respectively. $NER > 1$ indicates an advantage of N uptake in the intercropping system compared with the sole crop system.

(4) The aggressivity between maize and peanuts (A_{mp}) was calculated as follows [23]:

$$A_{mp} = \mathrm{Y}_{im}/\mathrm{Y}_{sm} - \mathrm{Y}_{ip}/\mathrm{Y}_{sp}$$

where Y_{im}, Y_{ip}, Y_{sm}, and Y_{sp} represent the yield of sole-cropped maize, intercropped maize, sole-cropped peanuts, and intercropped peanuts, respectively. $A_{mp} > 0$ indicates that maize has a stronger competitive ability than peanuts in the intercropping systems, while $A_{mp} < 0$ indicates that peanuts have a stronger competitive ability than maize.

(5) The competitive ratio of nitrogen (CR_{mp}) was calculated as follows [23]:

$$CR_{mp} = (NU_{im}/NU_{sm}) \times F_m/(NU_{ip}/NU_{sp}) \times F_p$$

where F_m and F_p represent the proportion of maize and peanut planting areas in the intercropping systems, respectively. In this experiment, both F_m and F_p are 0.50. $CR_{mp} > 1$ indicates that maize has a stronger competitive ability for N nutrition than peanuts in the intercropping systems, and vice versa.

(6) The partial factor productivity from applied N (PFP_N) was calculated as follows:

$$PFP_N\ (kg{\cdot}kg^{-1}) = Y_n/F_n$$

where Y_n and F_n represent the yield and N application rate per unit of land area.

(7) The nitrogen use efficiency (NUE) is the ratio of economic yield to N uptake by crops.
(8) The normalized grain yield (Y_i) was calculated as follows:

$$Y_i = PY_i \times HD_i$$

where PY_i represents the yield per plant, HD_i represents the planting density, and i represents maize or peanuts.

2.4.2. Statistical Analysis

ANOVA analysis was conducted using SPSS Statistics 23, followed by multiple comparisons using the Duncan test. Normality and homogeneity of the residuals were determined using Shapiro–Wilk and Levene's tests. The variables were transformed if necessary.

3. Results

3.1. Effect of Maize/Peanut Intercropping and Nitrogen Fertilization on Yield

Nitrogen fertilization had a significant impact on maize yield (Table 1, $p < 0.001$). The average yields over the two years for N0, N150, and N300 were 539.5 $g{\cdot}m^{-2}$, 883.5 $g{\cdot}m^{-2}$, and 912.5 $g{\cdot}m^{-2}$, respectively. Intercropping also significantly affected the normalized grain yield of maize ($p < 0.01$). In both 2019 and 2020, the normalized yield of maize in the intercropping system (IM) was lower than in the sole crop system (SM) at each N fertilization level. The average normalized yield of IM across the two years was 76.13% of that of SM, indicating that the yield of maize in the intercropping system was higher than that in the sole crop system on the same unit of land area. Additionally, the normalized maize yield was significantly influenced by the year and the interaction between planting pattern and year. The normalized maize yield in 2019 was significantly lower than in 2020 ($p < 0.01$).

Nitrogen fertilization significantly affected the number of ears per plant and the thousand kernel weight of maize (Table 1). Over the two years, the average number of ears per plant and thousand kernel weight for N150 and N300 were significantly higher than for N0. Specifically, the number of ears per plant was 513, 527, and 385, and the thousand kernel weight was 365 g, 381 g, and 341 g for N150, N300, and N0, respectively. Intercropping significantly affected the number of ears per plant, the number of grains per ear, and the thousand kernel weight of maize. Under the N300 treatment in 2019, the number of ears per plant in the intercropping system was significantly higher than that in the sole crop system, and under the N0 treatment in 2020, the thousand kernel weight in the intercropping system was significantly higher than that in the sole crop system. The two-year average for the number of ears per plant, the number of grains per ear, and the thousand kernel weight for intercropping and sole crop were 1.33 and 1.03, 506 and 444, and 376 g and 349 g, respectively. Overall, the intercropping system showed 29.03% more ears per plant, 14.05% more grains per ear, and 7.57% higher thousand kernel weight compared with the sole crop system.

Table 1. Maize grain yields and yield components in the sole crop and intercropping systems under different N application rates.

