EFFECTS OF MAIZE (*ZEA MAYS* L.) INTERCROPPING WITH LEGUMES ON NITROUS OXIDE (N_2O) EMISSIONS

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Abstract. To investigate the effects of maize/legume intercropping on soil N_2O emissions, six treatments were tested in the North China Plain: maize, M120 (N application rate 120 kg ha^{-1}); maize, M240 (N application rate 240 kg ha^{-1}); soybean (*Glycine max*), SS (120 kg ha^{-1}); maize/soybean intercropping, MS (120 kg ha^{-1}); peanut (*Arachis hypogaea*), PP (120 kg ha^{-1}); and maize/peanut intercropping, MP (120 kg ha^{-1}). The amounts of inorganic nitrogen for the 0–20 cm soil in MS were 24.0%, 5.3%, and 29.3% lower than in SS, M120, and M240, respectively ($P < 0.05$). The total N_2O emissions ranged from 0.41 ± 0.09 to 0.98 ± 0.14 kg ha^{-1}. MP and MS were statistically different at the 95% confidence level, whereas MP produced the least N_2O emissions at 0.41 kg ha^{-1}. The seasonal cumulative N_2O emissions and global warming potential in MS and MP were also significantly lower than those in the other three monoculture treatments ($P < 0.001$). The results demonstrated that maize/legume intercropping can increase the N uptake of crops and reduce the amount of soil inorganic nitrogen and N_2O emissions, thereby, ensuring the sustainability of the agricultural environment.

Keywords: *soybean, peanut, global warming potential, nitrogen rate, cumulative N_2O emissions*

Introduction

Nitrous oxide (N_2O) emissions are essentially derived from the microbial processes of nitrification and denitrification (Kweku et al., 2018). These processes can be influenced by agricultural management practices, such as fertigation, tillage, crop rotation, and cropping systems (Hénault et al., 2012; Nath et al., 2017; Perdomo et al., 2009). Various cropping patterns are being trialed in the North China Plain to reduce N_2O emissions with maize/legume intercropping proving to be promising (Huang et al., 2014). Intercropping prairie cordgrass with Kura clover was shown to effectively reduce fertilizer-derived N_2O emissions and the net global warming potential (Abagandura et al., 2020). A similar suggestion was reported by Senbayram et al. (2016) from intercropping wheat with legumes in Gottingen, Germany. However, global information on the effect of intercropping on N_2O emissions is quite limited.

The presence of nitrogen in the soil through applied fertilizer is the main reason for the increase of N_2O emissions from farmlands (Liu et al., 2019). Therefore, improving the nitrogen use efficiency is an effective method of reducing greenhouse gas emissions.

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A large number of studies have shown that intercropping can effectively improve the nitrogen use efficiency of the intercropped populations (Yong et al., 2018), increase the nitrogen uptake of crops (Li et al., 2011), and reduce the N_2O emissions (Yu et al., 2019). Studies have shown that the yield of maize/soybean intercropping systems is higher than that of monocultures (Gao et al., 2010; Seran and Brintha, 2010).

Currently, the majority of the intercropping studies focus on interspecific complementarity and competition for nutrients (Gao et al., 2010; Seran and Brintha, 2010), the nitrogen among crop species within intercropping patterns (Qiu et al., 2019), and how to improve the system yield and land equivalent ratio (Dariush et al., 2006). Many studies focused on achieving high yield and high efficiency of crops with only limited information regarding the importance of intercropping techniques for the mitigation of greenhouse gas emissions being reported (Dyer et al., 2012). Although there have been research results on greenhouse gas emissions from intercropping systems, the results are not consistent due to different intercropping patterns and sampling methods.

Few works have reported a relationship between soil N_2O emissions and different intercropping systems. A unique study by Dyer et al. (2012) indicated that, with regard to greenhouse gas (GHG) emissions, both CO_2 and N_2O showed a general trend of greater emission rates in the maize sole crop followed by the soybean sole crop and were the lowest in the intercrops. Thus, intercropping in Pampa, Argentina could be a more sustainable agroecosystem and land management practice. This was the first study to evaluate soil N_2O emissions from a temperate maize/soybean intercropping system.

Intercropping treatments of different varieties of barley and pea also showed the ability to significantly reduce N_2O emissions (Pappa et al., 2011). These studies, and that of Huang et al. (2014), which was conducted in the North China Plain, indicated that intercropping treatments (involving maize and different legumes) could be useful in controlling the N_2O emissions from soils in different agricultural ecosystems. However, some studies showed that maize/legume intercropping had no significant effect on soil N_2O emissions. Vachon (2008) showed that there was no significant difference in the soil N_2O cumulative emissions between corn/soybean intercropping at 1:2 and 2:3 and their single cropping system.

