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On-farm trial on the effectiveness of the nitrification inhibitor DMPP indicates no benefits under commercial Australian farming practices

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ABSTRACT

The trend of increasing nitrogen (N) fertilisation in commercial agriculture demands mitigation of negative impacts on the environment, such as emissions of the potent greenhouse gas nitrous oxide (N_2O). Laboratory and controlled field experiments have demonstrated that the nitrification inhibitor 3,4-Dimethylpyrazole phosphate (DMPP) has the potential to effectively mitigate N_2O emissions from dairy pasture and crop farming, and may increase yields. Yet, this has not been investigated in on-farm research trials under commercial production conditions. During the winter growing seasons 2014–2016 we performed an on-farm trial on five commercial broad-acre cropping and five dairy farms in North-East Victoria, Australia, to compare the performance of DMPP + urea (treatment) against conventional urea (control) fertiliser in mitigating N_2O emissions and increasing crop and pasture yields. Application rate was fixed at the regional industry standard of 46 kg N ha^{-1}, yet timing, number of applications and all other management decisions were left to the judgement of the participating farmers. Emissions of N_2O were highly variable over time and between farms. We recorded emission spikes of up to 250 g N_2O-N ha^{-1} d^{-1}, but 90% of measurements ranged between 1.0–62 g N_2O-N ha^{-1} d^{-1}. Thus, N_2O emissions were dominated by peak fluxes and correlated with soil moisture and the time since fertiliser application. However, there was no significant difference between N_2O emissions from DMPP-treated and control plots in all three seasons. Similarly, crop and pasture yield did not differ significantly between treatment and control. It is likely that the high N application rate was responsible for the poor performance of DMPP under commercial production conditions. Consequently, simply replacing conventional fertiliser with a DMPP-containing product cannot be recommended. Any commercial application of DMPP will need to be accompanied by changes in fertiliser management, of which reducing the N application rate appears most promising.

1. Introduction

Modern agriculture depends on high external inputs of nitrogen (N) to maintain productivity, and inputs are projected to increase further (FAO, 2017). Fertilisation with N in its mineral form as either nitrate (NO_3^-) or ammonium (NH_4^+, commonly applied as urea) has greatly increased food security, but has also been identified as a cause of major environmental problems. Leaching of NO_3^- from soils into waterways is responsible for pollution of groundwater, surface waters and estuaries (Cameron et al., 2013). Gaseous losses of N from agricultural activities in the form of nitrous oxide (N_2O) are the most important source of this greenhouse gas to the atmosphere, and thus contribute significantly to global warming (Denman et al., 2007; Syakila and Kroeze, 2011). Furthermore, volatilisation of ammonia (NH_3) and subsequent atmospheric deposition can cause over-fertilisation of pristine ecosystems and indirect emissions of N_2O (Cameron et al., 2013; Lam et al., 2017).

A number of options exist to reduce losses of N and thus mitigate environmental impacts of N fertilisation, but there is little consensus on the best practice under a commercial farming regime, while maintaining and improving yields. Managerial interventions to reduce losses of N include optimisation of fertiliser application rates and timing, while technological interventions may involve the application of enhanced N fertiliser products, such as nitrification inhibitors (NIs; Chen et al., 2008; Luo et al., 2010). Nitrification inhibitors impair the activity of ammonia-oxidising soil bacteria that catalyse the first and rate-limiting step in the nitrification process, the oxidation of NH_4^+ to nitrite (Ward et al., 2011). Subsequent oxidation of nitrite to NO_3^- is generally not affected. A consequence of nitrification inhibitors is thus a longer residence time of the applied fertiliser in the form of NH_4^+, which readily binds to clay minerals and is thus better protected against

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leaching than the more soluble NO_3^-. Furthermore, inhibiting nitrification leads to reduced emissions of N_2O, a side product in the turnover of mineral N, both under oxic conditions during nitrification, and under anoxic conditions during denitrification (the reduction of NO_3 to N_2; Butterbach-Bahl et al., 2013; Ruser and Schulz, 2015). Nitrification inhibitors therefore reduce losses of N via several pathways, and as a consequence, more of the applied N is plant available (Abalos et al., 2014; Rowlings et al., 2016). Thus, an increase in crop and pasture yield is expected as an indirect outcome.

