Nitrous oxide emissions in a winter wheat – summer maize double cropping system under different tillage and fertilizer management

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Abstract

An accurate estimation of nitrous oxide (N_2O) emission from 110 million ha of upland in China is essential for the adoption of effective mitigation strategies. In this study, the effects of different tillage practices combined with nitrogen (N) fertilizer applications on N_2O emission in soils were considered for a winter wheat (*Triticum aestivum* L.) – summer maize (*Zea mays* L.) double cropping system. Treatments included conventional tillage plus urea in split application (CTF1), conventional tillage with urea in a single application (CTF2), no-tillage with straw retained plus reduced urea in a split application (NTSF1) and no-tillage with manure plus reduced urea in a split application (NTMF1). The amounts of N input in each treatment were 285 and 225 kg N/ha for wheat and maize, respectively. Both NTSF1 and NTMF1 were found to reduce chemical N fertilizer rates by 33.3% (wheat) and 20% (maize), respectively, compared to CTF1 and CTF2. N_2O emissions varied between 3.2 (NTSF1) and 9.9 (CTF2) kg N_2O -N/ha during the wheat season and between 7.6 (NTSF1) and 14.0 (NTMF1) kg N_2O -N/ha during the maize season. The yield-based emission factors ranged from 21.9 (NTSF1) to 60.9 (CTF2) g N_2O -N/kg N for wheat and 92.5 (NTSF1) to 157.4 (NTMF1) g N_2O -N/kg N for maize. No significant effect of the treatments on crop yield was found. In addition to reducing production costs involved in land preparation, NTSF1 was shown to decrease chemical fertilizer input and mitigate N_2O emissions while sustaining crop yield.

Keywords: Conventional tillage, no-tillage, nitrous oxide emission, urea, straw retained, manure

Introduction

Agriculture is estimated to contribute 36% of the total anthropogenic N_2O emission in China, with approximately 0.275 Tg N_2O -N released per annum from cropland in 1990s (ADB-GEF-UNEP, 1998). However, there are large uncertainties associated with these estimates related to the cropping system, soil type, timing and method of fertilizer application and climate (Snyder *et al.*, 2009). China has approximately 140 million ha of cropland, of which 110 million ha and 30 million ha are in the form of upland-crop land and paddy fields, respectively. Although nitrous oxide emissions from rice fields and rice-winter wheat rotation systems in southern and south-eastern China have been well

studied (Liu *et al.*, 2010), only a few studies have directly addressed N_2O emissions from fertilized upland soils.

The North China Plain (NCP) is one of China's major breadbaskets, with annual double cropping of winter wheat and summer maize forming the dominant cropping system in the area. A relatively large rate of chemical N fertilizer (~256–450 kg N/ha) is usually applied in a cropping sequence (He *et al.*, 2009). N application in excess of crop uptake capacity is a driver of increased N_2O emission. Residual nitrogen left in the soil from the previous cropping season can exacerbate the effect on N_2O flux (Kim *et al.*, 2013). The large N application rates in double cropping will inevitably cause an increase in area-based N_2O emission. At present, however, there is limited information available concerning the timing of N_2O emissions during the winter period in the NCP (Holst *et al.*, 2008).

Increasingly no-tillage (NT) has been adopted in the NCP, and the practice has been found to increase N_2O loss from soils compared with conventional tillage (CT) (Mackenzie

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et al., 1998). However, other studies have suggested that NT can decrease or produce negligible effects on N_2O loss (Elmi *et al.*, 2003). These contrasting results may originate from differences in factors, such as water-filled porosity, soil temperature and texture, levels of available carbon and nitrate, and the distribution of microbial populations and potential enzyme activities (Linn & Doran, 1984). The effect of NT on N_2O loss during crop rotations in the NCP has seldom been investigated.

Urea application during NT is seeing increased use in combination with straw or manure amendments. NT and other CT practices have the potential to enrich the soil organic carbon pool by increasing residue and manure inputs and decreasing C loss (Baker *et al.*, 2006). However, these practices may also enhance N_2O emission, which offsets gains in soil C storage (Robertson *et al.*, 2000; Wang & Dala, 2006). Therefore, it is necessary to include the N in straw and manure as a crop nutrient to reduce the use of mineral N fertilizer in the NT systems. There is currently a lack of integrated assessments of these combined applications (i.e. NT with N management), and a limited understanding of their role in reducing N_2O loss and agronomical feasibility in the NCP.