Year (Y)	N Application Rate (N)	Planting Pattern (P)	Grain Yield ($g{\cdot}m^{-2}$)	Ear Number ($plant^{-1}$)	Kernel Number (ear^{-1})	1000-Kernel Weight (g)
2019	N0	SM	703 ± 43 a	1.00 ± 0.00 a	397 ± 33 a	346 ± 5 a
		IM	500 ± 29 b	1.33 ± 0.33 a	400 ± 47 a	414 ± 7 b
	N150	SM	1032 ± 113 a	1.13 ± 0.13 a	483 ± 45 a	369 ± 11 a
		IM	886 ± 52 b	1.60 ± 0.23 a	530 ± 43 a	374 ± 17 a
	N300	SM	996 ± 51 a	1.00 ± 0.00 a	492 ± 49 a	387 ± 22 a
		IM	918 ± 26 b	1.73 ± 0.27 b	550 ± 41 a	396 ± 13 a
2020	N0	SM	597 ± 14 a	1.00 ± 0.00 a	336 ± 40 a	285 ± 15 a
		IM	359 ± 9 b	1.00 ± 0.00 a	406 ± 35 a	318 ± 13 a
	N150	SM	933 ± 16 a	1.00 ± 0.00 a	476 ± 33 a	341 ± 15 a
		IM	682 ± 14 b	1.20 ± 0.12 a	564 ± 34 a	377 ± 1 a
	N300	SM	1043 ± 52 a	1.07 ± 0.07 a	478 ± 32 a	367 ± 2 a
		IM	693 ± 11 b	1.13 ± 0.07 a	587 ± 22 a	375 ± 3 a
2019–2020 mean	N0	SM	650 ± 16 a	1.00 ± 0.00 a	367 ± 26 a	316 ± 10 b
		IM	429 ± 11 b	1.17 ± 0.17 a	403 ± 29 a	366 ± 8 a
	N150	SM	983 ± 56 a	1.07 ± 0.03 a	480 ± 27 a	355 ± 5 a
		IM	784 ± 25 b	1.40 ± 0.17 a	547 ± 27 a	375 ± 9 a
	N300	SM	1019 ± 20 a	1.03 ± 0.03 a	485 ± 29 b	377 ± 11 a
		IM	806 ± 17 b	1.43 ± 0.17 a	569 ± 23 a	385 ± 6 a
p-value	Planting patterns (P)		<0.001	0.002	0.006	0.001
	N application rates (N)		<0.001	0.289	<0.001	<0.001
	Years (Y)		<0.001	0.013	0.974	<0.001
	P × N		0.943	0.542	0.681	0.061
	P × Y		0.015	0.024	0.233	0.895
	N × Y		0.622	0.866	0.696	0.001
	P × N × Y		0.189	0.613	0.972	0.176

Mean ± SE; SM and IM indicate maize in the sole crop and intercropping systems, respectively. N0, N150 and N300 represent N application rates at 0 kg $N{\cdot}ha^{-1}$, 150 kg $N{\cdot}ha^{-1}$, and 300 kg $N{\cdot}ha^{-1}$, respectively. Different small letters indicate significant differences between cropping patterns at the same N rate within the same year ($p < 0.05$).

The differences in peanut yield among the three N rates in 2019 and 2020 were not significant (Table 2). Intercropping, however, significantly affected the normalized grain yield of peanuts ($p < 0.01$). In both years, the normalized yield of peanuts in the intercropping system was lower than that in the sole crop system at each N fertilization level. Over the two years, the average normalized yield of peanuts in the intercropping system was only 43.88% of that in the sole crop system. Neither planting pattern nor N fertilization had a significant effect on the hundred-seed weight, the number of pods per plant, or the number of effective pods per plant.

Table 2. Peanut seed yield and yield components in sole crop and intercropping under different N application rates.

Year (Y)	N Application Rate (N)	Planting Pattern (P)	Seed Yield ($g{\cdot}m^{-2}$)	DW per 100-Seeds ($g{\cdot}100\text{-}seeds^{-1}$)	Seed Number ($seed{\cdot}plant^{-1}$)	Effective Pod ($pod{\cdot}plant^{-1}$)
2019	N0	SP	260 ± 29 a	57.12 ± 2.48 a	20.10 ± 1.78 a	11.69 ± 0.67 a
		IP	116 ± 72 b	55.32 ± 1.11 a	15.05 ± 1.46 b	9.40 ± 0.99 b
	N150	SP	272 ± 32 a	56.82 ± 3.53 a	26.03 ± 9.14 a	15.31 ± 5.76 a
		IP	122 ± 4 b	53.96 ± 2.02 a	21.36 ± 6.11 a	12.54 ± 3.91 a
	N300	SP	254 ± 34 a	51.29 ± 1.76 a	20.81 ± 2.53 a	12.03 ± 1.38 a
		IP	98 ± 19 b	49.49 ± 8.07 a	16.78 ± 4.14 a	9.90 ± 1.97 a