Among available nitrification inhibitors, 3,4-Dimethylpyrazole phosphate (DMPP; ENTEC©) appears to be a promising candidate for commercial application, as it is effective at low concentrations and thus relatively inexpensive, immobile and has no proven eco-toxicological side effects (Kong et al., 2016; Zerulla et al., 2001). Several recent global meta-analyses on the effect of nitrification inhibitors reported DMPP to be generally effective to reduce agricultural N_2O emissions and to increase yield (Akiyama et al., 2010; Feng et al., 2016; Gilsanz et al., 2016; Yang et al., 2016). Similarly, a number of recent field experiments in Australia discovered that DMPP effectively reduced N_2O emissions up to 75% (Kelly and Ward, 2016; Scheer et al., 2014; Suter et al., 2016a). However, this is contrasted by other Australian field studies that reported DMPP to be ineffective in mitigating N_2O emissions and increasing crop and pasture yield (Dougherty et al., 2016; Koci and Nelson, 2016; Rowlings et al., 2016). Furthermore, DMPP has also been linked to increasing N losses via volatilisation of ammonia (NH_3), which may lead to subsequent deposition and indirect N_2O emissions (Lam et al., 2017). Hence, there is growing uncertainty on the effectiveness of DMPP, particularly on a farm scale. This may relate to the fact that DMPP has mainly been tested in the laboratory, on experimental research stations or, at best, on a separated plot of a commercial farm, but with rigid control of all experimental factors and on a small spatial and short temporal scale. These conditions may not be representative for commercial farming enterprises, where the decisions on when, where and how much fertiliser is to be applied lies with the farmer and depends on a variety of external factors such as weather, market prices, and availability of machinery. Participatory on-farm trials have the advantage of integrating such practical, environmental, commercial and social factors when testing novel farming practices or products (Lawrence et al., 2007). While on-farm trials generally pose additional logistical and experimental challenges (Lawrence et al., 2007; Piepho et al., 2011), they provide a way to put new products or practices to the ultimate "real-life" test, and thus increase acceptance among the farming community (Crofoot, 2010; Guerin and Guerin, 1994). However, to our knowledge, DMPP has not been tested with a participatory on-farm trial under commercial production conditions in Australia and elsewhere.

Hence, our objectives were to investigate the potential benefits of DMPP, i) a reduction of N_2O emissions, and ii) an increase in yield, under typical commercial Australian farming practices for both dry land broad-acre cropping and dry land dairy farms. Farmers retained full control of the management, interventions into the farms' operational procedures were observational only. This allowed us to assess the "real-life" effectiveness of DMPP-amended fertilizers compared to business-as-usual practices in the important agricultural region of North-East Victoria in Australia.

2. Methods

2.1. Experimental sites

The DMPP fertiliser trial under commercial production conditions ran for three winter growing seasons in 2014–2016. Five broad-acre cropping farms (B) and five dairy pasture farms (D) were selected near Kiewa in North-East Victoria, Australia. The study area typically receives 700–900 mm rain each year (Bureau of Meteorology weather stations no. 082045, 82058 and 72023; Climate Data Online, http://www.bom.gov.au/climate/data/, accessed on 6/6/17). Rainfall is distributed throughout the year, but is typically highest in the winter months (Jun-Aug); this is also the main growing season, as hot and dry summer months (Dec-Feb) are common. Regional practice for non-irrigated pastures is to sow pasture species (dominantly ryegrass, *Lolium perenne* L.) in autumn (Mar-May), with paddock grazing during winter, and harvesting as conserved fodder during spring (Sep-Nov). Typical stocking rates for dairy farms are between 1.8-2.2 head ha^{-1}. For cropping farms, wheat and/or canola crops are sown in autumn, with the main growing period in winter and spring, and harvest in late spring or early summer. Farms in the trial were private commercial enterprises and participated freely with no economic incentives given, except that for participating farmers DMPP was available at urea market prices. Local agronomists liaised between research staff and farmers.

2.2. Experimental design

The on-farm experiment was planned as a multi-environment trial using a half-field design (Piepho et al., 2011). On each of the 10 farms, one field of ~8 ha for dairy and ~80 ha for broad-acre farms was subdivided into two adjacent plots, a "treatment" and a "control" plot of ~4 ha and ~40 ha each. To account for possible plot-scale heterogeneity, treatment and control plots were swapped on each farm from 2014 to 2015, and remained the same in 2016. The treatment plot was fertilised with urea fertiliser amended with the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP), the control plot was treated with urea fertiliser (Urea). Both fertilisers were spread with conventional machinery as part of the farms' common practice. Decision on the total amount and timing of fertiliser application was left to the judgement of the farmers. Amount of fertiliser spread was 100–200 kg urea ha^{-1} y^{-1} for broad-acre farms and 200–500 kg urea ha^{-1} y^{-1} for dairy farms, spread over 1–5 applications per year, each at 100 kg urea ha^{-1} (46 kg N ha^{-1}). Farmers notified the experimenters in advance or on the day the fertiliser was spread, and subsequent measurements were conducted within 1–3 days after application.