Materials and methods

Site description

A field experiment was conducted from October 2009 to June 2010 near Dezhou City (36°56'N, 116°36'E) of Shandong Province, China beginning 2009.10–2010.6, 7 yr after initiation of the long-term NT study in October 2003. The soil in this area is classified as a Calcaric fluvisol, formed from the sediments from the Yellow River. The soil is calcareous, alkaline and rich in phosphorus and potassium. The surface soil has a silt loam texture (sand, 13%; silt, 65%; clay, 22%), according to the USDA classification system, a pH value of 7.9 and contains 29 g organic C/kg and 3.1 g total N/kg in the top 20 cm. Winter wheat is usually planted in October, while summer maize is planted in June. The mean annual precipitation in this area is 585 mm, most of which occurs during the rainy months of July–August.

Field experiment design

The variation in N_2O emissions was determined in the field under different tillage and fertilizer N practices commonly used in the NCP. Four combinations of tillage and N treatments were included in the study. All treatments consisted of equivalent total N inputs, namely 285 kg N/ha for winter wheat and 225 kg N/ha for summer maize, with N originating from different sources. Under the CT system, urea was divided into applications with 95 kg N/ha as the

fertilizer and the remaining as supplementary fertilizer for wheat and then for maize during the early growth period (CTF1). For the second CT system, urea was applied in a single pre-plant application before sowing wheat and then surface applied at planting for maize (CTF2). Basal fertilizer for wheat was incorporated via rototiller in the top 20 cm of soil for both CT treatments. Under the NT system, the N sources included maize straw (95 kg N/ha) and urea (190 kg N/ha) for wheat, with wheat straw (45 kg N/ha) and urea (180 kg N/ha) for maize (NTSF1). Other treatments consisted of poultry manure (95 kg N/ha) and urea (190 kg N/ha) for wheat with the manure (45 kg N/ha) and urea (180 kg N/ha) for maize (NTMF1). In the winter wheat system, maize straw and poultry manure were surface applied in early spring. Urea was surface applied in two equal parts in late October and early spring of the following year for winter wheat and as a single application during the early growth period for maize. The poultry manure contained 22.5 g/kg total N and 4.1 g/kg alkali-hydrolysis N. The mean total N contents were 7.5 and 9.6 g/kg for winter wheat straw and maize straw, respectively. For the NTSF1 treatment, the maize straw was applied at 10 Mg/ha in late March for winter wheat and at 6.0 Mg/ha for wheat straw after sowing maize. For the NTMF1 treatment, poultry manure was applied at 4.2 Mg/ha in late March for winter wheat and at 2 Mg/ha after sowing maize. Details of field operations during the experiment are shown in Table 1. Three replicates of each treatment were established using a randomized block design with each plot measuring 7.5×40 m.

Winter wheat was seeded in rows at an interval of 20 cm and a rate of 180 kg/ha on 28 October, 2009. Maize was planted at a density of 66 400 plants per ha in rows at an interval of 60 cm without tillage on 27 June 2010. Winter wheat was irrigated using a surface flooding method with a water meter on 3 December 2009, 28 March 2010 and 15 April 2010 (75 mm water on each occasion).

Fluxes of N_2O were measured using the static chamber method following Chang *et al.* (1998). A field measurement was conducted once or twice per month during the period from December to March, and once per week during the period from March to November. Two chambers were installed per plot to provide duplicate measurements. Sampling events lasted for 30 min (total of 4 samples taken every 10 min) and were conducted between 09:00 and 11:30 h (Beijing time). The concentration of N_2O in samples was determined using a gas chromatograph HP-4890D equipped with an electron capture detector. Daily average N_2O fluxes and cumulative N_2O fluxes for cropping seasons were calculated (Lemke *et al.*, 1999). Soil temperature at a depth of 10 cm was measured in triplicate at each sampling occasion using digital thermometers. Soil bulk density samples were also collected 1–2 times per month from each plot using cores (6 cm tall by 6 cm diameter) collected from

Table 1 Crops grown and fertilizers used during the experiment in the rotation year (October 2009–June 2010)

