# Benchmarking and mitigation of nitrous oxide emissions in temperate vegetable cropping systems in Australia resulting in improved nitrogen use efficiency

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## Abstract

Vegetable producers in some temperate regions of Australia use up to 1 tonne of nitrogen (N) as inorganic (fertilizers) and organic N (chicken manure) to produce 3 to 4 crops from the same land each year. Trials in Victoria showed great potential to reduce N inputs and to mitigate $N_2O$ losses from soil by use of nitrification inhibitors on manures and fertilizers compared to the standard grower practice (SGP) used at the sites without reducing yield. Annual $N_2O$ emissions ranged from 9.1 to 12.5 kg-N/ha for the unfertilized soil, and the combined fertiliser and manure program, respectively. Higher daily emission rates occurred when manures were applied to the soil and these were up to 20-fold greater for a single event than those from fertilizers. The inhibitors, DMPP and to a lesser extent 3MP/TZ, reduced $N_2O$ emissions from the fertilizer and manure program, with a maximum reduction of 64% occurring over the three crops, compared to the SGP. Pre-plant application of chicken manure resulted in short periods where daily $N_2O$ fluxes ranged from 70-213 g $N_2O$-N/day and DMPP reduced the net $N_2O$ cumulative emission by 53% over this period. Annual cumulative $N_2O$ emissions were up to 40-fold higher at the Victorian site than reported in similar trials in Queensland and Tasmania. The Emission Factor of 0.45% from the SGP was considerably lower than the IPCC default value (1% of N applied). Nitrogen measurements indicate that up to 60% of the applied N may be lost to the atmosphere or leached in high N use vegetable systems in Victoria.

## Key Words

Nitrous oxide ($N_2O$) emissions, Nitrification inhibitors, $N_2O$ mitigation, Ozone depletion, Climate change

## Introduction

Nitrous oxide ($N_2O$) is a significant greenhouse gas and the only GHG which is accounted for in horticultural production internationally. In addition $N_2O$ is the fourth largest ever ozone depleting product, but due to controls on the major halon gasses being implemented under the Montreal Protocol, it is now the largest uncontrolled stratospheric ozone layer depleter (Kanter *et al.*, 2013). Global models predict that as much as 6-8 Tg $N_2O$-N are produced each year, with two-thirds of the emissions coming from direct and indirect fertilizer and manures emissions, including those from N leaching and atmospheric re-deposition, (Davidson, 2009). Globally, there is still much uncertainty in the levels of $N_2O$ emissions from various cropping systems, in particular those from high value horticultural systems where high inputs of N are expected to lead to very high $N_2O$ emissions. Additionally in these systems high rates of emissions are anticipated because N availability to microorganisms often exceeds carbon availability (Davidson, 2009).

This study was set up to benchmark annual emissions from high input cropping systems in temperate Australia where nitrogen was applied as inorganic fertilizers or organic sources in chicken manure. Additionally nitrification inhibitors (NIs) were evaluated for their ability to mitigate $N_2O$ emissions and allow for reduced dosage rates of both the manure and fertilizer inputs. The trials were conducted as part of a larger national program in three States of Australia, Queensland, Tasmania and Victoria. This paper reports on one of the studies in a sandy soil at Clyde in Victoria. Nitrous oxide ($N_2O$) emissions from the standard commercial practice were compared to those where two nitrification inhibitors (3,4-dimethylpyrazole phosphate (DMPP) and a combination of 3-methyl pyrazole (3MP) and 1H-1,2,4 triazole (TZ) were applied to fertilizers and manures in an attempt to mitigate emissions.

## Methods

### *Site description and treatments*

The site consisted of two trials on a Kurosol (Isbell, 2002) with uniform texture (>85% sand) down to approximately 70 cm depth. The only difference between the two trials was that the first trial utilized a modified grower program, whereas the second site used the full grower program which included an additional pre-plant chicken manure application. The fertilizer used at the site was Calgran® (23.9% N, 16.5% $NH_4^+$-N, 7.4% $NO_3^-$-N, Incitec Pivot, Australia). Composted poultry manure (5.4 t $ha^{-1}$) was applied as a pre-plant application or as a surface banded treatment in addition to inorganic fertilizers (Table 1, Fig 1). The standard grower practice (SGP) treatment included no NIs, while the NI treatments included either DMPP or 3MP+TZ with each fertilizer and manure application. Three crops were sown over a 12 month crop rotation (celery, leek and spinach). The final spinach crop was grown without any supplementary fertilizer or manure to assess the effect of residual soil N levels.