2.3. Nitrous oxide fluxes

Nitrous oxide fluxes were measured generally every 3–7 days for up to 11 times after each fertiliser application using the manual closed chamber method (Hutchinson and Mosier, 1981). Measurement days depended on the application of fertilisers by each farmer (which differed) and the logistics of being able to complete the measurement (not all farms could be reached and measured on the same day due to time restrictions). The chambers consisted of PVC cylinders with a radius of 7.5 cm and 15 cm height, mounted on a permanently installed collar inserted ~2–3 cm into the soil. Each plot had twelve chambers aligned in a straight line. After closing the chamber lid, four 20 mL gas samples per chamber were collected in 15 min intervals with a plastic syringe and injected into 12 mL gas-tight vials. Gas samples of chambers 1–4, 5–8 and 9–12 were combined in the field for each time interval using gas pooling (Arias-Navarro et al., 2013), resulting in three independent flux measurements per plot and sampling date. Concentrations of N_2O were determined using a gas chromatography system equipped with an electron-capture detector (GC-ECD; SRI Instruments, Torrance, CA, USA).

2.4. Soil parameters

For each N_2O flux measurement, soil moisture content was measured adjacent to the chamber using a handheld impedance probe (Theta Probe ML2, Delta-T Devices, Cambridge UK). Soil temperatures at 5 cm depth were measured on two locations next to the experimental plots using automated loggers (HOBO Pro v2, Onset Computer Corporation, Bourne, MA, USA). Soil samples from 0 to 10 cm depth were collected once for each farm and plot in 2014 and 2016, and regularly with every flux measurement in 2015, using a handheld soil corer. Note that when field access was restricted due to wet weather and saturated soils, no samples were collected. Sampled were oven-dried at 50 °C for 48 h and stored until completion of the project, then analysed in one batch. Dry soils were sieved to 2 mm, homogenised and extracted with 2 M KCl solution on an overhead shaker for 1 h. Mineral N concentrations (NO_3^- and NH_4^+) in filtered extracts were measured with segmented flow analysis. Other soil parameters (soil texture, pH, total N, total C) were determined for each farm from a carefully homogenised composite sample, with analyses conducted by an external laboratory according to standard protocols (CSBP laboratories, Bibra Lake WA, Australia)

2.5. Yield

For each farm and plot, yearly yield per hectare was determined with dry-matter cuts from 5 to 8 randomly selected 8 m^2 sub-plots. For broad-acre farms, this was done once each year, just before harvest. Grains from the cuts were harvested manually, thus values reported are grain yields. For dairy farms, plots were grazed several times each year. Cuts were done each time before grazing to calculate a growth rate, dividing dry-matter yield of each cut by time since last harvest. Growth rates were interpolated linearly and integrated over the measurement period for each plot, then scaled up to one year.

2.6. Statistical analyses

Fluxes of N_2O were calculated from concentrations based on linear regression. Regressions with a coefficient of determination < 0.8 were discarded; fluxes with a p-value < 0.1 were considered insignificant and thus set to 0. The few negative flux values that passed previous criteria were negligible in magnitude and thus set to 0 as well. Flux measurements were aggregated for each season by linear interpolation and integration. Aggregated flux measurements and yearly yields were then tested for treatment effects using a linear mixed-effects model with the treatment and year as fixed effects and individual plots nested within farms as random effect. In addition, individual flux measurements were tested for effects of soil moisture, temperature and days since fertiliser application (in addition to treatment and year) using a similar linear mixed-effects model. Residuals of the models were checked for normality, and variable transformations applied where checks indicated non-normality. Effects were considered significant for P-values < 0.05. All analyses were performed using R statistical software packages (Pinheiro et al., 2017; R Development Core Team, 2017; Wickham, 2011).

3. Results

3.1. Weather and soil conditions

Soil temperature was recorded on all farms throughout the trial period, while rainfall data was acquired from established weather stations in the region. The region of the study sites received average annual rainfall during the first two years of the trial, and above-average rainfall in the third year, although the distribution of rain throughout the year was atypical (Fig. 1). The first half of 2014 was wetter than most years, followed by a dryer winter and spring, and again a wetter summer. This somewhat inverse seasonal pattern compared to long-term observations was similar but less pronounced in 2015, while 2016 saw a dry autumn followed by wet conditions throughout the rest of the year. Soil temperatures at 5 cm depth oscillated between 5 and 30 °C and followed typical seasonal patterns, except for the warm (and dry) late summer and autumn in 2016.

In general, volumetric soil-moisture content was relatively high at all farms during the trial period (median was 0.32 $m^3\,m^{-3}$, with 0.25–0.36 1st to 3rd quantile), leading to good plant growth. For most farms, the highest soil moisture values (0.4–0.5 $m^3\,m^{-3}$) were observed at the start of the trial in autumn 2014, and the lowest values at the end of spring 2014 (Fig. 2). There was no significant and systematic difference in moisture content between treatment and control plots, although minor differences could be observed on certain days and farms.

