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RESEARCH ARTICLE

Effect of organic amendments on yield-scaled N_2O emissions from winter wheat-summer maize cropping systems in Northwest China

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Abstract

The effect of dairy manure amendments to agricultural soil on the yield-scaled nitrous oxide (N_2O) emissions remains unclear. We hypothesize that an optimum ratio of dairy manure to synthetic fertilizers leads to large nitrogen use efficiency (NUE) and small yield-scaled N_2O emissions. The aims of this study were to (1) quantify the variations in the crop yields and N_2O emissions from winter wheat-summer maize cropping systems in Northwest China, (2) determine the responses of the NUE and yield-scaled N_2O emission to the ratio of organic materials to synthetic fertilizers, and (3) evaluate the relationship between the NUE and yield-scaled N_2O emissions. Field measurements were conducted within long- and short-term fertilization experiments between the years of 2014 and 2016. Treatments included synthetic fertilizers, synthetic fertilizers plus crop residues, and synthetic fertilizers plus dairy manure at both sites. The annual grain yields and N_2O emissions varied from 13.3 to 18.0 Mg ha^{-1} and from 1.3 to 3.6 kg N ha^{-1}, respectively, across the treatments. The yield-scaled N_2O emissions related negatively to the NUE, suggesting that agronomic aims of improving NUE are an effective approach to mitigate N_2O emissions. The ratio of organic materials to synthetic fertilizers was not a significant limit on the NUE and yield-scaled N_2O emissions. We conclude that organic amendments appeared to play a minor influence on the promotion of the NUE and N_2O mitigation.

Keywords Grain yield · Nitrogen use efficiency · Nitrous oxide · Dairy manure · Synthetic fertilizer

Introduction

Agricultural soils are a dominant source of nitrous oxide (N_2O) that contributes approximately 6% to global radiative forcing (IPCC 2014). Soil N_2O is primarily produced via microbial processes such as nitrification, denitrification, and nitrifier denitrification (Butterbach-Bahl et al. 2013). The relative importance of each process varies greatly across climate, soil types, and field managements, leading to large spatial and temporal variations in N_2O emissions (Berger et al. 2013; Gu et al. 2013, 2016; van Groenigen et al. 2015). Annual N_2O emissions have been shown to increase with nitrogen (N) input rates, especially so when the applied N exceeds the crop demand (Hoben et al. 2011; van Groenigen et al. 2010). Fertilizer managements display a large potential of N_2O mitigation (Smith et al. 2008; Zhang et al. 2013). Reducing the input rate of N fertilizers appears technically feasible, as the N use efficiency (NUE) by crops is approximately 40–70% on a global basis (Dobermann 2005). It is difficult to realize indeed because of the societal and political concerns on food security (van Groenigen et al. 2010; Zhang et al. 2013). Best management practices (BMPs) that aim to increase NUE without damaging food production are urgently required to mitigate N_2O emissions (Smith et al. 2008; Zhang et al. 2013).

As one of the BMPs, application of organic materials, such as crop residues and animal wastes, reduces the usage of synthetic N fertilizers and has been widely adopted with promising benefits to increase soil fertility and alleviate

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environmental deterioration (Diacono and Montemurro 2010; Zhang et al. 2015; Li et al. 2016). The effect of organic amendments on N_2O emissions has been investigated by various experiments in the field and in the laboratory. Some studies reported a positive impact, revealing that organic amendments enhanced N_2O production through denitrification by serving as an energy source for denitrifiers and favoring the development of anaerobic microsites within soil aggregates (Baggs et al. 2006; Chen et al. 2017; Cui et al. 2016). Others reported a negative impact, showing that application of organic materials mitigated N_2O emissions by stimulating microbial N assimilation and subsequently limiting the availability of N substrates for N_2O production through nitrification and denitrification (Wei et al. 2010; Huang et al. 2004; Frimpong and Baggs 2010). These inconsistent observations were mostly owing to the differences in the applied organic materials, fertilization history, and climate and soil conditions in respective studies (van Groenigen et al. 2015; Cui et al. 2016; Jain et al. 2016). A long-term fertilization experiment has shown that the quantity of the applied organic materials appeared critical in soil organic carbon (SOC) accumulation and subsequently impacted on N_2O emissions (Gu et al. 2017). It is reasonable to assume that the substitution ratio of synthetic fertilizers by organic materials is a key factor regulating N_2O emissions. This effect needs to be tested by conducting field experiments.

The yield-scaled N_2O emissions have been proposed as a suitable metric for the evaluation of N_2O mitigation by considering the crop productivity (van Groenigen et al. 2010). van Groenigen et al. (2010) observed a negative correlation between the NUE and yield-scaled N_2O emissions on the basis of a global meta-analysis but due to shortage of data, did not quantify the effect of organic amendments. A better understanding of the impacts of application of organic materials on NUE and yield-scaled N_2O emissions from cereal cropland is essential to develop strategies for N_2O mitigation. It has been well documented that long-term application of organic amendments promoted soil fertility and crop yields (Pimentel et al. 2005; Diacono and Montemurro 2010). However, few studies presented the NUE and yield-scaled N_2O emissions following long-term application of organic amendments. Such information is critical for evaluating the benefits of BMPs in a variety of management scenarios.

We measured the grain yields and N_2O emissions from winter wheat-summer maize cropping systems in Northwest China between the years of 2014 and 2016. The primary aims of this study were to (1) quantify the variations in the crop yields and N_2O emissions within short- and long-term fertilization experimental sites, (2) determine the responses of the NUE and yield-scaled N_2O emissions to the ratio of organic materials to synthetic fertilizers, and (3) evaluate the relationship between the NUE and yield-scaled N_2O emissions.

Material and methods

Experimental design

Field measurements were conducted within a short-term fertilization experiment (STFE) and a long-term fertilization experiment (LTFE) that were approximately 50 m in distance. The experimental sites were located at the "Chinese National Soil Fertility and Fertilizer Efficiency Monitoring Base of Loessial Soil" (34° 17′ 51″ N, 108° 00′ 48″ E), in Shaanxi Province, Northwest China. This region displays a typical warm temperate continental monsoon climate, with a mean annual temperature of 12.9 °C and mean annual precipitation of 560 mm. The silty loam soil is derived from loess material and belongs to Eumorthic Anthrosol in WRB-FAO classification (Yang et al. 2012).

