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# EFFECTS OF UREA FORMULATION ON SUGARCANE YIELD, NITROGEN UPTAKE AND NITROUS OXIDE EMISSION IN TROPICAL QUEENSLAND

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**Controlled Release Fertiliser.**

## Abstract

THERE IS a genuine need to explore new management practices on sugarcane farms to improve fertiliser nitrogen (N) efficiency and reduce nitrous oxide ($N_2O$, a potent greenhouse gas) emissions while maintaining crop yield. A field experiment was conducted at Ingham in northern Queensland from October 2012 to October 2013 to assess the efficacy of two 'enhanced efficiency' nitrogen fertilisers: polymer-coated urea (PCU) and nitrification inhibitor-coated urea (NICU). $N_2O$ emissions were measured using both manual and automatic gas sampling chambers. The N release from PCU into soil was considerably slower, which resulted in lower mineral N concentrations in the first 1–2 months after application and maintained higher mineral N levels during the mid to late cropping season than the conventional urea treatments. Lower $NO_3^-$ contents in soil were recorded in the NICU treatment than the conventional urea treatment in the initial three months. The annual cumulative $N_2O$ emissions amounted to 11.4–18.2 kg N/ha with no significant differences between urea forms and between fertiliser application rates (0, 100 and 140 kg N/ha). The similar $N_2O$ emissions suggested that $N_2O$ production in this soil was mainly driven by other factors such as rainfall rather than soil mineral N concentrations. The urea formulation did not affect sugarcane yield at the same N application rate. Reduction in the fertiliser application rate from the recommended 140 kg N/ha to 100 kg N/ha decreased sugarcane yield for the conventional urea and PCU treatments but not for the NICU treatment. Crop N uptake also decreased with the decreasing N application rate for the conventional urea, but not for PCU and NICU. These results demonstrated that the coated fertilisers may potentially reduce N application rates without causing N deficiency to the crop. However, further studies are required to investigate the optimal management practices such as application time and rate in relation to soil and climatic conditions.

## Introduction

Nitrogen (N) fertiliser is one of the major investments farmers make to help achieve their yield targets. However, the efficiency of fertiliser N use by sugarcane crops is generally low, with about 40–60% of the applied N lost from the plant-soil system (Prasertsak *et al.*, 2002). Given that N fertiliser is now generally applied below the soil surface (8–10 cm), ammonia volatilisation is no longer a major pathway of N loss. However, other N loss processes such as denitrification, leaching and runoff remain a challenge as Australian sugarcane farms are mostly in the subtropics or tropics with high rainfall or irrigation.

Fertiliser nitrogen losses represent serious economic costs to farmers and introduce large amounts of reactive N compounds into the environment. These reactive N compounds alter natural N cycles, impose great pressure on ecosystem health and contribute to climate change (Galloway *et al.*, 2003). For example, nitrous oxide ($N_2O$) lost during the nitrification and denitrification processes is a powerful greenhouse gas with a global warming potential of ~300 times that of carbon dioxide ($CO_2$). Previous studies showed that $N_2O$ emissions from Australian sugarcane soils were generally high (2–12 kg $N_2O$-N/ha/yr), with the highest emission episodes in the first three to four months following N fertiliser application during the wet season (Wang *et al.*, 2008; Wang *et al.*, 2012).

Slow-release fertilisers and ammonium-based fertilisers containing nitrification inhibitors have been developed to enhance the efficiency of N fertilisers (Chen *et al.*, 2008). Many studies have demonstrated that that use of these modified forms of fertiliser can substantially reduce N losses from denitrification and leaching (Akiyama *et al.*, 2013; Chen *et al.*, 2008). Of the slow-release techniques, polymer-coating is relatively new and has the benefits of not substantially reducing N content in the fertiliser and allowing N to be released in a more controlled manner. Among the nitrification inhibitors commercially available, DMPP (3,4-dimethylpyrazole phosphate) was considered to have a number of advantages including high efficiency, low application rate and low toxicity (Zerulla *et al.*, 2001).

There have been few assessments of these newer urea forms in the tropical sugarcane growing regions of Australia where 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 potential of nitrification inhibitor or polymer coating of urea to increase fertiliser N efficiency, reduce application rates and mitigate $N_2O$ emissions while maintaining crop yield.

## Materials and methods

### Experimental site

The experiment was conducted at Ingham in northern Queensland (18°42’43’S, 146°08’48’E). This region has a tropical monsoon climate. Long-term (1968–2013) annual mean temperature is 24.0°C. Mean annual rainfall is 2110 mm (Bureau of Meteorology, Australia).

The soil was a silty clay loam (0–25 cm), underlain by a silty clay layer at 25–60 cm depth (Table 1). The sugarcane crop (Q208) was planted in the middle of ~1 m wide beds in August 2011 with a row spacing of 1.68 m. The plant cane crop was harvested on 27 September 2012, with a low fresh cane yield of ~55 t/ha due to poor seasonal conditions. Green cane trash blanketing has been practised on this farm since 1985.