Soil parameters differed little between farms (Table 1). All soils were dominated by sand (51–66%) with a clay content of 19–31%, and had a pH below 7. Organic C content and total N content was higher in pasture compared to cropping soil, leading also to a slight difference in the C:N ratio of 10–12 for cropping and 9–11 for pasture soil. In 2015 when regular soil sampling was conducted, total mineral N was highly variable and ranged between 15 and 330 mg N (kg dry soil)$^{-1}$ (Fig. 3). Ammonium was the dominating species, with concentrations ranging from 10 to 110 mg NH_4^+-N (kg dry soil)$^{-1}$, while NO_3^- was on average 5 times lower but more variable and ranging from 1.2–290 mg NO_3^--N (kg dry soil)$^{-1}$. There was no significant effect of treatment on NO_3^- and NH_4^+ concentrations. However, a significant negative correlation with days since fertilisation could be observed for NH_4^+, but not NO_3^-.

3.2. Nitrous oxide fluxes

Soil-atmosphere fluxes of N_2O were highly variable, within and between farms in each of the three measurement years (Fig. 4). The vast majority of fluxes were emission to the atmosphere, with 90% of measurements ranging between 1.0–62 g N_2O-N $ha^{-1}\,d^{-1}$. The overall mean flux was 16.7 g N_2O-N $ha^{-1}\,d^{-1}$, but 75% of all values were lower; the median was 8.7 g N_2O-N $ha^{-1}\,d^{-1}$. Generally dairy farms had higher N_2O emissions compared to broad-acre farms; however, in 2015 emissions were similar (Fig. 4). The highest N_2O fluxes generally occurred within the first few days after fertilisation, then values decreased with increasing days since fertilisation (e.g. Fig. 2). The highest fluxes were measured in 2014 on dairy farms, with peak values up to 250 g N_2O-N $ha^{-1}\,d^{-1}$. However, some emission spikes of > 100 g N_2O-N $ha^{-1}\,d^{-1}$ also occurred in other years after fertilisation. Up-scaled yearly N_2O fluxes ranged from 0.3–16 kg N_2O-N $ha^{-1}\,y^{-1}$ for broad-acre farms, and 0.3–35 kg N_2O-N $ha^{-1}\,y^{-1}$ for dairy farms. Note that the measurement period did not include the dryer summer months where N_2O fluxes are expected to be lower.

Plots treated with DMPP had similar N_2O emissions compared to control plots, regardless of the magnitude of fluxes, although there were some differences on individual days and farms (Figs. 2 and 4). Overall there was no discernible and statistically significant treatment effect on N_2O fluxes, neither on yearly aggregated N_2O fluxes (P = 0.9), nor when testing individual flux measurements (P = 0.92). Individual N_2O fluxes correlated best with soil moisture and days after fertilisation (both P < 0.001), while soil temperature had no significant effect (P = 0.17). When testing only data from 2015 and including mineral N in the model, mineral N had no significant effect on N_2O fluxes (P = 0.28).

3.3. Crop and pasture yields

Mean yields for the trial years for both broad-acre and dairy farms were determined from regular (pasture) or yearly (crop) dry-matter cuts (Fig. 5). Broad-acre farms were rotating crops between growing season, thus yields are reported separately for wheat and canola. The year 2014 resulted in twice the average pasture production (12 t $ha^{-1}\,y^{-1}$) compared to 2015 and 2016 (5.9 and 7.4 t $ha^{-1}\,y^{-1}$, respectively). For broad-acre farms 2015 was a slightly better year compared to 2014 and 2016, but differences were marginal. A higher pasture production was observed in DMPP plots in 2014, but this could not be confirmed in 2015 and 2016. Similarly, mean yields for canola and wheat in 2015 appeared to be marginally higher on DMPP fertilised plots. Combining data from all years, there were no statistically significant differences between DMPP and urea fertilised plots (P = 0.73).

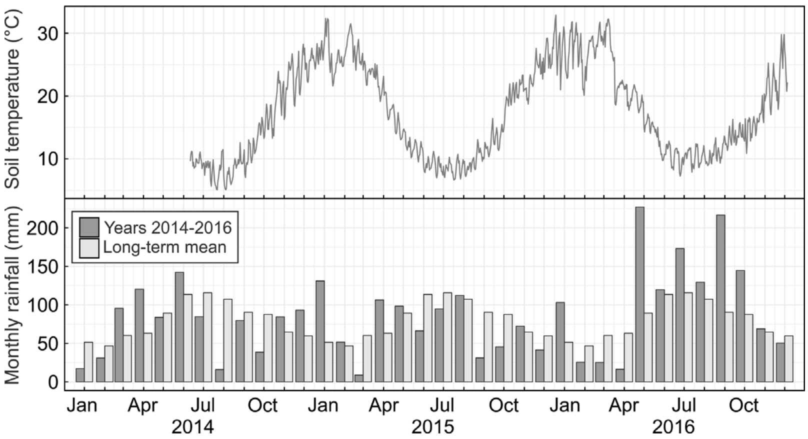

Fig. 1. Mean soil temperatures measured on participating farms at 5 cm depth from the start of the trial in May 2014 until completion in Dec 2016 (top panel); and monthly rainfall in the years of the trial and (dark grey bars) long-term monthly mean (years 1889–2017) (light grey bars) for the Yackandandah weather station located in the vicinity of the participating farms (bottom panel).