Table 2. *Cont.*

Year (Y)	N Application Rate (N)	Planting Pattern (P)	Seed Yield (g·m^{-2})	DW per 100-Seeds (g·100-seeds^{-1})	Seed Number (seed·plant^{-1})	Effective Pod (pod·plant^{-1})
2020	N0	SP	265 ± 5 a	58.84 ± 1.43 a	25.87 ± 4.69 a	13.66 ± 2.86 a
		IP	145 ± 7 b	61.11 ± 4.51 a	25.63 ± 2.79 a	13.31 ± 1.95 a
	N150	SP	311 ± 4 a	61.35 ± 0.84 a	22.40 ± 0.97 a	11.09 ± 0.18 a
		IP	130 ± 14 b	60.69 ± 1.25 a	17.74 ± 2.20 b	8.88 ± 1.13 a
	N300	SP	307 ± 20 a	63.17 ± 1.54 a	26.63 ± 3.61 a	13.54 ± 1.62 a
		IP	122 ± 2 b	54.54 ± 1.99 b	24.16 ± 3.30 a	12.42 ± 1.72 a
2019–2020 mean	N0	SP	262 ± 12 a	57.98 ± 0.90 a	22.98 ± 3.08 a	12.68 ± 1.71 a
		IP	130 ± 7 b	58.21 ± 2.29 a	20.34 ± 2.02 a	11.35 ± 1.44 a
	N150	SP	291 ± 16 a	59.08 ± 1.89 a	24.22 ± 4.89 a	13.20 ± 2.96 a
		IP	126 ± 7 b	57.32 ± 1.43 a	19.55 ± 1.98 a	10.71 ± 1.42 a
	N300	SP	281 ± 14 a	57.23 ± 0.86 a	23.72 ± 1.37 a	12.79 ± 0.46 a
		IP	110 ± 10 b	52.01 ± 3.60 b	20.47 ± 1.22 a	11.16 ± 0.65 a
p-value	Planting patterns (P)		<0.001	0.236	0.157	0.219
	N application rates (N)		0.523	0.219	0.989	0.999
	Years (Y)		0.023	0.004	0.136	0.815
	P × N		0.308	0.488	0.940	0.943
	P × Y		0.595	0.961	0.663	0.689
	N × Y		0.700	0.585	0.117	0.128
	P × N × Y		0.503	0.449	0.917	0.980

Mean ± SE; SP and IP indicate peanut in the sole crop and intercropping systems, respectively. N0, N150 and N300 represent N application rates at 0 kg N·ha^{-1}, 150 kg N·ha^{-1}, and 300 kg N·ha^{-1}, respectively. Different small letters indicate significant differences between cropping patterns at the same N rate within the same year ($p < 0.05$).

3.2. The Effect of Maize/Peanut Intercropping and Nitrogen Fertilization on the Crop Harvest Index

In 2019 and 2020, the harvest index (HI) of maize significantly increased with increasing N application rates (Figure 2a, $p < 0.01$), with average values of 0.43, 0.53, and 0.60 for N0, N150, and N300, respectively. Intercropping significantly increased the HI of maize ($p < 0.01$), with averages of 0.59 and 0.45 for IM and SM, respectively.

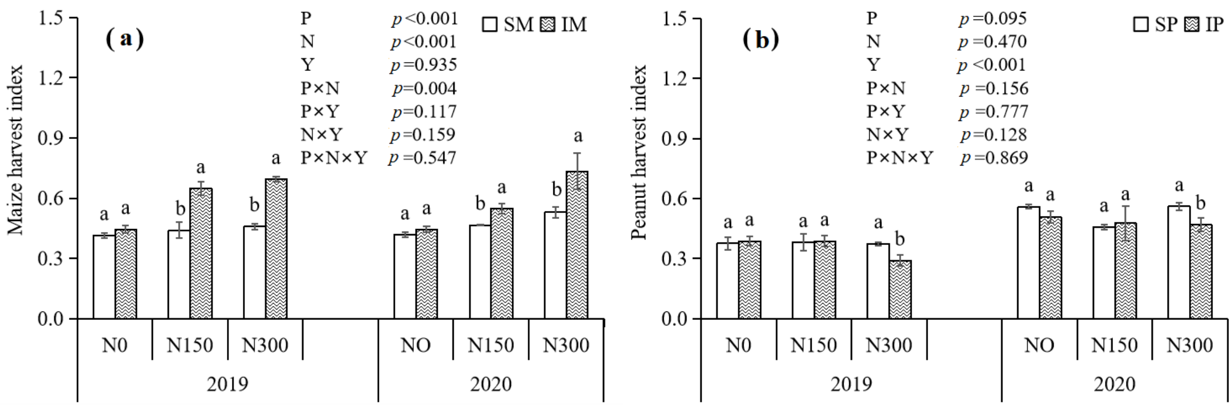

Figure 2. Harvest index of maize and (**a**,**b**) peanut in the sole crop and intercropping systems under different N application rates. Different lowercase letters above the bars indicate significant differences between sole crop and intercropping under the same nitrogen application rate in the same year ($p < 0.05$).

The HI of peanuts was significantly higher in 2020 than in 2019 (Figure 2b). The two-year average HI in SP and IP was 0.45 and 0.41, respectively. There were no significant differences between SP and IP under N0 and N150, while the HI in IP was significantly lower than in SP under N300. The two-year average HI for N0, N150, and N300 was 0.45, 0.43, and 0.42, respectively.

