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Short Communication

Direct and indirect greenhouse gas emissions from two intensive vegetable farms applied with a nitrification inhibitor

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ABSTRACT

Nitrification inhibitors are effective in decreasing direct nitrous oxide (N_2O) emission from agricultural soils but may stimulate ammonia (NH_3) volatilization. Part of the NH_3 deposited to land is converted to N_2O and emitted to the atmosphere, termed indirect N_2O emission. While vegetable production systems entail a considerable risk of NH_3 and N_2O loss from high nitrogen (N) input to the soil, the simultaneous effects of nitrification inhibitors on these N loss pathways have rarely been examined. We conducted paddock-scale (ca. four hectares) measurements using micrometeorological techniques to simultaneously quantify the effects of a nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) on NH_3 and N_2O emissions from two intensive vegetable farms. We found that DMPP decreased direct N_2O emission by 37–38% (2.2–7.3 kg N ha^{-1}) across the farms during the most intensive period of N input (18 days), but could increase NH_3 volatilization by 3–39% (1.6–4.8 kg N ha^{-1}). The results highlight the importance of considering multiple N loss pathways when developing a strategy for mitigating agricultural greenhouse gas emissions.

1. Introduction

A significant amount of nitrous oxide (N_2O) is emitted from agricultural soils as a result of the application of synthetic fertilizers and organic manures (Davidson, 2009). IPCC (2014) recommends the use of nitrification inhibitors to mitigate direct N_2O emission from agriculture by delaying the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) in soil. However, under the effects of these inhibitors, NH_4^+ may stay longer in soil, which is conducive to ammonia (NH_3) emission and deposition under desirable edaphic and environmental conditions (Asman et al., 1998; Zaman and Nguyen, 2012; Lam et al., 2017). About 1% of the NH_3 deposited to land is converted to N_2O through nitrification and denitrification processes (De Klein et al., 2006), which is referred to as indirect N_2O emission from NH_3 deposition. This indirect N_2O emission should also be included when evaluating the potential of nitrification inhibitors in mitigating agricultural greenhouse gas emissions.

There is a paucity of information on the simultaneous impact of nitrification inhibitors on NH_3 and N_2O emissions from agricultural lands (Lam et al., 2017), and none for intensive vegetable production systems. To address this knowledge gap, we conducted field experiments at two celery (*Apium graveolens*) farms, Boneo (38.4°S, 144.9°E) and Clyde (38.1°S, 145.3°E) in Victoria, Australia. The objective was to quantify the effects of a widely adopted nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) on NH_3 and N_2O emissions from chicken manure and synthetic fertilizers. To cope with the high spatial and temporal heterogeneity of gaseous emissions from agricultural fields (Röver et al., 1999; Grant and Pattey, 2003) we used micrometeorological techniques to obtain continuous, non-intrusive and paddock-scale gas measurements.

The measurements were conducted during the most intensive period of N input (manure application followed by fertilizer application within a week) of the whole growing season. At each farm, two paddocks of around 4 ha were used, one for the control and the other for the treatment with DMPP (~15% DMP active ingredient, applied at 6.6 kg ha^{-1} to the paddock at Boneo and 9.1 kg ha^{-1} at Clyde, after manure application). At Boneo, chicken manure (3.4% N) was surface broadcast at 255 kg N ha^{-1} to the celery growing beds on 7 May 2013 and Nitrophoska® (12% N) at 39 kg N ha^{-1} on 14 May. At Clyde, the surface application of chicken manure (4.3% N) at 353 kg N ha^{-1} occurred on 28 March 2014 and Cal-Gran® (a mixture of calcium ammonium nitrate and ammonium sulfate, 24% N) at 38 kg N ha^{-1} on 1 April. The application rates and methods of manure and fertilizers followed the local practice of commercial farms in that region. The soil at the Boneo farm is a Tenosol (Isbell, 1996) with 1% clay, 8% silt and 91% sand. The topsoil (0–15 cm) had a pH (H_2O) of 7.9, cation

