Received: 3 June 2019 | Revised: 16 September 2019 | Accepted: 4 October 2019

DOI: 10.1002/fes3.187

ORIGINAL RESEARCH

Food and Energy Security Open Access WILEY

Yield and nitrogen uptake of sole and intercropped maize and peanut in response to N fertilizer input

Huaxin Gao[1,2] | Weiwei Meng[2] | Chaochun Zhang[1] | Wopke van der Werf[3] | Zheng Zhang[2] | Shubo Wan[2] | Fusuo Zhang[1]

[1]Key Laboratory of Plant-Soil Interactions, Ministry of Education, College of Resources and Environmental Sciences, China Agricultural University, Beijing, China

[2]Shandong Academy of Agricultural Sciences, Jinan, China

[3]Centre for Crop Systems Analysis, Wageningen University, Wageningen, The Netherlands

Correspondence
Chaochun Zhang, Key Laboratory of Plant-Soil Interactions, Ministry of Education, College of Resources and Environmental Sciences, China Agricultural University, No. 2 Yuanmingyuan West Road, Beijing 100193, China.
Email: zhangcc@cau.edu.cn

Funding information
National Key R & D Program, Grant/Award Number: 2017YFD0200207; "973" project of Chinese Ministry of Agriculture, Grant/Award Number: 2015CB150400; National Natural Science Foundation, Grant/Award Number: 31601252; European Union's Horizon 2020 Program for Research & Innovation, Grant/Award Number: 727217

Abstract

Chinese agriculture needs to become less dependent on fertilizer inputs to enhance sustainability. Cereal/legume intercropping is a potential pathway to lower fertilizer inputs, but there is insufficient knowledge on the nitrogen (N) response in species mixtures. Here, we investigated N response in maize/peanut intercropping. Maize showed a stronger yield response to N input than peanut both in sole cropping and in intercropping, and so did sole crops relative to intercrops. Maize yield was the highest at the maximum level tested: 360 kg N/ha. Agronomic efficiency (AE) of sole maize was 7.8 kg/kg N input, averaged across five N levels (0, 90, 180, 270, and 360 kg/ha). Partial land equivalent ratios (pLERs) for maize decreased with N input, from 0.70 at zero to 0.64 at 360 kg/ha. Sole peanut showed an optimum yield response to N input, with the highest yield at 270 kg/ha and lower yield at 360 kg/ha. The average AE of sole peanut was 1.3 kg/kg. The pLER of peanut declined from 0.43 at zero to 0.32 at 360 kg/ha while the overall LER decreased from 1.13 to 0.96, indicating relative better performance of intercropping at low than at high N input. Apparent recovery (RE) for N was 27.2% for sole maize, 12.4% for sole peanut, and 7.2% for intercrops. Mean N uptake was 179 kg/ha in sole maize, 199 kg/ha in intercropping, and 264 kg/ha in sole peanut. Partial economic budgeting indicated that with the current low Chinese N fertilizer prices, gross margin is maximized with high N input in sole crops; however, for intercropping, the highest gross margin was attained at intermediate N inputs of 180 or 270 kg/ha. Fertilizer price incentives may facilitate a transition to intercropping at moderate N input in China.

KEYWORDS

intercropping, land equivalent ratio, N input, N uptake, yield

1 | INTRODUCTION

Chinese agriculture is characterized by high inputs of fertilizer and high nutrient emissions to the environment (Guo et al., 2010; Ju et al., 2009). Reducing inputs is necessary to lower emissions and improve environmental quality. There is interest from policy makers for including N fixing legume crops in cropping systems to boost natural N fixation and lower the use of artificial fertilizer (Nemecek et al., 2008; Rose, Kearney, Erler, & Zwieten, 2019; Thierfelder, Cheesman, & Rusinamhodzi, 2012).

Intercropping is defined as the cultivation of two or more crop species in the same field for the whole or a part of their growing period (Li, Zhang, & Zhang, 2013; Li, Zhang, Ma, et al., 2013). Intercropping contributes to high yields and high land use efficiency due to complementarity in resource requirements between plant species (Franco, King, & Volder, 2018; Yu, Stomph, Makowski, Zhang, & Werf, 2016). This complementarity enables a better overall capture of resources (Gou et al., 2017; Zhang et al., 2008, 2017). Cereal/legume intercropping reduces the need for N input compared with sole cereals due to biological N fixation by legumes (Bedoussac et al., 2015; Jensen, Peoples, & Hauggaard-Nielsen, 2010).

Globally, maize is a primary staple food crop, ranking third in terms of area and production after wheat and rice (Kandil, 2013; Tejada, Rodríguez-Morgado, Paneque, & Parrado, 2018). In China, maize represented more than 22% of cultivated area in 2016, producing 220 million tons of grain, exceeding demand (China Statistical Yearbook, 2017). The North China Plain (NCP) is responsible for 29% of China's maize production (NBSC, 2015). The Chinese Government aims to reduce maize production while increasing the production of oilseed crops, such as soybean or peanut, to become more self-sufficient in plant oils and protein (Ministry of Agriculture & Rural Affairs of the People's Republic of China, 2016).

Peanut provided 48% of the total oilseed production in China in 2016 (China Statistical Yearbook, 2017) and is attracting increasing interest due to its nutrition use (Mwale, Azam-Ali, & Massawe, 2007). Peanut grown in calcareous soil may suffer from low yields due to iron deficiency; however, intercropping peanut with maize mitigates this stress and improves peanut yield (Zhang & Li, 2003; Zuo, Liu, Zhang, & Christie, 2004; Zuo, Zhang, Li, & Cao, 2000). Thus, maize/peanut intercropping could be a good option for farmers.

Chinese farmers habitually apply in the order of 300 kg N/ha to their field crops (Tan et al., 2017; Xiao et al., 2019), far exceeding the recommended rates for maize of about 180 kg N/ha (Wu, Chen, Cui, Zhang, & Zhang, 2014). The recommended N rate for peanut depends on nutrient demand. Production of 4–6 t of peanut pods requires 100–190 kg of N fertilizer (Feng et al., 2016; Tao, Chen, & Zhang, 1998). With the high price of peanut in the Chinese market, N input for peanut has increased, reaching 300 kg/ha for farmers in Shandong Province (Wu, 2014). Excessive N input results in an average low N fertilizer apparent recovery efficiency (RE). In the NCP, RE for maize is about 16% (Cui, Chen, Zhang, Miao, & Li, 2008), much lower than reported values of 78% in Africa and 68% in Europe (Wu et al., 2014). Unutilized N fertilizer is lost to the atmosphere and surface water, leading to environmental pollution.

Here, we performed a 2-year field experiment to study the yield and N uptake of maize and peanut in sole crop systems and an intercrop at different levels of N input in the range of 0–360 kg/ha. We aimed to determine the response to N input for both the sole crops and the intercrop, and hypothesized: (a) that both maize and peanut yields would reach a plateau at a sufficient level of N input; (b) that the sufficient level would be lower for peanut than for maize, and intermediate for maize/peanut intercropping; and (c) that intercropping would be more resistant to N input reduction in terms of yield and N uptake than sole maize. Finally, we hypothesized that farmers are fertilizing their crops at levels above their economic optimum.