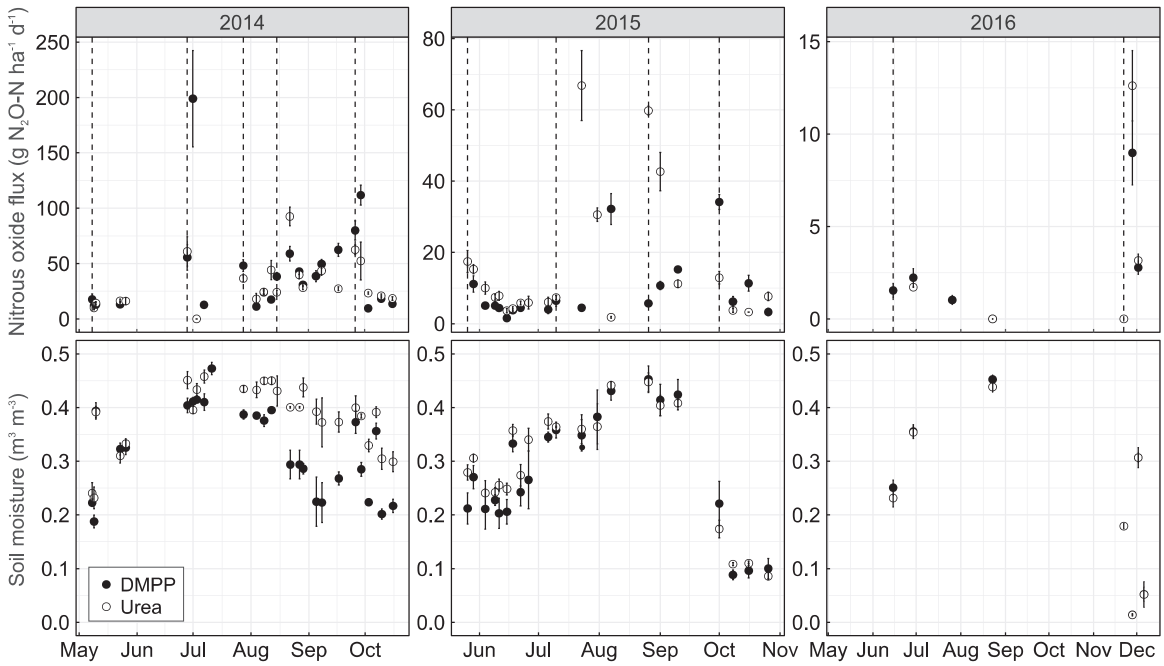

Fig. 2. Time series of nitrous oxide fluxes and soil moisture measurements for dairy farm D5 on DMPP treated plots (closed symbols) and control plots (open symbols) as an example of typical farm-based emissions and soil moisture contents. Vertical dashed lines indicate days of fertiliser application. Error bars indicate standard error of the mean of triplicate measurements on each plot. Flux measurements that did not meet the quality criteria outlined in Section 2.6 were discarded. Note the different scale of the y-axis for each year.

Table 1
Soil parameters of the farms participating in the trial. Farms B1-5 were broad-acre farms and farms D1-5 were dairy farms.

Farm	Texture class	pH ($CaCl_2$)	Electrical conductivity (ds cm-1)	Total nitrogen (%)	Organic carbon (%)	C:N ratio
B1	Sandy Clay Loam	4.9	0.045	0.15	1.5	9.9
B2	Sandy Clay Loam	5.7	0.068	0.12	1.2	10
B3	Sandy Clay Loam	5.7	0.092	0.16	1.6	10
B4	Sandy Loam	6.3	0.084	0.18	2.0	11
B5	Sandy Clay Loam	5.1	0.065	0.20	2.3	12
D1	Sandy Clay Loam	4.2	0.092	0.31	3.3	11
D2	Sandy Clay Loam	4.8	0.081	0.27	2.7	9.8
D3	Sandy Clay Loam	4.5	0.064	0.29	2.9	10
D4	Sandy Clay Loam	5.1	0.085	0.30	2.8	9.2
D5	Sandy Clay Loam	4.8	0.087	0.28	2.5	8.9

4. Discussion

The central aim of this on-farm trial was to assess the effectiveness of the nitrification inhibitor DMPP to reduce on-farm emissions of N_2O and to increase yield under commercial production practices for dry land dairy and broad-acre crop farming. After three years of measurements on five dairy farms and five broad-acre farms it was apparent that under current commercial production practices DMPP was ineffective in reducing emissions of N_2O, and equally ineffective in increasing crop yield or pasture production. There was no statistically significant difference in the magnitude of N_2O emissions between the two treatments, neither when all farms were considered, nor when

