Can agronomic management mitigate N_2O loss from high rainfall cropping systems?

Rob Harris[1], Sally Officer[1], Trish Hill[2], Roger Armstrong[2] and Deb Partington[1]

[1]Department of Primary Industries Victoria, Hamilton Vic 3300. rob.harris@DPI.vic.gov.au,
[2]Department of Primary Industries Victoria, Horsham Vic 3400.

Abstract
The impact of agronomic management on nitrous oxide (N_2O) emissions and income from wheat and canola planted on raised beds, two and three years after conversion from long-term pasture, was studied in south west Victoria. Management included four different rates of nitrogen (N) fertiliser, top-dressed with and without the nitrification inhibitor DCD (Dicyandiamide), which was applied in solution to the soil during the canola crop. Grain yields were measured, and static chambers used to identify relative differences in N_2O loss between agronomic managements. In the second crop following conversion (wheat), N_2O losses were up to 72% lower (P<0.05) in the furrows, receiving the lower rate of N fertiliser (LN, 25 kg/ha) compared with the highest rate (VN, 100 kg/ha), with less frequent reductions observed in the third crop (canola). Losses of N_2O from the beds appeared unaffected by N rate, perhaps from excess nitrate leakage into the adjacent furrows. Furthermore, the extra N did not significantly increase grain yield in either the wheat or the canola crops. The application of DCD in the canola crop reduced (P<0.05) N_2O production by up to 84% from the beds and 83% from the adjacent furrows, but did not affect grain yield, instead significantly (P<0.001) reducing canola income by $1407/ha, compared with no addition of inhibitor. Management will play some role in N_2O mitigation, but DCD application appears uneconomical; matching N fertiliser supply to meet crop demand could be a better option for avoiding unnecessary N_2O losses from high rainfall cropping.

Key Words Nitrous oxide, wheat, canola, water-filled pore space, raised bed, static chamber

Introduction
N_2O is a greenhouse gas capable of absorbing 300 times as much infra-red radiation per kilogram than carbon dioxide. Approximately 60% of annual global N_2O emissions occur from soil microbial activity (Mosier *et al*. 1998), largely a result of nitrification, where soil bacteria convert ammonium (NH_4) into nitrate (NO_3) in which N_2O is a by product, and denitrification, where soil microbes 'steal' oxygen from NO_3 under anaerobic conditions converting it into gaseous forms, including N_2O (Dalal *et al*. 2003). Denitrification takes place in soils when demand for oxygen exceeds supply, such as waterlogged conditions. Soil physical properties influence pore space, and as pores fill with water, oxygen diffusion is restricted. Therefore the proportion of water-filled pore space (WFPS) dictates oxygen diffusion and the potential rate of N_2O loss (Dalal *et al*. 2003). Normally when WFPS is below 40%, N_2O production is low, but increases rapidly as WFPS approaches 80% (Ciarlo *et al*. 2007), thereafter generally declining as N_2 becomes the major form of gas loss (Bouwman 1998). Other variables can also influence the rate of N_2O production, including soil temperature, soil organic carbon (C) and soil nitrate (NO_3) supply (Dalal *et al*. 2003).

Farming systems with high soil C and nitrogen (N) stores that are prone to prolonged periods of waterlogging are likely to produce high quantities of N_2O. In the high rainfall zone (>650 mm) of south west Victoria, paddocks are sometimes converted from long-term (>5 years) legume-grass pasture to wheat or canola. These paddocks have high soil organic C (>3.5%) and often experience prolonged waterlogging. Zhang *et al*. (2004) estimated up to 300 kg N/ha mineralising after the transition from long-term pasture legumes to cropping in south west Victoria. While previous research provides us with an understanding of the conditions that can create high N_2O loss, the role of agronomic management for reducing emissions remains unclear. This paper seeks to evaluate the role that agronomy might play in N_2O abatement, by comparing emissions and crop productivity under different strategies, imposed on a cropping paddock at Strathkellar in south west Victoria. The strategies include different rates of N fertiliser applied with and without the nitrification inhibitor (DCD – Dicyandiamide), to crops grown on raised beds.

Methods
The experimental site was in a long-term (10 year) mixed perennial grass subterranean clover pasture, followed by a wheat crop in 2009. Raised beds were constructed in autumn 2010, with beds 2 m wide and adjacent furrows 20 cm deep. The experiment was then imposed consisting of eight main treatments

replicated three times in a two factor, factorial design, including four N fertiliser rates: low (LN), medium (MN), high (HN) and very high (VN) input applied with and without DCD. Plots were 6 x 15m in dimension. Urea was top-dressed by hand at 25, 50 and 100 kg N/ha to the MN, HN and VN treatments respectively, on 23 August in both years. An additional 46 kg N/ha as urea was also top-dressed on 14 September 2010 and 21 kg N/ha was applied as sulphate of ammonia on 22 August 2011; both times by aeroplane, across all treatments. DCD was applied to canola at 10 kg/ha in solution to the soil on 3 June and 24 August 2011. Wheat cv. Pugsley was sown on 21 May 2010 and canola cv. Garnet on 3 May 2011, with a basal of 14 and 17 kg N/ha as DAP (Diammonium Phosphate), respectively.