2 | MATERIALS AND METHODS

2.1 | Experimental design and crop management

Field experiments were conducted in 2016 and 2017 in Zhangqiu City (36°72′N, 117°53′E), Shandong Province, China. The site has a warm-temperate continental monsoon climate. Weather data for the 2 years were obtained from the Shandong Meteorological Bureau (Table S1). Soil at the experimental site is a brown loam with a bulk density of 1.52 g/cm^3, organic matter content of 12.1 g/kg, total N content of 0.63 g/kg, alkaline hydrolytic N content of 65.7 mg/kg, Olsen phosphorus (P) content of 12.0 mg/kg, and NH_4OAc extractable potassium (K) content of 92.4 mg/kg in the top 30 cm.

The field experiment was laid out as a randomized complete block design with N input and cropping system (two sole crop treatments and one intercrop treatment) as factors. The N input had five levels: 0, 90, 180, 270, and 360 kg/ha (N0, N90, N180, N270, and N360, respectively); where 0 and 90 kg/ha are well below standard rates, 180 and 270 kg/ha are considered standard in the study area, and 360 kg/ha is considered high, but is nevertheless sometimes used in practice (Feng et al., 2016; Wu et al., 2014; Wu, 2014). There were three cropping systems: sole maize (*Zea mays*, "Denghai 605"), labeled SM, sole peanut (*Arachis hypogaea* "Huayu 25"), labeled SP, and maize/peanut intercropping, labeled MP (Figure 1). Crossing the factors N input and cropping system resulted in 15 treatments, each with three replicates. The plots were not changed from 1 year to the next, so cumulative effects of treatments might be observed.

Sole maize was grown at a row distance of 60 cm, with plant distance in the row of 27 cm, resulting in a density of 6.2 plants/m^2. Sole peanut was grown at a row distance of 40 cm, with plant distance in the row of 10 cm, resulting in a density of 25 plants/m^2. Row and plant distances of maize and peanut in the intercrop were the same as in the sole crop and the distance between neighboring maize and peanut rows in the intercrop was 47.5 cm, that is, slightly less than the

FIGURE 1 Photographs of the three cropping systems in this study. (a) sole maize, (b) sole peanut, and (c) maize/peanut intercrop with alternating strips of two rows of maize and four rows of peanut

average of the interrow distance of maize and the interrow distance of peanut (Figure 2). The short distance between maize and peanut rows resulted in relative densities of maize (0.46) and peanut (0.62) that were slightly higher than would have been the case in a replacement intercrop (Table S2). Here, we defined relative density as the plant density of a species in the intercrop divided by plant density in the sole crop, expressing density as the number of plants per unit area of the whole crop system (Zhang, Werf, Zhang, Li, & Spiertz, 2007).

Each plot had an area of 56 m^2 (10.4 m width × 5.4 m length), and the crop rows were oriented north–south. A sole maize plot comprised 17 maize rows, and a sole peanut plot comprised 26 peanut rows; an intercrop plot comprised eight alternating strips, four maize strips with two maize rows each (total: eight maize rows) and four peanut strips with four peanut rows each (total: 16 peanut rows).

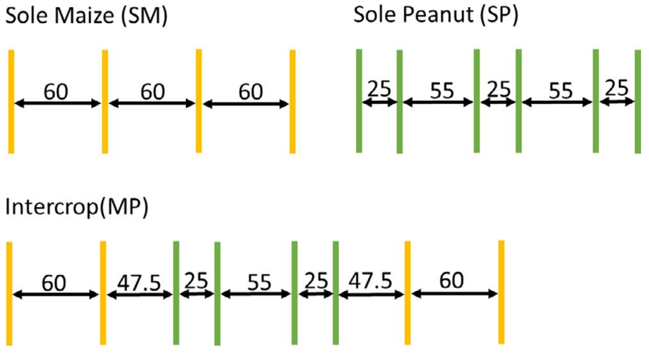

FIGURE 2 Schematic illustration of row placement of maize and peanut in sole maize, sole peanut, and maize/peanut intercrop. SM is sole maize sown at 60 cm row distance. SP is sole peanut on ridges of 80 cm width, 50 cm surface, and 10 cm height. Peanut row distance on the ridge is 25 cm while the gap to the nearest peanut row on the neighboring ridge is 55 cm. MP is an intercrop comprising alternating strips of two rows of maize and four rows of peanut. In this intercrop, the distances between the rows of the same species are the same as in the sole crops, that is, 60 cm for maize and 40 cm for peanut. The distance between adjacent peanut and maize rows was 47.5 cm. Total width of an entire strip of maize plus peanut was 260 cm

Maize and peanut were sown on 16 June and harvested on 1 October in 2016, and sown on 26 June and harvested on 1 October in 2017. The P and K fertilizers were broadcast on the field as basal fertilizer before sowing. The P was applied as calcium superphosphate at a rate of 150 kg P_2O_5/ha and K as potassium chloride at 150 kg K_2O/ha. The N was given as urea, split equally over two applications: a basal application before sowing (broadcast fertilization) and topdressing (row fertilization) on 26 July 2016 and 28 July 2017. Crops in our experiment were rain-fed. Weeds, pests, and diseases were controlled according to farmers' practice.

2.2 | Sampling for final yield and biomass

On 1 October of both years, when both peanut and maize were mature, we measured the sole crop yield in a 2.4 m^2 area for maize (2 m length × 2 rows) and 3.2 m^2 for peanut (2 m length × 2 ridges) per plot. In intercrops, we harvested two adjacent rows of maize and four adjacent rows of peanut over 2 m length. Maize cobs were air-dried to standard moisture content (~14%) and then threshed to assess final grain yield. Peanut pods were air-dried to standard moisture content (~10%) to calculate pod yield.

Additional aboveground plant samples were collected from a smaller area in each plot to determine total dry matter. The biomass sampling area for maize was 0.5 m length × 1.2 m width and correspondingly for peanut 0.5 × 1.6 m. After counting the number of plants, samples were separated into grain and straw and dried to constant mass (48 hr) at 70°C in a drying oven. The dried samples were weighed and then ground for N determination. The

N concentrations were determined as average of duplicate samples of 50 mg by the Dumas combustion method (at a pyrolysis temperature of 1,000°C, Winkler, Botterbrodt, Rabe, & Lindhauer, 2000) using an elemental analyzer (vario MACRO cube CNS; Elementar Analysensysteme GmbH).

The N use efficiency of different systems was evaluated using two indicators—agronomic efficiency (AE) and apparent recovery efficiency (RE)—calculated using the following equations (Paul et al., 2015):

$$\mathrm{AE}\,(\mathrm{kg\,kg^{-1}}) = (Y - Y_0)/F \tag{1}$$

where Y is yield with fertilizer application, Y_0 is yield without fertilizer, and F is the amount of fertilizer. AE was calculated for total grain yield in sole maize, sole peanut, and intercropping, separately for each N level.

Apparent recovery efficiency was calculated as:

$$\mathrm{RE}\,(\%) = (U - U_0)\,/\,F \tag{2}$$

where U is total nutrient uptake in the aboveground crop biomass with fertilizer, and U_0 is nutrient uptake in the aboveground crop biomass with no fertilizer. The recovery efficiency is "apparent" because in addition to fertilizer, there are other potential sources of N in the system: mineralization from organic matter, atmospheric N deposition, and biological N fixation by legumes. Biological N fixation is expected to be important especially low N input, resulting in a lower apparent recovery than would be observed if biological N fixation would not occur.

