The effect of variable nitrogen fertiliser rates on indirect nitrous oxide emissions and nitrate losses from furrow-irrigated cotton production

Alice Devlin[1], **Yvonne Ye Fen Chang[2]**, Ben Macdonald[3]

[1] CottonInfo, Gwydir Region, PO Box 1301, Moree NSW 2400
[2] CSIRO Agriculture Flagship, Australian Cotton Research Institute, 21888 Kamilaroi Hwy, Narrabri NSW 2390, Yvonne.Chang@csiro.au
[3] CSIRO Agriculture Flagship, Black Mountain Canberra ACT 2601, Ben.Macdonald@csiro.au

Abstract

Nitrous oxide (N_2O) is a potent greenhouse gas and a key causal agent in the depletion of stratospheric ozone. Current measurements of agricultural N_2O emissions have focused on direct losses from the soil surface; yet, indirect N_2O emissions are thought to be 29 to 67% of direct losses. IPCC estimates of indirect emissions suggest that 2.8 to 25 g of N_2O-N may be produced per kg of NO_3-N lost. Within the Australian cotton industry, nitrogen fertiliser rates average at 250 kg N ha^{-1}, though higher rates are not uncommon. We present the findings from a pilot study comparing nitrate losses from furrow irrigated cotton under variable N fertiliser application rates (363, 463 and 563 kg N ha^{-1}); and use these to estimate indirect N_2O emissions. N rate had no effect on nitrate run-off loss. Significantly more nitrate was lost from skip than water furrows. Increasing plant internal nitrogen use efficiency, using irrigation methods which reduce lateral water flow through the soil profile, and/or placing fertiliser deeper or more asymmetrically within plant beds are likely to decrease nitrate losses and, consequently, indirect emissions. Further study examining losses across a greater range of N rates, and with variation in timing and methodology of N application are necessary to obtain a better understanding of the variables associated with indirect emissions.

Key words

Nitrogen fertilizer, greenhouse-gas, run-off, IPCC emission factor

Introduction

Over the last century, anthropogenic reactive nitrogen (N) production has increased over a-hundred fold from 15 Tg year^{-1} in 1860, to 191 Tg year^{-1} in 2005 (Galloway et al. 2008). Agriculture is the dominant source of N_2O emissions. Emissions from fertiliser use and manure management represent 26-35% of total N_2O sources (Butterbach-Bahl et al. 2013; Syakila & Kroeze 2011). One consequence, of increased N production and use, has been a 0.2-0.3% per annum increase in nitrous oxide (N_2O) production (Conway & Pretty 2009). N_2O is a potent greenhouse gas, with an equivalent 100 year warming potential 298 times that of carbon dioxide, and a key causal agent in the depletion of stratospheric ozone (Butterbach-Bahl et al. 2013). Most N_2O is produced as an intermediate product of two microbial processes, nitrification and denitrification. Rates of N_2O emissions are controlled by numerous environmental factors including soil porosity, temperature, soil moisture, organic carbon content, oxygen availability, microbial community, pH and mineral N availability (Eichner 1990). Variations in agricultural management practices, e.g. irrigation method and crop rotations, influence both the rate and magnitude of direct N_2O emissions, by altering the availability of substrates and the conditions required for nitrification and denitrification (Eichner 1990).

Within the Australian cotton industry, application of N is required to maintain the quality and magnitude of yields. Average N rates in 2012-13 averaged at 243 kg N ha^{-1}, ranging between 93 to 370 kg N ha^{-1} (Roth Rural 2013); though at present, higher rates are not uncommon. Over fertilisation with N is problematic. A comparison of internal N use efficiency (iNUE = kg lint/kg crop N uptake) between commercial and optimum N rates for cotton, derived from a long term N rate trial, suggests that between 2004-9, the industry over fertilised by an average 49 kg N ha^{-1} (Rochester 2011). Excess N is lost via erosion, leaching, run-off and denitrification. A study by McHugh et al (2008), in Emerald QLD, found that N losses from run-off range between 0.92 to 37.57 kg ha^{-1} from furrow irrigated cotton which received 250 kg N ha^{-1}; though this may not be representative of industry. Nitrogen lost via run-off may be converted downstream to N_2O.

Indirect N_2O emissions, those resulting from the movement of N from human sewage and from N leaching and runoff into aquatic environments (Reay et al. 2005), are thought to be 29 to 67% the magnitude of direct losses (Syakila & Kroeze 2011). There have been few studies quantifying the rate and magnitude of indirect emissions. Indirect emissions are produced via the same mechanisms which occur in soil but within the water column and sediments (Harrison & Matson 2003). Nitrogen lost via run-off may be converted to N_2O downstream. Intergovernmental Panel on Climate Change (IPCC) estimates of indirect emissions suggest that 7.5 g of N_2O-N may be produced per kg of N lost via run-off and leaching (EF-5 of 0.0075) (IPCC 2006). Using the IPCC EF-5 and the data from McHugh et al, we could estimate indirect losses from cotton to range between 0.0069 to 0.281 kg ha^{-1}. Given the excess use of N fertiliser within the cotton industry, strategies minimising N loss provide potential mitigation options for indirect N_2O losses. We undertook a study to compare the effect of N fertilizer application rate on nitrate concentrations in run-off, and used this data to estimate indirect N_2O emissions. To the best of our knowledge, no studies have yet quantified indirect N_2O emissions in the Australian cotton industry.