**Table 1**—Some physiochemical properties of the soil profile.

| Depth (cm) | Clay (%) | Silt (%) | Sand (%) | TOC[1] (g/kg) | TN[2] (g/kg) | $pH_{water}$ | EC[3] (dS/m) | BD[4] ($g/cm^3$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Bed | Inter-row |
| 0–10 | 28 | 42 | 30 | 14.7 | 1.1 | 5.06 | 0.23 | 1.26 | 1.39 |
| 10–20 | 29 | 41 | 30 | 11.8 | 0.9 | 5.33 | 0.25 | 1.34 | 1.46 |
| 20–30 | 37 | 37 | 26 | 8.8 | 0.7 | 6.18 | 0.34 | 1.42 | 1.56 |
| 30–60 | 45 | 31 | 24 | 4.3 | <0.5 | 7.79 | 0.77 | 1.53 | 1.60 |
| 60–100 | 37 | 27 | 36 | 1.6 | <0.5 | 8.42 | 0.83 | 1.61 | 1.62 |

[1.] TOC: Total organic carbon; [2.] TN: Total N; [3.] EC: Electrical conductivity; [4.] BD: Bulk density.

### Treatments and layout

Seven treatments were applied in the first ratoon crop to compare polymer-coated urea (PCU) and nitrification inhibitor (DMPP)-coated urea (NICU; Incitec Pivot Fertilisers) with conventional urea (U) as follows:

(1) 0N
(2) 140N_U
(3) 140N_PCU
(4) 140N_NICU
(5) 100N_U (not measured for $N_2O$ emissions)
(6) 100N_PCU
(7) 100N_NICU

where 0N, 100N and 140N refer to fertiliser N application rates at 0, 100 and 140 kg N/ha, respectively. For example, 140N_PCU means that fertiliser N was applied at 140 N/ha as PCU. 140N and 100N were the recommended and a sub-optimal fertiliser N application rate, respectively. It was presumed that the potential of PCU and NICU to improve crop nitrogen use efficiency and yield should be more apparent at a sub-optimal N application rate.

The treatments were arranged in a randomised block design with four replicates. The plots were 20 m long and 8.4 m wide with five crop rows. The blocks were separated with a 1 m buffer zone. Nitrogen fertiliser was applied on 4 October 2012, ~10 cm below the soil surface in a slit cut in the middle of the sugarcane row. The crop was harvested on 6 August 2013.

### Measurement of greenhouse gas fluxes

$N_2O$ fluxes were measured using both manual and automatic gas sampling chambers from 5 October 2012 to 4 August 2013 and only automatic chambers from 9 August to 4 October 2013. The manual chambers (Wang *et al.*, 2011) consisted of a square stainless-steel base (0.5m W×0.5m L×0.15m H) and a cover box (50cm L×50cm W×55cm H). The cover box was fitted with a sampling outlet in the middle of the top panel, a mini fan inside the top panel for mixing air and a closed-cell foam seal under the bottom frame. Two chamber bases were installed in each plot by inserting them into the soil to a depth of ~10 cm. To measure greenhouse gas emission rates, the chambers were closed by clamping the cover boxes on to the bases for 1–1.5 h between 09:00 and 11:00 am. Subsequently, gas samples were taken with a 50 mL syringe at the beginning and end of the enclosure period. The gas samples were stored in pre-evacuated glass vials before being analysed in the laboratory with a gas chromatograph (Varian CP-3800, Varian Inc., the Netherlands).

Automatic gas sampling chambers were used to measure greenhouse gas fluxes at a sub-daily frequency (10 samplings/day). Limited by the number of chambers (nine in total), the automatic chambers were installed only for Treatments 1 (0N) and 2 (140N_U) with four or five chambers per treatment.

The automatic chambers (Wang *et al.*, 2011) consisted of a stainless-steel base identical to the manual chamber base and a cover box (0.3 m deep) with two lids on the top panel that could be opened and closed automatically at pre-set intervals. Placement of the chamber bases was similar to those described above for the manual chambers. Air samples were automatically extracted from the head-space of the chamber into a gas chromatograph (SRI 8610C, SRI Instruments, CA, USA) for the analysis of $N_2O$ concentration on site.

### Determination of soil mineral N contents

Soil samples were collected for two separate areas in each plot: (1) the centre of the sugarcane bed (fertilisation band); and (2) the bed shoulder and depressed inter-row area. The samples for each area were randomly taken from three points and bulked by depth for 0–10 and 10–30 cm layers. The samples were air-dried immediately after collection. Soil mineral N including ammonium ($NH_4^+$) and nitrate ($NO_3^-$) contents were determined using 2 M KCl extraction and colorimetric techniques (Rayment and Lyons, 2010). Gravimetric soil water content was determined by oven-drying at 105°C for 24 h. Soil mineral N contents were expressed on a dry mass basis.