The STFE was set up in 2014, with primary aims of quantifying the effect of substitution of synthetic fertilizers by organic materials on crop yields and N_2O emissions. Six treatments were (1) synthetic N, phosphorus (P), and potassium (K) fertilizers (S-NPK); (2) NPK plus winter wheat and maize residues from the plot (S-SNPK); and (3) 25%, (4) 50%, (5) 75%, and (6) 100% of the synthetic N substituted by dairy manure (S-25%M, S-50%M, S-75%M, and S-100%M) (Table 1). All treatments were arranged in a randomized complete block design (7.5 m × 4 m) with three replicates. The S-NPK treatment was added urea-N at a rate of 165 and 180 kg N ha^{-1} during the winter wheat and summer maize seasons, respectively, giving an annual N input rate at 345 kg N ha^{-1}. Synthetic calcium superphosphate-P and sulphate-K fertilizers were applied at a rate of 150 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} prior to winter wheat sowing. The S-SNPK treatment received the same amount of synthetic N, P, and K fertilizers as S-NPK and additional maize stalk (approximately 5.7 t dw ha^{-1} $year^{-1}$) in winter wheat season and winter wheat straw (approximately 7.9 t dw ha^{-1} $year^{-1}$) in maize season. The N, P, and K contents of maize stalk were 1.37%, 0.01%, and 3.85%, respectively. The N, P, and K contents of winter wheat straw were 0.42%, 0.03%, and 1.42%, respectively. All of the manure amendment treatments received the same N input rates as S-NPK on an annual basis, with corresponding ratio of synthetic N replaced by manure. In order to facilitate the farming operation, dairy manure was only applied in winter wheat season in each year. For example, dairy manure (approximately 11.9 t dw ha^{-1}, equaling 345 kg N ha^{-1}) was applied in winter wheat season and no N fertilizer was applied in maize season for S-100%M. The N, P, and K contents of the dairy manure were 2.9%, 1.3%, and 0.7%, respectively. The manure-amended treatments received less synthetic P and K fertilizers according to the manure substitution ratios. No synthetic P and K fertilizers were added to all treatments in maize season. All synthetic fertilizers and organic materials were surface applied and incorporated into the soil by rotary tillage

Table 1 Treatments and fertilizer application rates for the cropping system at the long- (LTFE) in 2014–2015 and short-term (STFE) sites in 2015–2016

Treatments	Wheat (kg ha^{-1})			Maize (kg ha^{-1})		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
L-NPK	165	132	82.6	187.5	56.4	93.8
L-SNPK	165 + 40.4	132 + 8.7	82.6 + 103.0	187.5	56.4	93.8
L-M1NPK	49.5 + 115.5	132 + 242.7	82.6 + 167.4	187.5	56.4	93.8
L-M2NPK	74.3 + 173.2	198 + 365.3	123.9 + 251.2	187.5	56.4	93.8
S-NPK	165	150	90	180	0	0
S-25%M	123.75 + 86.25	112.5 + 86.5	67.5 + 25.25	135	0	0
S-50%M	82.5 + 172.5	75 + 173	45 + 50.5	90	0	0
S-75%M	41.25 + 258.75	37.5 + 259.5	22.5 + 75.75	45	0	0
S-100%M	0 + 345	0 + 346	0 + 101	0	0	0
S-SNPK	165 + 78	150 + 1.7	90 + 266	180 + 33	0 + 5.5	0 + 135

L-NPK, L-SNPK, L-M1NPK, and L-M2NPK indicate the treatments that received synthetic fertilizers of N, P and K, NPK plus crop straw, and NPK plus low and high levels of dairy manure, respectively, in winter wheat season at the long-term fertilization experimental (LTFE) site. S-NPK, S-SNPK, S-25%M, S-50%M, S-75%M, and S-100%M indicate the treatments that received synthetic fertilizers of N, P and K, and NPK plus winter wheat and maize residues from the plot, 25%, 50%, 75%, and 100% of the synthetic N substituted by dairy manure, respectively, at short-term fertilization experimental (STFE) site. The numbers before and after "+" represent the amount of N, P, and K from synthetic fertilizers and organic material, respectively

(approximately 20 cm in depth) before winter wheat sowing. In maize season, the fertilizers were manually incorporated into the soil (approximately 20 cm in depth) between plants along a row about 1 month after seeding. In particular, the field measurements of this study were conducted from October 2015 to September 2016. The winter wheat was sowed and fertilized on October 10, 2015, and was harvested on June 6, 2016. The summer maize was sowed, fertilized, and harvested on June 9, July 5, and September 29, 2016, respectively. General soil properties (0–20 cm) of each treatment during the experimental period refer to Table 2.

The LTFE commenced in 1990, with primary aims of quantifying the long-term effects of organic amendments on crop yields and soil properties (Gu et al. 2017). Four treatments were synthetic N, P, and K fertilizers (L-NPK), NPK combined with crop residues (L-SNPK), and NPK combined with low (L-M1NPK) and high (L-M2NPK) levels of dairy manure (Table 1). The L-NPK treatment received synthetic N, P, and K fertilizers at 165 kg N ha^{-1}, 132 kg P_2O_5 ha^{-1}, and 83 kg K_2O ha^{-1}, respectively, during the winter wheat season, and synthetic N, P, and K at 187.5 kg N ha^{-1}, 56 kg P_2O_5 ha^{-1}, and 94 kg K_2O ha^{-1}, respectively, during the summer maize season. The L-SNPK treatment received the same quantity of synthetic fertilizers as the L-NPK treatment in both crop seasons and an additional maize stalk from the plot (ranging from 2.6 to 6.0 t dry weight ha^{-1} year^{-1} over the experimental years, with a mean 4.4 t dry weight ha^{-1} year^{-1}) prior to the winter wheat sowing. The L-M1NPK treatment was given 30% of N from synthetic fertilizers as L-NPK, and the remaining 70% of N from dairy manure. The L-M2NPK treatment involved 1.5-

Table 2 Soil properties (0–20 cm) at the long-term fertilization experiment (LTFE) site in 2014 and the short-term fertilization experiment (STFE) site in 2015