The research on the effect of maize/legume intercropping on N_2O emissions is not sufficient, and the influence mechanism is not clear, and little attention has been paid to the difference of N_2O emissions on the intercropping of maize with different legumes. The objective of this work was to evaluate the effects of maize/legume intercropping on N_2O emissions. The results will aid the development of maize/legume intercropping systems for the mitigation of greenhouse gas emissions and the sustainability of agriculture.

Materials and methods

Study area

The experiment was conducted at the Xinxiang Comprehensive Experimental Station (N35° 14′, E113° 76′, altitude 74 m) of the Chinese Academy of Agricultural Sciences from June to September 2018. The site is located in Qiliying Town, Xinxiang County, Xinxiang City, Henan Province. The station is at the Yellow River Irrigation Diversion Area of Renminshengli Canal in the west of the central part of the Huang-Huai-Hai Plain. This location belongs to the warm temperate continental monsoon climate. The sunshine duration was 2399 h, the annual average temperature was 14 °C, the annual average rainfall was 582 mm, the rainfall from June to September in 2018 was 357.4 mm, the maximum temperature was 39.6 °C, the minimum temperature was 8.8 °C, and the average temperature was 28.4 °C.

The temperature and rainfall during the study period are shown in *Figure 1*. The class of the soil was sandy loam (4.52% clay, 40.27% silt, 55.21% sand) according to world soil resources reference base, the parent material of soil was the sediment after the Yellow River alluvial, and the groundwater depth was more than 5 m (Si et al., 2020). The physical and chemical properties of the soil layer (0–20 cm) of the experimental field are shown in *Table 1*. Before sowing, the total nitrogen of the 0–100 cm soil was 0.9 g kg^{-1}, and the inorganic nitrogen reserves of the 0-100 cm soil were 244.58 kg ha^{-1}.

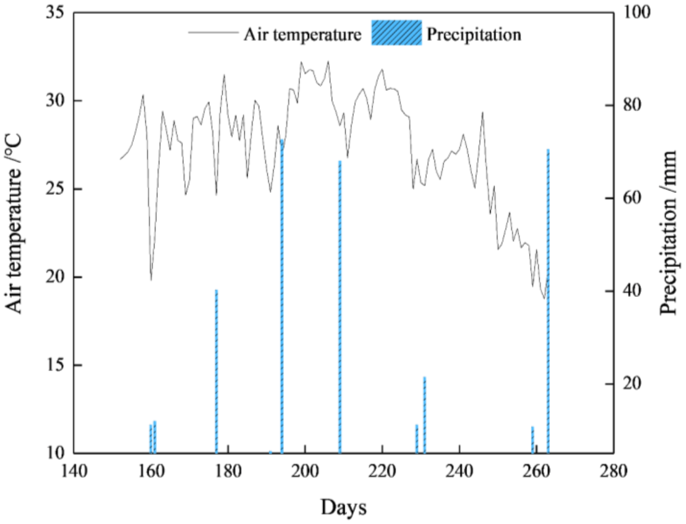

***Figure 1.** Air temperature and rainfall during the trial period in 2018*

***Table 1.** Soil parameters of the soil at the experimental site*

pH	**Organic matter ($g·kg^{-1}$)**	**Bulk density ($g·cm^{-3}$)**	**Alkali-hydrolyzed nitrogen content ($mg·kg^{-1}$)**	**Available K content ($mg·kg^{-1}$)**	**Available P content ($mg·kg^{-1}$)**	**Total nitrogen ($g·kg^{-1}$)**	**Mineral nitrogen ($mg·kg^{-1}$)**
8.7	14.4	1.51	90.7	125.9	25.7	0.9	30.2

Experimental design

The experiment consisted of six treatments laid in a Randomized Complete Block Design (RCBD) with three replications. The maize monoculture (M240) treatment with nitrogen (urea) application had a standard rate of 240 kg ha^{-1}. Other treatments included a soybean monoculture (SS), peanut monoculture (PP), maize/peanut intercropping (MP), and maize/soybean intercropping (MS), which received nitrogen (urea) at the rate of 120 kg ha^{-1} considering the potential of legumes for complementing nitrogen supply through fixation (Huang et al., 2014).

To compare and analyze the difference in the N_2O emissions between a monoculture of maize and intercropped population under the same nitrogen application rate, a single cropping of maize with 120 kg ha^{-1} nitrogen fertilizer (M120) was also set up (*Table 2*).

The maize variety used was “Denghai-605”, the peanut variety was “Haihua-1”, and the soybean variety was “Jidou-17”. Each plot was 7 m wide and 10 m long, planted in a north to south orientation. The row spacings applied for maize and legumes monocultures were 60 and 30 cm, respectively. Each hole received two grains at planting. The detailed configuration (showing both row and plant spacings) of the intercropping pattern is as shown in *Figure 2*.