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exchange capacity (CEC) of 6.9 cmol(+) kg^{-1}, and contained 0.64% organic carbon, 19 mg NH_4^+-N kg^{-1} and 54 mg NO_3^--N kg^{-1} prior to manure application. At Boneo, the average minimum temperature 7.7 °C and maximum temperature 17.4 °C across the study period, with 108 mm rainfall and 96 mm irrigation. The Clyde soil is a Chromosol (Isbell, 1996) with 14% clay, 1% silt and 85% sand. The topsoil (0–15 cm) had a pH (H_2O) of 7.2, CEC of 15.0 cmol(+) kg^{-1}, and contained 2.2% organic carbon, 52 mg NH_4^+-N kg^{-1} and 118 mg NO_3^--N kg^{-1} before manure application. At Clyde, the average minimum and maximum temperatures during the study period were 13.2 °C and 22.5 °C, respectively, with a total rainfall of 53 mm and irrigation of 34 mm.

A three-dimensional sonic anemometer (CSAT3, Campbell Scientific) was established at each experimental site to collect micrometeorological data including wind speed, wind direction and air temperature. At Boneo, an open-path Fourier transform infrared (OP-FTIR) spectroscopy (Matrix-M IRcube, Bruker Optik GmbH) was used to measure gas concentrations, and the gas fluxes were determined using a backward Lagrangian stochastic (bLS) model WindTrax 2.0 (Thunder Beach Scientific, Flesch et al., 1995). At the center of each paddock, the OP-FTIR spectroscopic system was established at 1.2 m height. Ammonia and N_2O concentrations were measured at 3-min intervals. At Clyde, a slant-path flux gradient technique (Flesch et al., 2016; Wilson and Flesch, 2016) coupled with the OP-FTIR spectroscopy was used for gas measurements. The OP-FTIR spectroscopic system was established at the center of the paddock for each treatment at 1.5 m height to measure line-averaged gas concentrations from two vertically offset slant-paths from high and low retroreflectors mounted at 1.8 and 0.8 m, respectively. Measurements were conducted at 5-min cycles alternating between the high and low paths. The slant-path flux gradient technique was used at Clyde to overcome the limitation of the lack of simultaneous measurements of background N_2O concentration that was encountered in our previous study at Boneo (Lam et al., 2015). Details of the micrometeorological techniques employed at the Boneo and Clyde sites are described in Bai et al. (2014, 2016). These techniques integrate gas fluxes over a large spatial scale, and the fluxes measured represent the spatial averages along the line of the wind (Denmead et al., 2015; Hensen et al., 2013). While replication was not possible due to limited resources for such large-scale measurements (e.g. availability of large farmland), our FTIR measurements were continuous throughout the experimental period covering the whole paddock (4 ha for each treatment) and captured the temporal and spatial variation in gaseous N emissions from the whole paddock.

Fifteen soil cores (0–15 cm depth, 2.5 cm diameter) were collected from each quadrant of the paddocks from both the bed and furrow areas. Subsamples (20 g, < 2 mm, dried at 40 °C) were extracted with 100 mL 2 M potassium chloride (Keeney and Nelson, 1982) for the analysis of soil NH_4^+ and NO_3^- concentrations by a segmented flow analyzer (Skalar SAN^{++}). The least significant difference (LSD) at $p = 0.05$ was used to compare the means of soil NH_4^+ and NO_3^- concentrations between treatments.

2. Nitrification inhibitor DMPP decreased N_2O emission

Nitrous oxide emission increased rapidly after manure and fertilizer applications at Clyde regardless of DMPP application (Fig. 1a). The same pattern was observed at the Boneo site (Lam et al., 2015). DMPP application decreased the cumulative N_2O emission by 37–38% over the measurement period (from 5.7 to 3.6 kg N ha^{-1} at Boneo, and 19.4 to 12.1 kg N ha^{-1} at Clyde) (Table 1). The percentage reduction is within the range of reduction (31–75%) observed in diverse agricultural systems including vegetable production systems (Akiyama et al., 2010; Pfab et al., 2012; Scheer et al., 2014; Qiao et al., 2015). We found that DMPP decreased soil NO_3^- content on the bed, where manure and fertilizer were applied, at the two locations by 44–52% ($p < 0.05$, Table 2). This indicates that DMPP suppressed nitrification and possibly subsequent denitrification at both farms, which explains the observed decrease in N_2O emission. The decrease in NO_3^- content also suggests that NO_3^- leaching might have been reduced in the DMPP-treated paddocks.