Treatments	Bulk density (g cm^{-3})	SOC (g C kg^{-1})	Total N (g N kg^{-1})	Total P (g P kg^{-1})
L-NPK	1.50	10.3	1.21	1.06
L-SNPK	1.42	12.1	1.39	1.17
L-M1NPK	1.40	15.8	1.75	1.54
L-M2NPK	1.35	17.6	1.96	2.25
S-NPK	1.29	8.1	2.01	0.96
S-25%M	1.31	7.8	2.03	1.00
S-50%M	1.28	7.9	1.98	0.90
S-75%M	1.24	10.0	2.26	0.93
S-100%M	1.21	9.7	2.20	1.00
S-SNPK	1.23	8.4	2.00	0.93

SOC, soil organic carbon

fold as much applications of synthetic N and dairy manure as L-M1NPK (Table 1). The application methods of synthetic fertilizers and organic materials were the same as at the STFE site. All treatments were arranged in a randomized complete block design (14 m × 14 m). In particular, the field measurements of this study were conducted from October 2014 to September 2015. The winter wheat was sowed and fertilized on October 9, 2014, and was harvested on June 6, 2015. The summer maize was sowed, fertilized, and harvested on June 7, July 17, and October 2, 2015, respectively. General soil properties (0–20 cm) of each treatment during the experimental period refer to Table 2.

At both sites, flood irrigation was conducted one to four times during each crop season, depending on the pattern of precipitation. All aboveground crop residues were removed after harvest except for the S-SNPK and L-SNPK treatments. The herbicides and pesticides were applied to control weeds and insect, respectively.

N_2O flux measurement

Gas fluxes were measured using static chambers, with three replicates for each treatment. Stainless steel base frames (50 cm × 50 cm × 15 cm) were inserted 10 cm into the soil prior to sowing and fixed in the field throughout the cropping season. The stainless steel chambers (50 cm × 50 cm × 50 cm) had styrofoam coating. Their height was increased to 100 cm by adding an open-top chamber when plants were taller than 50 cm.

Gas fluxes were measured once a week in general and up to four times a week following the fertilization and irrigation for at least 2 weeks. Gas samples were always taken between 09:00 and 11:00 (local time) on each sampling date. A chamber was put on the frame and sealed with water for 45 min, during which four samples (40 mL) were manually pulled into polypropylene syringes at an interval about 15 min. The N_2O concentrations were analyzed using a gas chromatograph equipped with an electron capture detector (GC-ECD, model 7890B, Agilent Technologies, USA). The reproducibility of the GC-ECD at 369 ppbv was 1.6 ppbv (standard deviation, $n = 12$). Accordingly, the detection limit of our measurement system was estimated at 0.8 g N ha^{-1} day^{-1}.

Crop yield measurement

The aboveground biomass of winter wheat and summer maize was manually harvested at maturity over an area of 2 m × 4 m and 5 m × 4 m, respectively, for each plot, giving three replicates for each treatment. Grains were collected by hand and were dried at 60 °C to a constant weight.

Data process and statistical analysis

The N_2O flux was calculated from a linear regression of the N_2O concentrations with time during the chamber deployment. The fluxes were accepted at the correlation coefficient (R^2) above 0.73 ($P > 0.1, n = 4$); otherwise, they were regarded as invalid and set to zero. Approximately 5% of the flux calculations were invalid, mostly occurring when N_2O emissions were within the detection limit. Cumulative N_2O emission (kg N ha^{-1}) was estimated by linear interpolation between data points by assuming the measured flux representing the daily flux.

The sum of wheat and maize yields (Mg ha^{-1}) was used to calculate the NUE (kg kg^{-1}) and yield-scaled N_2O emissions (mg N kg^{-1}), as follows:

$$\mathrm{NUE} = \mathrm{Grain\ yield}/\mathrm{N_{input}} \tag{1}$$

$$\mathrm{Yield{-}scaled\ N_2O\ emissions} = \mathrm{Cumulative\ N_2O\ emission}/\mathrm{Grain\ yield} \tag{2}$$

where N_{input} denotes the total N input rate (kg N ha^{-1}).

To quantify the effects of organic amendments, relative differences (RD, %) of the NUE and yield-scale N_2O emissions were calculated, as follows:

$$\mathrm{RD} = \left(\mathrm{V_{organic}}{-}\mathrm{V_{synthetic}}\right)/\mathrm{V_{synthetic}} \times 100\% \tag{3}$$

where $V_{organic}$ and $V_{synthetic}$ are the values of NUE and yield-scale N_2O emissions with organic amendments and synthetic fertilizers, respectively, at the same experimental site.

Statistical analysis was conducted using the SPSS software package (version 20.0, Beijing, China). One-way analysis of variance (ANOVA) was used to test the treatment effects on measured variables, with the least significant difference (LSD) at 5%. Curve fitting was conducted using SigmaPlot 12.5 (Systat Software Inc. San Jose, CA). The linear-plateau model was used to fit the responses of crop yield to N rate, while the linear model was used to fit the responses of NUE, N_2O and yield-scaled N_2O emissions to N rate, and yield-scaled N_2O emissions to NUE.

Results

N_2O emissions

At the LTFE site, the N_2O fluxes increased immediately following the fertilizer application and irrigation in the maize season, with the highest peak up to 601 g N ha^{-1} day^{-1} in the L-M2NPK treatment (Fig. 1a). Large N_2O fluxes occurred within 1–3 weeks after the fertilizer application in the winter wheat season, with the highest peak up to 113 g N ha^{-1} day^{-1} in the L-SNPK treatment. Except these peaks, the N_2O fluxes