Treatment	Winter wheat						Summer maize			
	1st application		2nd application		3rd application		1st application		2nd application	
	kg N/ha	Date	kg N/ha	Date	kg N/ha	Date	kg N/ha	Date	kg N/ha	Date
CTF1	95 (Urea)	25/10	190 (Urea)	28/03					225 (Urea)	12/07
CTF2	285 (Urea)	25/10					225 (Urea)	29/06		
NTSF1	95 (Urea)	25/10	95 (Maize straw)	15/03	95 (Urea)	28/03	45 (Wheat straw)	28/06	180 (Urea)	12/07
NTMF1	95 (Urea)	25/10	95 (Manure)	27/03	95 (Urea)	28/03	45 (Manure)	28/06	180 (Urea)	12/07

CTF1, conventional tillage in combination with mineral N in split application; CTF2, conventional tillage with mineral N in a single dose;

NTSF1, no-tillage with straw retained and addition of reduced mineral N in split application; and NTMF1, no-tillage with additions of manure and reduced mineral N in split application.

the 0–20 cm layer. Soil bulk densities, along with water content measurements were used to calculate the water-filled pore space (WFPS) (Soil Survey, 1996). The concentrations of NH_4^+ and NO_3^- were also measured (Buchkina *et al.*, 2010). Daily ambient air temperature and precipitation data were collected from a meteorological station located 300 m away from the experimental site.

Data analysis

Differences in seasonal fluxes and cumulative emissions of N_2O among treatments were evaluated using single-factor analysis of variances (ANOVA). Multiple comparisons of means were conducted with a Fisher's protected least significant difference (LSD) test ($P < 0.05$). In addition, the relationships between N_2O emissions and environmental variables (WFPS, soil inorganic N content and air temperature) were evaluated using Spearman correlation analysis.

Results and discussion

Nitrous oxide emission over the winter wheat season

Nitrous oxide emissions increased following addition of urea to the soil in autumn (Figure 1a) and reach a peak in early November. Several weak peaks in emissions were also measured in April after irrigation. The largest emission rates of N_2O from the CTF2 treatment were measured between November and March of the next year. The N_2O flux rates were highly variable and ranged from 16.5 to 1049.7 $\mu\text{g N}_2\text{O-N/m}^2 \text{ h}^{-1}$ across all treatments. In this preliminary study, the average flux rate was between 52.2 and 57.1 $\mu\text{g N}_2\text{O-N/m}^2 \text{ h}^{-1}$.

During autumn (late October–November) the mean flux rates for different treatments increased in the order of $\text{CTF2} > \text{CTF1} > \text{NTMF1} > \text{NTSF1}$ (Table 2). Emission of N_2O from CTF2 was greater than that from CTF1 due to

the larger quantity of urea applied in CTF2. N_2O emissions from CT treatments were larger than those measured from either NT treatment.

During the winter period (December–March), the N_2O emission rates varied between 24.4 and 246.3 $\mu\text{g N}_2\text{O-N/m}^2 \text{ h}^{-1}$, with mean emission rates following the same trend as rates calculated for autumn months (Figure 1a; Table 2). The soil temperatures at a depth of 10 cm ranged from -3.1 to -1.1 °C in four of six sampling events (Figure 2), indicating that denitrification and nitrification activities of micro-organisms produced N_2O in frozen soils (Tenuta & Sparling, 2011).

In spring (April–mid-June), the average N_2O emission under NTMF1 was significantly greater than that of the other three treatments, likely due to organic C stimulating denitrification (Table 2). Fertilizer application following irrigation in mid-April resulted in a short-lived pulse of N_2O in all treatments except NTMF1 (Figure 1a) and also coincided with the decrease in soil inorganic N content (Figure 1c,d). However, the peak in N_2O emissions from NTMF1 after irrigation on 15 April extended into late-April and was greater than losses from urea application. These phenomena may be attributed to denitrification of easily degradable C compounds and the development of anaerobic microsites following manure application (Chadwick *et al.*, 2000).