Table 2. *Description of the treatments applied*

Treatment Code	Description	Nitrogen application rate (kg ha^{-1})
M120	Maize monoculture	120
M240	Maize monoculture	240
SS	Soybean monoculture	120
PP	Peanut monoculture	120
MP	Maize/peanut intercropping	120
MS	Maize/soybean intercropping	120

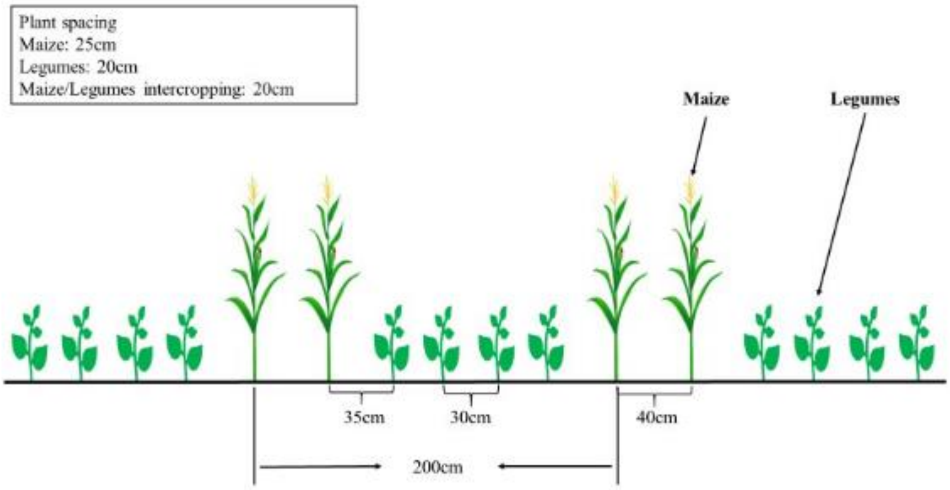

Figure 2. *Sketch of the planting patterns*

The sowing date of maize, soybean, and peanuts was June 10, 2018, while the harvest was on September 15. Before sowing, the application rates of phosphorus and potassium in all the treatments were the same; 105 kg ha^{-1} of K_2SO_4 and 120 kg ha^{-1} of P_2O_5. The nitrogen fertilizer was applied twice with the ratio of base to topdressing of 50:50. The topdressing time was July 12. Irrigation was conducted twice in the whole growth period. The first irrigation date was June 11, and the irrigation method was sprinkler with a quota of 45 mm. The second irrigation date was August 29 when the surface method was used to apply 45 mm.

Sampling and measurement procedures

Sampling and analysis of N_2O gas

Nitrous oxide (N_2O) samples were taken with a static box and analyzed with gas chromatography (Christiansen et al., 2015). Eleven sampling events were conducted during the whole growth period. The size of the static box was length × width × height = 100 cm × 50 cm × 10 cm. The static box was made of an acrylic plate with a thickness of 5 mm. The top of the box was open for plant growth and gas sample collection. The static box was sealed and fixed on each sampling point by the soil sealing method (the static box was designed and installed as shown in *Figs. 3* and *4*).

