Nitrous oxide emissions from wheat grown in a medium rainfall environment in SE Australia are low compared to overall nitrogen losses

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Abstract
Efficient management of nitrogen (N) is critical to the profitability and sustainability of agricultural systems. Losses of N can both reduce productivity and in the case of nitrous oxide (N_2O) emissions contribute to global warming and ozone depletion. The limited number of studies from medium rainfall cropping systems have indicated that N_2O losses tend to be low to moderate, but that there is the potential to reduce these losses through altered fertiliser management. This study investigated the magnitude of N_2O flux from a medium rainfall cropping system in south eastern Australia and the potential to mitigate N_2O losses through altered timing (at sowing compared with in-season) of N application and the use of both nitrification and urease inhibitors. This study also measured overall N fertiliser losses and crop productivity. Losses of N_2O and overall fertiliser losses were measured using static chamber and ^{15}N mass balance techniques respectively, as part of a field experiment conducted in the Victorian Wimmera during 2012. Cumulative N_2O loss from sowing until harvest of the wheat crop amounted to between 75 and 270 g N_2O-N/ha with fertiliser application significantly increasing losses. In contrast, total losses of fertiliser N ranged from 7-11 kg N/ha (14-22% of applied N), indicating that N_2O losses were low in comparison to both crop requirements and overall N losses.

Key Words
Nitrous oxide, fertiliser recovery, wheat, static chamber, ^{15}N mass balance

Introduction
Nitrous oxide (N_2O) is one of the major greenhouse gases emitted from Australian agriculture, constituting 15.5% of all agricultural emissions (Department of the Environment, 2015). It also represents the loss of a vital nutrient. N_2O is produced by a range of biochemical pathways within soils and in agricultural systems one of the major factors affecting these losses is nitrogen (N) fertiliser application (Shcherbak, Millar et al. 2014). It is important therefore to identify options to reduce N_2O loss through altered fertiliser strategies; however these strategies also need to be scrutinised from the perspective of overall N losses and the impact on crop productivity. While various studies have monitored N_2O loss from cropping systems in semi-arid environments (Barton, Kiese et al. 2008), few have assessed how fertiliser management strategies such as altered timing or the use of inhibitors affect N_2O loss in these systems despite studies showing their effectiveness in other environments (Ding, Yu et al. 2011). This study investigated the impact of altered N fertiliser management on N_2O flux and overall losses of applied N as well as crop productivity of wheat grown in a medium rainfall environment in south eastern Australia.

Methods
Experimental site, design and crop management
Nitrous oxide emissions, crop growth and fertiliser recovery were measured from a wheat crop grown during 2012 in the Wimmera region of Victoria (36°47’31.06”S, 142°23’38.48”E). The site was located on a Grey Vertosol (Isbell 2002) with low levels of total carbon and nitrogen and organic carbon (1.1%, 0.12% and 0.96% respectively in 0-10cm). Topsoil pH was neutral (7.5, $CaCl_2$), total mineral N (NO_3^- and NH_4^+) at sowing was 73kg N/ha (±5) to 120 cm and plant available water at sowing was 26 mm (±9) to 140 cm. The Wimmera region has a semi-arid climate with winter dominant rainfall and warm, dry summers. Mean annual and growing season (April-October) rainfall at the site is 444 mm and 309 mm respectively (Bureau of Meteorology 2015). The experiment comprised a complete randomised block design with five treatments replicated five times. Treatments included four N management strategies applied at a rate of 50 kg N/ha: urea banded 25 mm below the seed at sowing (50N), urea treated with 3,4-dimethylpyrazole phosphate (DMPP)

banded 25 mm below the seed at sowing (50N DMPP), urea surface applied during tillering (0:50N) and urea treated with n-butyl thiophosphoric triamide (NBPT) surface applied during tillering plus an unfertilised control (0N). Wheat (*cv.* Gregory) was sown on the 6^{th} of June. Harvest occurred on the 13^{th} of December with quadrats (approximately $1m^2$) taken from each plot to collect all above ground biomass. Samples were dried until constant weight at 70°C before being threshed to separate grain from straw. Both straw and grain samples were fine ground before being analysed for total N by dry combustion (LECO).