**Table 1. Activities and fertilizer/manure applications at Clyde, Trial 1 and Trial 2 in 2014/2015**

| Crop | Date | Activity | N Rate (kg $ha^{-1}$) | |
|---|---|---|---|---|
| | | | Trial 1 | Trial 2 |
| Celery | 7/2/14 | Preplant manure application (Incorporated) | - | 238 |
| | 25/2/14, 20/3/14, 18/4/14, 8/5/14 | Fertiliser application (at and after planting) | 192 | 192 |
| | 28/3/14 | Manure application (Surface) | 167 | 167 |
| | 5/6/14 | Celery harvest | - | - |
| | 13/6/14 | Residue incorporation | - | - |
| | | **Total N applied to crop*** | **473 (91)*** | **473 (91)*** |
| Leek | 19/8/14 | Preplant manure application (Incorporated) | 291 | 291 |
| | 20/8/14 | Leek planting | - | - |
| | 18/9/14, 15/10/14 | Fertiliser application | 96 | 96 |
| | 2/12/14 | Leek harvest | - | - |
| | 4/12/14 | Residue incorporation | - | - |
| | | **Total N applied to crop** | **425 (38)*** | **425 (38)*** |
| Spinach | 13/1/15 | Spinach planting | - | - |
| | 6/2/15 | Spinach harvest | - | - |
| | 17/2/15 | Residue incorporation | - | - |
| | | **Total N applied to crop** | **9.5 (9.5)*** | **9.5 (9.5)*** |
| All crops | | **Trial 1** | 907 (162) | 1145 (162) |

* includes N applied in the irrigation water (in parentheses)

### *$N_2O$, soil nitrogen and Environmental measurements*

GHGs ($N_2O$, $CH_4$ and $CO_2$) were measured using an automated GHG system as described in Scheer *et al.* (2014) for Trial 1 and the early part of Trial 2. Manual chambers were used to obtain data for the cropping phase of Trial 2. $N_2O$ fluxes were calculated for both the chamber and for the entire hectare by correcting for the untreated area of the plot outside the chamber. Direct $N_2O$ emission factors for fertilizer and manure treatments (proportion of applied N emitted as $N_2O$) were calculated by subtracting the $N_2O$ emission from the control treatment as the background emission. The nitrogen content of the irrigation water was measured in samples collected after each irrigation. Wetting front detectors (Full-stop) were installed in each auto-chamber plot to a depth of 45 cm to capture water samples which later were tested for N that was leached beyond the root zone. A partial N budget was calculated using measured values where available and modelled values where direct measurement was not possible (i.e. $NH_4$ and $N_2$ gaseous losses, nitrate leaching).

## Results

### *$N_2O$ flux and crop yields*

In Trial 1, peak emissions reached 100-120 g $N_2O$-N/ha/day and were greatest at the beginning of each cropping and fallow period or following a surface application of chicken manure (Figure 1). During the celery crop, the surface application of manure caused a large increase in $N_2O$ flux that persisted until shortly before harvest in the SGP treatment but not in the NI (DMPP and 3MP+TZ) or No fertilizer treatments. Each subsequent fertilizer application to the celery and leek crops resulted in a spike in $N_2O$ emission for the SGP treatment only. Following the incorporation of the celery and leek residue post-harvest and tillage during fallow periods there was an emission spike for all treatments. The pre-plant incorporated manure application in the leek crop resulted in a smaller and shorter duration spike in $N_2O$ flux than the surface applied manure in the celery crop. Over the 3 crop rotation there was a relatively high cumulative $N_2O$ flux in the 'No fertilizer' treatment of 9.13 kg $N_2O$-N/ha (Table 2). DMPP was more effective reducing cumulative $N_2O$ flux than 3MP+TZ. Most of the reduction in cumulative $N_2O$ emissions with the NI treatments occurred following the surface manure application in the celery crop although DMPP also reduced emissions during the leek crop. After the celery crop, emissions from the 3MP+TZ were similar to SGP for the rest of the trial.