2.3 | Economic performance of three cropping systems

N fertilization by farmers is driven by economic incentives. We therefore calculated partial budgets that included only the costs of fertilizer and seeds and the revenues from the yield. These simple budgets are relevant because other budget components do not depend on the fertilizer input. The gross margin (G) was defined as the product of yield and price minus the fertilizer and seed and costs (Huang et al., 2015):

$$G = Y \times P - C \tag{3}$$

where Y is crop yield, P is the market price in the study area during the study period, and C represents costs of fertilizer and seed. For intercrops, G was calculated as:

$$G = Y_m \times P_m + Y_p \times P_p - C \tag{4}$$

where indices "m" and "p" indicate maize and peanut, respectively. We use two price scenarios for fertilizer in our calculations to assess the effect of fertilizer price on the economic incentive for farmers to lower N input. The first scenario uses the real fertilizer price on the Chinese market, while the second scenario uses the real fertilizer price on the world market. The Chinese market price for urea was \$0.21 kg^{-1} in 2016 and \$0.23 kg^{-1} in 2017, and the global price was \$0.76 kg^{-1} averaged over 2014–2018. Calcium superphosphate cost \$0.10 kg^{-1} and potassium chloride \$0.38 kg^{-1} in both Chinese and global markets in the 2 years. In 2016 and 2017, maize seed cost \$5.56 and \$5.78 kg^{-1} and peanut seed cost \$2.78 and \$2.92 kg^{-1}, respectively. Farm gate prices for maize and peanut and prices of inputs were obtained through interviews with local dealers. In 2016 and 2017, the price for maize grain was \$0.28 and \$0.25 kg^{-1} and for peanut pods was \$0.82 and \$0.80 kg^{-1}, respectively.

2.4 | Data analysis

Land equivalent ratio (LER) was used to calculate the land use advantage provided by intercropping (Rao & Willey, 1980):

$$LER = pLER_m + pLER_p = Y_m\,/\,M_m + Y_p\,/\,M_p \tag{5}$$

where subscripts "m" and "p" indicate maize and peanut, respectively, Y is yield in the intercrop, M is yield in the sole crop, and pLER is partial LER for the species. An LER = 1.0 indicates the same land productivity for intercropping and sole crops, LER > 1.0 indicates a land use advantage for intercropping, often referred to as over-yielding, and LER < 1.0 indicates a disadvantage. LER and pLER were calculated using the intercrop and sole crop yields and biomass at the same fertilizer level in the same year. The same Equation (5) was used to assess complementarity between maize and peanut for uptake of N. The LER_N was based on the total N uptake by the maize and peanut crops in sole crops and intercropping.

Yield, biomass, N uptake, revenues, and gross margin in both years were analyzed using three-way ANOVA in SAS V8.0 (SAS Institute Inc., 2000) with N level, cropping system and year as factors. The LER, pLER, LER_N, and yield in intercropping system were analyzed using two-way ANOVA with N level and year as factors. The AE and RE were analyzed using two-way ANOVA with N level and cropping system as factors. Pairwise differences were analyzed using LSD at $p < .05$. Responses of yield, biomass, revenue, and gross margin to N input were fitted with quadratic models.

3 | RESULTS

3.1 | Yield

Maize yield was significantly affected by N level and cropping system but little affected by year and the interaction of the three factors (Table 1). Maize yield showed a monotonous yield increase with increased N input, without reaching a plateau. Compared with N0, maize yield increased by 11%, 20%, 23%, and 32% at N90, N180, N270, and N360, averaged over 2 years

TABLE 1 Yield and LER of maize and peanut as influenced by year, N level and cropping system

	Maize yield (t/ha)			Peanut yield (t/ha)			Maize relative yield ref N0 (t/ha)		Peanut relative yield ref N0 (t/ha)		Intercropping system		
	SM	MP	pLER	SP	MP	pLER	SM	MP	SP	MP	Total grain yield (t/ha)	Relative yield ref N0	LER
2016													
N0	7.98d	5.52c	0.69a	3.83d	1.64ab	0.43ab	1.00d	1.00c	1.00d	1.00a	7.16b	1.00b	1.12a
N90	8.93c	5.86bc	0.66ab	3.86cd	1.53ab	0.40ab	1.12c	1.06bc	1.01cd	0.93a	7.39b	1.03ab	1.05ab
N180	9.46b	5.44c	0.58c	4.11bc	1.82a	0.44a	1.19bc	0.99c	1.07bc	1.11a	7.26b	1.01b	1.02bc
N270	9.61b	6.31ab	0.66ab	4.71a	1.59ab	0.34b	1.20b	1.15ab	1.23a	0.98a	7.90a	1.10a	0.99bc
N360	10.45a	6.52a	0.62b	4.14b	1.39b	0.34b	1.31a	1.19a	1.08b	0.87a	7.92a	1.11a	0.96c
2017													
N0	7.61d	5.43c	0.72a	3.63a	1.54a	0.42a	1.00c	1.00b	1.00a	1.00a	6.97a	1.00a	1.14a
N90	8.36c	5.76bc	0.69a	3.64a	1.41ab	0.39ab	1.10bc	1.06ab	1.00a	0.92ab	7.17a	1.03a	1.08ab
N180	9.17b	6.15abc	0.67a	3.94a	1.42a	0.36bc	1.21ab	1.13ab	1.09a	0.92ab	7.56a	1.09a	1.03bc
N270	9.57ab	6.34ab	0.66a	4.14a	1.36ab	0.33c	1.26a	1.17ab	1.15a	0.88b	7.70a	1.10a	0.99bc
N360	10.00a	6.56a	0.66a	3.81a	1.19b	0.31c	1.32a	1.21a	1.05a	0.77c	7.75a	1.11a	0.97c
Source of variation													
Block	N.S.		N.S.	N.S.		N.S.	N.S.		*		N.S.	N.S.	N.S.
Year (Y)	N.S.		*	***		N.S.	N.S.		*		N.S.	N.S.	N.S.
Cropping system (C)	***			***			***		***				
N level (N)	***		*	***		**	***		**		**	N.S.	***
Y*C	**			N.S.			N.S.		N.S.				
Y*N	N.S.		N.S.	N.S.		N.S.	N.S.		N.S.		N.S.	N.S.	N.S.
C*N	***			***			***		**				
Y*C*N	N.S.			N.S.			N.S.		N.S.				

Note: LER and pLER are calculated by reference to sole crop yields at the same N input.
Abbreviations: MP, maize/peanut; SM, sole maize; SP, sole peanut.
***$p < .001$.
**$p < .01$.
*$p < .05$; N.S.: $p > .05$, based on three-way ANOVA considering the factors “Year” (2 levels), “Cropping system” (2 levels), and “N fertilizer” (5 levels).