Measurement of nitrous oxide flux

N_2O fluxes were measured using paired static chambers constructed of 250 mm diameter PVC tube. Sampling was undertaken prior to sowing, 1, 2, 7, 14, 21 and 28 days after sowing and monthly thereafter until harvest with the exception of sampling undertaken prior to, 1, 3 and 8 days after application of the 0:50N and 0:50N NBPT treatments. Additional samples were taken from a subset of plots (3 replicates of the 0N and 50N treatments) on a weekly basis from 15 August until 5 December. Gas samples were collected over a period of 1 hour between 9am and 1pm with three samples taken each hour and stored in 12 mL glass exetainers until analysis using an automated gas chromatograph (Agilent 7890A, Agilent Technologies Inc. Wilmington, USA. Soil samples were also taken from each plot at the time of N_2O sampling at depths of 0-5 and 5-10 cm to quantify soil water filled pore space (WFPS) and mineral N. Soil WFPS (0-5 cm) and temperature was also monitored in the 50N plots using continuous logging theta and temperature probes (Delta-T Devices Limited, Cambridge, UK). N_2O fluxes were calculated based on the linear increase in headspace gas density according to the method of Harris, Officer et al. (2013). Daily flux data were analysed using a residual maximum likelihood (REML) approach. Correlation analysis (two-sided test) was carried out comparing daily N_2O flux values to soil variables (WFPS, mineral N and temperature). Cumulative N_2O flux was calculated based on linear interpolation between sampling days excluding samples taken on a weekly basis from the 0N and 50N treatments for consistency across treatments.

^{15}N mass balance study

Steel micro-plots (53 x 30 cm) were inserted into the unfertilised buffer at the end of each plot to a depth of 20 cm. ^{15}N enriched (10% a.e.) urea was dissolved in water and applied at the same rates, timing and placement as the main plots including application of DMPP and NBPT where relevant. Micro-plots were harvested and processed in the same way as quadrats from the main plots. Soils from within each micro-plot were completely excavated at depths of 0-10 and 10-20 cm with additional cores taken from 20-40 cm. Soils were dried at 40°C then thoroughly mixed and subsampled prior to fine grinding in preparation for analysis. Plant and soil samples were analysed for total N and $\delta^{15}N$ by IRMS (SERCON 20-22, Sercon, UK) with samples from the 0N plots used to quantify natural abundance of ^{15}N. Fertiliser recovery was calculated using the approach of Malhi, Johnston et al. (2004) and analysed by ANOVA.

Results

Daily N_2O flux was low throughout the monitoring period, peaking at 4.1 g N_2O-N/ha/day in July (Figure 1). N_2O flux varied significantly ($P<0.05$) across the season with lowest flux rates measured from October onwards when WFPS (%) was typically <30%. Similar N_2O flux levels and seasonal dynamics were observed in the Wimmera by Officer, Phillips et al. (2015). Changes in N_2O flux were positively ($P<0.05$) correlated with soil WFPS (0-5 and 5-10 cm) and soil nitrate (5-10 cm) and negatively correlated with soil temperature. There was a trend towards higher daily flux rates from the 50N treatment compared to the 0N control during the winter peak, but fertiliser treatment did not significantly affect daily N_2O flux rates across the season.

Cumulative N_2O flux across the season was 0.075 kg N_2O-N/ha and 0.236 kg N_2O-N/ha for the 0N control and 50N treatment respectively (data not shown). Delaying fertiliser application until GS30 reduced cumulative N_2O flux compared to 50N as did the use of DMPP nitrification inhibitor where N was applied at sowing. Overall the magnitude of flux measured in this experiment was similar to that measured by studies from semi-arid environments such as Barton, Kiese et al. (2008) and significantly lower than studies from high rainfall cropping systems (Harris, Officer et al. 2013).