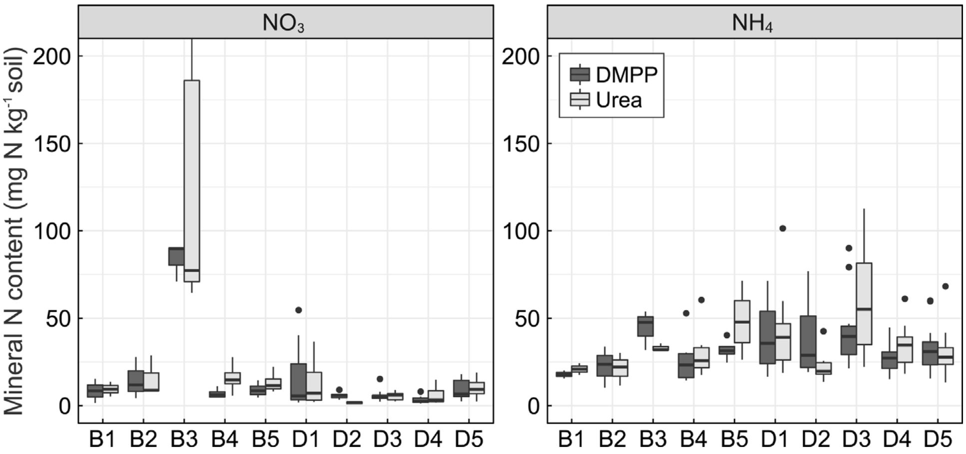

Fig. 3. Concentrations of nitrate (NO_3) and ammonium (NH_4) in soils of each farm in the year 2015.

selecting individual farms. Hence, our study confirms the growing number of recent Australian field studies where DMPP was also ineffective in mitigating N_2O emissions and increasing crop and pasture yield (Dougherty et al., 2016; Koci and Nelson, 2016; Rowlings et al., 2016). A number of recent global meta-analyses on the effect of nitrification inhibitors highlight the strong dependency of the effectiveness of DMPP on managerial factors (type of fertiliser, fertilisation rates, method of application, number of applications) and environmental conditions (soil moisture, soil pH, soil texture) (Akiyama et al., 2010; Feng et al., 2016; Gilsanz et al., 2016; Yang et al., 2016). We attribute a combination of commercial farming practices and environmental factors to be responsible for the lack of effectiveness of DMPP to reduce N_2O emissions or increase yield.

Farms in this trial applied N fertiliser in the form of urea at 46 kg N ha^{-1}, which is considered industry standard in the region. Several recent Australian studies compared DMPP with urea at similar application rates and reported no effect of DMPP fertilisation on N_2O emissions (Dougherty et al., 2016; Friedl et al., 2017; Koci and Nelson, 2016). Similar (negative) results were obtained when crop or pasture yield was investigated (Dougherty et al., 2016; Kelly and Ward, 2016; Koci and Nelson, 2016; Rowlings et al., 2016; Suter et al., 2016b). Interestingly, when the fertiliser application rate was halved, DMPP significantly increased yield compared to conventional urea, up to levels achieved with the standard application rate (Koci and Nelson, 2016; Rowlings et al., 2016). Reducing the N application rate is also one of the most effective ways to significantly reduce N_2O emissions, as any N input above plant uptake capacity causes N_2O emissions to rise exponentially (Kim et al., 2013; Shcherbak et al., 2014). The practice may also bear the potential of reducing indirect N_2O emissions following DMPP applications, resulting from increased NH_3 volatilisation (Lam et al., 2017). We measured high mineral N contents and calculated unusually high emission factors (0.3-35%) particularly on dairy farms in 2014, compared to controlled field trials (e.g. Dougherty et al., 2016; Kelly and Ward, 2016). Thus, N levels were likely above plant needs during most of our trial (certainly in 2014 on dairy farms), and additional N input triggered the observed episodic rise in N_2O emissions (Figs. 2 and 4). Pastures received substantial additional N input during grazing in the form of urine, which is difficult to quantify, unevenly distributed and in combination with trampling can significantly increase N_2O emissions (Ball et al., 2012; Giltrap et al., 2014). This was probably the main cause for the high and highly variable N_2O emissions and emission factors in 2014 on dairy farms, especially in combination with the abundant autumn rain and thus high soil moisture conditions. In addition, dairy farmers applied more fertiliser in 2014 than in other years, possibly wanting to make use of the good winter conditions; a clear indication that farmers tend to over-fertilise to avoid N limited soil conditions. Yet, DMPP is most effective under N limited conditions, when residual N content is low and plants can directly benefit from reduced N loss (Rowlings et al., 2016). Thus, simply replacing urea with DMPP under prevailing farming practices with standard application rates cannot be recommended.