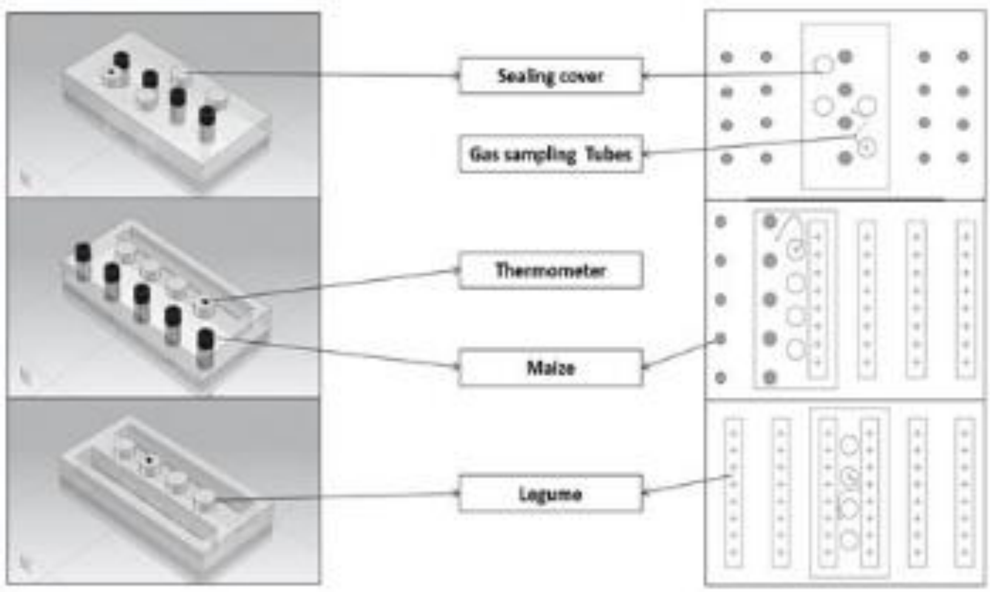

Figure 3. *Experimental layout and positioning of the static box*

Figure 4. *Static box installed at the experimental site*

In *Figure 3*, the left side is the structure diagram of three kinds of static boxes, and the right side shows the orientation of the static box under the three planting styles of single maize, intercrop of maize and legumes, and single legumes. The shaded circles in the figure represent Maize and “+” represents soybean or peanuts. Three static boxes were set up in each cell, and the average value of three observations was used. Soil N_2O gas samples were taken every 7 days starting on June 29 (the seedling stage on the 19th day after sowing) until September 27.

In the event of heavy rainfall, the samples were taken on the third day after rainfall to avoid the peak of N_2O emission flux caused by the increase of soil water filled porosity (WFPS). The sampling was conducted from 8:00 to 10:00 a.m., and 30 mL of gas samples (Scheer et al., 2008) were taken at 0, 10, and 20 min after all the covers on the static box were tightened, and the time was recorded with a stopwatch. After sampling, all covers were unscrewed for air circulation in the static box to ensure the normal growth of the crops.

The gas samples collected were analyzed in the laboratory using gas chromatography (model of gas chromatograph: Shimadzu 2010plus). The measuring conditions were as follows: the temperature of the electron capture detector (ECD) detector was 250 °C, the column temperature was 50 °C, the carrier gas was high-purity argon methane gas, and the flow rate was 40 mL min^{-1}. The gas emission flux was calculated using *Equation 1*.

$$F = \frac{M}{V} \times h \times \frac{d_c}{d_t} \times \frac{273}{(273+t)} \qquad \text{(Eq.1)}$$

where F is the emission flux of the gas (mg $(m^2 \cdot h)^{-1}$); M is the molecular weight of the gas (g); V is the volume of 1 mol gas in the standard state (L); h is the net height of the sampling box (m); $\frac{d_c}{d_t}$ is the rate of change of gas concentration in the sampling box, 273 is the gas state path constant, and t is the average temperature in the sampling box (°C).

Soil inorganic nitrogen

Soil samples were taken from 0-20 cm to determine the amount of nitrate and ammonium nitrogen. For monocultures, the samples were taken between rows of crops, while for intercropping, the samples were taken between adjacent rows of maize and legume strips, and each sampling point was repeated three times. The fresh soil was extracted with a KCI solution with a concentration of 2 mol L^{-1}. The ratio of soil to water was 1:5. The samples were agitated at 200 R min^{-1} at a constant temperature for 30 min on an oscillator and then filtered. The collected filtrate was determined using an AA3 flow analyzer (SEAL Analytical) (Anning et al., 2021). The formula used to calculate the soil inorganic nitrogen is as follows:

$$SIN = d \times BD(N_1 + N_2) \qquad \text{(Eq.2)}$$

where SIN is the soil inorganic nitrogen (kg ha^{-1}); d is the soil depth, taking 20 cm; BD is the soil bulk density (1.51 g cm^{-3}); and N_1 and N_2 are nitrate nitrogen and ammonium nitrogen in the 0-20 cm soil layer, respectively.

Soil water filled porosity

The moisture content of the soil was measured using the gravimetric method, and the water filled pore space (WFPS) was calculated using *Equation 3:*

$$WFPS = \frac{VSWC}{(1-BD/PD)} \qquad \text{(Eq.3)}$$

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where *VSWC* is the volumetric soil water content (*VSWC* = soil mass water content × *BD*); *BD* was taken as an average value of 1.51 g cm^{-3}; and *PD* is the soil particle density, taking the value of 2.65 g cm^{-3}.

Soil temperature

During gas sampling, the soil temperatures at 0 and 10 cm were also measured near the static box using a Testo Mini Probe Thermometer, and the average of the two readings was taken.

The cumulative N_2O emissions and the global warming potential

The cumulative N_2O emissions during the whole growth period were estimated using the linear interpolation method as shown in *Equation 4:*

$$TN = \sum (F_{i+1} + F_i)/2 \times (t_{i+1} - t_i) \times 24 \times 10^{-5} \quad \text{(Eq.4)}$$

where *TN* is the total N_2O emissions in the whole growing season (kg ha^{-1}); F_{i+1} is the average N_2O emission flux of the current experiment (μ g $(m^2 \cdot h)^{-1}$); F_i is the average N_2O emission flux from the previous experiment (μ g $(m^2 \cdot h)^{-1}$); and $(t_{i+1} - t_i)$ is the interval between two successive experiments (Li et al., 2013).

