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Using nitrification inhibitors to mitigate agricultural N_2O emission: a double-edged sword?

Running head

Dual effect of nitrification inhibitor on N_2O

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Abstract

Nitrification inhibitors show promise in decreasing nitrous oxide (N_2O) emission from agricultural systems worldwide, but they may be much less effective than previously thought when both direct and indirect emissions are taken into account. Whilst nitrification inhibitors are effective at decreasing direct N_2O emission and nitrate (NO_3^-) leaching, limited studies suggest that they may increase ammonia (NH_3) volatilization and subsequently, indirect N_2O emission. These dual effects are typically not considered when evaluating the inhibitors as a climate change mitigation tool. Here we collate results from the literature that simultaneously examined the effects of nitrification inhibitors on N_2O and NH_3 emissions. We found that nitrification inhibitors decreased direct N_2O emission by 0.2–4.5 kg N_2O-N ha^{-1} (8–57%), but generally increased NH_3 emission, by 0.2–18.7 kg NH_3-N ha^{-1} (3–65%). Taking into account the estimated indirect N_2O emission from deposited NH_3, the overall impact of nitrification inhibitors ranged from –4.5 (reduction) to +0.5 (increase) kg N_2O-N ha^{-1}. Our results suggest that the beneficial effect of nitrification inhibitors in decreasing direct N_2O emission can be undermined or even outweighed by an increase in NH_3 volatilization.

Introduction

Globally, agriculture contributes about 60% of the total anthropogenic emission of nitrous oxide (N_2O), a greenhouse gas approximately 300 times more potent than carbon dioxide (Ciais *et al.*, 2013). The mitigation of N_2O emission from agricultural systems is an important issue worldwide. Nitrification inhibitors are recommended by the IPCC as a potential mitigation option for agricultural N_2O emission (IPCC, 2014), and have been extensively investigated and widely used across a broad range of agroecosystems (Chen *et al.*, 2008; Qiao *et al.*, 2015). Nitrification inhibitors temporarily suppress the microbial conversion of ammonium (NH_4^+) to nitrite (NO_2^-) in soil. This reduces substrate availability for nitrate (NO_3^-) formation and subsequent denitrification, thereby decreasing N_2O emission and NO_3^- leaching (Bundy & Bremner, 1973; Chen *et al.*, 2008). Recent meta-analyses indicated that nitrification inhibitors decreased N_2O emission and NO_3^- leaching by 31–48% and 32–59%, respectively, across diverse agricultural ecosystems including upland, grassland and paddy fields (Akiyama *et al.*, 2010; Qiao *et al.*, 2015). Nitrate lost via leaching and runoff may be transported to groundwater, rivers or estuaries where part of it may be converted to N_2O (Nevison, 2000). This indirect N_2O emission can be estimated by the IPCC emission factor EF_5 with a default value of 0.75% (De Klein *et al.*, 2006).

The use of nitrification inhibitors, however, prolongs the retention of NH_4^+ in soil, which could potentially increase ammonia (NH_3) emission (Zaman & Nguyen, 2012). Deposition of emitted NH_3 not only poses a major threat to environmental quality and ecosystem biodiversity (Erisman *et al.*, 2008), but indirectly it also contributes to N_2O emission (van der Gon & Bleeker, 2005) through subsequent nitrification and denitrification. According to the IPCC guidelines (De Klein *et al.*, 2006), about 1% (a range of 0.2–5%) of the NH_3 emitted is converted to N_2O after deposition to land (IPCC emission factor EF_4).

While the effect of nitrification inhibitors on NH_3 volatilization is not as widely studied as that on N_2O emission, Qiao *et al.* (2015) recently summarized the available studies and concluded that nitrification inhibitors increased NH_3 volatilization from synthetic fertilizers and animal manures in agricultural systems by 33–67%. However most of the studies included in the synthesis focussed on one or other of these gases, and Qiao *et al*. (2015) expressed the impact of the inhibitor as percentage change, not absolute difference, in nitrogen (N). The overall inhibitor effect on N_2O emission (direct and indirect), which can be determined from studies that simultaneously measure N_2O and NH_3 emissions and NO_3^- leaching in the field, remains uncertain. The inclusion of indirect N_2O emission is critical for evaluating the effectiveness of nitrification inhibitors in mitigating greenhouse gas emissions from agriculture. We therefore conducted a literature review to address this knowledge gap.

Literature search

To assess the overall contribution of nitrification inhibitors to N_2O emission (direct and indirect), we performed extensive keyword searches of several databases (Web of Science, Scopus, CAB Abstracts, Academic Search complete and Google Scholar), and the reference list of cited references, for studies published prior to October 2015. The keywords used in the search included nitrification inhibitors, names of the inhibitors such as DCD and DMPP, nitrous oxide/N_2O emission, ammonia/NH_3 emission, volatilization, direct/indirect N_2O, greenhouse gas, nitrate/NO_3^- leaching, loss and/or mitigation, agriculture, cropping, pastures, and their combinations. Only studies that simultaneously examined N_2O and NH_3 emissions in the same field location were included. The search resulted in 18 observations in pasture and cropping systems (Table 1).