3.3. The Impact of Maize/Peanut Intercropping and Nitrogen Fertilization on Peanut Nodule Characteristics

The number of nodules was significantly impacted by N fertilization, intercropping, and planting year (Figure 3a, $p < 0.01$). Compared with SP, the number of nodules from the IP treatment significantly increased at N0 in both years with an average increment of 62.56%. In contrast, only minor differences were observed between SP and IP when the N supply was increased (Figure 3a and Table 3). Compared with N0, the average number of nodules across 2019 and 2020 decreased by 31.15% and 45.23% under N150 and N300, respectively.

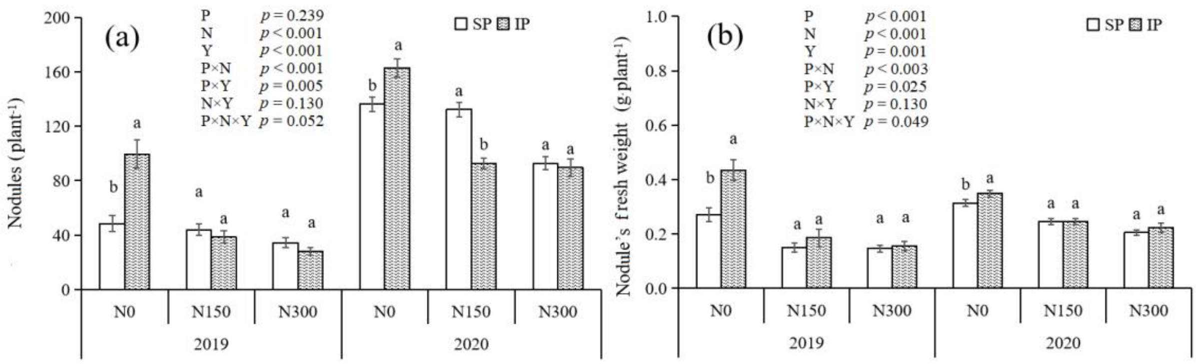

Figure 3. Nodule number (**a**) and nodule fresh weight (**b**) of peanuts in sole crop and intercropping systems under different N application rates. Different small letters indicate significant differences between cropping patterns at the same N rate within the same year ($p < 0.05$).

Table 3. Relative change in nodule number and fresh weight of peanuts under different N application rates (%).

Year	N Application Rate	Nodule Number	Nodule Fresh Weight
2019	N0	105.58	60.00
	N150	−12.21	24.48
	N300	−18.97	5.73
2020	N0	19.54	11.37
	N150	−29.88	−0.39
	N300	−3.48	8.86
2019–2020 mean	N0	62.56	35.69
	N150	−21.05	12.05
	N300	−11.23	7.30

N0, N150, and N300 represent N application rates at 0 kg N·ha^{-1}, 150 kg N·ha^{-1}, and 300 kg N·ha^{-1}, respectively.

The fresh weight of nodules was significantly affected by the planting pattern, N fertilization, and planting year (Figure 3b). Compared with SP, the average fresh weight of nodules per plant increased by 18.35% across 2019 and 2020 in IP. Nitrogen fertilization significantly reduced the nodule fresh weight (Figure 3b). Compared with N0, the average fresh weight of nodules per plant across 2019 and 2020 decreased by 39.60% and 46.67% under N150 and N300, respectively.

3.4. The Influence of Maize/Peanut Intercropping and Nitrogen Fertilization on Plant Nitrogen Content and Nitrogen Uptake

The N content of the maize plants was significantly influenced by planting patterns, N fertilization, and the interaction between planting patterns and year (Table 4). The N content of maize plants across different N rates followed the trend N300 > N0 > N150, with values of 0.068 g·kg^{-1}, 0.061 g·kg^{-1}, and 0.055 g·kg^{-1}, respectively. Significant differences in the N content of maize plants between SM and IM were observed under all three N rates in 2019, while differences were only significant under N150 in 2020. Sole-crop peanuts had significantly higher N content than intercropped peanuts. Overall, intercropping reduced the N content of both maize and peanut plants, whereas N fertilization significantly increased the N content of maize plants.

Table 4. Nitrogen content and nitrogen uptake of maize and peanut in the sole crop and intercropping systems under different N application rates.

