Effects of polymer- and nitrification inhibitor-coated urea on N_2O emission, productivity and profitability in a wet tropical sugarcane crop in Australia

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Abstract
Sugarcane crops are predominantly grown in warm and high rainfall or irrigated areas where substantial fertiliser nitrogen (N) losses can occur. This study was conducted in a wet tropical sugarcane cropping system to assess polymer-coated urea (PCU), polymer- and sulphur-coated urea (PSCU) and the denitrification inhibitor DMPP-coated urea (NICU) on sugar productivity, N use efficiency and profitability at the normal application rate (150 kg N/ha) and a reduced rate (110 kg N/ha). Nitrous oxide (N_2O) emissions were also measured for selected treatments using automatic and manual gas sampling chambers in combination. The results demonstrated that annual cumulative N_2O emissions in the treatment receiving conventional urea at 150 kg N/ha amounted to 4.74 and 9.51 kg N_2O-N/ha, with the fertiliser N emission factor of 1.90 and 3.01%, based on the manual and automatic chamber measurements, respectively. Application of NICU decreased the annual fertiliser-induced N_2O emission by approximately 83%. However, N_2O emissions in the PSCU treatment were about two times that in the conventional urea treatment, probably due to less N leaching from PSCU. Use of PCU, PSCU and NICU at 150 kg N/ha increased the sugar yield by 2.5, 3.3 and 2.8 t/ha, respectively, compared to the conventional urea treatment (8.4 t/ha). The crop N uptake in the aboveground biomass were significantly higher for the coated urea fertilisers than uncoated urea, and higher for PSCU and NICU than PCU at 150 kg N/ha. The farming profits also tended to be higher for the coated urea fertilisers than the conventional urea.

Key Words
Greenhouse gas, enhanced efficiency fertilisers, controlled release fertiliser, slow-release fertiliser.

Introduction
There are approximately 27 million hectares of harvested sugarcane (*Saccharum officinarum* L.) land in the world (FAO 2016), predominantly in tropical and subtropical areas where the annual rainfall exceeds 1000 mm or irrigation facilities are available. The wet and warm climatic conditions, along with high nitrogen (N) fertiliser application rates (c.a. 100-300 kg N/ha), are inductive to N losses through microbial denitrification in soil. Denitrification is the primary process for nitrous oxide (N_2O) production in many agricultural soils, particularly in high emission systems. N_2O is a potent greenhouse gas with a global warming potential of 298 times that of carbon dioxide. Agriculture is responsible for about 80% of the anthropogenic nitrous oxide emissions in the world (FAO 2016). Previous studies demonstrated that annual N_2O emissions from Australian sugarcane soils were generally high, mostly in the range of 2-12 kg N_2O-N/ha/yr with the highest measurement at 45.9 kg N_2O-N/ha/yr (Denmead *et al.* 2010; Wang *et al.* 2016b). With increasing concerns over climate change and fertiliser N loss to the environment including waterways, there is a genuine need to develop low-emission and N-efficient farm management practices for the sugarcane industry

Numerous studies have found that controlled-release fertilisers and addition of a nitrification inhibitor into ammonium-based fertilisers can enhance fertiliser N efficiency (Chen *et al.* 2008). These ‘enhanced efficiency fertilisers’ can also substantially increase crop yield, maintain productivity at reduced application rates, or mitigate N losses such as N_2O emissions (Chen *et al.* 2008; Akiyama *et al.* 2013). The efficacy of the polymer- or nitrification inhibitor-coated fertilisers may vary with the fertiliser formulation, soil properties, climatic conditions and management practices. There have been few assessments of these newer fertiliser forms in the tropical sugarcane growing regions of Australia where normal fertiliser N is susceptible to losses by denitrification, leaching and/or runoff due to high seasonal rainfall. The major objectives of this study were to investigate the efficacy of polymer- or the nitrification inhibitor DMPP-coated urea for mitigating N_2O emissions, enhancing fertiliser N use efficiency and improving crop productivity.