The significant correlation of N_2O emissions with soil moisture and days after fertiliser application reflects our current understanding of the underlying mechanisms (Butterbach-Bahl et al., 2013). The soil moisture level on our study sites was generally high (30–40 vol%) and sometimes close to saturation throughout most of the winter season, a result of the above-average autumn rains in the region of our trial (Figs. 1 and 2). Consequently, N_2O emissions were highly variable and at the higher end of previously reported values in Australian agricultural systems, specifically in 2014 (Dalal et al., 2003; Harris et al., 2013; Kelly and Ward, 2016; Mielenz et al., 2016). The lack of a significant treatment effect can be partially related to high soil moisture contents: DMPP is often less effective in moist soils (Chen et al., 2010; Menéndez et al., 2012) and ineffective at soil moisture contents close to

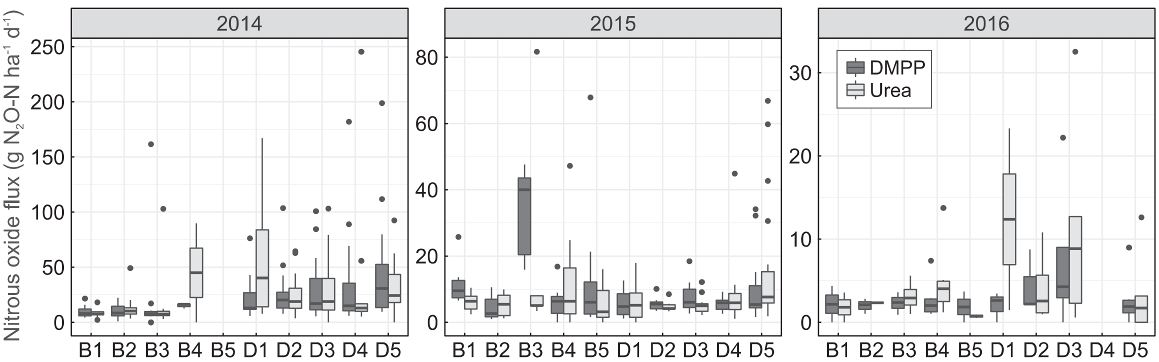

Fig. 4. Boxplots of daily N_2O fluxes for each farm and trial year for DMPP treated plots (dark boxes) and control urea fertilised plots (light boxes). Note the different scale of the y-axis for each year.

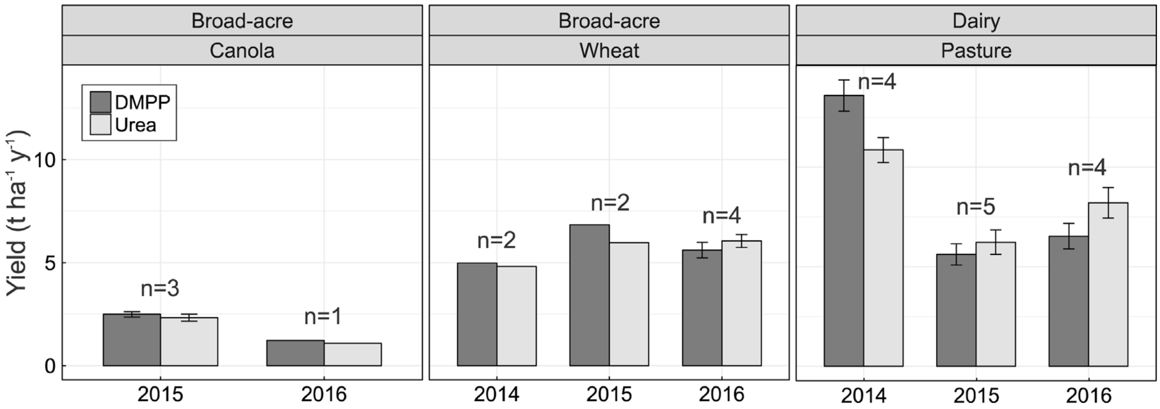

Fig. 5. Mean grain and dry-matter yield separated by farming system, crop and year for DMPP treated plots (dark bars) and urea control plots (light grey bars). Treatment and control plots were switched from 2014 to 2015, then remained in 2016. Crop yields are harvested grain yield; pasture yields were calculated by integrating growth rates of several dry-matter cuts over the winter season, then scaled up to one year. Error bars depict standard error of the mean.

saturation (Menéndez et al., 2009). Ideally, fertiliser application should thus be matched with lower rainfall and soil moisture, which not only improves DMPP efficiency but also reduces NO_3^- leaching and peak N_2O emissions due to denitrification (McTaggart et al., 1994). However, prevailing practice is to apply fertiliser shortly after rain to ensure sufficient N availability when plant water limitation is relieved. This makes it unlikely that DMPP can significantly reduce N_2O emissions in Australian high-rainfall areas without optimising fertiliser application timing.