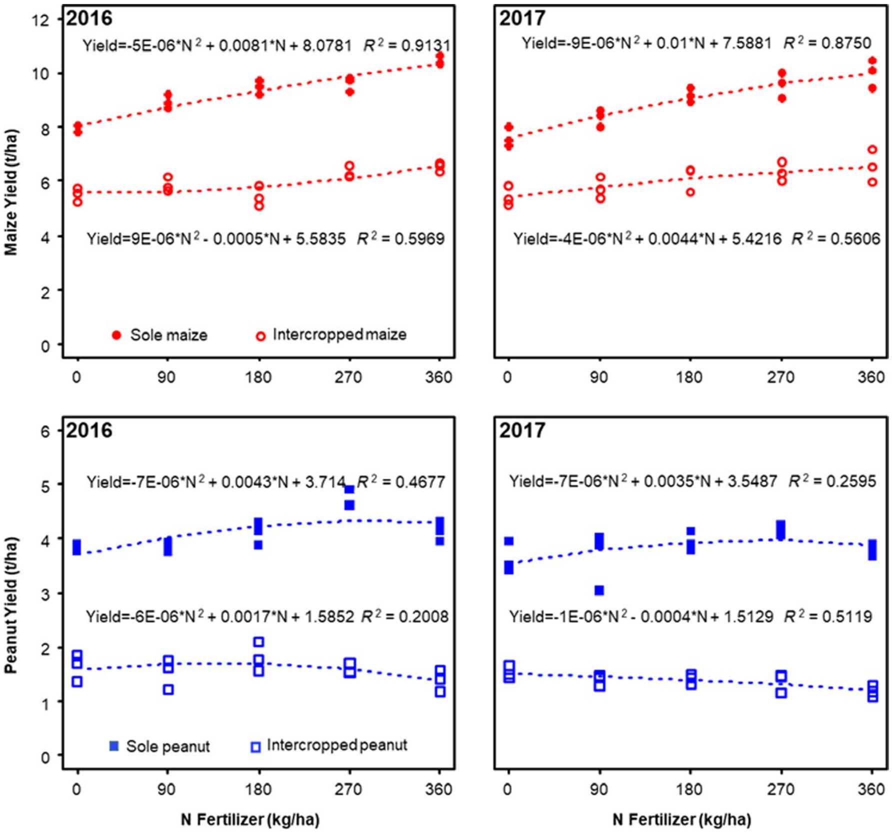

FIGURE 3 Yield response of sole and intercropped maize and peanut to N fertilizer rate in 2016 and 2017. Upper panels present sole and intercropped maize yield at five levels of fertilizer input: N0, N90, N180, N270, and N360 (kg N/ha) in 2016 and 2017. Lower panels present peanut yield in 2016 and 2017. Solid symbols are for sole crops while open symbols are for intercrops. Individual points represent yields of individual reps. Formulas represent fitted quadratic regression equations

TABLE 2 AE and RE of sole maize, sole peanut, and intercropping system as influenced by N level and cropping system

	2016						2017					
	AE kg grain kg^{-1} fertilizer N			RE (%)			AE kg grain kg^{-1} fertilizer N			RE (%)		
N treatment	SM	SP	MP	SM	SP	MP	SM	SP	MP	SM	SP	MP
N90	10.6a	0.4b	2.5a	36.2a	13.0ab	9.9a	8.3a	0.1a	2.2a	45.0a	6.1bc	8.0a
N180	8.2ab	1.6b	0.5a	20.9ab	7.5b	8.8a	8.7a	1.7a	3.3a	34.6ab	20.2ab	7.4a
N270	6.0b	3.3a	2.7a	15.3b	17.7a	8.6a	7.3a	1.9a	2.7a	26.3b	23.2a	7.3a
N360	6.9ab	0.9b	2.1a	15.7b	12.6ab	5.7a	6.6a	0.5a	2.2a	23.4b	−0.7c	2.3a
Average	7.9	1.5	2.0	22.0	12.7	8.3	7.7	1.1	2.6	32.3	12.2	6.2
Source of variation												
N level (N)	N.S.			*			N.S.			**		
Cropping system (C)	***			***			***			***		
N × C	**			*			N.S.			**		

***$p < .001$.
**$p < .01$.
*$p < .05$; N.S.: $p > .05$, based on two-way ANOVA considering the factors "Cropping system" (3 levels) and "N fertilizer" (4 levels).

in the sole cropping, while it increased by 6%, 6%, 16%, and 20% in intercropping, compared with N0 treatment in intercropping (Figure 3). Maize yield was lower in intercropping than in sole cropping, and the yield increase with increasing N input was also lower in the intercropping. The pLER for maize yield decreased with N input and varied between the 2 years.

N level, cropping system, and experimental year significantly affected peanut yield (Table 1). With increased N input, sole peanut yield reached a peak at N270 and declined when fertilizer input was increased from N270 to N360. N input had a negative effect on intercropped peanut yield (Figure 3). The pLER for peanut yield decreased with

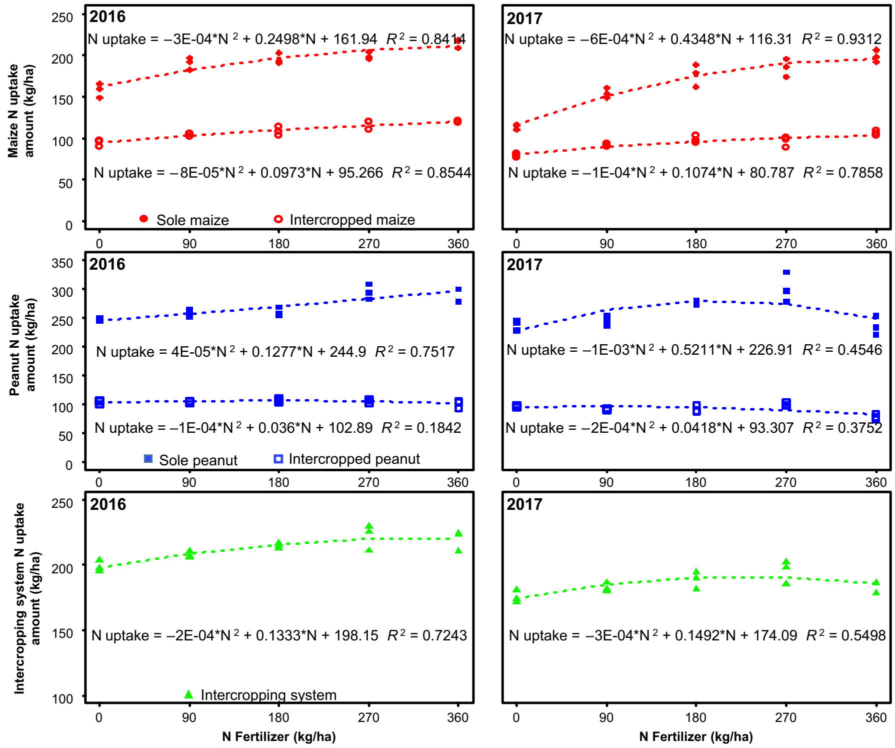

FIGURE 4 N uptake response of sole and intercropped maize and peanut and the whole intercropping system to N fertilizer input in 2016 and 2017. Upper panels present N uptake of sole and intercropped maize at five levels of fertilizer input: N0, N90, N180, N270, and N360 (kg N/ha) in 2016 and 2017. Middle and lower panels present N uptake of peanut and intercrops in 2016 and 2017. Solid symbols are for sole crops while open symbols represent intercropped crops in upper and middle panels. Individual points represent N uptakes of individual reps. Formulas represent fitted quadratic regression equations

N input from 0.43 at N0 to 0.34 at N360 in 2016 and from 0.42 at N0 to 0.31 at N360 in 2017.

Compared with N0, total grain yield in intercropping increased by 3%, 5%, 10%, and 11% at N90, N180, N270, and N360, averaged over 2 years (Table 1). The LER was significantly affected by N level, decreasing with N input from 1.13 at N0 to 0.97 at N360, averaged over 2 years. The LER was smaller than one for N inputs above 180 kg/ha.