Methods

Experimental site

The experiment was conducted at Ingham in north Queensland, Australia (18°37'30"S, 146°07'06"E). Long-term annual mean temperature in this region is 24.0 °C, with the lowest monthly mean temperature in July (19.3 °C) and the highest in January (27.7 °C). Mean annual rainfall is 2110 mm, with approximately 60% received from January to March. The total rainfall during the current cropping season was 1198 mm.

The soil was a loam containing 19% clay and 62% sand in the 0-20 cm layer and little variation in the 0-100 cm profile. The soil organic carbon content was 9.5 g/kg and the soil pH value (1:5 soil:water) was 4.9. The crop was a first ratoon (regrown) sugarcane (NQ239⁽ᵇ⁾). The previous crop was planted in August 2012 on raised beds with a row spacing of 165 cm and harvested on 25-26 August 2013. Green cane trash (residue) blanketing has been performed on this farm since 1987.

Nine treatments were included for comparison: urea (U), polymer-coated urea (PCU; Incitec Pivot Fertilisers, Australia), polymer and sulphur-coated urea (PSCU; Agrocote®) and the nitrification inhibitor DMPP-coated urea (NICU; Entec®). The fertilisers were applied at the recommended rate of 150 kg N/ha (150N) and a reduced rate of 110 kg N/ha (110N) on 9 October 2013, at ~8 cm below the soil surface in slits cut in the middle of the crop rows. An unfertilised treatment (0N) was also included. The treatments were arranged in a randomised block design with four replicates. The plots were 20 m long and 8.4 m wide containing 5 crop rows. The crop was harvested on 13 October 2014.

Measurement of N_2O emissions

Emissions of N_2O were measured with a combination of manual and automatic gas sampling chambers in six selected treatments. The manual chambers consisted of a square stainless-steel base (50 cm W × 50 cm L × 15 cm H) and a cover box with white plastic panels (55 cm H). Two chamber bases were installed in each plot with one covering across the bed centre and another covering one side of the bed shoulders and half of the furrow area (Wang *et al.* 2016a), both inserted into about 10-15 cm below the soil surface. Emissions of N_2O were measured by closing the chambers for 1-1.5 h between 09:00 and 11:30 am (Reeves *et al.* 2016).

The automatic chambers were installed only for the 0N and 150N_U treatments with four and five chambers per treatment, respectively. Each automatic chamber consisted of a base identical to that of the manual chambers, an extension (30 cm H) and a cover box (30 cm H) with two lids on the top panel that could be opened and closed automatically. Placement of the chamber bases was similar to that for the manual chambers. The measurement methodology was described in detail by Wang *et al*. (2016a).

Determination of soil mineral N contents

Soil samples were taken to a depth of 1 m (divided into 0-10, 10-30, 30-60, 60-100 cm depths) at pre-fertilisation and post-harvest. The bed centre and shoulder/furrow areas were sampled separately, from three points in each area per plot. Soil mineral N including NH_4^+ and NO_2^- + NO_3^- contents in the soil samples were determined using 2 M KCl extraction and colorimetric techniques (Rayment and Lyons 2010).

Measurements of crop yield and N uptake

Sugarcane yield was measured by harvesting the middle two rows (2×20 m) with a plot harvester and a truck that contained a bin mounted on load cells. An additional 5 m section was manually harvested from an adjacent row, and the millable cane and leaf & cabbage (immature stalk) were separated, weighed, cut into small pieces and sub-sampled. Dry matter contents of the fresh cane and leaf & cabbage were determined by placing a portion of each sample in an oven at 60 °C for > 48 hours. Total N content was determined using the Kjeldahl digestion and distillation method (Rayment and Lyons 2010). Total N in the millable cane and leaf & cabbage was calculated by multiplying the N content in the plant samples by the dry biomass yield. Total above-ground N uptake was the sum of the total N uptake in the millable cane and leaf & cabbage.