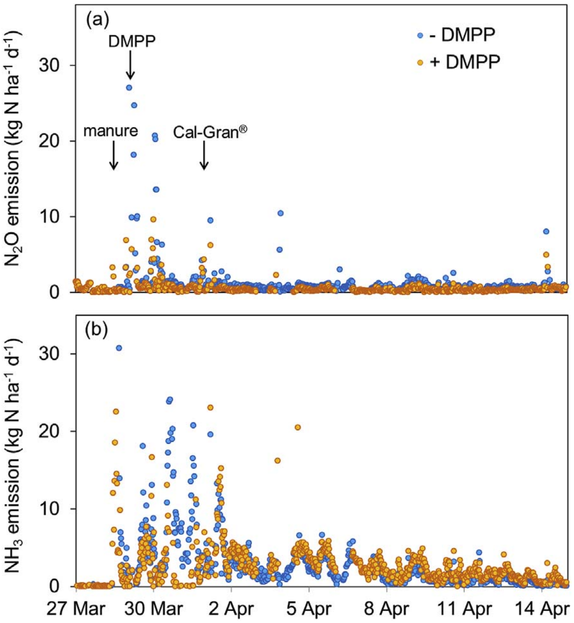

Fig. 1. Effects of DMPP application on (a) N_2O and (b) NH_3 emissions measured by OP-FTIR spectroscopy at Clyde. Arrows represent the timing of applications of manure, DMPP and Cal-Gran®.

3. Nitrification inhibitor DMPP increased NH_3 emission

Ammonia emission increased sharply upon manure application (on 28 March at Clyde and 7 May at Boneo) (Figs. 1b and 2). The pH of the soil (7.9 at Boneo and 7.2 at Clyde) was favorable for NH_3 volatilization (Freney et al., 1983). DMPP application increased the cumulative NH_3 emissions over the measurement period by 3–39% (from 12.4 to 17.2 kg N ha^{-1} at Boneo, and 46.7–48.3 kg N ha^{-1} at Clyde). The increase in NH_3 emission agrees with the range of increase (3–65%) reported for other agricultural soils treated with nitrification inhibitors (Qiao et al., 2015; Pan et al., 2016; Lam et al., 2017). Although NH_3 emission can be negligible from acidic soils, the adverse effect of nitrification inhibitors on the emission may still exist at localized zones of high pH due to urea hydrolysis (Zaman and Blennerhassett, 2010).

It is worth noting that the increase in NH_3 emission induced by DMPP application was greater at the vegetable farm at Boneo (39%) than at Clyde (3%). This could be attributed to the lower clay content and CEC of the Boneo soil than the Clyde soil (clay content: 1% vs. 14%; CEC: 6.9 vs. 15.0 cmol(+) kg^{-1}). The lower percentage of clay particles and lower CEC at Boneo resulted in less adsorption of NH_4^+ that was not nitrified under the DMPP treatment. As a result, unlike that at Clyde, the NH_4^+ maintained by DMPP application at Boneo was mostly volatilized as NH_3 rather than being adsorbed. This is evidenced by the DMPP-induced increase in soil NH_4^+ content at Clyde from 236.1 to 307.2 mg kg^{-1} ($p < 0.05$, Table 2) but the non-significant difference in NH_4^+ content between the DMPP-treated (31.1 mg kg^{-1}) and untreated (31.2 mg kg^{-1}) paddocks at Boneo (Table 2). This highlights the importance of soil texture and CEC on the effect of nitrification inhibitors on NH_3 emission (Kim et al., 2012).

4. Taking indirect N_2O emission into consideration

Approximately 0.2–5% (IPCC emission factor EF_4) of the NH_3 deposited from the atmosphere to the soil will be converted to N_2O