Over the entire growing period of wheat, mean N_2O flux rates varied significantly among the four treatments in the order of $\text{CTF2} > \text{CTF1} > \text{NTMF1} > \text{NTSF1}$ (Table 2). As expected, CT treatments showed larger N_2O emissions than NT treatments. Greater cumulative fluxes were recorded in winter than in autumn and spring in all treatments except NTMF1. From late autumn to March of the next year, the percentage of N_2O emissions after application of one-third of N accounted for 61.0, 91.4, 60.4 and 42.2% of seasonal accumulated losses for CTF1, CTF2, NTSF1 and NTMF1 treatments, respectively. Therefore, the autumn–winter period was shown to be the

Figure 1 Environmental variables and N₂O emissions during the rotation year. (a) N₂O emissions (mean $\pm$ standard error, $n = 3$). (b) Precipitation (Vertical arrows denote time of irrigation) and soil water-filled pore space (SWFS, 0–20 cm depth) (mean $\pm$ standard error, $n = 3$). (c) Soil mean NO₃-N and (d) NH₄-N concentrations (mean $\pm$ standard error, $n = 3$). CTF1, CTF2, NTSF1 and NTMF1 refer to conventional tillage with mineral N in split application, conventional tillage with mineral N in a single dose, no-tillage with straw retained and reduced mineral N in split application, and no-tillage with additions of manure and reduced mineral N in split application.

largest contributor to N₂O emissions from fertilized wheat systems in the NCP.

The temporal pattern of N₂O emissions tended to correspond with that of NO₃-N levels in the upper 0–20 cm (Figure 1a,c). However, no correlation was found between daily N₂O flux rates and soil NO₃⁻ content over the same depth range (Table 3). Daily N₂O flux (log-transformed) was positively correlated with soil NH₄⁺ content in the upper 0–20 cm except with NTMF1. During peaks in N₂O emission, NH₄-N content decreased, while NO₃-N content increased, suggesting that nitrification had occurred after urea application (Figure 1c,d). Daily N₂O fluxes (log-transformed) for CTF1, NTSF1 and NTMF1 plots were positively correlated with WFPS at 0–20 cm except with the CTF2 treatment (Table 3). N₂O emission from CTF2

plots was mainly controlled by the amount of urea, which was nonlinearly related to increasing N input (Kim *et al.*, 2013).

N₂O flux rates were negatively correlated with air temperature for all treatments, with a significant correlation found only for treatment CTF2 (Table 3). Peak emissions of N₂O with the CTF2 treatment occurred at lower air temperatures of 3.7–8.4 °C (autumn) while lower N₂O emissions were observed with higher air temperatures (14.0–25.8 °C) from April to June.

Nitrous oxide emissions during summer maize season

During the maize season, N₂O emissions increased following fertilizer application, reached a peak within 1 week and then gradually declined over the following week (Figure 1a). The

Table 2 Seasonal emission rates ($\mu\text{g N}_2\text{O-N/m}^2 \text{ h}^{-1}$) and cumulative flow ($\text{kg N}_2\text{O-N/ha}$) of N_2O emission from treated plots

Treatment	Winter wheat				Summer maize
	Autumn (Oct–Nov)	Winter (Dec–Mar)	Spring (Apr–June)	Total	Total
N_2O emission rates					
CTF1	130.4b	76.1b	111.8b	101.8b	493.2b
CTF2	472.8a	149.9a	61.8c	200.1a	471.4b
NTSF1	63.4d	48.3c	63.8c	60.0d	318.3c
NTMF1	76.6c	52.6c	157.5a	96.3c	593.0a
LSD _{0.05}	13.2	4.7	6.0	4.2	46.0
Cumulative flow					
CTF1	1.19Bb	2.21Ab	2.17A (0.18)b	5.6b	11.9b
CTF2	4.31Aa	4.35Aa	1.20B (0.17)c	9.9a	10.8b
NTSF1	0.58Cd	1.40Ad	1.24B (0.08)c	3.2d	7.6c
NTMF1	0.70Cc	1.53Bc	3.06A (0.08)a	5.3c	14.0a
LSD _{0.05}	0.12	0.14	0.12	0.2	1.1

Means in the same column followed by the same lower case letter and means in the same row followed by the same capital letter are not significantly different. LSD_{0.05} is the values of 5% L.S.D. for multiple comparisons. The values in parentheses are the LSD_{0.05} for multiple comparisons between autumn, winter and spring. LSD, least significant difference; CTF1, conventional tillage with mineral N in split application; CTF2, conventional tillage with mineral N in a single dose; NTSF1, no-tillage with straw retained and reduced mineral N in split application; and NTMF1, no-tillage with additions of manure and reduced mineral N in split application.

