Journal of Soils and Sediments (2020) 20:3825–3834
https://doi.org/10.1007/s11368-020-02711-2

SOILS, SEC 1 • SOIL ORGANIC MATTER DYNAMICS AND NUTRIENT CYCLING • RESEARCH ARTICLE

Effect of various doses of 3,4-dimethylpyrazole phosphate on mineral nitrogen losses in two paddy soils

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Received: 30 April 2020 / Accepted: 2 July 2020 / Published online: 14 July 2020

Abstract

Purpose Nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) has been widely proposed to reduce nitrogen (N) loss and improve N availability in paddy soil. However, little knowledge exists regarding the optimum dose of DMPP required for inhibiting nitrification in different soil types.

Materials and methods In undisturbed soil columns under greenhouse conditions, dynamics of ammonium (NH_4^+–N) and nitrate (NO_3^-–N) in floodwater and leachate, and ammonia (NH_3) volatilization were studied in two paddy soils (hydragic and gleyed), amended with urea-N at 180 N kg/ha with DMPP applied at 0, 0.45, 0.675, and 0.90 kg/ha (0.25%, 0.375%, and 0.5% of urea-N, respectively). The source of DMPP was Entec® 46 (46% urea-N and DMPP at 0.5% of urea-N) that was mixed with pure urea (fertilizer mixture).

Results and discussion DMPP application rates and soil types significantly influenced NH_4^+–N and NO_3^-–N concentrations in floodwater and leachate; however, DMPP application rates did not significantly impact NH_4^+–N concentrations in floodwater. Results indicate that concentrations of both NH_4^+– N and NO_3^-–N in leachate and floodwater were peaked between 10 and 20 days after fertilizer application. Increased DMPP application rates increased floodwater and leachate NH_4^+–N concentrations, while significantly decreasing NO_3^-–N concentrations in floodwater and leachate, with largest decrease seen in the 0.90-kg/ha DMPP treatment. NH_3 emissions were observed after fertilizer was applied and decreased gradually, with no significant differences in response to the DMPP amount. The total N losses via leaching and NH_3 emission were significantly decreased at treatments of 0.675 kg/ha and 0.90 kg/ha DMPP, and positively correlated with sand fraction in soil. Compared with the gleyed paddy soil, higher total N loss was observed in the hydragic paddy soil, which was related to the higher sand fraction of the hydragic paddy soil and the better behavior of DMPP in this soil type.

Conclusions Considering economic factors, mineral N concentrations in floodwater and leachate, together with N losses via leaching and volatilization, application of 0.675 kg/ha DMPP could significantly inhibit nitrification in the hydragic paddy soil while application of 0.90 kg/ha DMPP was shown to be the best choice to inhibit nitrification in the gleyed paddy soil.

Responsible editor: Weixin Ding

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11368-020-02711-2) contains supplementary material, which is available to authorized users.

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Keywords 3,4-Dimethylpyrazole phosphate (DMPP) · Nitrogen losses · Nitrification inhibitor · Nitrate leaching · Ammonium volatilization

1 Introduction

N loss is a significant issue for soil nutrition and has received considerable attention from researchers. In soil, N exists as organic or/and inorganic compounds. The inorganic species have been studied intensively because they are more available for plants than organic species (Macadam et al. 2003). Inorganic forms such as NO_3^-–N, NH_4^+–N, and NH_3 are commonly found in soil and can be lost via runoff, leaching, and gaseous emissions (Abalos et al. 2014; Liu et al. 2020), as well as soil respiration accompanying reduction-oxidation metabolism (i.e., denitrification and nitrification) of organisms (Rowlings et al. 2016). For instance, an estimated 30–40% of N was demonstrated to be lost by leaching, runoff, NH_3 volatilization, and denitrification (Dougherty et al. 2016). It is also reported that 20% NO_3^-–N leaching, 13% NH_3 volatilization, and 2% N_2O emission were detected from urinary deposited of N by herd animals (Selbie et al. 2015).

Such heavy loss, therefore, increases demand for more N fertilizer input to the soil to enhance the N uptake by crops. However, the application of high N fertilizers causes some adverse problems including NO_3^-–N leaching and nitrogenous gas release (Huérfano et al. 2015; Xu et al. 2019) as well as high cost (Lam et al. 2018). Thus, it is necessary to decrease fertilizer-induced N loss and improve N use efficiency. In recent years, enhanced efficiency fertilizers (EEFs) have been frequently studied to decrease N loss from agriculture via changing N transformation rates or increasing the longevity of fertilizer granules (Suter et al. 2016). Nitrification inhibitors (NIs) such as 3,4-dimethylpyrazole phosphate (DMPP) and dicyandiamide (DCD) were widely employed to decrease the N loss (Qiao et al. 2015; Yang et al. 2016). Although some studies suggested that DCD had a superior performance for N loss to DMPP, especially in the field of grain yield, DMPP was still recommended due to its lower application rate and minor eco-toxicological side impacts for plant seeding (Li et al. 2019; Vilas et al. 2019).

The use of DMPP offered a chance to reduce NO_3^-–N loss from agricultural fields. By applying DMPP, the NO_3^-–N concentrations in leachate were reduced significantly (Koci and Nelson 2016; Nair et al. 2020). In our previous study, 44.9% of NO_3^-–N concentrations in leachate during rice-growing season were reduced when 1% DMPP was applied with urea, compared with urea alone (Li et al. 2008a). Higher NH_4^+–N concentrations in leachate and surface soil are generally observed in DMPP treatment (Anderson et al. 2014; Lam et al. 2018; Vitale et al. 2013), because nitrification inhibitors can retain N in the form of NH_4^+–N (Di and Cameron 2005). Also, the previous study reported that DMPP-amended sandy loam soils retain relatively high contents of NH_4^+–N, low levels of NO_3^-–N, and nitrification (Barth et al. 2019; Wu et al. 2007). In our on-farm research, DMPP increased soil NH_4^+–N concentrations by 12.4–24.1% 10 days after the fertilizer application with rice growth (Li et al. 2008a).