The AE was significantly influenced by cropping system but little affected by N level (Table 2). The AE was the greatest in sole maize (7.9 kg/kg in 2016 and 7.7 kg/kg in 2017, averaged across all N levels), intermediate in intercropping (2.0 and 2.6 kg/kg), and the lowest in sole peanut (1.5 and 1.1 kg/kg).

3.2 | Biomass

Maize biomass increased with N input in both sole cropping and intercropping (Figure S1). Intercropping decreased maize biomass irrespective of N input. Experimental year significantly affected maize biomass (Table S3). The pLER for maize biomass decreased significantly with N fertilizer from 0.61 at N0 to 0.53 at N360, averaged over the 2 years.

The effect of N input on peanut biomass varied among cropping systems (Figure S1; Table S3). In sole cropping, N input increased peanut biomass from 9.3 at N0 to 11.6 t/ha at N360 in 2016 and from 9.1 at N0 to 11.8 t/ha at N360 in 2017. The greatest biomass in sole crop was obtained at 270 kg N/ha in both years. In intercropping, increasing N input had no effect on peanut biomass in 2016 but it significantly reduced peanut biomass from 3.8 at N0 to 3.1 t/ha at N360 in 2017. The pLER for peanut biomass showed a decrease with N input.

Increasing N input increased total biomass in the intercrop but the response was not as strong as for sole maize (Table S3). Highest biomass occurred at N360 in 2016 and at N270 in 2017. The LER for biomass decreased from 1.03 at N0 to 0.87 at N360 and was significantly larger than one only at N0.

3.3 | N uptake and recovery efficiency (RE)

Relationships between N input and N uptake were nonlinear, irrespective of species and cropping system (Figure 4). N level, cropping system, year, and several interactions had significant effects on maize and peanut N uptake (Table S4). In maize, N uptake increased with N input both in sole cropping and in intercropping. In peanut, N uptake behaved differently in the two cropping systems. Sole peanut achieved the highest N uptake at N270 in both years, but N input negatively affected the N uptake of intercropped peanut (Figure 4; Table S4). Sole maize and sole peanut had greater N uptake than intercropped maize and peanut, respectively. Among the three cropping systems, sole peanut had the largest N uptake of 264.0 kg/ha averaged across years and N levels, followed by intercropping and sole maize (Figure 4). N uptake in the intercropping was in both years lower at N360 than at N270.

N level, cropping system, and their interaction significantly influenced RE (Table 2). On average, across all N levels, RE of sole maize was 22.0% in 2016 and 32.3% in 2017, while RE of sole peanut was 12.7% in 2016 and 12.2% in 2017. N input

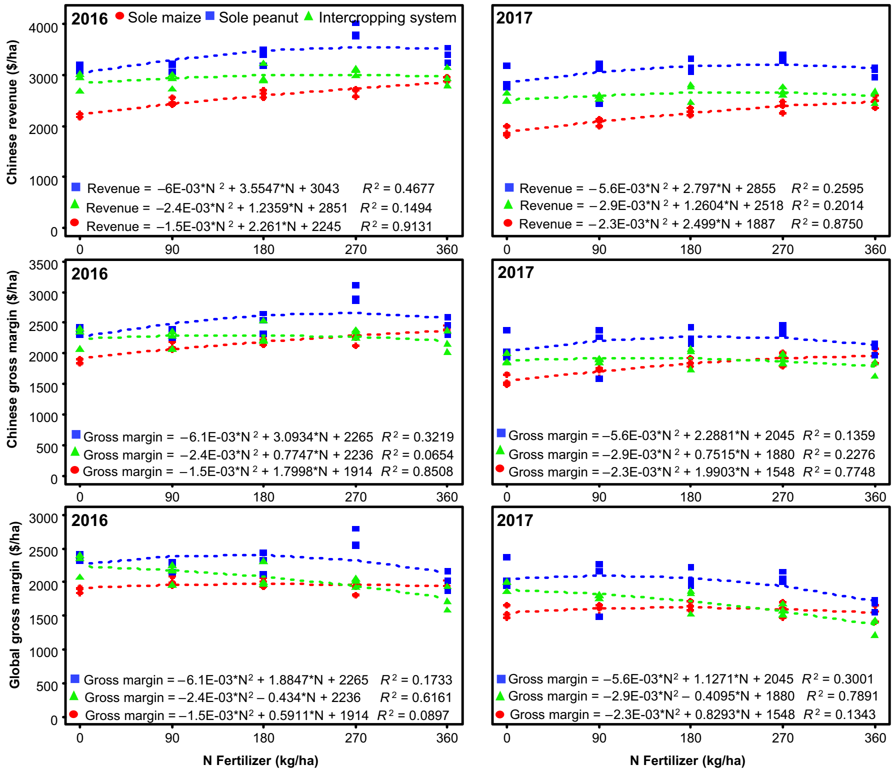

FIGURE 5 Effect of N input (0, 90, 180, 270, and 360 kg N/ha) on revenue and gross margin (Chinese and global market price for urea) of sole maize (red circles), sole peanut (blue squares), and maize/peanut intercropping (green triangles) in 2016 and 2017. Upper panels present revenue when using the Chinese market price for urea. Middle panels present gross margin, when using Chinese market price for urea, while the bottom panels present gross margin using world market prices for urea. Individual points represent revenues and gross margins of individual reps. Formulas represent fitted quadratic regression equations

had little effect on RE of the whole intercropping system, with an average value of 8.3% in 2016 and 6.2% in 2017.

3.4 | Analysis of revenue and gross margin (G)

Across cropping systems, sole peanut had the highest revenue at all levels of N input ($3,235 ha^{-1} on average across years and N levels), followed by maize/peanut intercropping ($2,781 ha^{-1}) and sole maize ($2,403 ha^{-1}) (Figure 5). The effect of N input on revenue was the greatest for sole maize, followed by sole peanut, and the smallest for intercropping.

Sole peanut had the highest gross margin among the three cropping systems at all N input levels when using the Chinese urea price ($0.22 kg^{-1}; Figure 5; Table S5). Gross margin increased with N input in sole maize, but decreased with N input in intercropping (Figure 5). Gross margin was higher for intercropping than for sole maize when N input was below 270 kg/ha, but at N360, sole maize a higher gross margin than intercropping (Figure 5).

Using a world price for urea ($0.76 kg^{-1}) reduced gross margin in all cropping systems (Figure 5). In this scenario, sole peanut had still the highest gross margin among the three systems, while intercropping had a higher gross margin than sole maize at an N input of 0, 90, or 180 kg/ha while sole maize had higher gross margin than intercropping at 360 kg N/ha. At 270 kg N/ha, sole maize and intercropping had the same gross margin. In this price scenario, increasing N input lowered gross margin in intercropping, while it scarcely affected gross margin in sole maize.

4 | DISCUSSION

We hypothesized that maize and peanut yields would plateau at high N inputs. Our data show that maize yields increased up to the highest level tested (360 kg N/ha) and would perhaps have further increased at higher input levels (that we did not test). Peanut yield increased with N input up to a level of 270 kg N/ha, after which it decreased. Maize yield in intercropping increased with N input up till the highest level tested, but peanut yield in intercropping decreased with N input. Thus, the overall grain yield response to N input in intercropping was flatter than in sole crops. This also means that lowering N inputs has less severe negative consequences for yields in intercropping than for yields in sole crops. These yield responses to N input were reflected in the economics of fertilizer application. With Chinese fertilizer prices, high input levels of 360 kg N/ha in maize and 270 kg N/ha in peanut were economically profitable. Intercropping was comparatively insensitive to N input, both in terms of yield, N uptake, and gross margin. Increased fertilizer price would make it economically more interesting for farmers to lower inputs and adopt intercropping to profit from the resilience of this system to lower input.