Methods

Site selection and field set up

The N rate trial was conducted at 'Red Mill' farm in Moree NSW, Australia (29°24′S, 149°57′E) over the 2014/15 cotton season. The soil at this site is a shrink-swell grey vertosol. The site was managed with a back to back cotton rotation, under a commercial rate of 363 kg N ha^{-1}. The trial site was randomly divided into 9 plots (12 by 950 m) and each plot assigned a rate of 363, 463 or 563 kg N ha^{-1} (n=3). N was applied in split applications using a combination of methods (Table 1). Approximately 6.1ML ha^{-1} water was applied, using alternate furrow irrigation, over 9 irrigations (Table 1). Farm staff estimated 10 to 15% of water was lost as run-off; we used a conservative run-off loss of 10% per irrigation.

Table 1. Nitrogen rate trial field management summary for "Red Mill" for 2014/15: cotton was sown 24/10/2014. Variable N rates were applied 71 or 77 days after sowing to give final rates of 363, 463 and 563 kg N ha^{-1}.

Days after sowing	Irrigation No.	Water used (ML ha^{-1})	N rate (kg N ha^{-1})	N application method
- 4 months		-	150	Anhydrous ammonia
-14	PRE	1.4		
39	1	0.587	58	Water run, N26®[1]
59	2	0.587	62	Water run, N26®[1]
71 or 77		-	0, 100, or 200	Side dress, liquid spray N42®[2]
77	3	0.587	61	Water run, N26®[1]
89	4	0.587	32	Water run, N26®[1]
105	5	0.587		-
113	6	0.587		-
123	7	0.587		-
134	8	0.587		-

[1]N26® liquid urea at a concentration of 20-26% N

[2]N42® liquid N solution at a concentration of 42.5% N, as urea (50%), nitrate (25%) and ammonium (25%).

Sample collection and analysis

Where feasible, water samples were collected each irrigation. Samples were not collected for irrigations 2, 3, 4 and 6 due to operational challenges. Samples were collected from the head ditch, and 2m in from the tail end of one water and one skip furrow for each plot. Nitrate concentration was measured using a Merck RQ Easy® meter. Concentrations below 5mg L^{-1} were considered to be negligible and given a value of 0. Total nitrate lost per irrigation was calculated using run-off estimates. Cumulative nitrate run-off loss was calculated by summation of total nitrate lost per irrigation. Given that not all irrigations were sampled and that nitrate concentrations were obtained from point samples, it is possible that total N loss may differ to the numbers reported in this study. N_2O emissions were estimated using the revised IPCC EF-5 for agricultural losses of nitrate via leaching or runoff of 0.0075 (IPCC 2006).

Data analysis

Data was analysed using R (R Core Team 2014). Analysis of variance (ANOVA) was used to determine the effect of N rate, irrigation number and furrow type (skip or water) on nitrate losses using the model:

NO_3 loss = Irrigation number + N rate + Furrow type

The relative importance of each of the model components was then determined through decomposition of the model using the 'lmg' metric in the 'relaimpo' package (Grömping 2006).

Results & Discussion

On average, 2.40% of the total N applied, or 11.29 kg $NO_{3-}N$ ha^{-1}, was lost as nitrate run-off across all plots (Table 2). Irrigation number ($p<0.001$) and furrow type ($p<0.001$), but not N rate, significantly affected variation in concentration of nitrate lost, with 55% of the variation in nitrate losses explained by the model (see methods); of this, 68.6%, 30.9% and 0.5% of the variation in nitrate run-off was explained by irrigation number, furrow type and N rate, respectively. Nitrate run-off losses were highest at the start of the season, with losses from the pre and first irrigations significantly greater than other irrigations (Figure 1). More nitrate was lost from skip than water furrows ($p<0.001$); water moves through the dry furrow beds into the skip furrows, carrying nitrate. Irrigation strategies which minimize lateral flow of water (e.g. drip irrigation) and/or movement of water through mounds; and varying timing and placement of N fertilizer application (e.g. deeper and asymmetrical, closer to the water furrow) may decrease nitrate loss (McHugh et al. 2008).

Table 2. Nitrate run-off loss (range and average cumulative loss) and estimated indirect N_2O emissions, under continuous cotton crop managed with variable N rates of 363, 463 or 563 kg N ha^{-1}. Run-off was estimated at 0.14 ML ha^{-1} for the first irrigation and 0.058 ML ha^{-1} for subsequent irrigations. Indirect N_2O emissions were estimated from nitrate concentrations using the IPCC EF-5 of 0.0075.