The higher NH_4^+–N concentrations in surface soil, floodwater, or rainfall of rice fields would increase the risk of ammonia (NH_3) volatilization (Harris et al. 2016). However, just a few works had been conducted to study the effects of DMPP on the loss of NH_3. Recent meta-analyses demonstrated that DMPP had no significant effect on NH_3 volatilization (Qiao et al. 2015; Yang et al. 2016). Lam et al. (2018) found that DMPP in conjunction with urea slightly decreased NH_3 volatilization by 0.6 N kg/ha N in a subtropical pasture.

Different concentrations of DMPP may affect the efficacy of nitrification inhibition. Compared with other NIs, such as DCD and nitrapyrin (CP), the dose of DMPP was extremely low. An application of 0.5–1.5 kg/ha DMPP was sufficient under field conditions to securely inhibit nitrification for 4–10 weeks (Rodríguez et al. 2011). DMPP inhibited nitrification during the complete incubation period (95 days) averaging from 56 to 64% at DMPP application rates of 0.89 to 1.79-mg/kg soil (Chaves et al. 2005). In liquid form, however, DMPP dose did not affect the oxidation of NH_4^+, with the exception of the sandy loam, where at day 25, slightly more NH_4^+ oxidation was observed with the highest DMPP concentration of 34.6 mg/kg soil. When applied as a solution, increasing the amount of DMPP (0.7 up to 7.1 mg/kg) to the soil did not lead to a change in the ammonium levels (Barth et al. 2001). The observation was documented that doubling the application rate of DMPP from 1.0 to 2.0 kg/ha did not significantly influence the inhibitory effect of DMPP (Xue et al. 2012). Besides, the efficacy and dose of DMPP can be highly influenced by site-specific states including soil properties such as pH, texture, water content, and temperature (Di and Cameron 2016; Florio et al. 2016). Therefore, the optimal dose of DMPP based on those factors is still unknown.

In this study, we hypothesized that differences in N losses could occur in two paddy soils treated with various doses of DMPP. To test this hypothesis, we examined the characteristics of N losses in two different types of soil. The concentrations of N species such as NH_4^+–N and NO_3^-–N in floodwater and leachate, and NH_3 volatilization rates before and after the amendment of urea fertilizer with various doses of DMPP were analyzed. Finally, the optimal doses of DMPP for both types of soil were obtained based on the experimental data. These findings would greatly contribute in understanding the influence of DMPP in paddy soils.

2 Materials and methods

2.1 Experimental materials and soil sampling

Soils were collected from Qianxi village, Yuhang town (30° 21′ N, 119° 53′ E) and Jiaxing Agricultural Research Station (30° 50′ N, 120° 40′ E), respectively, in Zhejiang Province, China. The Yuhang soil is classified as hydragic paddy soil (silt loam, mixed, mesic Mollic Endoaquepts), and the Jiaxing soil type is gleyed paddy soil (clay loam, mixed, mesic Mollic Endoaquepts). The gleyed and hydragic paddy soils represented two dominant soil types in Taihu Lake basin. The orders of muddy layer thickness and pressure head at the muddy layer bottom of the paddy soils follow gleyed > hydragic, whereas the infiltration rate and saturated hydraulic conductivity follow hydragic > gleyed. The saturated hydraulic conductivity of the hydragic is about 1.5 times higher than the gleyed paddy soil (Li et al. 2008b). Properties of soils are shown in Table 1.

The undisturbed soil columns were collected similar to the method of Yu et al. (2007). Briefly, soil was excavated from around a free-standing cylindrical soil column of 30 cm diameter by 60 cm depth. When the soil column was properly shaped, a polyvinyl (PVC) pipe of 30 cm diameter and 75 cm depth was placed around the column, and liquefied soil mud was placed in the space between the soil and the PVC. An acid-washed fine sand with 2-cm thickness was spread on the bottom for filtration of soil water, and leachate collector was installed for sampling the leachate at a depth of 60 cm depth.

2.2 Experimental design

Four DMPP levels were arranged in a completely randomized design with three replicates for each soil type: urea-N (urea alone at 180 N kg/ha), 0.25% urea-N (urea 90 N kg/ha combined with Entec® 46 90 N kg/ha (0.45 kg/ha DMPP)), 0.375% urea-N (urea 45 N kg/ha combined with Entec® 46 135 N kg/ha (0.675 kg/ha DMPP)), 0.5% urea-N (Entec® 46 alone at 180 N kg/ha (0.90 kg/ha DMPP)). All the treatments were 180 kg/ha N. The source of DMPP was Entec® 46 with 46% urea-N and DMPP at 0.5% of urea-N. All the nitrogen fertilizers together with 40 kg/ha P_2O_5 were applied as base fertilizers.