Equation 5 was used to calculate the N_2O based global warming potential (Mehmood et al., 2019):

$$GWP\ (N_2O) = TN \times 265 \quad \text{(Eq.5)}$$

where *TN* is the cumulative N_2O emissions (kg ha^{-1}), and 265 is the global warming potential coefficient for N_2O (Stocker et al., 2013).

Statistical analysis of data

The data obtained from the experiments were statistically analyzed by Microsoft Excel, and the significance test was conducted using one-way ANOVA in Spss-23.0 software. The graphs were plotted using Origin Lab software 2018.

Results

Dynamic change characteristics of the soil moisture and temperature

Figure 5 shows the variation trend of water filled pore spaces (WFPS) and the soil temperature under different treatments. For the soil moisture, the soil WFPS of each treatment will peak after rainfall or irrigation; however, the WFPS was generally higher in the M120 treatment. The average WFPS in the M120 treatment was significantly higher than that in other treatments, except for M240, which was similar at ($P < 0.05$) (*Table 3*). In terms of the soil moisture, the average soil WFPS values of maize/legume intercropping (MS) and (MP) were significantly lower than those of monocultures of maize (M120 and M240). However, there was no significant difference in the WFPS between MS and MP nor between PP and SS as shown in *Table 3*.

For the soil temperature, the trend was similar across treatments; however, the general shape initially rose and then decreased with the crop's growth period. At the end of the growth period, the temperature dropped to the lowest level (*Fig. 5b*). The average soil temperature of the treatments are also shown in *Table 3*. Generally, there was no significant difference in the soil temperature between intercropping and monocultures.

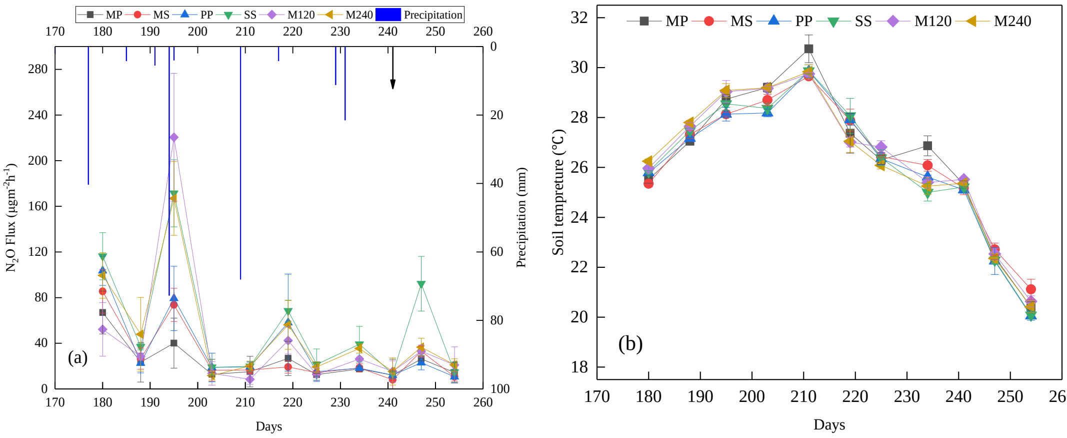

Figure 5. *Changes of the (a) water-filled pore space (WFPS) and (b) soil temperature in different treatments. MP = Maize/peanut intercrop, MS = Maize/soybean intercrop, PP = peanut monoculture, SS = Soybean monoculture, M120 = Maize monoculture (N = 120 kg/ha), M240 Maize monoculture (N = 240 kg/ha)*

Table 3. *The cumulative N_2O emissions, global warming potential, seasonal means of WFPS, temperature $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, and inorganic-N of the soils in different treatments during the trial period*

Treatment	**WFPS (%)**	**Temperature (^{0}C)**	**$N\text{-}NH_4^+$ (mg kg^{-1})**	**$N\text{-}NO_3^-$ (mg kg^{-1})**	**SIN (kg ha^{-1})**	***TN* (N_2O) (kg ha^{-1})**	***GWP* (N_2O) (kg ha^{-1})**
MP	44.50 ± 0.99c	26.35 ± 0.15a	3.25 ± 0.19a	7.21 ± 0.76bc	31.60 ± 2.50bc	0.41 ± 0.09c	109.63 ± 23.70c
MS	43.89 ± 1.33c	26.23 ± 0.05ab	3.31 ± 0.09a	6.07 ± 0.77c	28.32 ± 2.60c	0.50 ± 0.02b	132.41 ± 6.46b
PP	46.06 ± 2.51bc	26.03 ± 0.04b	3.20 ± 0.07a	7.70 ± 1.57bc	32.90 ± 4.72bc	0.59 ± 0.06b	155.61 ± 26.16b
SS	45.91 ± 2.11b	26.10 ± 0.07b	3.36 ± 0.22a	8.98 ± 1.48ab	37.26 ± 4.68ab	0.98 ± 0.14a	260.12 ± 36.81a
M120	51.00 ± 1.76a	26.32 ± 0.06a	3.34 ± 0.07a	6.57 ± 0.09c	29.91 ± 0.29c	0.79 ± 0.11a	209.29 ± 28.96a
M240	48.80 ± 2.19a	26.24 ± 0.08a	2.95 ± 0.03b	10.32 ± 1.09a	40.08 ± 3.30a	0.86 ± 0.21a	226.64 ± 55.85a