Despite trends toward higher yields in the NI plots compared to the unfertilized control and SGP treatments for the celery and leek crops, yields generally did not differ significantly between treatments for any of the crops (Table 2).

In Trial 2, the pre-plant and surface applied chicken manure applications caused higher spikes in $N_2O$ flux (up to 350 g $N_2O$-N/day) from both the standard grower treatment and the DMPP treated plots than when the pre-plant manure had not been added (Figure 2 cf. Figure 1a.).

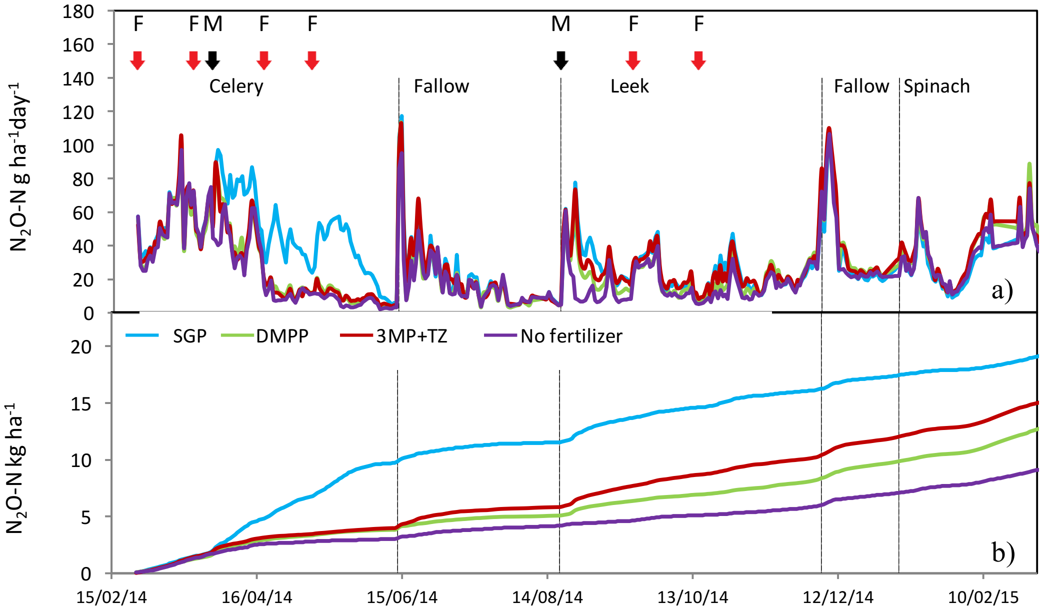

**Figure 1. Daily (a) and cumulative (b) $N_2O$ emission for the chamber area for Trial 1 (3 crops) at Clyde, Vic., 2014. Red arrows - fertilizer applied (F), black arrows – manure applied (M). SGP=standard grower practice.**

**Table 2. Annual[A], net[B] and daily $N_2O$ emissions, Emission Factors and Yields at Clyde, Vic., 2014 (Trial 1)**

| Treatment | Annual crop $N_2O$-N flux (kg $ha^{-1}$)# | Net total crop $N_2O$-N flux (kg $ha^{-1}$) | Ave daily $N_2O$-N flux (g $ha^{-1}$ $d^{-1}$) | (%)Applied N* emitted as $N_2O$-N | Marketable Yield (t $ha^{-1}$) | | |
|---|---|---|---|---|---|---|---|
| | | | | | Celery | Leek | Spinach |
| No Fertilizer | $9.13^a$ | - | 24.4 | - | 69.4 | 79.7 | 14.1 |
| DMPP | $10.30^a$ | 1.17 | 27.6 | 0.16 | 75.7 | 90.7 | 12.6 |
| 3MP+TZ | $11.08^{bc}$ | 1.95 | 29.7 | 0.26 | 84.3 | 86.7 | 11.4 |
| SGP | $12.46^d$ | 3.33 | 33.4 | 0.45 | 72.4 | 80.3 | 13.0 |
| L.s.d.(P=0.05) | 1.272 | - | - | - | 7.9 | NS | NS |

[A] –Annual crop emissions adjusted to account for untreated areas within plots; [B]-Net emissions =Treatment emissions – No fertilizer emissions.