### Other measurements

Sugarcane yield was measured by harvesting the entire middle row (20 m) with a commercial harvester and a weighing truck. A 5 m section was manually harvested, and the millable cane and leaf & cabbage were separated, weighed, cut into small pieces and sub-sampled. Dry matter contents of the fresh cane and leaf & cabbage were determined by placing sub-samples 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 above-ground N uptake by the crops was calculated using the fresh cane yield, cane/leaf and cabbage ratio, dry matter contents and total N contents.

Rainfall and air temperature were recorded using a weather station on site (Campbell Scientific Australia Pty. Ltd., Qld).

### Data processing and statistical analysis

Hourly emission rates during the chamber closure period were calculated from the increase of gas concentration in the head space. Daily emission rates for the automatic chamber measurements were obtained by averaging all hourly emission rates for that day. Daily emission rates for the manual chamber measurements were estimated by extrapolating the hourly emission rates measured between 09:00 and 11:00 am.

Automatic chamber measurements showed that $N_2O$ emission rates during this time were generally close to the daily averages (Wang *et al.*, 2011). The daily emission rates between the days of manual chamber measurements were estimated by linear interpolation.

All statistical analyses were performed using GenStat V.14 (VSN International Ltd, UK). Prior to analysis of variance, data were tested for normality and log-transformed where appropriate. Differences and interactions among treatments were tested using the analysis of variance procedure and the least significant difference (LSD) at $P < 0.05$.

## Results and discussion

### Dynamics of soil mineral nitrogen

Soil $NH_4^+$ and $NO_3^-$ contents (0–30 cm layer) were mostly low ($\leq$ 5 mg N/kg) in the bed shoulder and inter-row area throughout the cropping season (Figure 1a,c,e). The $NH_4^+$ contents in the middle of the beds, where fertiliser was applied in a band, increased substantially in the initial three weeks after fertilisation, with those for the PCU treatments significantly lower than other fertilised treatments (Figure 1b,d,f).

$NH_4^+$ concentrations in the fertiliser band remained high (> 95 mg N/kg) for more than three months for the fertilised treatments, indicating that nitrification was slow in this soil. Consequently, soil $NO_3^-$ contents increased slowly and remained at low levels (< 55 mg N/kg). The NICU treatments consistently had lower $NO_3^-$ contents in soil than the other fertilised treatments in the first 3–4 months.

The PCU treatments appeared to have higher $NH_4^+$ concentrations than other fertilised treatments during the late cropping season, demonstrating that polymer coating retarded N release from the fertiliser. Soil mineral N contents in the bed of the unfertilised control were 8–13 mg N/kg, significantly lower than the fertilised treatments, from late October 2012 to April 2013.

### Dynamics of $N_2O$ emissions and key driving factors

$N_2O$ emissions generally remained low during the initial two and half months when the weather was dry (Figure 2), although soil mineral N contents were high following fertilisation (Figure 1).

The manual chamber measurements showed no significant differences in the $N_2O$ emission rates between different treatments, but the automatic chambers recorded higher emissions for the fertilised treatment than the unfertilised control during this dry period ($P$ < 0.05). High $N_2O$ emissions (>200 g $N_2O$-N/ha/d) occurred following the substantial rainfall events in late December 2012 and early January 2013.