Figure 2 Air temperature and soil temperatures (10 cm depth) during observation period.

extremely large N_2O emissions only lasted for approximately 7 days. The cumulative N_2O losses from sowing to mid-August accounted for 92.9, 90.7, 92.0 and 93.7% of the total N_2O emissions for CTF1, CTF2, NTSF1 and NTMF1, respectively. Liu *et al.* (2011) also found that high N_2O emissions occurred for 41 days after fertilizer application in July.

Peak values of N_2O emissions for the treatments were 4049.5, 4310.8, 2993.9 and 5682.8 $\mu\text{g N}_2\text{O-N/m}^2 \text{ h}^{-1}$ for CTF1, CTF2, NTSF1 and NTMF1, respectively. These

values are comparable to a previously reported value of 5516 $\mu\text{g N}_2\text{O-N/m}^2 \text{ h}^{-1}$ in a cropped soyabean system (Ciampitti *et al.*, 2008). During the time period of post-rainfall N_2O peaks, WFPS were approximately 68.5% for CTF2 and 82.5% for the other three treatments plots (Figure 1b), respectively. Greater soil water content in upland soils usually restricted aeration and resulted in larger denitrification rates, as large values of WFPS together with the addition of N fertilizers tend to stimulate the microbial denitrifiers (Davidson, 1991).

N₂O emissions (log-transformed) for the four treatments were positively correlated with soil NO₃-N and NH₄-N in the surface layer (Table 3). However, soil NO₃-N concentrations measured 1 week after urea surface application were relatively small (ca. 26.3 mg NO₃-N/kg¹ in soil for CTF2 and 40 mg NO₃-N/kg in soil for the other three treatments) (Figure 1c). These results indicate that N₂O emissions are more likely to depend on soil N turnover rather than mineral N pool size under dry–wet cycles during the summer season (Harrison & Webb, 2001).

Different treatments produced significantly different mean N₂O emission rates and cumulative N₂O emissions (Table 2). The cumulative N₂O emissions from NTMF1 were 17.6, 29.6 and 84.2% greater than those from CTF1, CTF2 and NTSF1, respectively. Several other factors also produced greater N₂O emission in the NTMF1 plots. The addition of available C with manure increased denitrification of NO₃⁻ and NT with manure application also lengthened the period of N₂O emission by the reduction of urea or loss of NO₃⁻ through surface runoff. The smaller N₂O emissions observed under NTSF1 may have several causes, such as a decrease in urea application resulting in a decrease in N₂O loss potential or immobilization of N following the addition of fresh wheat with a high C/N ratio.

Table 3 Spearman correlation coefficients (*R*) and *P* values (*P*) for N₂O production and soil variables (0–20 cm) and average air temperature (AA)

Treatment		NO ₃ -N	NH ₄ -N	% WFPS	AA
Winter wheat season					
CTF1	<i>R</i>	−0.11	0.73	0.61	−0.29
	<i>P</i>	0.82	0.06	< 0.01	0.25
CTF2	<i>R</i>	0.23	0.96	0.32	−0.51
	<i>P</i>	0.61	< 0.01	0.20	0.03
NTSF1	<i>R</i>	−0.14	0.91	0.50	−0.29
	<i>P</i>	0.76	< 0.01	0.04	0.25
NTMF1	<i>R</i>	0.55	0.43	0.47	−0.07
	<i>P</i>	0.20	0.34	0.04	0.79
Maize season					
CTF1	<i>R</i>	0.88	0.762	0.19	0.38
	<i>P</i>	0.02	0.08	0.54	0.20
CTF2	<i>R</i>	0.77	0.995	0.03	0.25
	<i>P</i>	0.07	< 0.01	0.91	0.40
NTSF1	<i>R</i>	0.83	0.85	0.28	0.31
	<i>P</i>	0.04	0.03	0.36	0.31
NTMF1	<i>R</i>	0.77	0.85	0.16	0.47
	<i>P</i>	0.07	0.03	0.60	0.10

Spearman correlation analysis was performed using logarithm-transformed data of N₂O flux and untransformed data of water-filled pore space (WFPS), and untransformed data of N₂O flux and NO₃-N and NH₄-N contents and air temperature observations. Treatments CTF1, CTF2, NTSF1 and NTMF1 are the same as in Table 1.