Dual effects of nitrification inhibitors on N_2O emission

From the literature review, we found that nitrification inhibitors consistently decreased direct N_2O emission from fertilizers (urea and ammonium based) and animal wastes (slurry and urine), applied at between 97 and 625 kg N ha^{-1}, by 0.2–4.5 kg N_2O-N ha^{-1} (8–57%) (Table 1). On the other hand, NH_3 volatilization was increased by 0.2–18.7 kg NH_3-N ha^{-1} (3–65%) following the application of the inhibitors in all but three observations. Applying the default emission factor value of 1% (De Klein *et al.*, 2006) for indirect N_2O emission from NH_3 volatilization and deposition (EF_4), we found there was an overall N_2O-N reduction of 0.1–4.5 kg N ha^{-1} from the use of nitrification inhibitors. However, when the upper range of EF_4 (5%) (De Klein *et al.*, 2006) was used, the change in N_2O-N ranged from –4.4 (reduction) to +0.5 (increase) kg N ha^{-1} (Table 1).

We found that only two studies reported the effect of nitrification inhibitors on NO_3^- leaching in addition to that on N_2O and NH_3 emissions. This precludes the estimation of indirect N_2O emission from measured NO_3^- leaching for the studies included in Table 1. Nonetheless, NO_3^- leaching is assumed to be an insignificant source of indirect N_2O emission in dryland cropping systems, and grassland systems where the amount of precipitation plus irrigation does not exceed 80% of the potential evapotranspiration (IPCC, 2006; U.S. EPA, 2014). A global process-based simulation of terrestrial N cycle estimated that the annual leaching load is around 20 kg N ha^{-1} for most regions with fertilizer application of >100 kg N ha^{-1}. Based on the default EF_5 value of 0.75% (De Klein *et al*., 2006), and an average reduction in NO_3^- leaching of 47% by nitrification inhibitors (Qiao *et al*., 2015), we estimated that the inhibitors may decrease indirect N_2O emission associated with NO_3^- leaching by 0.07 kg N ha^{-1} or have no effect on the emission when NO_3^- leaching is negligible. This has minimal impact on the overall effect of nitrification inhibitors on N_2O emission.

The results of our literature review (Table 1) indicate that nitrification inhibitors effectively and consistently decrease direct N_2O emission from agricultural systems. Nonetheless, this beneficial effect can be weakened, negated or even reversed by the estimated concomitant increase in indirect N_2O emission from deposited NH_3. This highlights the importance of considering both gases when evaluating the use of nitrification inhibitors as a climate change mitigation option. An alternative approach would be to use a double inhibitor (a combination of a nitrification inhibitor and urease inhibitor). Urease inhibitors slow the hydrolysis of urea and consequently reduce NH_3 volatilization and can be effective on urea (Chen *et al.*, 2008). A recent study showed that both NH_3 volatilization and N_2O emission were decreased when urea was treated with a double inhibitor (Zaman & Blennerhassett, 2010). However this double inhibitor approach is impractical for decreasing NH_3 volatilization from N sources containing negligible urea but high NH_4^+ content, such as animal manure and ammonium fertilizers. In this regard, substances with a high affinity for binding onto NH_4^+ ions may be used as additives to mitigate NH_3 volatilization. For instance, zeolite and, more recently, lignite were shown to effectively lower NH_3 volatilization when mixed with animal manure (Ndegwa *et al.*, 2008; Chen *et al.*, 2015). Alternatively, where practical, manure should be incorporated into soil rather than being surface applied to prevent NH_3 loss.

Summary and implication

Nitrification inhibitors decrease direct N_2O emission and indirect N_2O emission due to NO_3^- leaching from agroecosystems. Yet this beneficial effect is weakened by any accompanying increase in indirect N_2O emission that can result from increased emission and deposition of NH_3. Appropriate NH_3 mitigation measures should be taken where nitrification inhibitors are being used to decrease direct N_2O emissions, to enable effective and viable climate change mitigation.