Table 1 Initial properties of hydragic paddy soil and gleyed paddy soil

Soil locations	Jiaxing	Yuhang
pH	6.8	7.2
Total N (g/kg)	2.65	2.34
Total P (g/kg)	1.53	0.93
Organic carbon (g/kg)	35.0	19.7
CEC (cmol/kg)	8.10	5.36
Bulk density (g/cm^3)	1.33	1.04
Sand (%)	12.1	15.2
Silt (%)	36.2	47.9
Clay (%)	51.7	37.0
Soil textural class	Clay loam, mixed	Silt loam, mixed
Soil classification	Gleyed paddy soil	Hydragic anthrosol

Sand, 1–0.05 mm; silt, 0.05–0.001 mm; clay, < 0.001 mm

Rice seedlings were transplanted into each undisturbed column after fertilizer application. When water levels were less than 5 millimeters (mm), all soil columns were regularly irrigated to a depth of 80 mm through day 28, excepting a period of soil drying from days 11 to 13, and then, the soil was kept moist with zero-drainage of runoff through the period. The whole experiment was conducted in an artificial greenhouse.

2.3 Sampling and analysis

In the flooding period, floodwater (surface water) was collected at an interval of 5 days, and leachate water was collected at an interval of 10 days after fertilization. Samples for NH_3 analysis were collected every 2 days for the 10 days following fertilization. Soil samples were collected 60 days after experiments begin.

All the floodwater and leachate samples were stored in a refrigerator (4 °C) and analyzed within 2 days. Concentrations of NO_3^-–N and NH_4^+–N were determined using a continuous-flow analyzer (AA3, Bran+Luebbe, Germany). NH_3 volatilization rate was measured using a continuous airflow enclosure method (Li et al. 2008b; Tian et al. 2001).

2.4 Statistical analysis

The experiment was a completely randomized design. We performed a two-way analysis of variance (ANOVA) to test soil types and DMPP application rate interactions. The Kruskal-Wallis method was used to identify differences in floodwater, leachate, and NH_3 volatilization among the DMPP application rate ($P < 0.05$). Duncan's test was used to test the significance of differences between N losses form leaching and NH_3 volatilization within each soil type ($P < 0.05$). Spearman correlations were conducted to analyze the correlations between total mineral N losses via leaching and NH_3 volatilization and soil properties.

3 Results

3.1 Effect of soil types and DMPP application rates on mineral nitrogen concentrations in floodwater

Differing DMPP application rate and soil types resulted in significant differences in the floodwater NO_3^-–N concentrations; however, only differing soil types significantly affected floodwater NH_4^+–N concentrations (Table 2). Compared with the gleyed paddy soil, the

Table 2 Two-way ANOVA analysis of the effects of soil types and DMPP levels on mineral N concentrations and losses

	Soil types		DMPP levels		Soil type*DMPP levels	
	F	*P*	*F*	*P*	*F*	*P*
NH_4^+–N in paddy water	6.6	*0.01*	0.586	0.625	0.005	1
NO_3^-–N in paddy water	426	*< 0.001*	73	*< 0.001*	4.3	*0.007*
NH_4^+–N in leachate	3.9	*0.05*	2.7	*0.04*	0.17	0.91
NO_3^-–N in leachate	8.5	*0.004*	26.1	*< 0.001*	0.015	0.99
NH_3 emission	3.9	*0.05*	0.034	1	0.005	1
N loss from leachate	1545	*< 0.001*	250	*< 0.001*	7.83	*0.002*
N loss via NH_3	93.3	*< 0.001*	0.514	0.68	0.217	0.883
Total mineral N loss	694	*< 0.001*	45	*< 0.001*	2.5	0.09

The italics values indicate significant effect by soil types and DMPP levels

NH_4^+–N and NO_3^-–N concentrations in floodwater were significantly lower than those in the hydragic paddy soil (Figs. 1 and 2). Compared with the urea treatment, NH_4^+–N and concentrations in floodwater increased to about 4–13%, 9–40%, and 16–65% in the 0.45-kg/ha DMPP, 0.675-kg/ha DMPP, and 0.90-kg/ha DMPP treatments respectively in the hydragic paddy soil, and increased to about 7–13%, 18–30%, and 31–60% respectively in the gleyed paddy soil. Significant differences in NH_4^+–N concentrations between urea treatment and 0.90-kg/ha DMPP and 0.675-kg/ha DMPP treatments were observed, while no significant difference was observed between 0.45 kg/ha DMPP and urea treatments in the hydragic paddy soil (Fig. 1). Therefore, adding 0.675 kg/ha DMPP could significantly increase NH_4^+–N concentrations in floodwater of the hydragic paddy soil, and increasing the DMPP to 0.90 kg/ha may affect NH_4^+–N concentrations the most. For the gleyed soil, the same trend was observed except for differences between 0.675 kg/ha DMPP and urea treatments in three sampling time. Thus, 0.90 kg/ha DMPP may be the best choice to inhibit nitrification in the gleyed paddy soil.

Compared with urea treatment, NO_3^-—N concentrations in floodwater decreased to about 2–7%, 14–24%, and 41–61% in 0.45-kg/ha DMPP, 0.675-kg/ha DMPP, and 0.90-kg/ha DMPP treatments, respectively in the hydragic paddy soil (Fig. 2). The respective contents in the gleyed paddy soil decreased by 12–22%, 35–44%, and 63–70%, respectively. Significant differences were observed among 0.90-kg/ha DMPP, 0.675-kg/ha DMPP, and 0.45 -kg/ha DMPP treatments in both soils.