Year	N Application Rate	Planting System	N Content (g·kg^{-1})		N Uptake (kg·ha^{-1})	
(Y)	(N)	(P)	Maize	Peanut	Maize	Peanut
2019	N0	Sole crop	0.075 ± 0.006 a	0.15 ± 0.01 a	139.57 ± 2.34 a	134.20 ± 5.41 a
		Intercropping	0.045 ± 0.001 b	0.10 ± 0.01 b	116.83 ± 2.20 b	66.70 ± 0.36 b
	N150	Sole crop	0.069 ± 0.001 a	0.15 ± 0.04 a	161.73 ± 2.15 a	146.90 ± 3.70 a
		Intercropping	0.045 ± 0.001 b	0.10 ± 0.02 a	123.97 ± 1.98 b	77.80 ± 0.29 b
	N300	Sole crop	0.082 ± 0.002 a	0.17 ± 0.02 a	161.77 ± 2.55 a	144.37 ± 1.08 a
		Intercropping	0.056 ± 0.004 b	0.09 ± 0.01 b	117.87 ± 0.91 b	67.33 ± 0.48 b
2020	N0	Sole crop	0.065 ± 0.003 a	0.16 ± 0.03 a	104.30 ± 2.02 a	124.83 ± 0.70 a
		Intercropping	0.058 ± 0.007 a	0.06 ± 0.01 b	96.77 ± 1.01 b	55.70 ± 1.25 b
	N150	Sole crop	0.062 ± 0.001 a	0.17 ± 0.01 a	123.63 ± 2.22 a	149.03 ± 3.44 a
		Intercropping	0.045 ± 0.001 b	0.10 ± 0.01 b	112.60 ± 2.49 b	70.37 ± 0.99 b
	N300	Sole crop	0.073 ± 0.005 a	0.16 ± 0.02 a	126.93 ± 3.27 a	137.13 ± 1.12 a
		Intercropping	0.060 ± 0.002 a	0.08 ± 0.01 b	109.13 ± 2.32 b	63.07 ± 0.95 b
2019–2020 mean	N0	Sole crop	0.078 ± 0.002 a	0.16 ± 0.01 a	121.93 ± 1.00 a	129.52 ± 2.95 a
		Intercropping	0.058 ± 0.002 b	0.08 ± 0.01 b	106.80 ± 1.43 b	62.33 ± 0.75 b
	N150	Sole crop	0.065 ± 0.001 a	0.16 ± 0.02 a	142.68 ± 1.79 a	147.97 ± 3.17 a
		Intercropping	0.045 ± 0.001 b	0.10 ± 0.01 b	118.28 ± 1.81 b	74.08 ± 0.35 b
	N300	Sole crop	0.070 ± 0.004 a	0.17 ± 0.01 a	144.35 ± 2.91 a	141.75 ± 1.10 a
		Intercropping	0.051 ± 0.003 b	0.09 ± 0.01 b	113.50 ± 1.29 b	65.20 ± 0.59 b
p-value	Cropping patterns (P)		<0.001	<0.001	<0.001	<0.001
	N application rates (N)		0.002	0.683	<0.001	<0.001
	Years (Y)		0.192	0.626	<0.001	<0.001
	P × N		0.862	0.715	<0.001	0.021
	P × Y		0.005	0.381	<0.001	0.320
	N × Y		0.365	0.706	0.191	0.148
	P × N × Y		0.401	0.592	0.138	0.196

Mean ± SE; N0, N150, and N300 represent N application rates at 0 kg N·ha^{-1}, 150 kg N·ha^{-1}, and 300 kg N·ha^{-1}, respectively. Different small letters indicate significant differences between cropping patterns at the same N rate within the same year ($p < 0.05$).

The N uptake of maize plants ranged from 96.77 kg·ha^{-1} to 161.77 kg·ha^{-1} (Table 4). In both 2019 and 2020, the N uptake of maize plants under the three N fertilization rates followed the trend N150 > N300 > N0. Compared with N0, the average N uptake across 2019 and 2020 increased by 14.09% and 12.73% for N150 and N300, respectively. Nitrogen uptake was significantly lower in intercropped maize than in sole-cropped maize across all three N application rates. This is because the intercropped maize occupied 50% of the land area, and the N uptake of intercropped maize was 82.79% of that of sole-crop maize. Similarly, the N uptake of peanut plants first increased and then decreased with N fertilization rates, regardless of whether they were intercropped or sole-cropped (Table 4). The N uptake of peanut plants at N0 was 16.43% and 8.51% lower than at N150 and N300, respectively. Nitrogen uptake was significantly lower in intercropped peanuts than in sole-cropped peanuts across all three N application rates.

3.5. The Influence of Maize/Peanut Intercropping and Nitrogen Fertilization on the Nitrogen Uptake Equivalent Ratio (NER)

The maize-biased N uptake equivalent ratio (NER_m) exceeded 0.5 in both 2019 and 2020, ranging from 0.73 to 0.93 (Table 5). Compared with N0, the NER_m was significantly higher than that for N150 and N300, but there was no significant difference between N150 and N300 in 2019. There was no significant difference in NER_m among the three N treatments in 2020. As for maize, N fertilization significantly affected NER_p only during the 2019 trial, having values of 0.50, 0.53, and 0.47 for N0, N150, and N300, respectively. However, NER_p was less than 0.5, ranging from 0.46 to 0.45, with no significant differences among the three N treatments in 2020. The *NER* for the intercropping system exceeded 1 under each N treatment, with the order of N0 > N150 > N300 in both 2019 and 2020.