Statistical analysis

All statistical analyses were performed using GenStat V.14 (VSN International Ltd, UK). Prior to analysis of variance, data were tested for normal distribution and log-transformed where appropriate. Differences and interactions among treatments were assessed using the analysis of variance procedure and Duncan's multiple range test at $P < 0.05$ unless specified otherwise.

Results

Annual cumulative N_2O emissions

The annual emissions were 1.89 kg N/ha for the unfertilised control and 4.74 kg N/ha for the 150N_U treatment based on the manual chamber measurements (Figure 1). The automatic chamber measurements resulted in an annual emission of 5.00 kg N/ha for the 0N treatment and 9.51 kg N/ha for the 150N_U treatment. At the N application rate of 150 kg N/ha, NICU reduced the fertiliser-induced N_2O emission by approximately 83% compared to the conventional urea ($P < 0.05$). However, the PSCU substantially increased N_2O emissions in comparison to the uncoated urea. A reduction in the PSCU application rate from 150 kg N/ha to 110 kg N/ha decreased the cumulative N_2O emission by about 50%.

The average N_2O emission factor for the 150N_U treatment was 3.01% and 1.90% based on automatic chamber and manual chamber measurements, respectively. The N_2O emission factor decreased to 0.33% for 150N_NICU but increased to 6.91% for 150N_PSCU. With a reduction in the N application rate to 110 kg N/ha, the N_2O emission factor increased to 1.28% for NICU and decreased to 4.32% for PSCU.

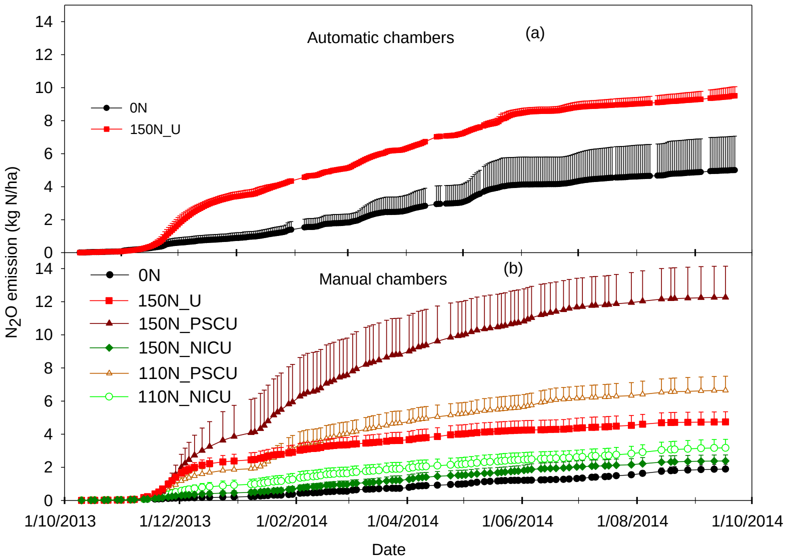

Figure 1. Cumulative N_2O emissions (mean+SE) as measured with the automatic chamber (a) and the manual chamber (b) methods. 0N, 110N and 150N: fertilised at 0, 110 and 150 kg N/ha, respectively; U: conventional urea; PSCU: polymer and sulphur-coated urea; NICU: nitrification inhibitor-coated urea.

Sugar yield and profitability

Nitrogen fertiliser application consistently increased sugarcane and sugar yield (Table 1). The sugar yield in the 150N_U treatment was 8.4 t/ha. Application of PCU, PSCU and NICU at 150N increased the sugar yield by 2.5 t/ha, 3.3 t/ha and 2.8 t/ha, respectively ($P < 0.05$). At the suboptimal N application rate of 110N, sugar yields also tended to be higher for the coated urea formulations but were significantly higher only for the NICU ($P < 0.05$) compared to the uncoated urea. There were no significant differences in the sugar yield between 150N and 110N, regardless of fertiliser formulations. At the same N application rate, the farming profits tended to be consistently higher for the coated urea treatments than the conventional urea treatment but the profit increases were mostly insignificant at $P < 0.05$.