3.2 Effect of soil types and DMPP application rates on mineral nitrogen concentrations in leachate

Both soil types and DMPP application rates significantly affected the NH_4^+–N and NO_3^-–N concentrations in the leachate (Table 2). The NH_4^+–N and NO_3^-–N concentrations in the hydragic paddy soil were higher than those in the gleyed paddy soil (Figs. 3 and 4). With the

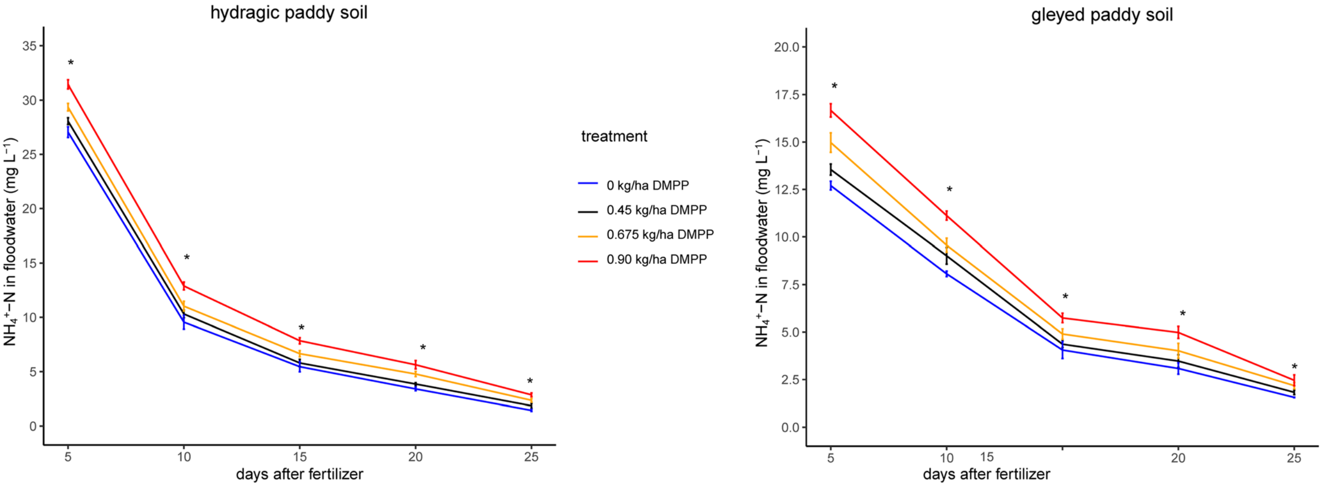

Fig. 1 NH_4^+–N concentrations in floodwater after fertilizer application in gleyed and hydragic paddy soils. Comparing across treatments within each sampling time, the lines with the asterisk are significant at $P < 0.05$. 0.45 kg/ha DMPP as 0.25% urea-N, 0.675 kg/ha DMPP as 0.375% urea-N, 0.90 kg/ha DMPP as 0.5% urea-N. Vertical bars indicate standard errors of the mean ($n = 3$)

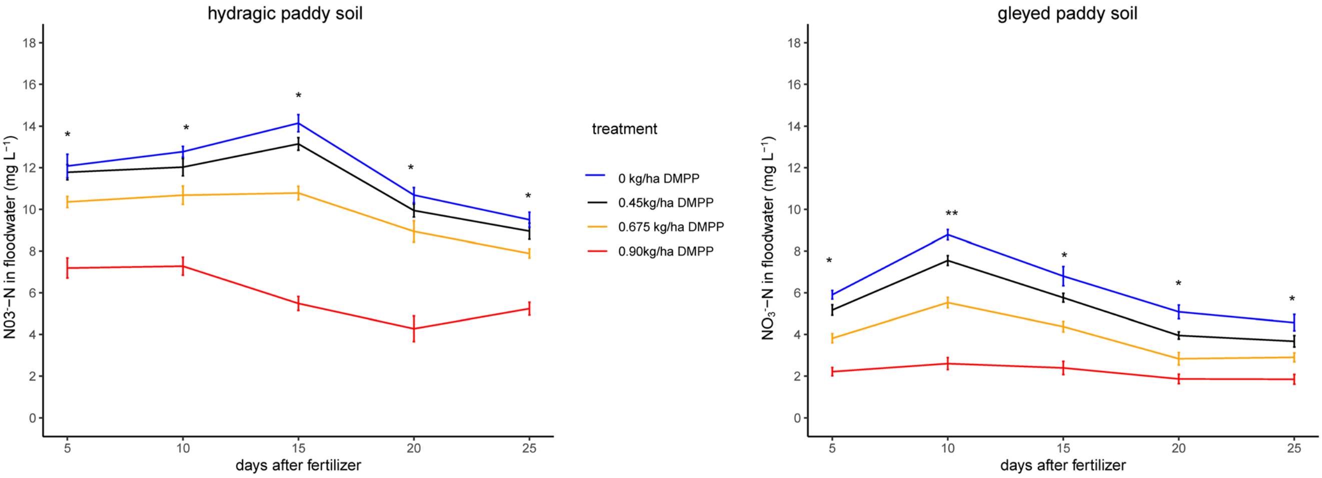

Fig. 2 NO_3^-–N concentrations in floodwater after fertilizer application in gleyed and hydragic paddy soils. Comparing across treatments within each sampling time, the lines with the asterisk are significant at $P <$ 0.05. 0.45 kg/ha DMPP as 0.25% urea-N, 0.675 kg/ha DMPP as 0.375% urea-N, 0.90 kg/ha DMPP as 0.5% urea-N. Vertical bars indicate standard errors of the mean ($n = 3$)

increase of DMPP application, the NH_4^+–N concentrations in leachate increased significantly, while NO_3^-–N concentrations in leachate decreased significantly. The highest NH_4^+–N concentrations in leachate was found in 0.90-kg/ha DMPP treatment, with 4.85 mg/L in the gleyed paddy soil and 3.95 mg/L in the hydragic paddy soil. The significant differences were observed between 0.675 kg/ha DMPP, 0.90 kg/ha DMPP, and urea treatments in the hydragic and gleyed paddy soils, and between 0.675- and 0.90-kg/ha DMPP treatments in the gleyed paddy soil (Fig. 3). Therefore, 0.90 kg/ha DMPP worked best in the gleyed paddy soil while 0.675 kg/ha DMPP could achieve the most efficiency to inhibit nitrification in the hydragic paddy soil.