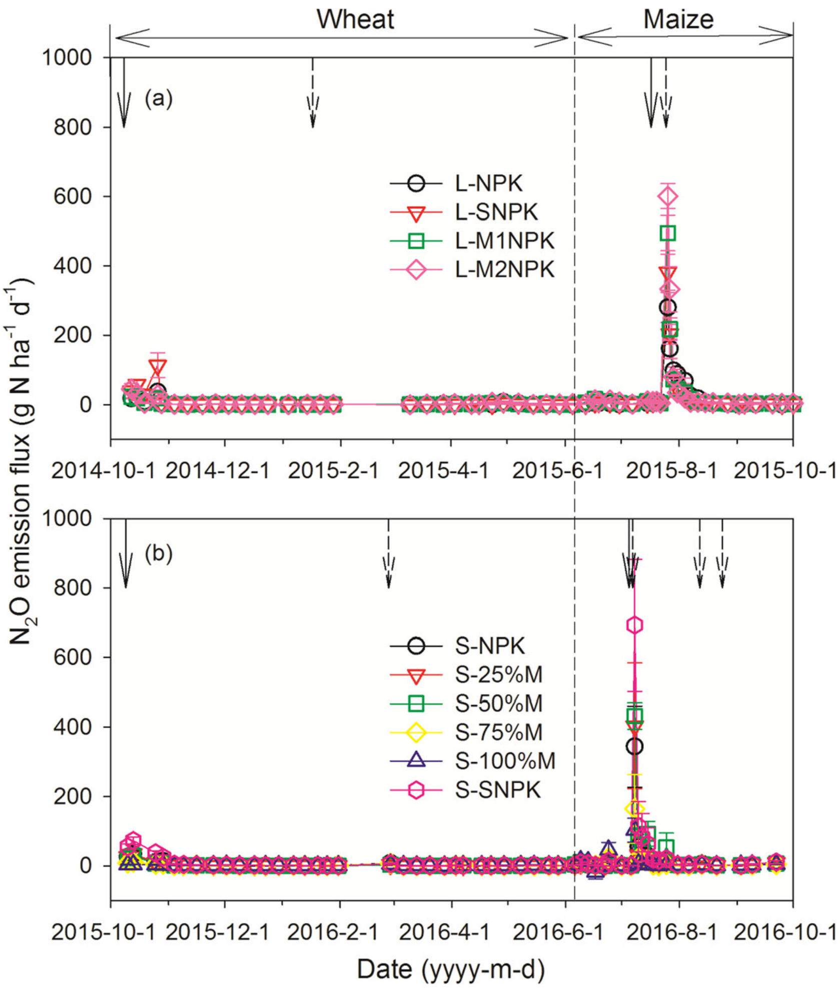


Fig. 1 Seasonal dynamics of nitrous oxide (N_2O) emission from the winter wheat-summer maize rotation system under different treatments at (a) the LTFE site in 2014–2015, and (b) the STFE site in 2015–2016. The solid and dashed arrows indicate the fertilization and irrigation, respectively. The vertical bars are standard errors (*n* = 3)

were generally below 3 g N ha^{-1} day^{-1}. Annual N_2O emissions ranged from 2.6 to 3.6 kg N ha^{-1} across the treatments (Table 3). Emissions of N_2O did not differ significantly among the treatments except that the emission from the L-M2NPK treatment was 38% larger ($P < 0.05$) than that from the L-NPK treatment.

At the STFE site, the N_2O fluxes responded mostly to the fertilization across the treatments (Fig. 1b). The highest peaks,

Table 3 Annual N_2O emission, grain yield, nitrogen use efficiency (NUE), and yield-scaled N_2O emission for the wheat-maize rotation system under different treatment at the long- (LTFE) and short-term (STFE) sites

Treatments	N_2O (kg N ha^{-1})	Grain yield (Mg ha^{-1})	NUE (kg kg^{-1})	Yield-scaled N_2O emission (mg N kg^{-1})
L-NPK	2.6 ± 0.1b	13.3 ± 0.3a	37.6 ± 0.9a	196 ± 5b
L-SNPK	3.4 ± 0.4ab	14.5 ± 1.0a	36.9 ± 2.6a	237 ± 18a
L-M1NPK	2.9 ± 0.2ab	13.9 ± 0.3a	39.4 ± 0.9a	209 ± 5ab
L-M2NPK	3.6 ± 0.3a	15.0 ± 0.0a	34.5 ± 0.2a	240 ± 2a
S-NPK	2.0 ± 0.1bc	15.5 ± 0.3 cd	45.0 ± 0.9bc	130 ± 8ab
S-25%M	2.1 ± 0.3bc	16.4 ± 0.6bcd	47.5 ± 1.7abc	126 ± 22ab
S-50%M	2.3 ± 0.2ab	17.0 ± 0.5abc	49.3 ± 1.4ab	135 ± 12ab
S-75%M	1.4 ± 0.0c	17.7 ± 0.5ab	51.1 ± 1.3a	77 ± 3b
S-100%M	1.3 ± 0.1c	15.3 ± 0.6d	44.3 ± 1.7c	84 ± 6b
S-SNPK	2.9 ± 0.5a	18.0 ± 0.4a	39.5 ± 0.9d	165 ± 32a

The data are mean ± standard error (*n* = 3). Different letters within the same column indicate significant difference between treatments ($P < 0.05$) for each experimental site up to 73 and 692 g N ha^{-1} day^{-1} during the winter wheat and summer maize seasons, respectively, occurred always in the S-SNPK treatment. Except these peaks, the N_2O fluxes were generally below 5 g N ha^{-1} day^{-1}. Annual N_2O emissions ranged from 1.3 to 2.9 kg N ha^{-1} (Table 3). The emission from the S-SNPK treatment was 45–123% larger ($P < 0.05$) than that from the S-NPK, S-75%M, and S-100%M treatments.

Grain yield, NUE, and yield-scaled N_2O emissions

At the LTFE site, the grain yield and NUE ranged from 13.3 to 15.0 Mg ha^{-1} and from 34.5 to 39.4 kg kg^{-1}, respectively, with non-significant differences across the treatments (Table 3). The yield-scaled N_2O emissions ranged from 196 to 240 mg N kg^{-1}. The yield-scaled N_2O emissions of the L-SNPK and L-M2NPK treatments were 21–22% larger ($P < 0.05$) than those of the L-NPK treatment. The difference in the yield-scaled N_2O emissions was not significant between the L-M1NPK and L-NPK treatments.

At the STFE site, the grain yield ranged from 15.5 to 18.0 Mg ha^{-1} with non-significant differences across the treatments except that the data of the S-75%M and S-SNPK treatments were 14–16% larger ($P < 0.05$) than those of the S-NPK treatment (Table 3). The NUE ranged from 39.5 to 51.1 kg kg^{-1}. The NUE of S-75%M and S-SNPK treatments was 14% larger ($P < 0.05$) and 12% lower ($P < 0.05$), respectively, than that of the S-NPK treatment. The yield-scaled N_2O emissions ranged from 77 to 165 mg N kg^{-1} with non-significant differences across the treatments. The lowest and highest yield-scaled N_2O emissions occurred in S-75%M and S-SNPK treatments, respectively.