Fertiliser N uptake, recovery and efficiency

The aboveground N uptake was also substantially higher for the fertilised treatments than the unfertilised Control, as expected (Table 1). At the recommended rate of 150N, use of PCU, PSCU and NICU resulted in significantly higher crop N uptake and fertiliser N recovery in the aboveground biomass compared to uncoated urea. At the lower N application rate of 110N, however, there were no significant differences in N uptake between different urea formulations. Compared to 110N, applying fertiliser at 150N resulted in significantly higher crop N uptake for the PSCU and NICU treatments but not for uncoated urea. Averaged across different N application rates, the coated urea treatments tended to have higher fertiliser N use efficiency (21.8-28.3 kg sugar/kg N) than the uncoated urea treatments (5.3 kg sugar/kg N; $P < 0.05$). The fertiliser N recovery in the aboveground biomass was also significantly higher for the coated urea than the uncoated urea, and higher for PSCU and NICU than PCU among the coated products.

Table 1. Sugar yield, aboveground crop N uptake and fertiliser N efficiency under different fertilisation schemes (mean±SE). The numbers followed by same letter(s) in a column are not significantly different at P < 0.05.

Treatment	Cane yield (t/ha)	Sugar yield (t/ha)	Aboveground N uptake (kg N/ha)	Fert. N recovery (%)	Fertiliser N efficiency (kg sug./kg N)	Gross profit margin* ($000s/ha)
0N	51.5±6.5[a]	8.0±1.3[a]	47.5±6.3[a]			1.92[a]
110N_U	62.4±4.6[bc]	8.8±1.1[abc]	63.2±7.5[bc]	14.3±2.7	7.8±6.0	1.99[a]
150N_U	53.7±6.1[ab]	8.4±1.5[ab]	57.5±7.5[ab]	6.6±3.3	2.7±5.3	2.02[ab]
110N_PCU	66.5±2.8[cd]	10.7±0.4[cd]	68.3±3.6[bc]	18.9±2.7	24.4±7.1	2.63[ab]
150N_PCU	70.3±3.5[cd]	10.9±0.8[cd]	74.5±6.6[c]	18.0±3.0	19.2±5.8	2.62[ab]
110N_PSCU	69.7±2.8[cd]	10.3±0.9[bcd]	74.3±3.2[c]	24.4±6.9	20.9±10.0	2.40[ab]
150N_PSCU	74.2±2.9[de]	11.7±0.3[d]	89.6±7.1[d]	28.1±3.7	24.8±6.6	2.87[b]
110N_NICU	69.3±2.2[cd]	11.8±1.0[d]	68.6±1.7[bc]	19.1±4.7	35.1±13.2	2.98[b]
150N_NICU	81.5±4.5[e]	11.2±0.8[d]	90.6±5.9[d]	28.7±2.5	21.5±8.5	2.48[ab]
ANOVA *P* value	< 0.001	0.008	< 0.001	0.01[#]	0.001[#]	0.068

*Gross margin ($000s/ha) = sugarcane sale value – operational costs. #Between fertiliser types only.

Conclusion

Emissions of N_2O from this sugarcane cropping system were high, amounting to 4.74-9.51 kg N/ha/yr under the conventional fertilisation practice (150N_U). NICU reduced total N_2O emissions (including those from the background soil) by 50% or fertiliser-induced emissions by 83% compared to conventional urea. However, application of PCU resulted in substantially higher N_2O emissions than other urea formulations probably due to less N loss through leaching.

At the recommended application rate, NICU, PCU and PSCU significantly increased sugar yield and fertiliser N efficiency compared to conventional urea. Further studies are required to verify the potential of the ‘enhanced efficiency fertilisers’ to maintain sugar productivity at substantially reduced application rates and to understand the variability in the efficacy of different fertiliser formulations under different seasonal and site conditions.

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