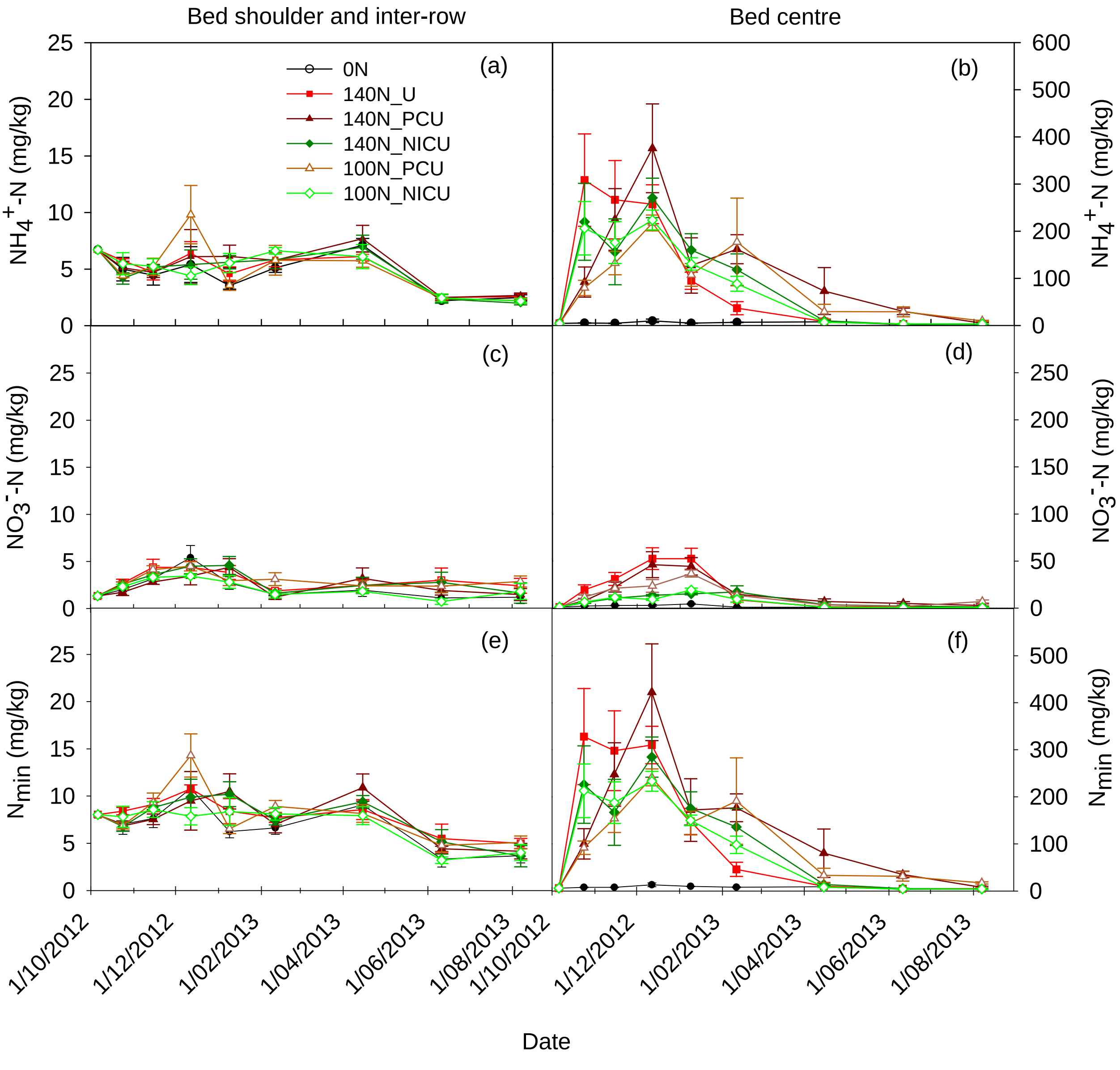

Fig. 1–Dynamics of soil mineral N contents (mean+SE in 0–30 cm) in the bed shoulder/inter-row and bed centre areas.

In the subsequent two weeks with no more substantial rainfall, $N_2O$ emission rates declined gradually with time. The large rainfall events in late January 2013 accelerated $N_2O$ emissions again but at lower magnitudes compared to the previous emission spikes. From February to April 2013, several emission peaks were recorded following rainfall events. $N_2O$ emissions remained low in the dry months of the late cropping season and in the two months following harvest.

Apart from the initial 1–2 months' measurements with the automatic chambers (Figure 2b), there were no consistent differences in the $N_2O$ emission rates between the different treatments based on both the automatic chamber and the manual chamber measurements.