For the NO_3^-–N concentrations, no significant differences were observed between urea and 0.5% DMPP treatments in the hydragic paddy soil; lowest concentrations were found in the 0.90-kg/ha DMPP treatment. While in the gleyed paddy soil, the NO_3^-–N concentrations significantly decreased with the increasing DMPP application rates (Fig. 4).

3.3 Effect of soil types and DMPP application rates on NH_3 volatilization

The volatilization rates of NH_3 were only significantly influenced by soil types (Table 2), with higher NH_3 volatilization rates observed in the hydragic paddy soil than those in the gleyed paddy soil (Fig. 5). After 2 days of DMPP and urea application, the NH_3 volatilization rates peaked, then decreased within 10 days. Although no significant differences were observed among DMPP application rates for each soil type, the highest rates of NH_3 volatilization were observed

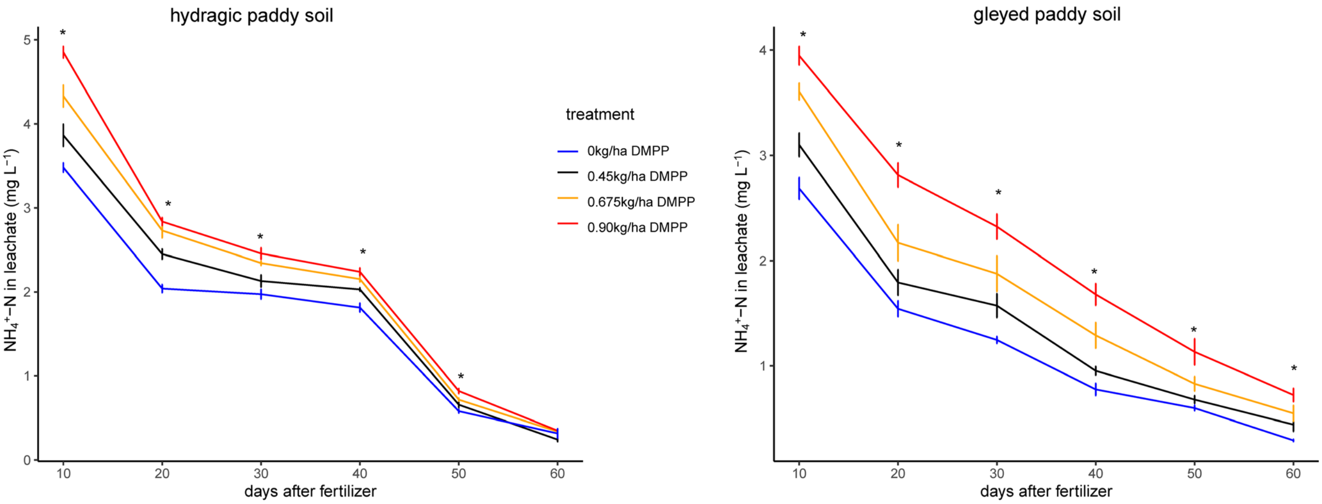

Fig. 3 NH_4^+–N concentrations in leachate after fertilizer application in gleyed and hydragic paddy soils. Comparing across treatments within each sampling time, the lines with the asterisk are significant at $P <$ 0.05 (the same in all figures). 0.45 kg/ha DMPP as 0.25% urea-N, 0.675 kg/ha DMPP as 0.375% urea-N, 0.90 kg/ha DMPP as 0.5% urea-N. Vertical bars indicate standard errors of the mean ($n = 3$)