Different small letters in the same column indicate significant differences at the 0.05 level among treatments

Effects of the different planting patterns on the soil inorganic nitrogen

Table 3 shows the changes in the WPFS, temperature, ammonium, nitrate, inorganic nitrogen, total emissions, and global warming potential (GWP) within the 0-20 cm soil for each treatment. There was no significant difference in the amounts of ammonium in the 0-20 cm soil among treatments with the same amount of nitrogen application. The results of one-way ANOVA showed that the planting patterns had significant effects on the soil nitrate over the whole crop season ($P < 0.05$). The average soil inorganic nitrogen content of the MS treatment was 24.0% lower than SS, 5.3% lower than M120, and 29.3% lower than M240.

On the other hand, the average soil inorganic nitrogen content of the MP and PP treatments were statically similar to M120 but significantly ($P < 0.05$) lower than M240 by 21.1%. The average soil inorganic nitrogen content of the MS treatment was 10.4% lower than MP, and the average soil nitrate nitrogen content in the MS treatment was 15.9% lower than MP, although there were not significant differences in both parameters. The average soil nitrate nitrogen content in the MS treatment was 32.5% lower than SS and 41.2% lower than M240 at a significance level of 95%. The single factor analysis of variance showed that the planting pattern comparing monocultures and intercropping had a significant effect on the soil nitrate content of 0-20 cm in the whole growth period ($P < 0.05$).

Effects of different treatments on the soil N_2O emission flux and global warming potential

Figure 6 shows the dynamics of the N_2O emission fluxes. The peak value of N_2O was as a result of rainfall, which increased the soil WFPS. The graph indicates that the N_2O emission fluxes of each treatment had a peak value after rainfall. It can also be seen from *Table 3* that the average N_2O emission fluxes of the MS and MP treatments were lower than those of the other four treatments.

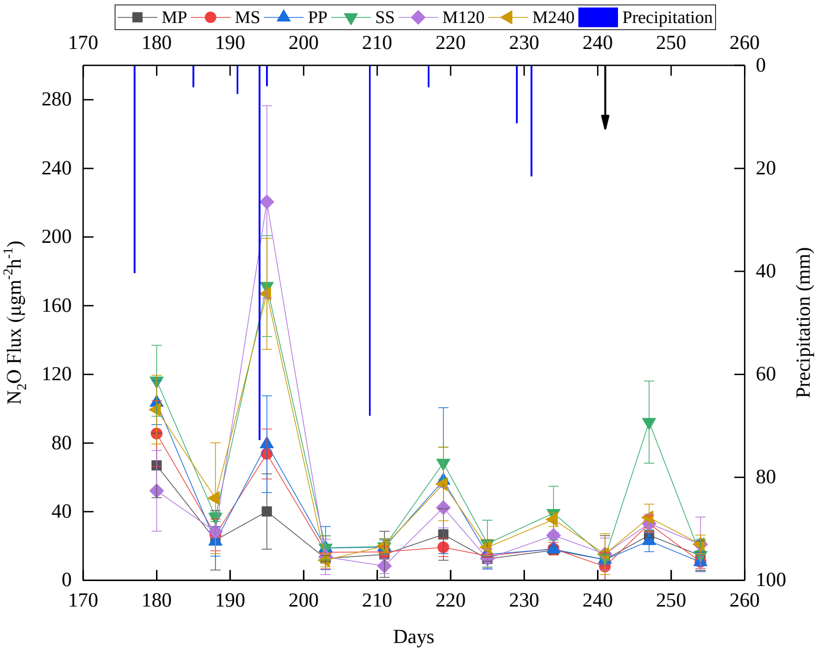

Figure 6. *Dynamics of the soil N_2O emission flux with different treatments. MP = Maize/peanut intercrop, MS = Maize/soybean intercrop, PP = peanut monoculture, SS = Soybean monoculture, M120 = Maize monoculture (N = 120 kg/ha), M240 = Maize monoculture (N = 240 kg/ha)*

Compared with M120, M240, and SS, the average N_2O emission flux of the MS treatment was significantly lower by 32.0%, 39.2%, and 47.4%, respectively ($P < 0.001$). Similarly compared with M120, M240, and PP, the N_2O flux from MP treatments was lower by 43.4%, 49.4%, and 29.6%, respectively. These results indicate that maize legume intercropping significantly reduced the N_2O emission flux of the soil. The difference in the N_2O emission flux between SS and PP was also significant.