N rate (kg N ha^{-1})	Range NO_3-N loss (mg L^{-1})	Average cumulative loss of NO_3-N (kg ha^{-1})	Cumulative N_2O-N emissions (g ha^{-1})
Head ditch	0 – 9.26	1.23	9.19
363	5.20 – 172	7.25	54.3
463	6.78 – 172	12.8	96.2
563	7.23 – 201	13.8	103

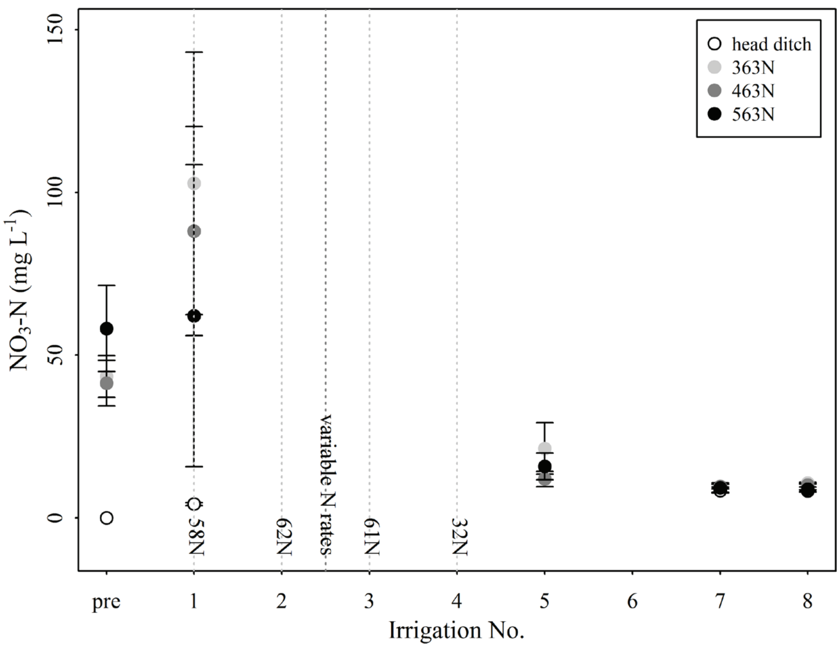

Figure 1. Nitrate concentration, with standard error, (mg L^{-1}) in run-off water from cotton fields fertilized with 3 different N rates (363, 463 and 563 kg N ha^{-1}). Vertical lines (···) represent in-season N (kg ha^{-1}) application.

There was no significant difference in nitrate losses under the different N rates. This was in contrast to what we expected, given 1) the positive relationship between direct N_2O emissions and N rates shown in other studies (e.g. Bouwman 1996; Gao et al. 2013); and 2) additional data collected from the first two irrigations from an N rate trial in Gunnedah NSW, with N rates of 200, 250 and 300 kg N ha^{-1} added pre-planting, which showed a significant, positive relationship between nitrate run-off and N rate (unpublished data). The discrepancy between our results and what we expected could be explained by the late application of variable N rates. In this study, and in another study measuring nitrate loss (unpublished data), we found that most nitrate loss occurred at the start of the season. Peak N uptake by cotton occurs around 80 to 100 days after planting, and plants which have greater access to mineralised N are able to assimilate higher amounts of N (Boquet & Breitenbeck 2000). Given variable rates were applied around 80 days after planting, effects due to N rates may have appeared as changes to cotton N nutrition. Alternatively, excess N may have been loss via other pathways rather than through run-off.

IPCC estimates of indirect N_2O emissions from tail water, for a single irrigation event, ranged from $3.90E^{-4}$ to $1.51E^{-2}$ kg ha^{-1}. The average cumulative emission from tail water, across all plots, was estimated at $8.46E^{-2}$ kg N_2O-N ha^{-1} (Table 2). Optimising NUE and reducing the industry's dependence on N fertilizers (e.g. biological N fixation), would minimize N loss and the resultant indirect emissions (Reay et al. 2012). There are a number of limitations associated with this study. In particular, IPCC estimates of indirect emissions may not be suitable for Australian cotton systems. The range of uncertainties for the IPCC EFs for nitrous oxide are from 0.0005 to 0.025 kg N_2O-N ha^{-1}; and result from variation in sampling conditions, microbial activity and on-farm practices (IPCC 2006). Whilst current IPCC emission factors for N_2O have been reduced (e.g. reduction in EF-5 from 0.025 to 0.0075), due to a lack of congruence between field measurements and EFs (IPCC 2006; Reay et al. 2005), the lack of data from within Australian systems mean that IPCC EFs are unlikely to provide good estimates within the Australian cotton industry. If we are to have a good grasp of indirect N_2O emissions, direct measurements of emissions across the whole irrigation network should be undertaken. Furthermore, our understanding of the temporal and spatial variation in N_2O production within furrow irrigation is limited. A better understanding of these variables would allow us to better estimate indirect losses within the industry and better shape proposed mitigation strategies.

Within this study, about 2.40% of N applied, was lost as nitrate run-off; which translated into an average indirect N_2O emission of 0.085 kg N_2O-N ha^{-1}. IPCC estimates of indirect emissions hold a large degree of uncertainty. Further work is required at broader temporal and spatial scales to better understand the processes associated with N_2O production and to quantify total indirect emissions from the Australian cotton industry.

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