The LER was well above one if N input was <180 kg/ha. LER decreased at higher N input due to a weak performance of peanut. Maize tends to have greater LAI (leaf area index) at higher N input resulting in greater shading of peanut and lower peanut yield (Liu, Rahman, et al., 2017). The results indicate that maize/peanut intercropping is a suitable system if N input is low to moderate, consistent with previous studies in other cereal/legume systems (Hauggaard-Nielsen, Ambus, & Jensen, 2003; Li, Zhang, & Zhang, 2013; Li, Zhang, Ma, et al., 2013; Luo et al., 2016; Naudin, Corre-Hellou, Pineau, Crozat, & Jeuffroy, 2010). At high N inputs, sole crops are equally or more efficient in terms of land use than intercrops. Given the comparatively easier management of sole crops, intercropping would not be an attractive alternative to sole crops at high N input.

Economic benefits drive farmer decision making. According to Cui et al. (2008), maize yield response curve to N input tends to a linear-plateau with an optimal N rate ranging from 40 to 250 kg/ha because of different initial soil N_{min} and soil N supply. In our experiment, the highest maize yields were obtained at 360 kg N/ha, indicating lower inputs do not meet maize demand despite an uptake of only slightly over 200 kg N/ha. At the price levels in China, cultivation of peanut was more profitable than cultivation of maize, and their economic optimal N rates were 270 and 360 kg/ha, respectively, both exceeding recommendations that take into account environmental sustainability criteria (Feng et al., 2016; Tao et al., 1998; Wu et al., 2014). Maize/peanut intercropping decreased the economic optimal N rate to 180–270 kg/ha. This is still a high level of input with a risk of N losses.

Zhang et al. (2015) found that fertilizer-to-crop price ratio and crop mix (i.e., the crops cultivated) are two important factors affecting fertilizer use per hectare. The urea price in the Chinese market (\$0.22 kg^{-1}) was 3.4 times lower than in the global market (\$0.76 kg^{-1} averaged over 5 years, General Administration of Customs & The People's Republic of China, 2014, 2015, 2016, 2017, 2018) due to large subsidies, for example, US\$18 billion in 2010 (Li, Zhang, & Zhang, 2013; Li, Zhang, Ma, et al., 2013). The low fertilizer price incentivizes farmers to use high N inputs. With world market prices for fertilizer, assuming unchanged product prices, lower N input levels would be economically more attractive for farmers.

China faces the challenge of feeding its population and livestock and improving the environment by reducing nutrient spillovers from agriculture. In our study, averaged over 2 years, AE was 7.8, 1.3, and 2.3 kg/kg for sole maize, sole peanut, and intercropping systems, respectively (Table 2). The agronomic efficiencies of N fertilizer for peanut and for maize/peanut intercropping are very low, because peanut can fix its own nitrogen from air, and thus, the yield response to increasing input is shallow. Hence, compared with sole maize, mixing peanut in the intercropping system greatly reduced the sensitivity to a reduction in N input.

The RE for the whole intercropping system was 7.2%, much lower than 27.2% for sole maize and 12.4% for sole peanut. The pLER of maize was greater for yield (ranging from 0.71 at N0 to 0.64 at N360 averaged over 2 years; Table 1) than for N uptake (ranging from 0.65 at N0 to 0.55 at N360; Table S3). The difference in pLER suggests that the competitiveness of maize for yield was greater than its competitiveness for N uptake. A high competitiveness of maize for yield formation in intercropping is not surprising because maize is highly competitive for light due to the size of the plants (Liu, Rahman, et al., 2017; Liu et al., 2018; Liu, Zhu, et al., 2017). On the other hand, maize plants do not have a strong competitive advantage for N uptake from the soil because N fertilizer was applied homogeneously over the intercropped area, and fertilizer applied to inner rows of peanut strips would be difficult for maize to acquire. In the intercrop, N uptake is constrained because maize plants cannot easily reach N applied to peanut rows, while the ability of peanut to capture N is limited because of its comparative poor light capture and growth. Taking crop demand into account and applying more fertilizer to the dominant species, that is, maize, and less to peanut, could contribute to better N recovery in intercropping.

Our values of AE were lower than the worldwide average of 24 kg/kg but more similar to values of around 12 kg/kg obtained previously in China (Paul et al., 2015). A low AE under Chinese conditions may be related to high fertilization levels over the last decades, resulting in high levels of soil N (Tan et al., 2017). The soil organic matter was 12.1 g/kg, and atmospheric deposition of nitrogen has substantially increased in Huantai, near to our experimental site, from 28 to 85 kg/ha, during 1985–2015 (Ballarby et al., 2018). Consequently, the yield of nonfertilized maize reached 8.0 t/ha in 2016 and 7.6 t/ha in 2017, after one season without N input. Multiple years of low N input may be needed to attain a situation with higher recovery and agronomic efficiency of N fertilizer. In addition, there are several technologies available for reducing N loss and increasing N utilization, such as application of nitrification inhibitor or biochar (Sun, Lu, Chu, Shao, & Shi, 2017; Sun, Zhang, Powlson, Min, & Shi, 2015). Rather than subsidizing fertilizer, the government might invest in technology adoption and professionalization of farm management (including farm size adjustment; Wu et al., 2018). Such investments might help to boost productivity and resource use efficiency, while decreasing environmental degradation.

Intercropping advantages in this study were relatively small with LERs ranging from 1.13 at N0 to 0.97 at N360. There are several pathways to increase LER in intercropping. Yu, Stomph, Makowski, and Werf (2015) demonstrated that relay intercropping, in which the two crop species do not overlap completely in time, has on average a higher LER than simultaneous intercropping. However, if there is insufficient “growing time” available for relay intercropping, the shading effect in the intercropping could be mitigated by widening the gap between maize rows to allow more light penetration to the legume (Liu, Rahman, et al., 2017; Ren, Liu, Wang, & Zhang, 2016). Furthermore, the consequences of shading for peanut could be mitigated by choosing a shade-tolerant peanut variety, which has a high harvest index when shaded (Liu et al., 2018). In addition, fertilizer in intercropping needs to be placed at the place where it is needed, thus better tailoring supply to crop demand (Snyder, Davidson, Smith, & Venterea, 2014).

The current study showed critical trade-offs between yield, N input, and N uptake and comparative productivity of intercropping and sole cropping. Intercropping remains an interesting option to combine high yields with high resource use efficiency to achieve a sustainable production system for cereal and legume grains. It also provides an example for achieving sustainable agriculture in other countries, especially developing countries.

5 | CONCLUSIONS

We studied the productivity of maize, peanut, and maize/peanut intercropping in 2 years at five levels of N input in the North China Plain. Results over the 2 years showed a consistent decline in LER with higher N input. LERs were >1 for N input below 180 kg N/ha. Intercropping showed the smallest yield penalty of lowering N input. Economic profitability was highest with sole crops at high N input and intercrops at moderate N input. The economic optimum occurred at lower N inputs with world market prices for N fertilizer than with Chinese market prices, highlighting the possible role of fertilizer price incentives in a transition to more environmentally benign cropping systems with lower fertilizer inputs. The results show that maize/peanut intercropping is a suitable land use system if environmental considerations lead to a reduction in N input.