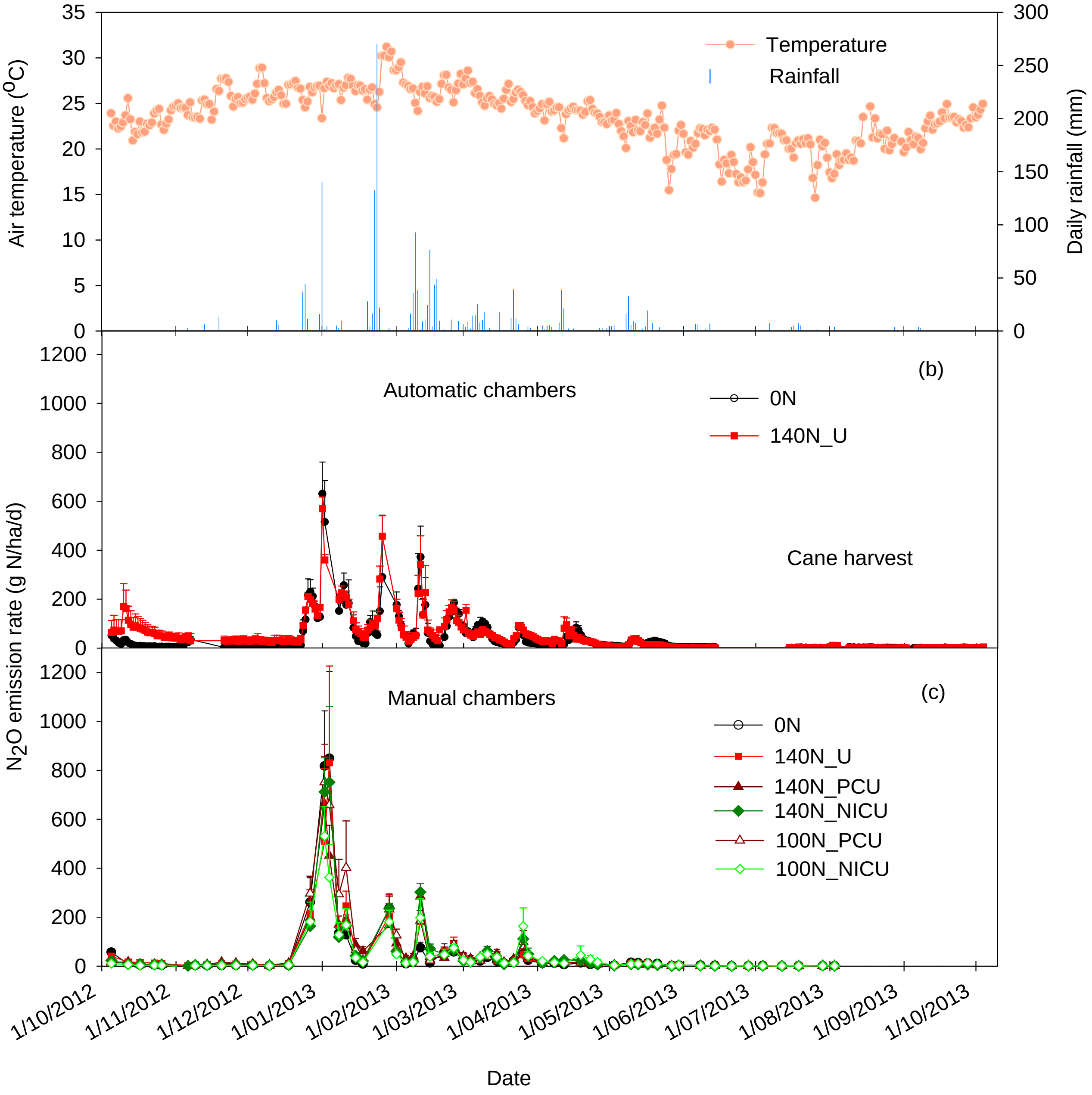

Fig. 2—Dynamics of $N_2O$ emissions (mean+SE) under different treatments in relation to the climatic conditions.

## Cumulative $N_2O$ emissions

Cumulative $N_2O$ emissions during the 12 months amounted to 14.0 and 18.2 kg N/ha for the unfertilised and fertilised treatments, respectively, based on the automatic chamber measurements (Figure 3a).

The annual cumulative $N_2O$ emissions measured with the manual chambers were 13.6 and 13.2 kg N/ha for the 0N and 140N_U treatments, respectively, and ranged from 11.4–16.1 kg N/ha for all treatments (after adding 0.07 kg N/ha for the period between 04 August and 04 October 2013, based on the automatic chamber measurements). There were no significant differences in the annual $N_2O$ emissions between different N fertiliser application rates (0, 100 and 140 kg N/ha) or among conventional urea, PCU and NICU (Figure 3b).