Yield-based N₂O emission factors

The amount of N emitted as N₂O/kg from wheat and maize grains was calculated for each season using grain yield and grain N concentration (Pelster *et al.*, 2011). Yield-based N₂O emissions ranged from 21.0 to 60.9 g N₂O-N/kg N exported in grains for wheat and 92.5–157.4 g N₂O-N/kg N exported in grains for maize (Table 4). The larger values for maize in the current study may be attributed to greater N₂O losses and smaller N uptake due to rainy and cloudy days encountered during the maize grain-fill period. The emissions for maize were greater than the values of 6.6–22.7 g N₂O/kg N exported in maize grain reported by Pelster *et al.* (2011), but comparable to values of 50.7–134.7 g N₂O/kg N exported in maize grain in the Beijing area (Liu *et al.*, 2003). Similar to seasonal cumulative N₂O emissions, the yield-based N₂O emissions displayed significant differences between treatments with NTSF1 producing the lowest emissions among treatments for both wheat and maize seasons.

There was no marked effect of treatment on wheat and maize yield or grain N uptake (Table 4). This suggests that the 27.45% reduction in urea application rates (33.3% reduction for wheat and 20% for maize) did not affect the crop yields. Rather the reduction in urea application resulted in a decrease in N₂O emissions of 38.29 and 47.83% for NTSF1 compared to CTF1 and CTF2, respectively. The decrease in urea input and increase in fertilizer efficiency along with the decreased production costs of land preparation under no-tillage represent a significant monetary savings to farmers. However, according the values of the

Table 4 Effect of treatment on crop yield (kg/ha, at 86% dry matter), grain N uptake (kg/ha) and yield-based N₂O emission (g N₂O-N/kg grain N)

Treatment	Grain yield	Grain N uptake	Yield-based N ₂ O emission
Winter wheat season			
CTF1	6582.3	150.1	39.4b
CTF2	6772.0	162.3	60.9a
NTSF1	6445.0	153.9	21.0c
NTMF1	6617.3	169.4	31.3bc
LSD _{0.05}	ns	ns	11.49
Summer maize season			
CTF1	6858.9	77.7	154ab
CTF2	7257.2	89.4	123bc
NTSF1	7549.2	82.9	92.5c
NTMF1	7522.6	90.8	157.4a
LSD _{0.05}	ns	ns	32.1

Means in the same column followed by the same letter are not significantly different, and LSD_{0.05} is the value of 5% L.S.D. for multiple comparisons. Treatments CTF1, CTF2, NTSF1 and NTMF1 are the same as in Table 1. LSD, least significant difference.

yield-based N_2O emissions, CTF2 for wheat and NTMF1 for maize are expected to decrease. To avoid this decrease, results from this study show that farmers should consider applying manure only in the winter wheat season and straw in the maize season. Given that a large percentage of applied N was lost to ammonia volatilization and nitrate leaching following high nitrogen input in the NCP (Huang *et al.*, 2011), the use of NTSF1 should be encouraged as the best management practices (BMP), as this treatment reduces N_2O emissions without affecting crop yield.

Conclusions

Several peak emissions were associated with fertilizer application for wheat in autumn and maize from mid-July to early August. The percentage of N_2O emissions after application of one-third of N ranged from 42.2% for NTMF1 to 91.4% for CTF2 during the winter period, while approximately 90.7–93.7% of the total N_2O emissions for the four treatments occurred during maize sowing from late-June to mid-August. N_2O emissions varied from 3.2 (NTSF1) to 9.9 (CTF2) kg N_2O -N/ha during the wheat season and from 7.6 kg N_2O -N/ha for NTFS1 to 14.0 kg N_2O -N/ha for NTMF1 during the maize season. There was no significant effect of treatment on crop yields. The yield-based emission factors ranged from 21.9 (NTSF1) to 60.9 (CTF2) g N_2O -N/kg N exported in wheat grains and from 92.5 (NTSF1) to 157.4 (NTMF1) g N_2O -N/kg N exported in maize grains. As expected, the practice of retaining crop residue together with a reduced urea rate under no-till (NTSF1) was shown to significantly mitigate N_2O emissions while sustaining crop yield, in turn reducing production costs. NTSF1 treatment should therefore be encouraged in this region of China.

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