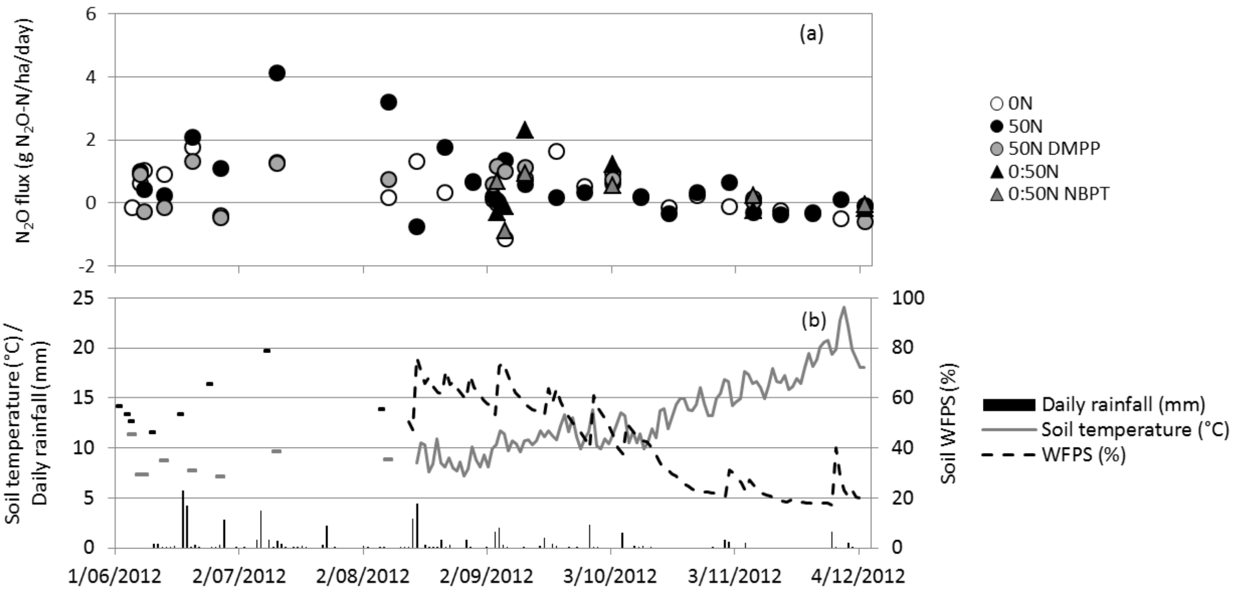

Figure 1. Daily N_2O flux for various N fertiliser management treatments, daily rainfall, soil temperature* (0-5 cm) and soil WFPS* (0-5 cm, %).
* Soil temperature and WFPS data prior to 15-August based on soil samples taken at the time of N_2O sampling. Measurements after 15-August are based on continuous logging theta and temperature probes installed in the 50N treatment.

Total recovery of applied fertiliser at harvest ranged from 78-86%; similar to studies such as Abdel Monem, Lindsay et al. (2009), however differences between treatments were small (Figure 2). There was a statistically significant ($P<0.05$) reduction in recovery of fertiliser N in soil (10-20 cm) where N was applied at GS30 rather than at sowing irrespective of the use of nitrification or urease inhibitors. Applying N when crop demand was higher and soil water content was trending downwards (Figure 1) appeared to reduce the likelihood of N being leached below 10 cm prior to crop uptake. Crop uptake (straw and grain) of applied N ranged from 49-54% of applied N (data not shown) which is at the higher end of the estimates of Abdel Monem, Lindsay et al. (2009) which was conducted in a similar environment.