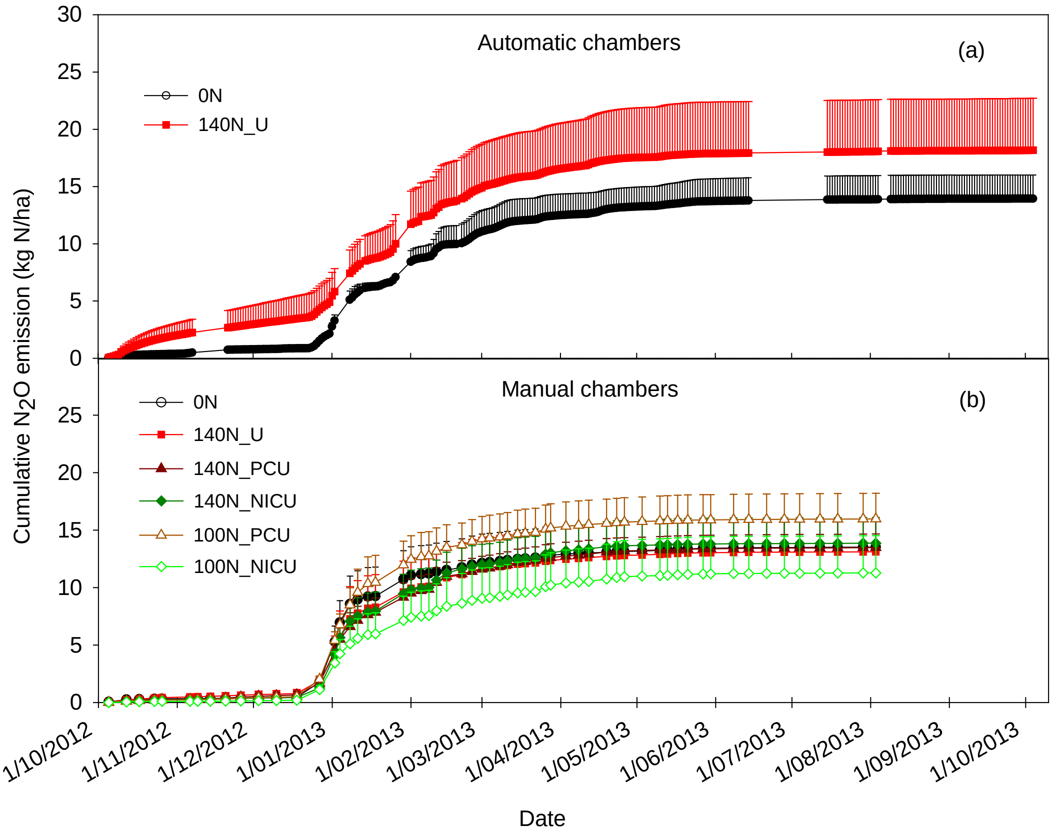

Fig. 3—Cumulative $N_2O$ emissions (mean+SE) for different treatments as measured with (a) the automatic chamber and (b) the manual chamber methods.

### Sugarcane yield and N uptake

Sugarcane yields ranged from 55 to 81 t/ha (Figure 4). Almost all the fertilised treatments had higher yields than the unfertilised control. There were no significant differences in the cane yield between different fertiliser types at the recommended N application rate of 140 kg N/ha. Reduction in the fertiliser N application rate from 140 kg N/ha to 100 kg N/ha resulted in yield losses of 9–10 t/ha for the conventional urea and PCU treatments.

However, no yield loss was recorded at the suboptimal N application rate for NICU. At this lower N application rate, NICU appeared to have outperformed the other urea forms by 7.5 to 8.9 t sugarcane/ha, but such differences were not significant at $P < 0.05$.

The total N uptake in the above-ground biomass was about 80 kg N/ha for all the treatments receiving 140 kg N/ha, regardless of the fertiliser form (Figure 5). Without application of fertiliser N, the plant N uptake was significantly lower (55 kg N/ha) in the control treatment.

Reducing the fertiliser application rate from 140 kg N/ha to 100 kg N/ha decreased the crop N uptake by 21% (17 kg/ha) when conventional urea was used. However, use of PCU and NICU at the lower rate did not affect the crop N uptake relative to the higher N application rate.

## Discussion

### $N_2O$ emissions: key drivers, magnitudes and effects of N fertilisation

Following application of conventional urea, the prolonged dominance of $NH_4^+$ over $NO_3$ in the first four months demonstrated a low nitrification capacity in this soil. In spite of the differences in soil mineral N contents, $N_2O$ emissions were similar between the unfertilised (0N) and the fertilised treatments (140N_U) during the high emission periods, as demonstrated consistently by both automatic and manual chamber measurements.

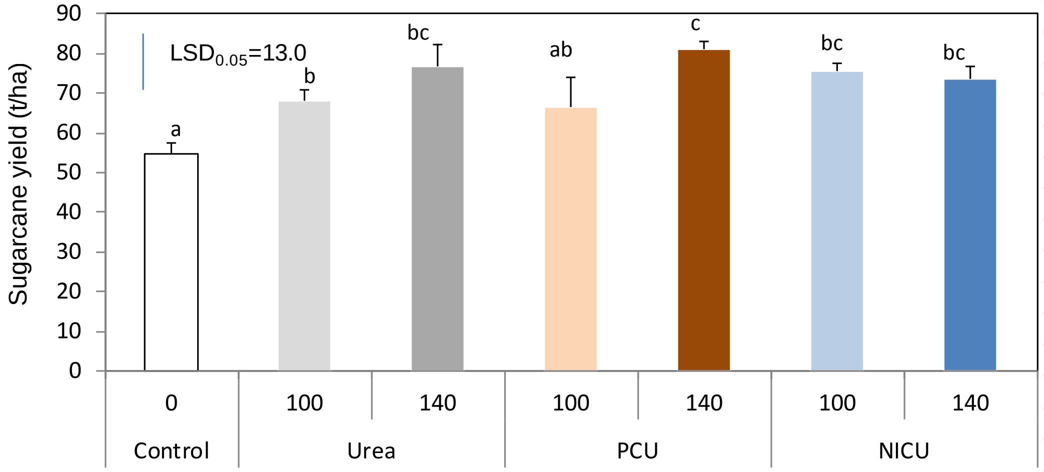

Fig. 4—Sugarcane yield responses (mean+SE) to different forms of urea and application rates at Ingham in the 2012–13 cropping season. The yields labelled with the same letter were not significantly different at $P < 0.05$.