The grain yield of wheat was measured by mechanically harvesting, and canola by hand harvesting before windrowing, followed by drying (30^{o}C) and threshing to separate seed from stubble. Variable costs of $350 and $450/ha were assumed for respective wheat and canola crops; urea and sulphate of ammonia fertiliser were $500 and $575/t respectively and each application of DCD cost $666/ha. Returns from Australian Premium White wheat with 10.5% grain protein and canola with 42% oil content, were those that applied in February 2011. Partial budgets were calculated by multiplying grain yield by price less associated costs.

N_2O was captured in vented static chambers, constructed from 25 L PVC canoe drums (internal diameter of 300 mm), , with the base cut off which were inserted into the soil to a depth of 5 cm, between crop rows in the LN, HN and HN+DCD treatments. A rainfall collector was built to funnel all available rainfall into the chamber over the same diameter as the base. When gas sampling, the rainfall collector was replaced with a canoe lid, fitted with an 'S' valve and rubber septum, and a battery powered computer fan provided continuous gas circulation. The valve filled with water released any pressure built up during sampling. In each plot, two chambers were installed one on the bed top and one on the adjacent furrow. Fluxes were measured between 10 am and 2 pm, with 20 ml air samples collected by syringe at 0, 20, 40 and 60 minute intervals and injected into 12 ml evacuated exetainers. Dataloggers were placed inside one chamber in each replicate during sampling, to monitor changes in air temperature. Gas samples were analysed by Gas Chromatograph to quantify N_2O ($N_2O_{(g)}$) concentration and then converted to gas density ($N_{(g)}$) by the equation $N_{(g)} = N_2O_{(g)} \text{ x } (P \text{ x } 2Mw)/(R \text{ x } T)$. Where P is atmospheric standard air pressure of 101.31 kPa, Mw is the molecular weight of N, R is the universal gas constant (8.314 j K/mol), and T is chamber air temperature (Kelvin). Gas density was also adjusted for chamber height and fluxes calculated from a linear increase in gas density in the chamber headspace with time. Daily changes in soil water content and soil temperature were measured with one Theta and TinyTag probe respectively, placed on the bed top and adjacent furrow of each replicate. Rainfall was measured with an automated tipping bucket gauge. Treatment differences in grain yield and income were tested using analysis of variance (ANOVA). Logarithmic (base 10) transformations were calculated to normalise the N_2O flux data before Residual Maximum Likelihood (REML) analyses to identify treatment differences only, actual measured fluxes are presented hereafter. N_2O fluxes from the beds and furrows were analysed separately.

Results

Nitrogen application did not significantly affect grain yield in either wheat or canola and DCD application did not affect canola grain yield (data not shown). Wheat and canola yielded 6.8 (±0.5) and 3.7 (±0.4) t of grain/ha across all treatments respectively. However, the cost of applying DCD reduced canola income. The mean net income from the VN+DCD treatment was -$204/ha, compared with $1203/ha if DCD was not applied (mean of LN and VN treatments).

The only significant N_2O flux reduction from the beds in response to N rate, was observed on 14 October 2011, when emissions were 53% lower (P<0.05) from the LN compared with the VN treatment (Figures 1a and 1b). DCD significantly reduced flux from the beds on 22 September, 7, 14 and 28 October 2011. Fluxes were up to 84% lower (P<0.05) from the VN+DCD compared with the VN treatment. Applying VN increased N_2O flux from the furrows between 28 September and 19 October 2010, and again on 3 November 2010 and between 29 September and 14 October 2011 when fluxes were up to 72% higher (P<0.05) compared with the LN treatment. On all sampling dates between 8 September to 14 October 2011, emissions from the furrows were up to 83% lower (P<0.05) from the VN+DCD treatment compared with the VN treatment (Figures 1e and 1f).

WFPS responded to rainfall, runoff and evapotranspiration events on the beds (Figures 1c and 1d) and adjacent furrows (Figures 1g and 1h). From August 2010 to January 2011 soil temperatures trended upwards,