Total loss of applied N based on ^{15}N data, ranged from 7-11 kg/ha; far greater than cumulative N_2O loss which was <0.3 kg N_2O-N/ha indicating that some other loss mechanism/s were responsible for the measured loss. While WFPS was not generally high enough to be conducive to prolonged periods of denitrification, studies such as Weier, Doran et al. (1993) indicate that denitrification can release N_2 at significantly higher rates than N_2O under appropriate conditions and in the current study this may have occurred in short bursts as suggested by Groffman, Butterbach-Bahl et al. (2009). Soil cores taken at a depth of 20-40 cm also indicated a significant ($P<0.05$) increase in $\delta 15N$ compared to natural abundance samples for the 50N and 50N DMPP treatments, suggesting movement of N below 20 cm. Where N was surface applied at GS30 there was potential for losses to ammonia volatilisation (Turner, Edis et al. 2012). In this case N was applied to moist soil and rainfall in the 4 days following application amounted to 16 mm which may partly explain the relatively low measured losses. Use of inhibitors showed little reduction of fertiliser losses despite other studies suggesting their utility, although this may be related to the low magnitude of losses overall.

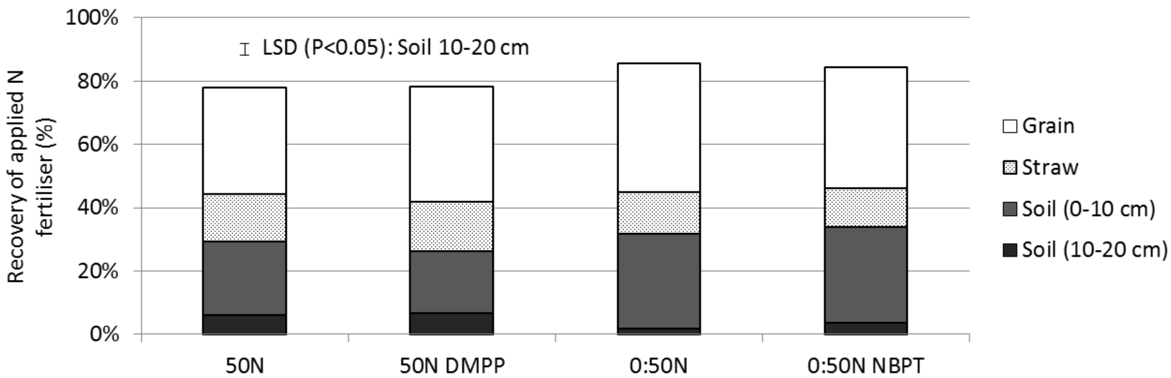

Figure 2. Recovery of applied N fertiliser in soil and above ground biomass at harvest for various fertiliser management treatments.

Fertiliser application significantly increased grain yield ($P<0.05$) from 2800 kg/ha (0N) to 3700-4600 kg/ha where N was applied, highlighting the importance of N fertiliser addition to these farming systems in years with average yield potential (Table 1). Total above ground N uptake also increased significantly following addition of fertiliser N with the proportion of N derived from fertiliser ranging from 29.5-34.3%, however differences amongst fertiliser treatments were not statistically significant. Cumulative N losses as N_2O were clearly low in comparison to the amount of N required to maintain the crop.

Conclusion

This study suggests that in a medium rainfall cropping system of western Victoria losses of N as N_2O are low compared to the overall N requirements of the wheat crop. N_2O losses also appear to be a minor contributor to overall losses of applied N. This presents a challenge to policy makers and industry as the environmental impact of N_2O loss can be much higher than its productivity impact, hindering the case for mitigation. We suggest that successful reduction of N_2O loss will result from the development of practices that profitably increase overall N use efficiency; reducing more than just N_2O loss. Examples may include greater understanding of seasonal forecasts to better predict yield potential and precision placement of fertiliser such as side-banding in season to potentially reduce microbial tie-up and losses.

Acknowledgements

This study was funded by DEDJTR, the GRDC and the Department of Agriculture and Water Resources (Project DAV00125). The authors wish to thank Fischer family for hosting this experiment and Debra Partington for guidance in relation to statistical analysis. They also wish to acknowledge the technical assistance provided by Mel Munn, Liana Warren and Roger Perris.

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