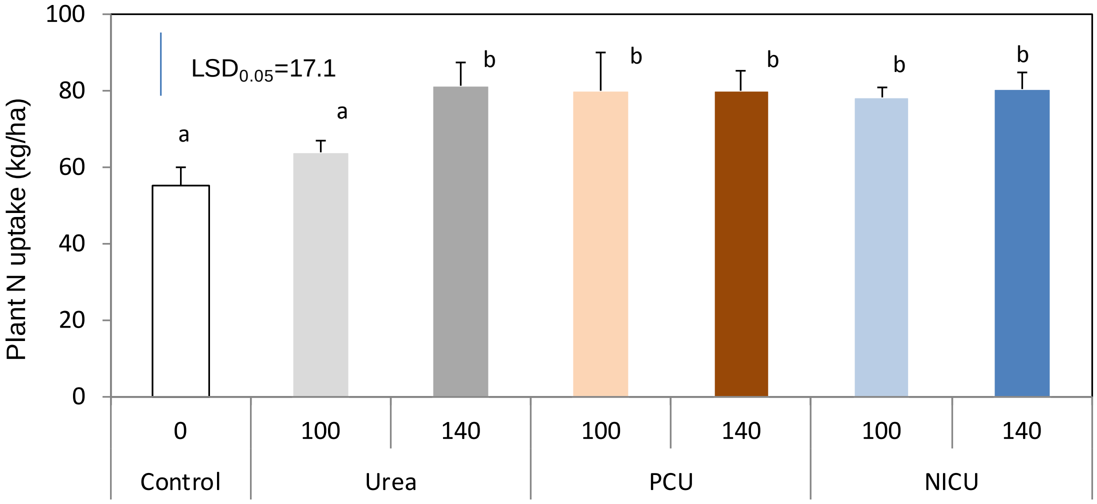

Fig. 5—Nitrogen uptake (mean+SE) in the above-ground biomass at harvest in response to different urea forms and application rates.

This suggested that the mineral N contents in the unfertilised treatment did not limit $N_2O$ production in this soil. The episodic occurrence of high $N_2O$ emissions following every high rainfall event (Figure 3) suggested that soil water content was the key driving factor of temporal variations in $N_2O$ emissions.

However, very high $N_2O$ emissions (> 400–800 g N/ha/d) like those in early January 2013 have seldom been recorded in Queensland cereal or cotton cropping systems even after similar rainfall or irrigation events (e.g. Scheer *et al.*, 2013; Wang *et al.*, 2011).

Therefore, other factors such as the large amounts of crop residues retained (providing a source of readily available carbon), high temperature, low soil pH and perhaps inadequate drainage could also have contributed, maybe in an interactive manner, to the high $N_2O$ emissions observed in this sugarcane cropping system.

The higher $N_2O$ emissions recorded with the automatic chambers compared with the manual chambers for the 140N_U treatment during the first two and half months (Figure 2b, c) were unexpected and the causes for such differences were unclear. The automatic chambers might have overestimated the $N_2O$ emissions during this dry period as enclosure by the automatic chambers could reduce evaporation from the soil inside the chamber. As a result, the wetter soil conditions inside the automatic chambers could have promoted $N_2O$ emissions from nitrification and/or denitrification of the fertiliser N.

The annual cumulative $N_2O$ emissions of 13.2 kg N/ha (with manual chambers) and 18.2 kg N/ha (with auto-chambers) for the 140N_U treatment were comparable to those observed in sugarcane cropping systems at Murwillumbah (Denmead *et al.*, 2010; Wang *et al.*, 2008) and Mackay (Wang *et al.*, 2012). They were considerably higher than the annual $N_2O$ emissions recorded for the treatments fertilised at 90 kg N/ha in a rain-fed cereal cropping system in Southern Queensland (0.5–1.6 kg N/ha; Wang *et al.*, 2011) and the world average for arable cropland (1.1 kg N/ha; Stehfest and Bouwman, 2006). In addition to contributing global greenhouse gas emissions, the high $N_2O$ emissions represent considerable N losses and indicate the potential of N loss as $N_2$, which is generally released simultaneously with $N_2O$ during denitrification, sometimes in greater magnitudes than $N_2O$ (Weier, 1999).