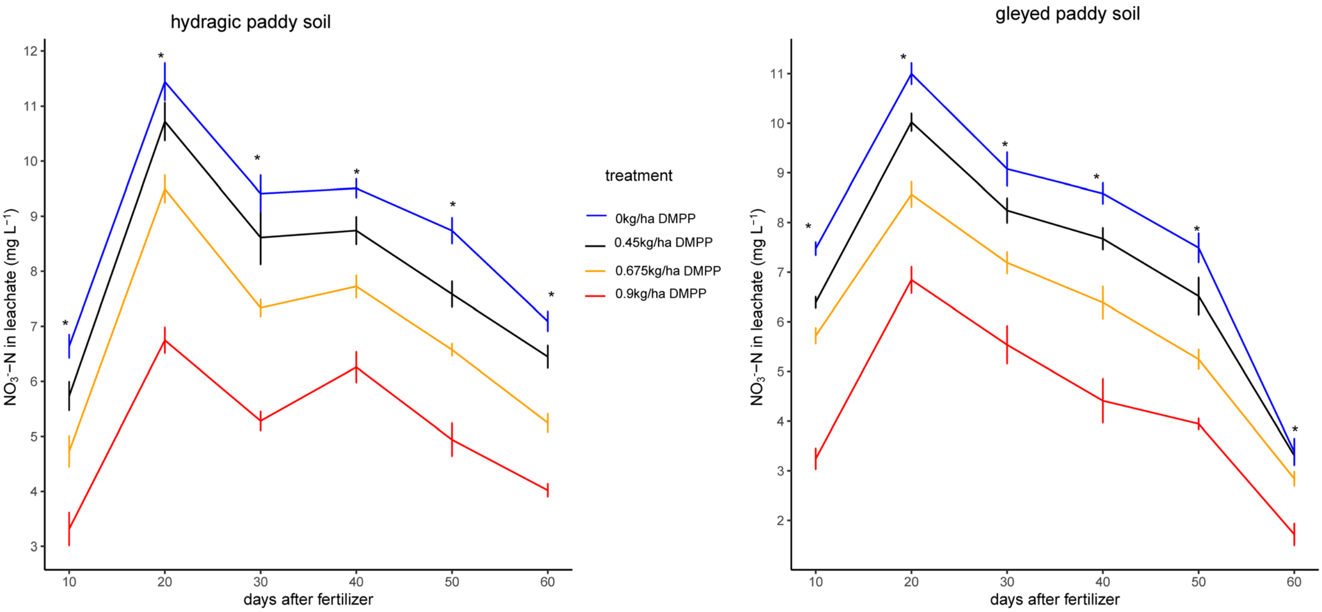

Fig. 4 NO_3^-–N concentrations in leachate as after fertilizer application in gleyed and hydragic paddy soils. Comparing across treatments within each sampling time, the lines with the asterisk are significant at $P <$ 0.05. 0.45 kg/ha DMPP as 0.25% urea-N, 0.675 kg/ha DMPP as 0.375% urea-N, 0.90 kg/ha DMPP as 0.5% urea-N. Vertical bars indicate standard errors of the mean (n = 3)

when DMPP was applied to the hydragic paddy soil at a rate of 0.90 kg/ha DMPP and to the gleyed paddy soil at a rate of 0.675 kg/ha DMPP.

3.4 Effect of soil types and DMPP application rates on mineral N losses via leaching and NH_3 volatilization

Two-way ANOVA revealed that N losses via leaching and NH_3 emission was significantly affected by soil types, but N losses via leaching and total mineral N losses significantly changed in response to DMPP application rates (Table 2, Fig. S1). The total mineral N losses were significantly decreased in response to the increased DMPP application rate; losses were higher in the hydragic soil than those in the gleyed soil. The ratio of total N losses via leachate and NH_3 were nearly 14% and 10% of the total N applied in the gleyed and hydragic paddy soils, respectively (Fig. 6). The mineral N losses via leaching and NH_3 volatilization significantly and positively correlated with soil pH and sand fraction, and negatively correlated with clay fraction and soil total N, and total phosphorus (Fig. S2).

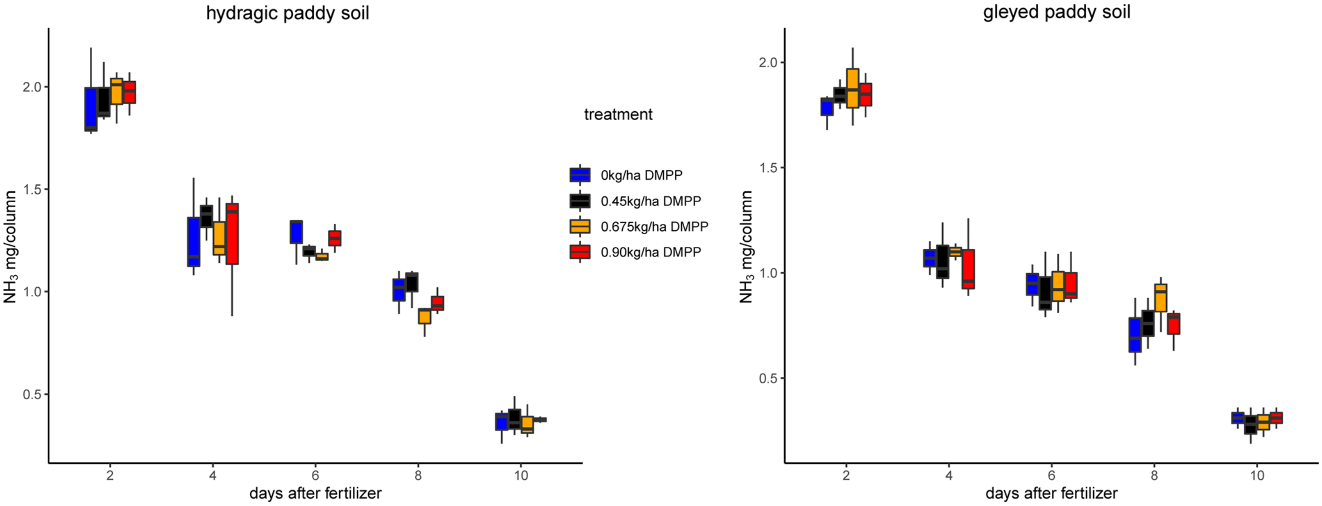

Fig. 5 NH_3 volatilization rates as after fertilizer application in gleyed and hydragic paddy soils. Comparing across treatments within each sampling time, the lines with the asterisk are significant at $P < 0.05$. 0.45 kg/ha DMPP as 0.25% urea-N, 0.675 kg/ha DMPP as 0.375% urea-N, 0.90 kg/ha DMPP as 0.5% urea-N. Vertical bars indicate standard errors of the mean (n = 3)