ACKNOWLEDGMENTS

This work received financial support from the National Key R & D Program (Grant Number 2017YFD0200207), the “973” project of Chinese Ministry of Agriculture (Grant Number 2015CB150400), and the National Natural Science Foundation Project (Grant Number 31601252). We thank all staff at the Shandong Academy of Agricultural Sciences in the county of Jinan for help and support. The authors acknowledge support through the European Union's Horizon 2020 Program for Research & Innovation under Grant Agreement Number 727217 (ReMIX: Redesigning European cropping systems based on species MIXtures).

CONFLICT OF INTEREST

None declared.

ORCID

Chaochun Zhang https://orcid.org/0000-0002-1278-8400

REFERENCES

Ballarby, J., Surridge, B. W. J., Haygarth, P. M., Liu, K., Siciliano, G., Smith, L., … Meng, F. Q. (2018). The stocks and flows of nitrogen, phosphorus and potassium across a 30-year time series for agriculture in Huantai County, China. *Science of the Total Environment*, *619*, 606–620. https://doi.org/10.1016/j.scitotenv.2017.10.335

Bedoussac, L., Journet, E. P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E. S., … Justes, E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development*, *35*(3), 911–935. https://doi.org/10.1007/s13593-014-0277-7

China Statistical Yearbook (2017). Beijing China: China Statistics Press. (in Chinese).

Cui, Z. L., Chen, X. P., Zhang, F. S., Miao, Y. X., & Li, J. L. (2008). On-farm evaluation of the improved soil Nmin-based nitrogen management for summer maize in North China Plain. *Agronomy Journal*, *100*, 517–525.

Feng, H., Wu, Z. F., Lin, J. C., Yu, T. Y., Zheng, Y. M., Sun, X. W., … Wang, C. B. (2016). Simple and efficiency cultivation technology for the peanut under the standardization mode of single-seed sowing. *Asian Agricultural Research*, *8*(6), 61–64.

Franco, J. G., King, S. R., & Volder, A. (2018). Component crop physiology and water use efficiency in response to intercropping. *European Journal of Agronomy*, *93*, 27–39. https://doi.org/10.1016/j.eja.2017.11.005

General Administration of Customs, The People's Republic of China (2014). Retrieved from http://www.customs.gov.cn/customs/302249/302274/302276/310446/index.html

General Administration of Customs, The People's Republic of China (2015). Retrieved from http://www.customs.gov.cn/customs/302249/302274/302276/310446/index.html

General Administration of Customs, The People's Republic of China (2016). Retrieved from http://www.customs.gov.cn/customs/302249/302274/302276/310446/index.html

General Administration of Customs, The People's Republic of China (2017). Retrieved from http://www.customs.gov.cn/customs/302249/302274/302276/702163/index.html

General Administration of Customs, The People's Republic of China (2018). Retrieved from http://www.customs.gov.cn/customs/302249/302274/302276/702163/index.html

Gou, F., van Ittersum, M. K., Simon, E., Leffelaar, P. A., van der Putten, P. E. L., Zhang, L. Z., & van der Werf, W. (2017). Intercropping wheat and maize increases total radiation interception and wheat

RUE but lowers maize RUE. *European Journal of Agronomy*, *84*, 125–139. https://doi.org/10.1016/j.eja.2016.10.014

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., … Zhang, F. S. (2010). Significant acidification in major Chinese croplands. *Science*, *327*, 1008–1010. https://doi.org/10.1126/science.1182570

Hauggaard-Nielsen, H., Ambus, P., & Jensen, E. S. (2003). The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutrient Cycling in Agroecosystems*, *65*, 289–300.

Huang, C. D., Liu, Q. Q., Heerink, N., Stomph, T. J., Li, B. S., Liu, R. L., … Zhang, F. S. (2015). Economic performance and sustainability of a novel intercropping system on the North China Plain. *PLoS ONE*, *10*(8), e0135518.

Jensen, E. S., Peoples, M. B., & Hauggaard-Nielsen, H. (2010). Fababean in cropping systems. *Field Crops Research*, *115*(3), 203–216.

Ju, X. T., Xing, G. X., Chen, X. P., Zhang, L. J., Liu, X. J., Cui, Z. L., … Zhang, F. S. (2009). Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(19), 8077–8078.

Kandil, E. E. (2013). Response of some maize hybrids (*Zea mays* L.) to different levels of nitrogenous fertilization. *Journal of Applied Sciences Research*, *9*, 1902–1908.

Li, L., Zhang, L. Z., & Zhang, F. S. (2013). Crop mixtures and the mechanisms of overyielding. In S. A. Levin (Ed.), *Encyclopedia of Biodiversity*, (2nd edn) (pp. 382–395). Waltham, MA: Academic Press.

Li, Y. X., Zhang, W. F., Ma, L., Huang, G. Q., Oenema, O., Zhang, F. S., & Dou, Z. X. (2013). An Analysis of China's Fertilizer Policies: Impacts on the Industry, Food Security, and the Environment. *Journal of Environmental Quality*, *42*, 972–981.

Liu, X., Rahman, T., Song, C., Su, B. Y., Yang, F., Yong, T. W., … Yang, W. Y. (2017). Changes in light environment, morphology, growth and yield of soybean in maize-soybean intercropping systems. *Field Crops Research*, *200*, 38–46.

Liu, X., Rahman, T., Song, C., Yang, F., Su, B. Y., Cui, L., … Yang, W. Y. (2018). Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crops Research*, *224*, 91–101.

Liu, Z., Zhu, K. L., Dong, S. T., Liu, P., Zhao, B., & Zhang, J. W. (2017). Effects of integrated agronomic practices management on root growth and development of summer maize. *European Journal of Agronomy*, *84*, 140–151.

Luo, S. S., Yu, L. L., Liu, Y., Zhang, Y., Yang, W. T., Li, Z. X., & Wang, J. W. (2016). Effects of reduced nitrogen input on productivity and N_2O emissions in a sugarcane/soybean intercropping system. *European Journal of Agronomy*, *81*, 78–85.

Ministry of Agriculture and Rural Affairs of the People's Republic of China (2016). Retrieved from http://www.moa.gov.cn/govpublic/ZZYGLS/201604/t20160422_5104295.htm

Mwale, S. S., Azam-Ali, S. N., & Massawe, F. J. (2007). Growth and development of bambara groundnut (*Vigna subterranea*) in response to soil moisture - Dry matter and yield. *European Journal of Agronomy*, *26*, 345–353. https://doi.org/10.1016/j.eja.2006.09.007

Naudin, C., Corre-Hellou, G., Pineau, S., Crozat, Y., & Jeuffroy, M. H. (2010). The effect of various dynamics of N availability on winter pea-wheat intercrops: Crop growth, N partitioning and symbiotic N_2 fixation. *Field Crops Research*, *119*(1), 2–11. https://doi.org/10.1016/j.fcr.2010.06.002

NBSC (2015). *China statistical yearbook 2014*. Beijing, China: National Bureau of Statistics of China (NBSC).