Table 5. N uptake equivalent ratio and aggressivity between maize and peanuts in the intercropping system, and the competitive ratio of N under different N application rates.

Year	N Application Rate	N Uptake Equivalent Ratio			Aggressivity	Competitive Ratio of N
(Y)	(N)	NER_m	NER_p	NER	(A_{mp})	(CR_{mp})
2019	N0	0.84 ± 0.01 a	0.50 ± 0.02 ab	1.34 ± 0.03 a	0.67 ± 0.03 b	1.68 ± 0.04 a
	N150	0.77 ± 0.01 b	0.53 ± 0.01 a	1.30 ± 0.02 a	0.82 ± 0.06 b	1.45 ± 0.04 b
	N300	0.73 ± 0.02 b	0.47 ± 0.01 b	1.20 ± 0.01 b	1.43 ± 0.20 a	1.56 ± 0.06 ab
2020	N0	0.93 ± 0.02 a	0.46 ± 0.01 a	1.39 ± 0.03 a	0.55 ± 0.01 b	2.00 ± 0.01 a
	N150	0.91 ± 0.03 a	0.47 ± 0.02 a	1.38 ± 0.02 a	0.69 ± 0.03 a	1.94 ± 0.14 a
	N300	0.86 ± 0.04 a	0.45 ± 0.01 a	1.31 ± 0.03 a	0.63 ± 0.04 ab	1.90 ± 0.12 a
2019–2020 mean	N0	0.88 ± 0.02 a	0.48 ± 0.01 ab	1.36 ± 0.03 a	0.61 ± 0.02 b	1.84 ± 0.01 a
	N150	0.83 ± 0.02 ab	0.50 ± 0.01 a	1.33 ± 0.02 a	0.76 ± 0.03 b	1.69 ± 0.08 a
	N300	0.80 ± 0.03 b	0.46 ± 0.01 b	1.26 ± 0.02 b	1.03 ± 0.08 a	1.73 ± 0.08 a
p-value	N application rates (N)	0.014	0.029	0.003	0.003	0.209
	Years (Y)	<0.001	0.008	0.001	0.001	<0.001
	N × Y	0.543	0.293	0.502	<0.001	0.525

Mean ± SE; N0, N150, and N300 represent N application rates at 0 kg N·ha^{-1}, 150 kg N·ha^{-1}, and 300 kg N·ha^{-1}, respectively. Different small letters indicate significant differences between cropping patterns at the same N rate within the same year ($p < 0.05$).

3.6. The Influence of Maize/Peanut Intercropping and Nitrogen fertilization on Interspecific Competition and the Nitrogen Nutrition Competition Ratio

The interspecific aggressivity between maize and peanuts (A_{mp}) was greater than 0 for all three N fertilization treatments in both 2019 and 2020 (Table 5). Over the two years, the A_{mp} generally followed the trend N0 < N150 < N300, with N300 being significantly higher than N0. As N application increased, maize competitiveness strengthened, while peanut competitiveness decreased.

The CR_{mp} ranged from 1.45 to 1.68 in 2019, with significant differences among the three N rates (Table 5), following the order N0 > N300 > N150. In 2020, the CR_{mp} ranged from 1.90 to 2.00. In both years, the CR_{mp} for all N treatments was greater than 1, indicating that maize was consistently more competitive than peanuts under all fertilization conditions.

3.7. The Impact of Maize/Peanut Intercropping and Nitrogen Fertilization on Nitrogen Fertilizer Partial Productivity and Nitrogen Use Efficiency

The partial factor productivity (PFP_N) for maize ranged from 3.48 kg·kg^{-1} to 11.81 kg·kg^{-1}, while for peanuts, it ranged from 0.66 kg·kg^{-1} to 2.07 kg·kg^{-1} (Figure 4). High rates of N fertilization significantly decreased PFP_N for both maize and peanut ($p < 0.01$). Intercropping increased maize PFP_N but decreased peanut PFP_N.