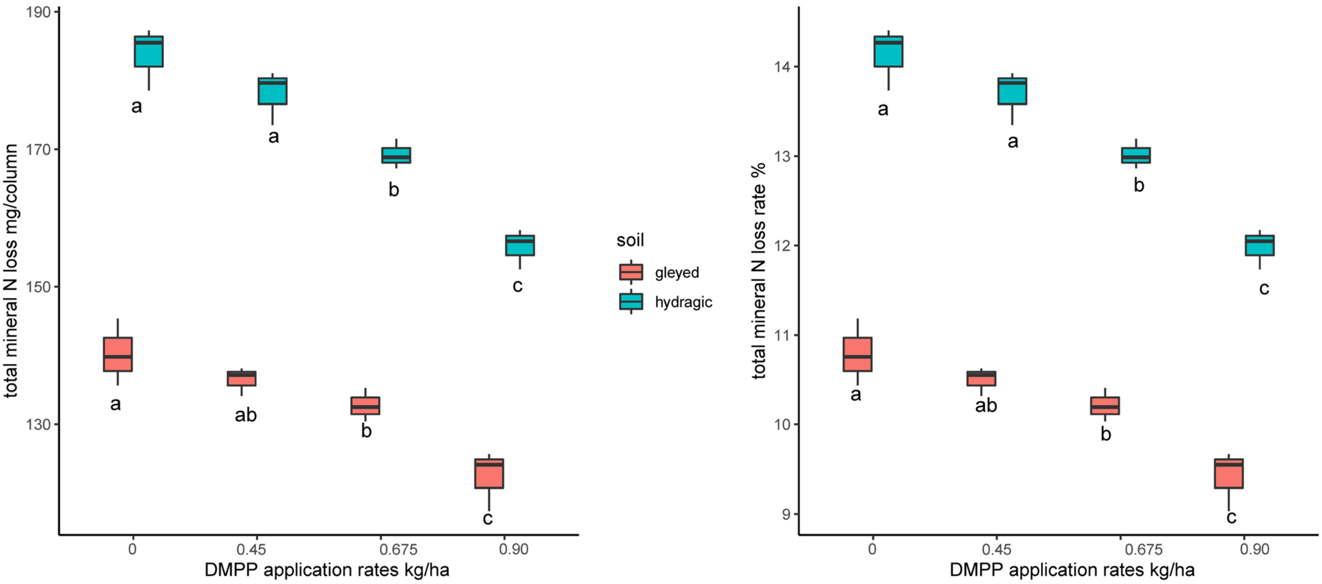

Fig. 6 The total mineral N losses via leaching and NH_3 emissions in each soil and the ratio of total mineral N loss to total N applied (1.3 g N/column). Different letters indicate significance at $P < 0.05$

4 Discussion

Soil environmental parameters may vary significantly in different locations, affecting the performance of N fertilizer and the longevity of NIs (Florio et al. 2016; Guardia et al. 2018; Yang et al. 2016). Soil properties such as temperature, water content, pH, charge, residual carbon to nitrogen (C/N) ratio and cationic exchange capacity (CEC), and soil texture were commonly considered in the discussion of the mechanism of N preservation, and several studies had reported some of those indices. It has been reported that DMPP effectively impeded nitrification at 5–15 °C and even reduced N_2O emission at 40–60% water-filled pore space after 42 days; however, this efficiency declined when temperature was elevated (25 °C in this article) (Chen et al. 2010). These results could be interpreted to mean cold weather retards microbial nitrification rates, while warmer periods contribute to the biological degradation of non-volatile DMPP. In this study, temperatures in both sites are annually recorded at 15–16 °C in the greenhouse, which indicate that other factors play important roles in the N losses.

Soil properties, such as CEC, and texture could affect the mineral nitrogen retention and water transport in soil. The observed the higher CEC of the gleyed paddy soil (Table 1) resulted in stronger retention of NH_4^+–N by surface soil and lower NH_3 volatilization rates, corroborating our previous study (Li et al. 2008b). The gleyed paddy soil was clayey with lower sand and silt content and higher clay content (51.7%) than the sandy hydragic paddy soil. The muddy layer thickness and pressure head at the muddy layer bottom of the gleyed paddy soil were higher than those of the hydragic paddy soil, whereas the infiltration rate and saturated hydraulic conductivity of the hydragic paddy soil were higher than those of the gleyed paddy soil (Li et al. 2008b). The leaching amount in the hydragic paddy soil is 1.3–1.6 times than that of the gleyed paddy soil in this study. In addition, the leachate concentrations of NO_3^-–N and NH_4^+–N from the hydragic paddy soil were higher than those from the gleyed paddy soil, which caused the higher mineral leaching losses from the hydragic paddy soil. The results also indicated that the differences between various DMPP doses were more obvious in the hydragic paddy soil than in the gleyed paddy soil. This is consistent with findings by other researchers (Barth et al. 2019; Shi et al. 2016) that DMPP works better in sandy soil than in clayey soil, which also evidenced by the significantly positive correlations between sand concentrations with total mineral N loss in our study.

Compared with other NIs, DMPP has a higher sorption towards the soil substrate (Di and Cameron 2016). Thus, those variations between both sites could also be explained by DMPP sorption. DMPP could be attached to soil mineral surface easier than other NIs due to its negative charge and heterocyclic compound, and the fact that is not easily degradable (Barth et al. 2008; Shi et al. 2016). This sorption within the soil could be affected by the organic content and residual N level (Marsden et al. 2016). Recent studies demonstrated that the efficiency of DMPP was closely correlated to increasing levels of soil inorganic constituents and that the adsorption of DMPP to the soil clay fraction played a major role in controlling the inhibition effect (Di and Cameron 2012; Marsden et al. 2016). In our study, the mineral N losses via leaching were reduced at both sites with increased DMPP application rates with lower in more clay gleyed paddy soil. It further confirmed that the soil clay fraction would restrain the inhibition effect of DMPP.