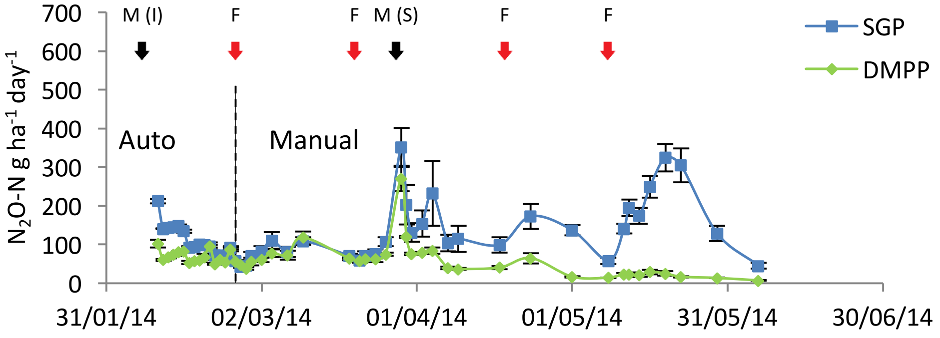

**Figure 2. Daily $N_2O$ emission for the chamber area for Trial 2 (Celery crop only) at Clyde, Vic., 2014. Red arrows - fertilizer applied (F), black arrows – manure (M) incorporated (I), (S) surface applied. SGP=standard grower practice. DMPP – nitrification inhibitor. Auto=Automatic GHG system, Manual=manual chambers.**

## Discussion

This study showed that $N_2O$-N emissions from manures and fertilizers can be reduced by up to 64% by use of NIs and this confirms previous findings (Riches *et al,* 2016). As daily emissions were up to 10-20 fold higher from manures compared to inorganic fertilizers, greater benefit was obtained by use of NIs on manures. The average daily $N_2O$ emission from the standard grower practice (SGP, Trial 1) where fertilizers and manures were applied to the soil surface was 33.4 g $N_2O$-N/ha/day. This was approximately 10 fold higher than from studies in other vegetable regions of Australia where manures are not used (Sheer *et al*, 2014). An increase in $N_2O$-N emissions where animal manures have been applied have also been observed in other studies (Dalal *et al.,* 2009; Mori and Hojito, 2012). The high $N_2O$ emissions in this region of Victoria were similar to the high N input systems in China (Zhang *et al.*, 2016). Both systems are highlighted by the high N inputs either directly or through irrigation water. A significant proportion of the Victorian growers use chicken manure to improve soil quality, however the interaction with N fertilizers and the resultant losses of N are often overlooked. In our study, spikes of $N_2O$-N, and $CO_2$ emissions (not shown), occurred when the manures were applied to these highly fertilized soils, suggesting that fertilizer N was contributing to rapid decomposition of the manures, rather than being available for the crop. The high cumulative $N_2O$ flux in the 'No fertilizer' treatments and the inability to demonstrate clear yield differences to the SGP also suggests that the N inputs into these temperate crops are often in excess of crop requirements. In addition, at our site, runoff water from the farm and recycled town water was used for irrigation and this water contained enough N to grow a crop without supplementary N additions. In the dry/hot summer months when intensive irrigation was needed, irrigation water supplied over 100 kg ha/N per the first celery crop, and this helps explain why yields of this crop and subsequent crops were so high in the 'No fertilizer' treatments. Soil tests showed increased retention of ammonium in the soil when NIs were used. The emission factor for the standard grower treatment and the DMPP inhibited treatment at the Clyde trial site were 0.45 and 0.16 respectively and this indicates excellent potential for the use of NI's for emission mitigation in temperate Australian vegetable production. Nitrogen budgets showed that up to 60% of the N was lost to the atmosphere or leached from the high N vegetable systems in Victoria and although results are not shown, the study also indicated that NI's potentially reduced leaching losses of N. There appears to be good potential to use NI's to manage N from manures and possibly fertilizers in these systems.

## Conclusion

Vegetable cropping in highly productive regions of temperate Australia have very high $N_2O$ emissions compared to other cropping systems throughout Australia, predominantly because of the high manure use, its interactions with added fertilizer N and the recycling of N in irrigation water. The use of NI's very effectively reduced $N_2O$ emissions from both manures and fertilizers, and evidence suggests they may reduce leaching and improve nutrient use efficiency by crops. In order for growers to gain the full environmental and economic benefits of using NI's they should use them with reduced N inputs, otherwise the benefits will be lost.

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