From *Table 3*, the MS and MP treatments significantly reduced the cumulative N_2O emissions and global warming potential. The results of one-way ANOVA showed that there were significant differences in the N_2O emissions and global warming potential between MS, MP, and the other four treatments ($P < 0.001$); however, the differences

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among SS, M120, and M240 were not significant. Compared with M120, M240, and SS, the average cumulative emissions of the MS treatment were lower by 36.7%, 41.6%, and 49.1%, respectively. Compared with M120, M240, and PP, the average cumulative emissions of MS treatment were lower by 47.6%, 51.6%, and 29.5%, respectively, and the average cumulative emissions of the MS treatment were 20.8% higher than MP.

Therefore, the maize legume intercropping modes significantly reduced the cumulative N_2O emissions and global warming potential compared with the other monocultures. *Table 4* presents the Pearson correlation coefficients of soil moisture, inorganic nitrogen, and temperature as they affect the average N_2O emissions under different treatments. The correlation coefficients of the soil moisture, inorganic nitrogen, and average N_2O emission flux were different among different treatments; however, they were all positive correlations except for the inorganic nitrogen coefficients in the SS treatment. Additionally, the WFPS showed a consistent significant correlation with N_2O across all treatments.

Table 4. *Pearson correlation analysis between the N_2O, WFPS, soil temperature, and inorganic nitrogen*

Treatment	WFPS (%)	Inorganic N ($\mu g\ m^{-2}\ h^{-1}$)	Temperature (°C)
MP	0.708*	0.740**	-0.17 ^{ns}
MS	0.860**	0.579^{ns}	0.064 ^{ns}
PP	0.737**	0.233 ^{ns}	0.254 ^{ns}
SS	0.860**	-0.027 ^{ns}	0.135 ^{ns}
M120	0.664*	0.165 ^{ns}	0.262 ^{ns}
M240	0.772**	0.248 ^{ns}	0.285 ^{ns}

*Significance ($p < 0.05$), **significance ($p < 0.01$), and ns = no significance

Discussion

Effects of intercropping on N_2O emissions from farmland soil

Intercropping can improve the yield, land equivalent ratio, and resource utilization efficiency of crop systems (Meng et al., 2016). The research results of Chen et al. (2017) on a wheat/garlic intercropped population showed that intercropping increased the wheat yield, and (Huang et al., 2015) concluded that it could also significantly reduce the N_2O emissions from farmland soil in the North China Plain, which is consistent with the results of this study. The highest cumulative N_2O emissions in this study were from the soybean monoculture and maize treatments. The research results of Huang et al. (2019) reported the highest cumulative N_2O emissions from the monoculture of maize treatment which partly agrees with the results of this work.

This inconsistency in conclusions may be due to differences in the planting density, rate of nitrogen fertilizer applied, soil nutrient content, and crop variety in the soybean monoculture treatments of the two studies. In this study, the planting density of soybeans was higher, and the nitrogen application rate was lower; thus, the nitrogen fixation and nitrogen utilization capacity of the monoculture soybeans were changed, resulting in a difference in the soil N_2O emissions between the studies.

The authors in Dyer et al. (2012) also concluded that maize/legume intercropping could reduce greenhouse gas emissions from farmland soils. The average N_2O emission flux of maize/legume intercropping farmland was greater than in the monoculture of maize. After a comparative observation, we speculated that this phenomenon may be due to different planting varieties, the planting density, nitrogen use, and the proportion of Gramineae and leguminous crops in the intercropping. Therefore, it is necessary for continuous investigation of different types of intercropping patterns on greenhouse gas emissions to better understand the impacts on the soil carbon and nitrogen dynamics.

Intercropping may change the environmental factors related to soil N_2O production. In this study, the N_2O emissions of monoculture systems was 2.39 times that of intercropping, which may be caused by a higher soil moisture in the monocultures. Soil moisture supports the activity of nitrification and denitrification bacteria in the soil, promoting the formation of nitrate and ammonium, consequently, leading to a significant increase in the N_2O emission rate (Smith et al., 2003). There was a significant and positive correlation between the concentrations of nitrate and ammonium and the N_2O emission rate (Simojoki and Jaakkola, 2000; Avrahami and Bohannan, 2009). The WFPS of intercropping was significantly lower than that of the maize and soybean monocultures, which may be related to the root distribution of the crops in the intercropping system. The researchers in Gao et al. (2009), in a study of the crop root distribution in a maize/soybean intercropping system, found that most of the roots of maize and soybean were distributed in the 0–30 cm soil layer, and the maize roots in the 16–22 cm soil layer could extend laterally to the inter row of soybean strips.