Nemecek, T., von Richthofen, J. S., Dubois, G., Casta, P., Charles, R., & Pahl, H. (2008). Environmental impacts of introducing grain legumes into European crop rotations. *European Journal of Agronomy*, *28*, 380–393. https://doi.org/10.1016/j.eja.2007.11.004

Paul, F., Frank, B., Tom, B., Fernando, G., Rob, N., & Shamie, Z. (2015). Chapter 2: Nutrient/fertilizer use efficiency: Measurement, current situation and trends.. In P. Drechsel, P. Heffer, H. Magen, R. Mikkelsen, & D. Wichelns (Eds.), *Managing Water and Fertilizer for Sustainable Agricultural Intensification* (pp. 8–38): Paris, France: International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI).

Rao, M. R., & Willey, R. W. (1980). Evaluation of yield stability in intercropping: Studies on sorghum/pigeonpea. *Experimental Agriculture*, *16*, 105–116. https://doi.org/10.1017/S0014479700010796

Ren, Y. Y., Liu, J. J., Wang, Z. L., & Zhang, S. Q. (2016). Planting density and sowing proportions of maize-soybean intercrops affected competitive interactions and water-use efficiencies on the Loess Plateau. *China. European Journal of Agronomy*, *72*, 70–79. https://doi.org/10.1016/j.eja.2015.10.001

Rose, T. J., Kearney, L. J., Erler, D. V., & van Zwieten, L. (2019). Integration and potential nitrogen contributions of green manure inter-row legumes in coppiced tree cropping systems. *European Journal of Agronomy*, *103*, 47–53. https://doi.org/10.1016/j.eja.2018.11.008

SAS Institute Inc (2000). *SAS/STAT® 8.0 user's guide*. Cary, NC: SAS Institute Inc.

Snyder, C. S., Davidson, E. A., Smith, P., & Venterea, R. T. (2014). Agriculture: Sustainable crop and animal production to help mitigate nitrous oxide emissions. *Current Opinion in Environmental Sustainability*, *9–10*, 46–54. https://doi.org/10.1016/j.cosust.2014.07.005

Sun, H. J., Lu, H. Y., Chu, L., Shao, H. B., & Shi, W. M. (2017). Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH_3 volatilization in a coastal saline soil. *Science of the Total Environment*, *575*, 820–825. https://doi.org/10.1016/j.scitotenv.2016.09.137

Sun, H. J., Zhang, H. L., Powlson, D. S., Min, J., & Shi, W. M. (2015). Rice production, nitrous oxide emission and ammonia volatilization as impacted by the nitrification inhibitor 2-chloro-6-(trichloromethyl)-pyridine. *Field Crops Research*, *173*, 1–7. https://doi.org/10.1016/j.fcr.2014.12.012

Tan, Y. C., Xu, C., Liu, D. X., Wu, W. L., Lal, R., & Meng, F. Q. (2017). Effects of optimized N fertilization on greenhouse gas emission and crop production in the North China Plain. *Field Crops Research*, *205*, 135–146. https://doi.org/10.1016/j.fcr.2017.01.003

Tao, S. X., Chen, D. X., & Zhang, L. F. (1998). Experimental report of optimal application rate on nitrogen, phosphorus and potassium in coated peanut. *Peanut Science and Technology*, *4*, 18–20. (in Chinese).

Tejada, M., Rodríguez-Morgado, B., Paneque, P., & Parrado, J. (2018). Effects of foliar fertilization of a biostimulant obtained from chicken feathers on maize yield. *European Journal of Agronomy*, *96*, 54–59. https://doi.org/10.1016/j.eja.2018.03.003

Thierfelder, C., Cheesman, S., & Rusinamhodzi, L. (2012). A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Research*, *137*, 237–250. https://doi.org/10.1016/j.fcr.2012.08.017

Winkler, R., Botterbrodt, S., Rabe, E., & Lindhauer, M. G. (2000). Stickstoff/Proteinbestimmung mit der Dumas-Methode in Getreide und Getreideprodukten. *Getreide Mehl Brot*, *54*, 86–91.

Wu, L., Chen, X. P., Cui, Z. L., Zhang, W. F., & Zhang, F. S. (2014). Establishing a regional nitrogen management approach to mitigate greenhouse gas emission intensity from intensive smallholder maize production. *PLoS ONE*, *9*(5), e98481. https://doi.org/10.1371/journal.pone.0098481

Wu, Y. Y., Xi, X. C., Tang, X., Luo, D. M., Gu, B. J., Lam, S. K., … Chen, D. L. (2018). Policy distortions, farm size, and the overuse of agricultural chemicals in China. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(27), 7010–7015. https://doi.org/10.1073/pnas.1806645115

Wu, Z. F. (2014). *Nitrogen management for high yield and high efficiency of peanut*. Ph.D. dissertation. Beijing, China: China Agricultural University. (in Chinese).

Xiao, G. M., Zhao, Z. C., Liang, L., Meng, F. Q., Wu, W. L., & Guo, Y. B. (2019). Improving nitrogen and water use efficiency in a wheat-maize rotation system in the North China Plain using optimized farming practices. *Agricultural Water Management*, *212*, 172–180. https://doi.org/10.1016/j.agwat.2018.09.011

Yu, Y., Stomph, T. J., Makowski, D., & van der Werf, W. (2015). Temporal niche differentiation increases the land equivalent ratio of annual intercrops: A meta-analysis. *Field Crops Research*, *184*, 133–144. https://doi.org/10.1016/j.fcr.2015.09.010

Yu, Y., Stomph, T. J., Makowski, D., Zhang, L. Z., & van der Werf, W. (2016). A meta-analysis of relative crop yields in cereal/legume mixtures suggests options for management. *Field Crops Research*, *198*, 269–279. https://doi.org/10.1016/j.fcr.2016.08.001

Zhang, F. S., & Li, L. (2003). Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil*, *248*, 305–312.

Zhang, L. Z., van der Werf, W., Bastiaans, L., Zhang, S., Li, B., & Spiertz, H. J. (2008). Light interception and utilization in relay intercrops of wheat and cotton. *Field Crops Research*, *107*, 29–42. https://doi.org/10.1016/j.fcr.2007.12.014

Zhang, L., van der Werf, W., Zhang, S. P., Li, B., & Spiertz, J. H. J. (2007). Growth, yield and quality of wheat and cotton in relay strip intercropping systems. *Field Crops Research*, *103*, 178–188. https://doi.org/10.1016/j.fcr.2007.06.002

Zhang, W. P., Liu, G. C., Sun, J. H., Fornara, D., Zhang, L. Z., Zhang, F. S., & Li, L. (2017). Temporal dynamics of nutrient uptake by neighbouring plant species: Evidence from intercropping. *Functional Ecology*, *31*, 469–479. https://doi.org/10.1111/1365-2435.12732

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, *528*, 51–59. https://doi.org/10.1038/nature15743

Zuo, Y. M., Liu, Y. X., Zhang, F. S., & Christie, P. (2004). A study on the improvement of iron nutrition of peanut intercropping with maize on nitrogen fixation at early stages of growth of peanut on a calcareous soil. *Soil Science and Plant Nutrition*, *50*(7), 1071–1078.

Zuo, Y. M., Zhang, F. S., Li, X. L., & Cao, Y. P. (2000). Studies on the improvement in iron nutrition of peanut by intercropping with maize on a calcareous soil. *Plant and Soil*, *220*, 13–25.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Gao H, Meng W, Zhang C, et al. Yield and nitrogen uptake of sole and intercropped maize and peanut in response to N fertilizer input. *Food Energy Secur*. 2019;00:e187. https://doi.org/10.1002/fes3.187