Relationship between NUE and yield-scaled N_2O emissions

A negative correlation was fitted between the yield-scaled N_2O emissions against NUE in North China ($R^2 = 0.37$, $P < 0.001$, Fig. 2) and in this study ($R^2 = 0.78$, $P < 0.001$, Fig. 2), most likely as a result of the competition for N substrates between crop and soil microbes. This correlation was significant when all data points in our field experiments were pooled together, because it increased the range of variations in the NUE and yield-scaled N_2O emissions, compared with that of the individual sites. The yield-scaled N_2O emissions decreased from 240 to 77 mg N kg^{-1} when the NUE increased from 34.5 to 51.1 kg kg^{-1}.

Effects of organic amendments on NUE and yield-scaled N_2O emissions

The straw amendments appeared to reduce the NUE at both of the STFE and LTFE sites, with RD below − 1% (Fig. 3a). The manure amendments increased and reduced the NUE across the treatments, with RD ranging from − 8.2 to 13.6%. Altogether, organic amendments did not display a significant impact on NUE, with a mean RD of 3.5% which did not differ significantly with zero ($P > 0.05$). Additionally, a clear trend was lacking for the RD in NUE against the ratio of organic materials to synthetic fertilizers.

The straw amendments appeared to increase the yield-scaled N_2O emissions at both of the STFE and LTFE sites, with RD above 20% (Fig. 3b). The manure amendments increased the yield-scaled N_2O emissions at the LTFE sites but increased and reduced the yield-scaled N_2O emissions across the treatments at the STFE sites, with RD ranging from − 40.3 to 27.0%. Altogether, organic amendments did not display a significant impact on the yield-scaled N_2O emissions, with a mean RD of − 5.4% which did not differ significantly with zero ($P > 0.05$). Additionally, a negative correlation was fitted to the RD in the yield-scaled N_2O emissions against the ratio of organic materials to synthetic fertilizers (Fig. 3b). This finding suggests that organic amendments may favor N_2O mitigation at a substitution ratio above 45%.

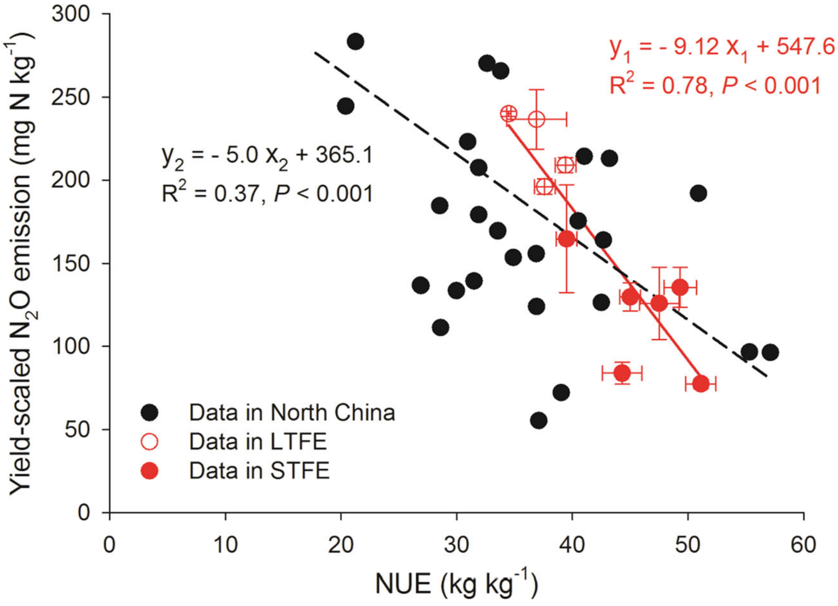
Discussion

Variations in grain yields

Grain yields varied from 13.3 to 18.0 Mg ha^{-1} across the treatments at both of the STFE and LTFE sites (Table 3), which were within the wide range (varying from 8.4 to 20.4 Mg ha^{-1}) in North China (Table 4). Although the correlation was not significant at field scale, a clear linear-plateau regression was fitted between the grain yields and N application rates in North China (Fig. 4a), indicating that a maximum grain yield could be achieved at an optimum annual N input rate of approximately 314 kg N ha^{-1}. This finding coincides with previous reports showing that grain yields responded to the N application rates following a linear-linear, linear-plateau, or Mitscherlich-type exponential model, and the value of inflection point varied moderately from 320 to 370 kg N ha^{-1} in different regions (Zhang et al. 2015; Wang et al. 2014; Cui et al. 2013; Zhu and Zhang 2010). It was evident that the N input above the inflection point led to no increase in grain yield. Approximately 75% of the observations in the dataset were based on crop field receiving N fertilizer above the optimum N input rate, denoting an intensive overuse of N fertilizers for food production in these regions.

Additionally, organic amendments further contributed to the variations in grain yields. The crop yields of the combined application of organic manure with synthetic fertilizer were 4.5 to 16.1% higher, though not significant ($P > 0.05$), than those of the application of synthetic fertilizer alone at both of the STFE and LTFE sites. This was consistent with previous studies, demonstrating that combinations of synthetic

Fig. 2 The negative correlation between the yield-scaled N_2O emission and nitrogen use efficiency (NUE) under winter wheat-summer maize cropping systems in North China. Vertical and horizontal bars indicate standard errors (n = 3). The solid and dashed lines represent linear regression for the data in this study and all data in North China, respectively



fertilizers and organic manure had the ability to improve the crop yields in wheat-maize systems by 5.6 to 12.4% (Diacono and Montemurro 2010; Zhao et al. 2010; Duan et al. 2014; Kong et al. 2014; Zhang et al. 2016). Similarly, application of organic amendments tended to increase grain yield by 8.1% (ranging from − 6.9 to 42.9%) on average in North China (Table 4). This non-significant effect might be related to the over-application of synthetic fertilizers that provided more nutrients than crop demand.