### Efficacy of polymer-coated urea

Compared to the 140N_U treatment, soil mineral N contents in the PCU treatments initially increased slowly but were sustained at higher levels during the late cropping season (Figure 1b, d). Thus the PCU fertiliser clearly demonstrated the expected slow-release characteristics and extended the time of fertiliser N supply to crops. In spite of this, the effects of PCU on mitigating $N_2O$ emissions was not shown even during the first two months after fertiliser application when the soil mineral N contents were lower in the PCU than the conventional urea treatment. This might be attributed to the dry conditions in this period and the unimportance of soil mineral N concentration among all the driving factors for $N_2O$ production in this soil as discussed above.

At the recommended fertiliser N application rate (140 kg N/ha), PCU was not markedly superior to the conventional urea in terms of crop yield and N uptake (Figures 4 and 5) probably because the crop demand for N was not limited by the N availability.

At the sub-optimal fertiliser application rate (100 kg N/ha), the aboveground plant N uptakes were significantly higher in the PCU treatment than the uncoated urea and were comparable to those in the 140N_PCU treatment.

These results suggested that PCU had the potential to reduce fertiliser N application rate from the recommended rate without affecting the total plant N uptake during the whole cropping season. However, the similar sugarcane yield in the 100N_U and 100N_PCU treatments and the significantly lower yield at 100N than at 140 N of PCU (Figure 4) suggested that inadequate N supply due to the slow release of N from the PCU during the early stages might have restricted crop growth at the lower N application rate.

The sustained N supply in the 100N_PCU treatments during the late crop growing season (Figure 1b) seemed unable to recover the early growth losses, but increased the N concentration in the aboveground biomass (3.3 g N/kg for 100N_PCU *vs*. 2.6–2.9 g N/kg for other treatments). Mixing conventional urea with the PCU at a sub-optimal N application rate might offer a solution to meet the N requirements by the crops during the early growing season and also reduce the fertiliser cost compared to using PCU only.

### Efficacy of nitrification inhibitor-coated urea

The significantly lower soil $NO_3$ contents in the NICU treatment compared to other fertilised treatments (Figure 1d) indicated that DMPP effectively inhibited nitrification of the fertiliser N, especially in the first three months.

Despite the slower nitrification in the NICU treatments, the capability of the nitrification inhibitor to mitigate $N_2O$ emissions was not shown, perhaps due to the initial dry soil conditions following fertiliser application and the insignificance of soil $NH_4^+$ and $NO_3^-$ contents in the regulation of $N_2O$ production in this soil. The results differed from our previous observation at Mackay in the 2010–2011 cropping season, where NICU reduced annual $N_2O$ emissions by ~44% (Wang *et al.*, 2012). These results suggested that the effects of nitrification inhibitors on mitigating $N_2O$ emissions vary with soil and climate conditions.

The significantly higher plant N uptake at the sub-optimal N application rate for the DMPP-coated urea compared to the conventional urea suggested that the nitrification inhibitor increased the availability of the fertiliser N to plants. This might have resulted from reduced $NO_3^-$ leaching during the high rainfall period in January 2013 (Figure 1f) since gaseous N losses, as indicated by $N_2O$ emissions, were not affected by the urea forms.

The similar sugarcane yields and the aboveground plant N uptakes observed between the recommended and reduced fertiliser application rates (Figs. 4 and 5) with NICU demonstrated the potential of fertiliser N reduction without sacrifice of crop yield. However, further research is needed to investigate appropriate reductions in fertiliser N if NICU is used, particularly in relation to soil properties, environmental conditions and other management practices.

## Conclusions

Annual $N_2O$ emissions from soil under the conventional N fertilisation regime (140N_U) was high in this sugarcane cropping system, amounting to 13.2 kg N/ha as measured with manual chambers or 18.2 kg N/ha as recorded with the automatic chambers.

$N_2O$ emissions at the study site appeared to be regulated largely by rainfall events rather than by the availability of mineral N in soil. As such, different N fertiliser forms (urea, PCU and NICU) or application rates (0, 100 and 140 kg N/ha) did not significantly alter $N_2O$ emissions in this cropping system.

The PCU demonstrated the slow-release characteristics with longer-lasting supply of available N as expected. However, compared to uncoated urea at the same N application rate, PCU did not significantly increase sugarcane yield.

In spite of this, PCU displayed the capacity to enhance the aboveground plant N uptake and the fertiliser N use efficiency at the sub-optimal N application rate of 100 kg N/ha.

Application of NICU resulted in lower $NO_3^-$ concentrations in soil for at least three months as compared to conventional urea. Similar sugarcane yields and N uptakes were recorded for the sub-optimal (100N) and recommended (140N) N application rates when NICU was applied. This represented a saving of 40 kg N/ha without yield loss.

The similar yields at 100N and 140N with NICU and the similar plant N uptakes at 100N and 140N for both PCU and NICU demonstrated the potential of reducing N application rates with these new fertiliser forms. However, the efficacy of PCU and NICU and the extent of reduction in the application rate in relation to the N-supplying capacity of soil and the climatic conditions need to be investigated.

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