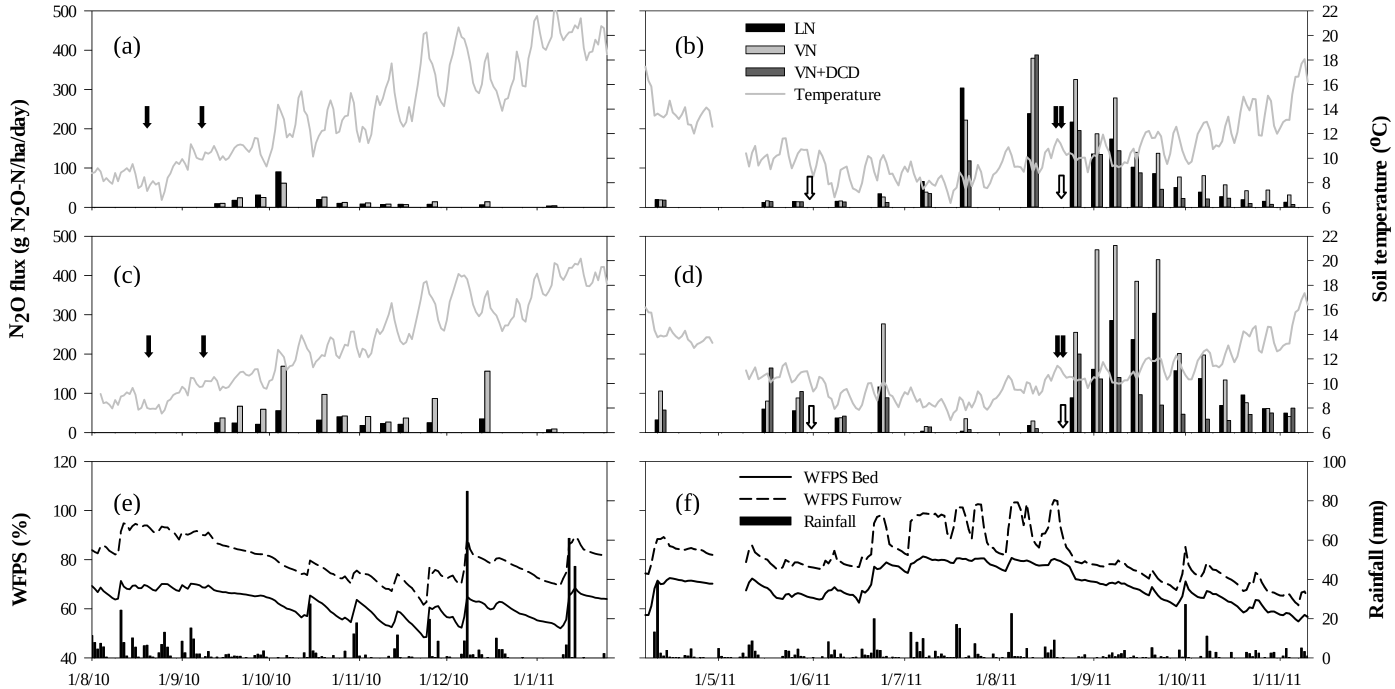

Figure 1. Mean temporal changes in N_2O fluxes and soil temperature on the bed (a and b) and in the furrow (c and d), daily rainfall and WFPS (e and f), for the LN, VN and VN+DCD treatments, at Strathkellar in south west Victoria. Closed arrows indicate top-dressed N fertiliser application, open arrows indicate DCD application.

while from April to November 2011, temperatures trended downwards until 16 July, then upwards for the remainder of the period on the beds (Figure 1b) and adjacent furrows (Figure 1f).

Discussion

Neither the application of N fertiliser (above the base rate) nor DCD improved the grain yield of wheat and canola. Based on potential grain yield models (French and Shultz 1984) and assuming a water use efficiency of 10 kg per mm of plant available water for canola (Robertson and Kirkegaard 2005), we estimate potential grain yields were 6.5 and 3.8 t/ha for respective wheat and canola crops. Given that potential yields were achieved in the LN treatment, there appeared to be no requirement to apply additional N fertiliser to the MN, HN and VN treatments. Although mineralisation was not measured in our study, applying the model of Baldock (2003) at Strathkellar, with high organic soil C (3.61%) suggests upwards of 115 kg N/ha may have mineralised during both growing seasons, preventing a yield response from the extra N fertiliser. While DCD is effective at inhibiting the conversion of NH_4 into NO_3 and thereby temporarily keeping N in a less mobile, but plant available form

(McTaggart *et al*. 1997), the potential benefits to crop yield were not observed in our study. Perhaps the high N mineralisation potential at Strathkellar might also explain the non response in canola yield to applied DCD; the retention of plant available N maybe more beneficial to crop yield under low soil N supply.

Oversupply of N fertiliser to wheat and canola, did not necessarily translate into frequently higher N_2O loss. Nitrate availability is a key factor in the production of N_2O; but NO_3 is highly mobile and prone to losses in either runoff or leaching with excess water (Di and Cameron 2005). Bakker *et al*. (2005) showed significantly higher runoff from raised beds than from conventional no-till, level seed beds. Another possible pathway for NO_3 escape was subsurface lateral flow, where water perches on the heavy clay 'B' horizon of the soil profile and subsequent rainfall causes subterranean lateral drainage (Ridley *et al*. 2003). Both theories raise the possibility of water and NO_3 leakage from the bed into the furrow and may partly explain why there was largely no effect of N rate on fluxes from the beds, but instead observed in the furrows after rainfall (Figure 1e and 1f).

Conclusion

Our research demonstrates a high degree of difficulty in separating environmentally driven episodic N_2O flux events in response to rainfall and soil temperature, and inherent field variability from genuine anthropogenic influences. We have produced evidence suggesting that N fertiliser management and the application of DCD will directly affect emissions and income from grain production in high rainfall cropping environments. The application of DCD appeared to make a significant contribution to N_2O abatement, but is currently uneconomical. Matching N fertiliser input with plant demand to avoid excessive NO_3 availability appears a more practical option for reducing unnecessary N_2O emissions.

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