It is of interest that the grain yields at the STFE sites were 17% larger ($P < 0.05$) than those at the LTFE sites despite lower SOC content at the STFE sites (Table 2). The most

Fig. 3 The responses of the RD (relative difference) in (a) the nitrogen use efficiency (NUE) and (b) yield-scaled N_2O emission to the ratio of organic materials to synthetic fertilizers. The linear regression was RD in yield-scaled N_2O emission with ratio of organic materials to synthetic fertilizers for the data in this study

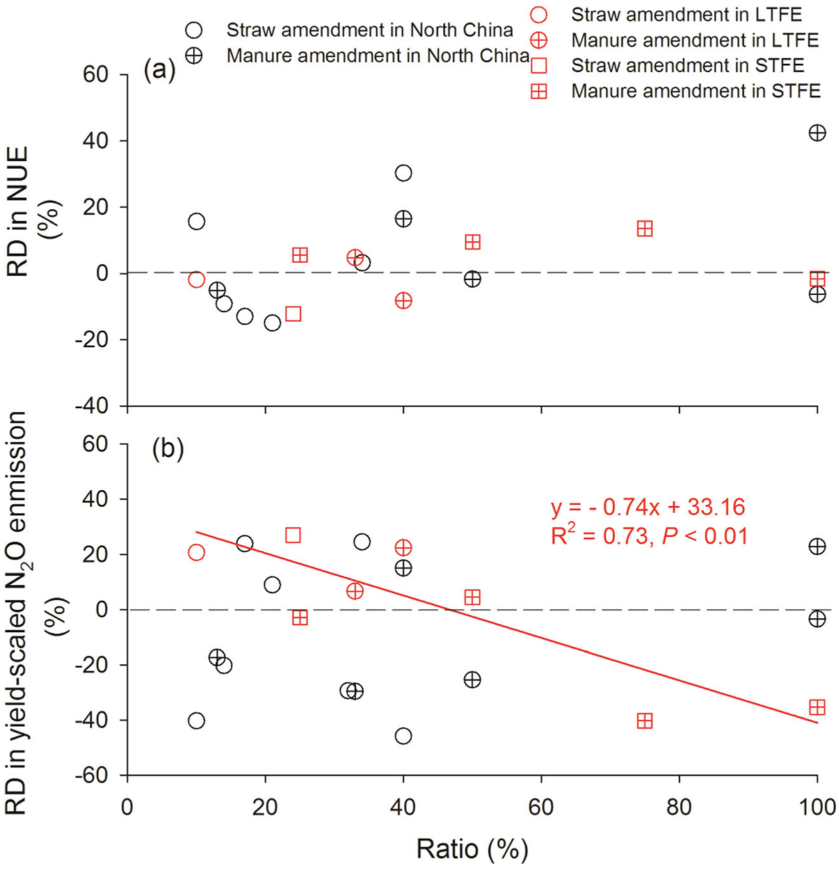


Table 4 Summary of N_2O emissions, yield, and related indicates for winter wheat-summer maize rotation systems in North China

Year	Rain (mm)	Irrigation (mm)	SOC (g C kg^{-1})	TN (g kg^{-1})	N source	N rate (kg ha^{-1})	Ratio (%)	N_2O (kg N ha^{-1})	Yield (Mg ha^{-1})	Reference
2008–2009	562	380–550	11.3	1.1	Urea	390	0	3.5	13.2	Liu et al. (2011)
					Urea + straw	390	34	4.5	13.6	
2009–2011	556	610	14.7	0.9	Urea	380	0	2.2	12.8	Hu et al. (2013)
					Urea + straw	478.5	21	2.5	13.7	
2004–2007	615	156	6.4	0.7	Urea + manure	300	50	1.6	12.7	Cai et al. (2013)
			8.0	0.9	Manure	300	100	2.1	12.1	
			5.4	0.6	Urea	300	0	2.8	13.0	
2011–2012	543	500	18.8	0.4	Urea	600	0	2.2	16.1	Shi et al. (2013)
		375			Urea + straw	295	32	1.6	16.3	
2008–2010	627	590	10.3	1.1	Urea	600	0	4.6	13.4	Yan et al. (2013)
2008–2010	586	480	10.3	1.1	Urea + DP	420	0	3.7	13.7	Yan et al. (2015)
					Urea + DP + manure	420	13	2.9	13.0	
					Urea	390	0	3.5	13.2	
2012–2013	836	0	8.8	0.8	Manure	280	100	2.0	12.0	Liu et al. (2016)
					NH_4HCO_3	280	0	1.1	8.4	
					NH_4HCO_3 + manure	280	40	1.5	9.8	
					NH_4HCO_3 + straw	280	40	0.8	10.9	
2013–2015	620	0	8.1	1.0	Urea	375	0	1.7	11.8	Zhang et al. (2017)
					Urea + straw	435.8	14	1.4	12.5	
2013–2015	620	210	8.1	1.0	Urea + straw	375	0	0.8	13.9	Chen et al. (2017)
2008–2009	543	0	6.3	0.4	Urea	600	0	2.2	16.1	Nyamadzawo et al. (2017)
					Urea + manure	286	33	1.6	16.3	
2012–2014	615	80	7.4	0.9	Urea	400	0	3.9	20.4	Niu et al. (2017)
2011–2014	500–700	90	7.1	0.8	Urea	560	0	2.8	11.5	Huang et al. (2017)
					Urea + straw	676	17	3.6	12.0	
2009–2010	586	0	10.3	1.1	Urea	420	0	2.8	13.4	Yao et al. (2017)
					Urea + straw	420	10	1.9	15.5	