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Tables

Table 1 Summary of studies that simultaneously investigated the effects of nitrification inhibitors on N_2O and NH_3 emissions, and the estimated overall impacts

Agricultural system	N form	N rate kg N ha^{-1}	Season	Inhibitor	Effect of NI: Direct N_2O emission % [a]	Effect of NI: Direct N_2O emission Amount [b] (kg N ha^{-1}) (I)	Effect of NI: NH_3 volatilization % [c]	Effect of NI: NH_3 volatilization Amount [d] (kg N ha^{-1}) (II)	Overall NI effect on N_2O emission (kg N ha^{-1}) (I + II × EF_4) [e]: EF_4 = 1%	Overall NI effect on N_2O emission (kg N ha^{-1}) (I + II × EF_4) [e]: EF_4 = 5%	Country	Gas measurement technique: N_2O	Gas measurement technique: NH_3	Reference
Cropping-rice	urea	180	summer	N-serve	–49.9	–0.57	+64.9	+12.75	–0.44	+0.07	China	CC	OC	Sun *et al.*, 2015
Cropping-rice	urea	240	summer	N-serve	–19.2	–0.27	+37.5	+15.80	–0.11	+0.52	China	CC	OC	Sun *et al.*, 2015
Cropping-maize	slurry	165	summer	DCD	–20.4	–0.79	–3.7	–0.40	–0.79	–0.81	Brazil	CC	CC	Aita *et al.*, 2015
Cropping-wheat	slurry	135	winter	DCD	–52.3	–1.36	+3.1	+0.35	–1.35	–1.34	Brazil	CC	CC	Aita *et al.*, 2015
Cropping-wheat/barley; pasture	urea	120–200	whole year	DCD	–46.5	–0.52	+6.1	+2.20	–0.50	–0.41	UK	CC	WT	Misselbrook *et al.*, 2014
Cropping-wheat/barley; pasture	AN	120–200	whole year	DCD	–28.7	–0.48	+5.4	+0.15	–0.48	–0.47	UK	CC	WT	Misselbrook *et al.*, 2014
Pasture	urine	365–625	spring-autumn	DCD	–56.8	–1.24	–0.8	–0.97	–1.25	–1.29	UK	CC	WT	Misselbrook *et al.*, 2014
Pasture	urine	365–625	spring-autumn	PD	–10.6	–0.23	+4.0	+4.87	–0.18	+0.01	UK	CC	WT	Misselbrook *et al.*, 2014
Pasture	slurry	106–181	spring/autumn	DCD	–30.1	–0.38	+7.7	+2.55	–0.36	–0.26	UK	CC	WT	Misselbrook *et al.*, 2014
Pasture	urine	600	autumn	DCD	–42.1	–2.93	+35.5	+18.65	–2.74	–2.00	New Zealand	CC	OC	Zaman *et al.*, 2013
Pasture	urine	600	spring	DCD	–40.5	–2.15	+13.3	+13.87	–2.01	–1.46	New Zealand	CC	OC	Zaman *et al.*, 2013
Pasture	urine	600	autumn	DCD	–37.1	–4.47	+43.4	+12.60	–4.34	–3.84	New Zealand	CC	OC	Zaman & Blennerhassett 2010
Pasture	urine	600	spring	DCD	–46.8	–4.33	+18.2	+8.00	–4.25	–3.93	New Zealand	CC	OC	Zaman & Blennerhassett 2010
Pasture	urine	600	spring	DCD	–38.6	–4.40	+9.1	+2.00	–4.38	–4.30	New Zealand	CC	OC	Zaman *et al.*, 2009
Pasture	urine	600	summer	DCD	–20.0	–0.30	+17.2	+8.60	–0.21	+0.13	New Zealand	CC	OC	Zaman *et al.*, 2009
Pasture	slurry	123	spring-summer	DMPP	–7.9	–0.18	+13.9	+1.80	–0.16	–0.09	Spain	CC	OC	Menéndez *et al.*, 2009
Pasture	ANS	97	spring	DMPP	–8.8	–0.39	–51.7	–0.15	–0.39	–0.40	Spain	CC	OC	Menéndez *et al.*, 2006
Pasture	slurry	181	spring	DMPP	–29.1	–4.51	+42.0	+3.16	–4.48	–4.35	Spain	CC	OC	Menéndez *et al.*, 2006

[a] The value was calculated by: (N_2O emission in the treatment with NI – N_2O emission in the control) / N_2O emission in the control × 100%

[b] The value was calculated by: N_2O emission in the treatment with NI – N_2O emission in the control

[c] The value was calculated by: (NH_3 volatilization in the treatment with NI – NH_3 volatilization in the control) / NH_3 volatilization in the control × 100%

[d] The value was calculated by: NH_3 volatilization in the treatment with NI – NH_3 volatilization in the control

[e] EF_4 of 1% and 5% represent the mean and upper range, respectively, of the IPCC default emission factor for indirect N_2O emission[14]

AN: ammonium nitrate

ANS ammonium nitrate sulphate

CC: closed chamber

DCD: dicyandiamide

DMPP: 3,4-dimethylpyrazole phosphate

EF_4: emission factor for indirect N_2O emission

NI: nitrification inhibitor

OC: open chamber

PD: pyrazole derivatives 1H-1,2,4-triazole and 3-methylpyrazole

WT: wind tunnel