Soil temperature has been identified as an important control on the effectiveness of DMPP, with the majority of studies reporting decreasing DMPP effectiveness, possibly due to microbial degradation, when temperatures increase above 20 °C (Chen et al., 2010; Irigoyen et al., 2003; Zerulla et al., 2001). However, soil temperatures during our trial measurement seasons were rarely above 20 °C, and generally around 10 °C during periods with peak N_2O emissions in June-July. It is thus unlikely that soil temperature reduced the effectiveness of DMPP in a significant way during our trial. Yet, other soil parameters can also affect DMPP performance. Controlled laboratory experiments and recent meta-analyses have found DMPP to be less effective in acidic soils (Barth et al., 2001; Feng et al., 2016; Liu et al., 2015; Yang et al., 2016). In laboratory incubations of 30 Australian soils pH was positively correlated with the inhibitory effect of DMPP on nitrification and N_2O emissions (Suter et al., 2016a). Soils on our farms all had a pH < 6.5 (Table 1), thus soil conditions for DMPP applications were unfavourable. High acidity is also linked to aluminium (Al) toxicity, thus most farmers in the region regularly apply lime to control pH; yet, they accept a sub-optimal pH due to the high costs associated, and generally rely on Al-tolerant species (Scott et al., 2000). However, given that other field experiments on similar soils and climates reported DMPP to be effective in reducing N_2O emissions (Kelly and Ward, 2016), soil and environmental conditions other than soil moisture seem of minor importance in influencing DMPP performance, compared to managerial factors.

This study was carried out under on-farm conditions that were less optimal than rigorously controlled small-scale scientific experiments. Compared to the latter, the current study likely introduced additional variability due to the irregular timing of fertiliser application, the large plot sizes, surface application of the granular fertiliser with large machinery, and other unknown farm-specific factors. However, we aimed to minimise any errors in fertiliser application by keeping the experiment as simple as possible, and including a sufficient number of farms made sure the experimental design of the study was robust enough to test the effectiveness of DMPP under "real-world" conditions. In addition, the trial had the support of the local farming community, and farmers were motivated and diligent in their participation, which reduced the risk of misapplications and mismanagement.

In summary, merely replacing conventional urea with DMPP-amended urea fertiliser is not an effective strategy to reduce greenhouse emissions in dry land dairy and broad-acre farming systems in South Eastern Australia. It is also unlikely to gain popularity among farmers, as they will not be able to recoup the 20–30% higher costs for DMPP-amended urea fertiliser when using industry standard application rates. Even in experiments where DMPP application led to reduced N losses and a gain in yield, a cost-benefit analysis revealed only small monetary gains (Yang et al., 2016). Furthermore, as DMPP is ineffective in reducing GHG emissions under current fertilisation practices, farmers will not be able to gain carbon credits under GHG abatement programs. However, the necessary increase in crop or pasture yield to recoup additional costs for DMPP is only 1–5%, according to a simple calculation that is based on average yield in 2014–2016, average Australian commodity prices from 2014 to 2016 and assuming a direct gain in milk production of 0.17 kg milk solid for each additional kg dry matter feed (National Research Council, Subcommittee on Dairy Cattle Nutrition, 2001). This is well within the typical variability between years, thus the risk of significant losses when using DMPP is low. Furthermore, as demonstrated by Koci and Nelson (2016) and Rowlings et al. (2016), conventional N fertilisation rates can potentially be reduced by half (from 46 kg N ha^{-1} to 23 kg N ha^{-1}) without significant losses in yield when using DMPP-amended urea. With the current price difference between DMPP-amended and conventional urea, farmers would save 30% costs in fertiliser when switching to DMPP-amended urea at half the current application rates. Such a practice bears high potential to reduce N leaching and gaseous losses to the environment while giving farmers the necessary incentive to change current fertiliser management. In addition, in regions with acidic soils such as North-East Victoria, the use of legumes as an alternative management option to mineral N fertilizers is limited: legumes can cause additional soil acidification (McLay et al., 1997), while nodulation and symbiotic N fixation is diminished (Zahran, 1999). Thus, further on-farm trials with DMPP and urea applied at reduced rates are highly encouraged.

5. Conclusion

Our results clearly demonstrate that simple replacement of urea fertiliser with a DMPP-amended product is ineffective in reducing agricultural N_2O emissions under current Australian commercial crop and dairy farming practices. The employed on-farm trial design has been a useful compromise to incorporate farmer-led management decisions into experimental research on cropping and dairy farming as practiced "on the ground". We thus advocate for future on-farm trials with DMPP and urea at half the industry's standard fertiliser application rates; a practice that has been shown to maintain and even increase crop and pasture yield in controlled research trials, with the potential of significant cost-savings for farmers. Furthermore, DMPP at reduced fertiliser application rates may offer the farmer a further incentive via potential gains through carbon credits, but this remains to be adequately quantified. Yet, under current fertilisation practices DMPP cannot be recommended as an effective option within GHG abatement programs.

Conflicts of interest

None.

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