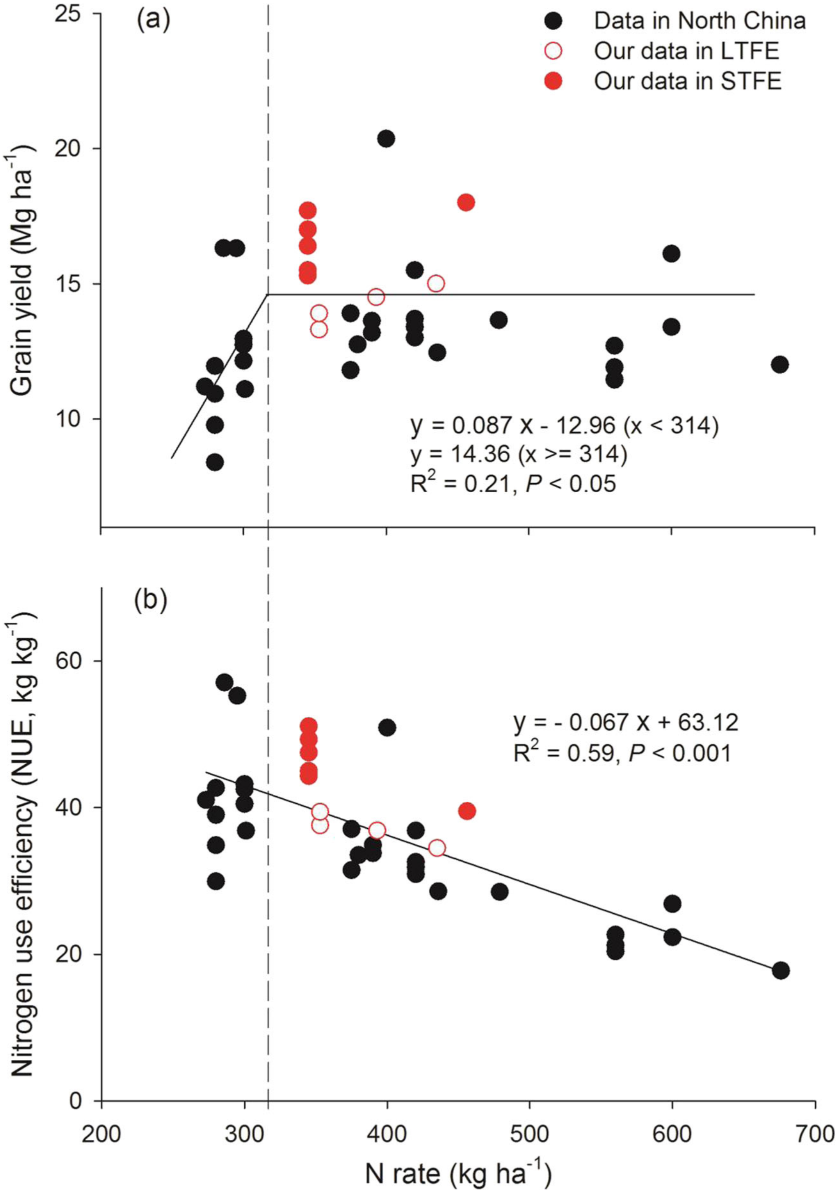
SOC and TN are soil organic carbon and total nitrogen contents within 0–20 cm soil layer, respectively. DP is diammonium phosphate

plausible explanation for this inter-annual variation was that the combination of organic materials and synthetic fertilizers boosted crop yields in the short term and enhanced soil organic matter in the long term (Palm et al. 2001; Dawe et al. 2003; Diacono and Montemurro 2010; Zhang et al. 2012; Yan et al. 2012). Multiple-year measurements are therefore required to fill the data gap.

Variations in nitrogen use efficiency

The NUE varied from 34.5 to 51.1 kg kg^{-1} across the treatments in this study, which were well above the mean of the large range in North China (ranging from 17.8 to 57.1 kg kg^{-1}) (Fig. 4b). Compared with the application of synthetic fertilizer alone, the effect of combination of organic materials and synthetic fertilizers were not significant in the long-term experiments, whereas 75% synthetic fertilizer substituted by manure significantly increased NUE by 13.6% in the short-term experiments. Duan et al. (2014) reported that 70% synthetic fertilizer substituted by organic significantly improved NUE by 6% in North and Central China, while higher proportion of organic fertilizers input was needed in Southern China. The difference was mostly originating from high precipitation, low soil cation exchange capacity, and soil acidity in Southern China, and more organic materials helped adjust soil physical and synthetic properties and achieve efficient utilization of fertilizers. Our measurements showed that the ratio of organic materials to synthetic fertilizers had no significant effect on

Fig. 4 The responses of the grain yield (a) and nitrogen use efficiency (NUE) (b) to N application rate of winter wheat-summer maize cropping system in North China. The dashed line indicates the optimum N application rate of 314 kg N ha^{-1} $year^{-1}$



NUE (Fig. 3a). This was consistent with the results by Li et al. (2016), showing that the NUE did not differ significantly between manure amendments (with the ratio of organic materials to synthetic fertilizers ranging from 25 to 100%) than that of synthetic fertilizer alone. Other studies showed that the NUE of the treatments with 10–20% synthetic N substituted by organic fertilizers was higher than or equal to that of the treatments with synthetic fertilizers applied alone (Meng et al. 2009; Zhou 2012). Similarly, in North China, the organic amendments had no effect on NUE (Fig. 3a). Nonetheless, the availability of N substrates in organic fertilizers rather than the ratio of organic N to total N applications appeared critical to determine whether the organic amendments can improve NUE.

Dobermann et al. (2000) reported that the N fertilization management was better or had low rate of N application rate at NUE above 60 kg kg^{-1}. However, all the values of NUE in this study as well as in North China were below this critical value despite that the N application rate was within the appropriate range. This finding suggests that more efforts are required to improve the potential grain yields (Zhang et al. 2008). A negative regression between the NUE and N application rate (Fig. 3b) reinforced the idea that the overuse of N fertilizer led to small NUE (Ju et al. 2009). The NUE was 42 kg kg^{-1} at the optimum N input rate, which was within a range of 40–70 kg kg^{-1} proposed by Dobermann (2005).

Variations in N_2O emissions

Annual N_2O emissions varied from 1.3 to 3.6 kg N ha^{-1} across the treatments in this study, which were within the variation in