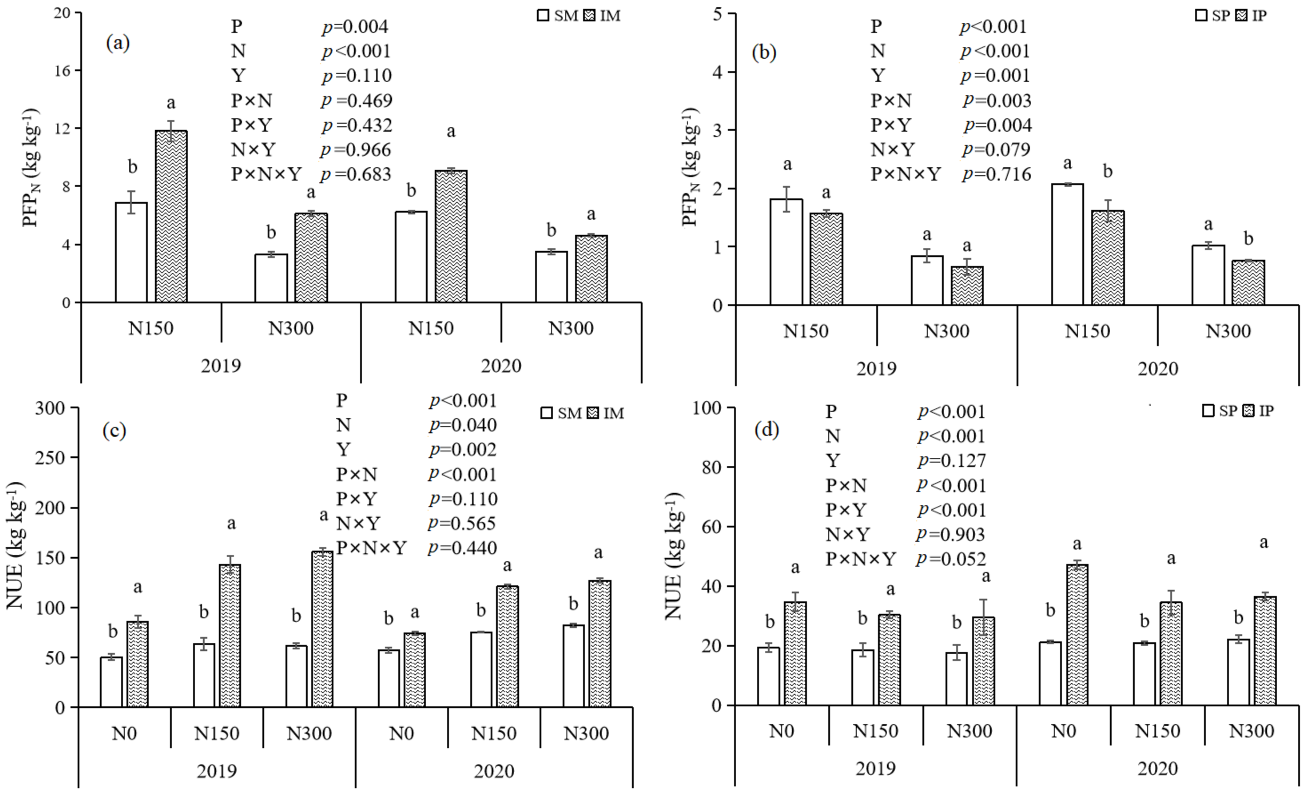

Figure 4. PFP_N and NUE of maize (**a**,**c**) and peanuts (**b**,**d**) in the sole crop and intercropping systems under different N application rates. Different small letters indicate significant differences between cropping patterns at the same N rate within the same year ($p < 0.05$).

Nitrogen fertilization significantly increased the N use efficiency (NUE) of maize. The NUE of sole-cropped maize was 53.84 $kg \cdot kg^{-1}$, 69.57 $kg \cdot kg^{-1}$, and 71.80 $kg \cdot kg^{-1}$ for N0, N150, and N300, respectively. In contrast, the NUE of intercropped maize was 79.95 $kg \cdot kg^{-1}$, 132.03 $kg \cdot kg^{-1}$, and 141.42 $kg \cdot kg^{-1}$, respectively. For sole-cropped peanuts, the NUE was 20.24 $kg \cdot kg^{-1}$, 19.70 $kg \cdot kg^{-1}$, and 19.84 $kg \cdot kg^{-1}$ under N0, N150, and N300, respectively, while the NUE of intercropped peanuts was 40.84 $kg \cdot kg^{-1}$, 32.34 $kg \cdot kg^{-1}$, and 32.92 $kg \cdot kg^{-1}$. There was no significant difference in NUE between sole-cropped and intercropped maize or peanuts under N150 and N300. The NUE of both maize and peanuts in the intercropping system was significantly higher than in the sole crop system (Figure 4).

4. Discussion

Maize/peanuts intercropping significantly impacts crop yields, but there are considerable differences in the performance of maize and peanuts. In this study, the yields of intercropped maize and peanuts were significantly different from those of their sole-cropped counterparts. Although maize and peanuts each accounted for 50% of the land in the intercropping system, the yield of intercropped maize was 76.13% of that of sole-cropped maize, whereas the yield of intercropped peanuts was only 43.88% of that of sole-cropped peanuts. This indicates that in the intercropping system, maize shows an advantage in yield, while peanuts exhibit a disadvantage. In the maize/peanut intercropping system, maize with a relatively tall stem can fully utilize strong light, resulting in higher light interception capacity and a significant increase in the conversion of photosynthetic products from "source" to "sink". In contrast, peanuts, shaded by the taller maize, have reduced access to strong light, which weakens their interception of light. Thus, peanuts mainly utilize weak light as their energy source, leading to a decrease in the photosynthetic rate and a reduction in the conversion of photosynthetic products [24,25]. Regarding interspecific competition, maize and peanuts occupy different ecological niches, with maize showing stronger competition for resources such as water and N compared with peanuts in the intercropping system (as indicated by $A_{mp} > 0$ and $CR_{mp} > 1$). This competitive advantage allows maize to outperform peanuts in terms of yield within the intercropping system [11,14,19].