Rice farming could be a significant source of water pollution. As shown in Fig. 1, NH_4^+–N concentrations in floodwater at the first 20 days after fertilization, all the samples exceed China's surface water quality standards (class V, 2 mg/L). Figure 4 also shows that NO_3^-–N concentrations on day 20 in urea and 0.45-kg/ha DMPP treatments exceeded the groundwater quality standard (10 mg/L) set by China. These data indicated that without DMPP or if DMPP is less than 0.45 kg/ha, groundwater beneath the rice paddy would have NO_3^-–N exceedance. Further study should focus on determining the amount of urea to maintain rice yield and without contaminating groundwater.

DMPP inhibited the oxidation of ammonium in both soils, but this effect was more pronounced in the sandy loam than in the loamy soil (Barth et al. 2019). Soil types significantly affected the NH_4^+– and NO_3^-–N concentrations both in leachate and floodwater in our study, with higher effect in the hydragic paddy soil. This may be due to the higher soil sand fraction in the hydragic paddy soil. In the loamy soil, DMPP delayed NH_4^+ oxidation efficiency than in the sandy loam. Also, in the clayey loam soil such as vegetable soil, it impeded the accumulation of NO_3^-–N concentration in the leachate (Xu et al. 2005). It was observed in our previous research that DMPP could inhibit ammonia oxidization through inhibiting ammonia-oxidizing bacteria (Florio et al. 2014; Yang et al. 2012), resulting in more NH_4^+–N and less NO_3^-–N in the soil and leachate after urea application. In a column study, Wu et al. (2007) observed significantly lower NO_3^-–N concentrations in surface soils receiving DMPP amendment. And especially in dryland soils treated with 0.90 kg/ha DMPP, NO_3^-–N concentration was 23% lower than in soils treated with ammonium sulfate nitrate (ASN) alone (Weiske et al. 2001). Even when the NO_3^-–N concentration in leachate was higher than 10 mg/L in our study, the application of DMPP decreased it to below 5.5 mg/L. Overall, DMPP reduced NO_3^-–N leaching fluxes by 44.3–51.9%, potentially reducing NO_3^-–N migration to the groundwater. In soil columns with the same gleyed paddy soil, NO_3^-–N leaching loss fluxes were reduced by 69.5% when DMPP was added (Yu et al. 2007).

On the other hand, due to its high concentration in soil, higher NH_4^+–N concentration in leachate from the urea + DMPP plots were also observed, which was 13.0–33.3% higher than in the urea plots (Li et al. 2008a). In column experiments with the same gleyed paddy soil, NH_4^+–N concentration in soil solution at the top 20-cm soil was increased by 0.9 kg/ha DMPP (Yu et al. 2007). The greater amount of NH_4^+–N in leachate when DMPP was applied was also found by other researchers (Guardia et al. 2018; Xu et al. 2019; Yang et al. 2016). The slightly higher NH_4^+–N contents in the urea + DMPP plots may play an important role in enhancing N availability in soil (Yang et al. 2016). In previous studies, DMPP did not reduce or even increase crop and vegetable yields (Hu et al. 2013; Merino et al. 2005). In this study, the total N content in the gleyed paddy soil was higher than that in the hydragic paddy soil (Table 1), and for most samples in both 3sites; however, the N losses via leaching and volatilization were higher in the hydragic paddy soil than those in the gleyed paddy soil with the same N application. It may indicate that soil properties are the dominant role of in N losses when DMPP is applied.

Application of DMPP could inhibit ammonium oxidization for 4–10 weeks in farmland soils (Guardia et al. 2018), and the inhibition was more evident with more NH_4^+–N available soon after urea application. In 2 days after urea application, the addition of DMPP could maintain a large amount of N in NH_4^+–N, leading to higher NH_3 volatilization rates in the urea + DMPP than those in the urea alone application. However, the observed accumulative NH_3 emission losses were not significantly affected by DMPP. Qiao et al. (2015) and Yang et al. (2016) also found that DMPP had no significant effects on NH_3 volatilization, which may be explained by the similar soil pH for the two soils.

5 Conclusion

Soil type significantly affected the concentration of NH_4^+– and NO_3^-–N in floodwater and leachate and the total N losses via leaching and NH_3 emission; however, only NO_3^-–N in floodwater and leachate was affected significantly in response to DMPP application rates. The total mineral N losses in the hydragic paddy soil were more pronounced than those in the gleyed paddy soil, which was greatly related to the soil properties such as particle size distribution, CEC, and organic matter which could affect the performance of DMPP in soil, particularly the soil sandy fraction. DMPP could significantly inhibit nitrification in paddy soil: Considering economic factors, mineral N concentrations in floodwater and leachate, together with N losses via leaching and volatilization, 0.675 kg/ha DMPP could significantly inhibit nitrification in the hydragic paddy soil while 0.90 kg/ha DMPP was the best choice to inhibit nitrification in the gleyed paddy soil. This difference needs to be further explored via focusing on the soil and interaction of different types of indigenous microorganisms such as nitrite-oxidizing bacteria, ammonia-oxidizing bacteria, and archaea.

Funding information This work was financed by National Natural Science Foundation of China (41671300), National Key Research and Development Plan of China (2016YFD0200804), and Science and technology cooperation project of agricultural and rural Department of Zhejiang Province (2018SNLF027). Shaoxian Wang is grateful for funding from Open Fund from Key Laboratory for Water Pollution Control and Environmental Safety.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and/or animals This article does not contain any studies involving human participants and/or animals performed by any of the authors.

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