As a result, the water consumption of monoculture system was much higher than that of intercropping. Therefore, the soil moisture status in the intercropping system was lower than that in the monoculture system, which affects the N_2O emissions. There was no significant difference in the soil temperature, nitrate nitrogen, ammonium nitrogen, and inorganic nitrogen between maize monocultures and intercropping with 120 kg ha^{-1} N application, and inorganic nitrogen was significantly lower than for the maize monoculture with 240 kg ha^{-1} N application. The maize monoculture produced higher N_2O emissions compared with the maize/legume intercropping even the N application was reduced to 120 kg ha^{-1}.

Analysis on influencing factors of N_2O emissions from farmland soil

It is generally understood that N_2O is produced in the process of nitrification and denitrification dominated by bacteria (Wunderlin et al., 2012; Zhao et al., 2017). The factors affecting soil microbial activities can directly or indirectly influence the production and emissions of N_2O gas from agricultural soils. These factors include the soil water filled pore spaces (WFPS), soil pH, electrical conductivity (EC) value, temperature, fertilizer use, farming system, and crop planting type (Tang et al., 2016). Soil moisture contents lower than 97% to 84% were found to have the highest correlation with N_2O emissions (Vejan et al., 2016).

However, the soil WFPS in this study were all lower than 84%–86% indicating that intercropping reduced the soil WFPS, which was a major factor in reducing the N_2O emission flux. At the end of the growth period, the amount of inorganic nitrogen in the 0-20 cm soil increased, but the N_2O emission rate decreased. This may be due to the decrease in soil temperature at about 20 ^{0}C. The decrease in temperature became the dominant factor affecting N_2O production, which was verified by Xie and Li (2005). Among the six different treatments in this study, there was no significant difference in the average temperature from the 0-20 cm soil of the intercropping treatments.

From the results, we deduced that the amount of nitrate nitrogen in the 0-20 cm soil was greater than that of ammonium nitrogen, indicating that the soil environment within the growth period was suitable for nitrification. Inorganic nitrogen is the direct substrate of nitrification-denitrification, and its concentration determines the production and emission process of N_2O (Bai et al., 2017; Liu et al., 2010). Thus, maize/legume intercropping significantly reduced the production and emissions of soil N_2O by reducing the level of soil inorganic nitrogen. From this study, there were significant differences found in the N_2O emissions between maize/peanuts and maize/soybeans.

The average cumulative emissions of the MS treatment were 20.8% higher than MP. However, there were no significant differences in the soil WFPS, inorganic nitrogen, or temperature between MS and MP. Therefore, the difference in gas emissions may be due to the variations in the rhizosphere microbial community caused by different crop species, which will affect the activity of the nitrification and denitrification bacteria (Vejan et al., 2016).

A study by Chen et al. (2018) found that maize/peanut intercropping increased the number of microflora involved in the nitrogen cycle, sulfur cycle, and other beneficial bacteria in the rhizosphere. These microflora promote more of the decomposition and reuse of carbohydrates in the maize/peanut treatments. The researchers also observed a significant reduction in the copies of various genes for denitrification. Similarly, Subbarao et al. (2012) reported that peanut plants released phytochemicals from the roots to inhibit the activities of soil nitrifying microorganisms. Therefore, the difference in the N_2O emissions between MS and MP in the current study is indicative of these findings.

In this study, we focused on the differences in N_2O emissions from cropland soils caused by cropping patterns. The main reason is that intercropping can change the micro-environment of a crop–soil system. Compared with a monoculture, intercropping can significantly affect the composition of the crop-root soil bacterial community, promote soil enzyme activity, and improve the soil nutrient utilization rate (Chen et al., 2018).

We also demonstrated that the intercropping mode had a significant effect on the soil water and heat status. The synergistic utilization of nitrogen in a crop system with the intercropping of cereal and legumes is an important approach to realizing high-efficiency in the utilization of nitrogen (Wang, 2015). Compared with monocultures, maize/legume intercropping improved the nitrogen uptake (Du et al., 2018; Dwivedi et al., 2015), thus, reducing the amount of inorganic nitrogen in the soil, forming a basis for reducing the N_2O emissions from farmland.

Conclusion

The results of this study revealed the contribution of legume intercropping with maize in the reduction of the environmental risks associated with the emissions of N_2O. This understanding will be helpful in ensuring the sustainable production of maize in the study area. Maize intercropping with a legume (peanut or soybean) significantly reduced the cumulative emissions of N_2O compared to the sole cropping of maize, peanuts, or soybeans.

The lowest cumulative emissions of 0.41 kg ha^{-1} were observed in the maize/peanut (MP) treatment, and this was significantly lower than the emissions of maize/soybean (MS). This is despite the fact that the WPFS, inorganic minerals, and nitrate were similar in both the MP and MS treatments. The difference could be attributed to the biological effects of peanut roots on nitrifying bacteria. As our study did not measure the mechanisms of the microbial community in the production of N_2O, this is suggested for further investigations of the best intercropping combinations to achieve higher sustainability in crop production.

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