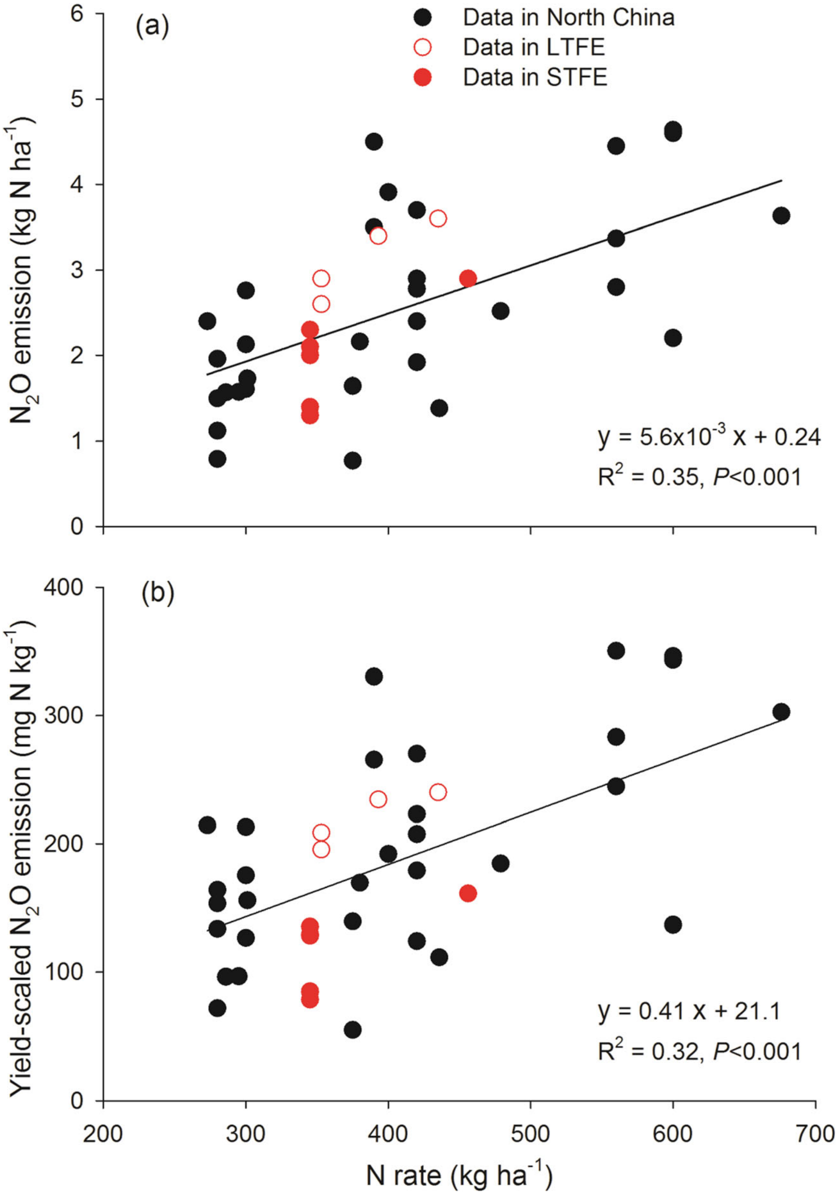


Fig. 5 The responses of N_2O emissions (a) and yield-scaled N_2O emissions (b) to N application rates in winter wheat-summer maize cropping system in North China

North China (ranging from 0.8 to 4.6 kg N ha^{-1}, Table 4). Non-significant differences were observed between the N_2O emissions with organic amendments and that with single synthetic fertilizer application at both of the long-term and short-term experiments (Table 3), most likely due to the large C:N ratio of the organic materials (70 and 13 for straw and manure, respectively, in this study) favoring microbial N assimilation. Similar results were also reported within a long-term fertilization experiment by Wei et al. (2010). Several studies reported that the combination of organic manure and synthetic fertilizers significantly reduced N_2O emissions in agriculture soils (Baggs et al. 2006; Chen et al. 2017; Yao et al. 2017) while others reported that organic amendments stimulated N_2O emissions (Sarkodie-Addo et al. 2003; Guardia et al. 2016; Cheng et al. 2017). The contradictory results were probably dependent on the differences in organic manure characteristics, climate, and soil texture which in turn controlled the major source of N_2O through nitrification or denitrification (Berger et al. 2013; Gu et al. 2013; van Groenigen et al. 2015).

A linear relationship was found between the N input rates and N_2O emissions in North China (Fig. 5a). The specific emission factor (0.56%), as derived from the linear correlation, was lower than the IPCC (2006) default value (1%) and the mean value (0.65%) in China (Zheng et al. 2004). This small emission factor was properly a result of the relatively low SOC content at regional scale (ranging from 5.4 to 18.8 g C kg^{-1}; Table 2) that limited denitrification (Cui et al. 2012). We propose this emission factor to calculate N_2O emissions from cereal croplands in North China; otherwise, the regional emissions could be overestimated.

The yield-scaled N_2O emissions varied from 77 to 240 mg N kg^{-1} across the treatments in this study, which were within the range (varying from 55 to 346 mg N kg^{-1}) in North China (Fig. 5b). A significant linear correlation was fitted for the yield-scaled N_2O emissions against N application rates (Fig. 5b). This regression, with N application rates always above 280 kg N ha^{-1}, could be an extension of a U-shaped curve in van Groenigen et al. (2010) which was fitted between the yield-scaled N_2O emissions and N application rates below 300 kg N ha^{-1}.

Organic amendments displayed a minor influence on yield-scaled N_2O emissions in North China, with RD averaged 2% (ranging from − 46 to 24%) which did not differ significantly to zero ($P > 0.05$) (Fig. 3b). It had been reported that application of organic manure increased SOC content, favored the formation of an anaerobic environment by consuming soil oxygen, and thus promoted denitrification and N_2O emissions (Davidson 1991; Smith et al. 2003). However, the effect of application of organic manure on N_2O emission was not significant in this study, mainly due to the relatively low SOC content in this region (Table 4). Application of organic manure stimulated the growth and reproduction of soil heterogeneous microorganisms, fixed free ammonium ions, and inhibited the activity of soil nitrifying microorganisms (Recous et al. 1990). At the same time, nitrification was the major source of N_2O emission in the area (Wei et al. 2009; Cui et al. 2012), while strong denitrification occurred following irrigation in maize season but quickly diminished with the decline of soil water content (Gu et al. 2017). A clear trend was lacking between the RD of yield-scaled N_2O emissions and the ratio of organic materials to synthetic fertilizers in North China, regardless a significant correlation at field scale in our experiments (Fig. 3b).

Implication of this study

The results did not support the primary hypothesis because the ratio of organic materials to synthetic fertilizers played a potent role in regulating the NUE and yield-scaled N_2O emissions (Fig. 3). Nonetheless, the negative correlations between the yield-scaled N_2O emission and NUE were significant in our field experiments ($P < 0.001$, Fig. 2) and when the data in North China were pooled together ($P < 0.001$, Fig. 2). This is a clear evidence that agronomic aims of improving crop NUE are the most effective means to mitigate N_2O emissions (van Groenigen et al. 2010). Our results show that the organic amendments appeared not an effective practice to increase the NUE in North China. Other approaches, such as the root-zone N management strategy (Cui et al. 2013) and the comprehensive management for soil and crop (Chen et al. 2011, 2014), have been developed to enhance the NUE. Their potential to mitigate N_2O emissions needs to be further evaluated.

Conclusion

The yield-scaled N_2O emissions related negatively to the NUE at both field and regional scales, suggesting that agronomic aims of improving NUE are an effective approach to mitigate N_2O emissions. However, organic amendments did not promote the NUE and N_2O mitigation in the studied region, regardless a wide range of ratio of organic materials to synthetic fertilizers. The effect of other management practices needs to be further evaluated.

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