In this study, applying N at a rate of 150 kg·ha^{-1} resulted in the highest overall yield for the maize–peanut intercropping system compared with N fertilization rates of 0 kg·ha^{-1} and 300 kg·ha^{-1}. Previous studies suggest that although peanut is a N-fixing crop, both low and high N fertilization rates can adversely affect its biological N fixation [26]. Long-term excessive application of exogenous N significantly inhibits the N-fixing ability of leguminous crops, leading to the "N inhibition" effect on nodulation [27–29]. As N application increased in this study, both the number and fresh weight of peanut nodules significantly decreased. This indicates that N fertilization can significantly inhibit the formation and development of peanut nodules, demonstrating a significant "N inhibition" effect. Many studies have shown that intercropping maize with legumes can promote N fixation in legumes, alleviating the "N inhibition" effect. This is primarily because maize competes with leguminous crops for soil N, maintaining relatively low levels of available N, especially nitrate [30–32]. Research by Zhang et al. [33] shows that, compared with sole crops, intercropping significantly increased the number and fresh weight of peanut nodules during the flowering period but significantly decreased them after the pegging stage. In this study, intercropping without N application increased the number of peanut nodules compared with the sole crop, but this trend reversed with increased N application. Intercropping significantly increased the fresh weight of peanut nodules, but the effect decreased as N application increased. Overall, intercropping did not significantly mitigate the inhibitory effect of high N fertilization on nodule formation. This may be due to strong interspecific competition between maize and peanuts, which decreases the allocation of photosynthetic products to nodules during later growth stages. In this study, the minimum N fertilization rate was 150 kg·ha^{-1}, and N fertilizer did not significantly affect peanut yield. This suggests that the fertilizer application rate for peanuts can be lower than this level, and lower N fertilizer rates may promote increased nodule formation in the intercropping system. Moreover, under high N conditions, maize growth may be negatively affected (for example, the leaf area index is no longer increased, the root biomass is decreased [34], etc.), which impacts the utilization of nutrients other than N and consequently affects yield negatively.

Maize and peanut intercropping can promote N uptake and the N use efficiency in crops, demonstrating a clear intercropping advantage in N nutrition (Table 5, $NER > 1$). In this regard, maize (with NER_m ranging from 0.73 to 0.93) contributes more to N uptake than peanuts in the intercropping system (with NER_p ranging from 0.45 to 0.53). However, as N applied increases, the intercropping effect diminishes. This finding highlights the crucial role of N fertilizer application in maximizing the benefits of intercropping maize and peanuts. This observation aligns with the results of Feng et al. [19] and Jiao et al. [25], who showed that compared to sole crop, maize/peanut intercropping significantly increased N uptake in maize and the entire system, although the intercropping advantage decreased with higher N application rates. Liu et al. [16] found that in intercropping systems, the ^{15}N in maize tissues significantly increased. The authors attributed this to maize's utilization of biologically fixed N from peanuts through root interactions, thereby improving the N use efficiency of the entire system. Moreover, this study found that excessive N fertilization can significantly reduce the N fertilizer partial factor productivity in both sole-crop and intercropped maize. However, intercropping increases the N fertilizer partial factor productivity of maize and the N use efficiency of both maize and peanuts, while it reduces the N fertilizer partial factor productivity of peanuts. This suggests that when N fertilization exceeds 150 kg·ha^{-1}, the capacity of N fertilizer to increase the yields of maize and peanuts may be limited, especially for peanuts. Therefore, the intercropping model of maize and peanuts should be optimized with a rational application of N fertilizer to achieve the benefits of intercropping. Excessive N fertilizer not only leads to the wastage of resources but also contributes to environmental pollution [35]. Moreover, N requirements can vary significantly depending on different maize/peanut intercropping patterns, such as different row ratios and seeding densities. Future research should systematically investigate the N demand characteristics of both crops, soil N supply capacity, nutrient uptake and utilization characteristics, and the biological N fixation ability of peanuts in various maize–peanut intercropping patterns using ^{15}N tracing methods and high-throughput sequencing technologies.

5. Conclusions

In this study, intercropping significantly increased the yield of maize while decreasing the yield of peanuts, particularly under higher N application rates, because of enhanced interspecific competition. However, intercropping combined with an appropriate amount of N fertilization could significantly increase the overall system yield. Intercropping enhanced the N uptake of maize, which cannot be ascribed to an increase in N fixation capacity, as intercropping only supports the development of peanut nodules under lower N addition conditions. Nonetheless, intercropping improved N use efficiency.

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