Fertiliser ^{15}N loss increases in response to the N surplus in tropical sugarcane systems

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Abstract
High N inputs in Australian sugarcane systems have raised concerns about N pollution. The response of fertiliser-N loss to N fertiliser rates in sugarcane systems is virtually unknown, hindering the optimisation of N rates. This study investigated the effects of N fertiliser rates from 100–250 kg N ha^{-1} on yield, plant N uptake and N losses using ^{15}N-labelled urea on sugarcane farms in the Burdekin and Mackay districts, QLD. Increasing fertiliser-N rates had no effect on sugar yield across sites. Fertiliser-N recovered in the soil remained constant at higher N rates while fertiliser-N taken up by the plant increased with N rates up to a maximum of 26% of the N applied. The loss of fertiliser-N ranged from 47 to 60% of the N applied and was correlated with N surplus (N rate – total plant N uptake). These findings highlight the importance of matching N rates with crop N demand to minimise N loss to the environment.

Keywords
N use efficiency, Fertiliser N recovery

Introduction
Conventional high N inputs in the Australian sugar industry have raised concerns about N pollution, despite the current N fertiliser rate guidelines designed to align N rates with the district yield potential (Schroeder et al. 2010). Losses of N from sugarcane systems are estimated to account for 46–65% of dissolved inorganic N loads to the Great Barrier Reef (Bartley et al. 2017) and 25% of fertiliser-induced N_2O emissions in the Australian agricultural sector (DISER, 2018). Understanding the fate of N fertiliser in response to N rates is required to evaluate N application rates in terms of contributions to both crop growth and environmental loss. Historical studies on ^{15}N fertiliser recoveries have been limited to single N rate trials showing a fertiliser N uptake efficiency (NUpE) from 20 to 40% in Australian sugarcane systems, with fertiliser N loss to the environment up to > 60% of the applied fertiliser N (Chapman et al. 1994; Prasertsak et al. 2002; Vallis et al. 1996). Comparable ^{15}N fertiliser recoveries in the plant were reported across different N rates in Brazil, yet the lack of measurements of ^{15}N recovered in the soil prevented the quantification of overall ^{15}N fertiliser loss (Franco et al. 2011). The response of fertiliser N losses across different N rates is virtually unknown in sugarcane systems, hindering optimisation of N rates incorporating environmental costs of N losses. This study investigated the effects of N fertiliser application rates on fertiliser ^{15}N recovery in the plant and soil, and on fertiliser N losses in intensive tropical sugarcane systems.

Methods
Study sites and experimental designs
The field experiments were conducted on commercial sugarcane farms in Burdekin, QLD (19° 37' 4" S, 147° 20' 4" E) from October 2018 to August 2019 growing 3rd ratoon Q240 and in Mackay, QLD (21° 14' 4" S, 149° 04' 6" E) from October 2019 to August 2020 growing 3rd ratoon Q208. Sugarcane was burnt before harvest at the Burdekin site and furrow irrigation was applied at monthly intervals during the 2018/19 growing season. 'Green cane trash blanketing (GCTB)' is practised in Mackay, and overhead sprinkler irrigation was applied three times early in the 2019/20 growing season. The field experiment at the Burdekin site had a randomised strip design with four plots across two strips for each

N treatment. The experiment at the Mackay site had a completely randomised block design with three replicates per N treatment and the unfertilised control. At the Burdekin site, N fertiliser rate treatments were control (0N, nil N-fertiliser applied), 150 kg N ha^{-1} (150N), 200 kg N ha^{-1} (200N) and 250 kg N ha^{-1} (250N). At the Mackay site, 100 kg N ha^{-1} (100N) was additionally included. The recommended N rate in SIX EASY STEPS was 150N at the Mackay site and 200N at the Burdekin site. Urea was applied by banding the fertiliser 10 cm deep and 30 cm from the bed centre on both sides of the cane row at the Burdekin site and by stool splitting at the Mackay site. A section with a length of 2.0 m was exempted from the application of N fertiliser in each plot and ^{15}N enriched urea fertiliser (5 atom % excess) in solution was manually applied into the soil at the corresponding rate.

Plant and soil sampling and ^{15}N calculations

The complete 2 m section was harvested prior to the farmer's harvest at both sites and separated into tops, stalk, dead leaves and trash (Prasertsak et al. 2002). Fertiliser ^{15}N recovered in the plant in the adjacent rows was estimated using the green leaves at the 3rd node (Franco et al. 2011). The remaining stools and major roots were sampled from a 0.5 × 0.5 m quadrat in the middle of the 2 m section by excavating to 0.15 m depth. Soil samples were taken at 3–4 points between the bed and furrow centres to capture the distribution of fertiliser N using a soil corer down to 1.0 m depth. Each 1.0 m soil core was separated into 0–0.2, 0.2–0.4, 0.4–0.7, 0.7–1.0 m soil depths. Fertiliser ^{15}N recovery in the plant and soil was then measured by ^{15}N mass balance. Plant N uptake efficiency was calculated by summing ^{15}N recovered in plant parts (^{15}NUpE) as well as by the difference in plant N uptake between fertilised and control 0N plots (Apparent NUpE) and shown as a proportion of the N rate.

Results and Discussion

Biomass, plant N uptake and fertiliser N uptake

Sugar yield was 19.2–19.7 Mg ha^{-1} at the Burdekin site and ranged from 18.4 to 24.2 Mg ha^{-1} at the Mackay site across fertilised treatments and did not respond to N rates, with marginal increases in stalk yield countered by decreasing sugar content. Total biomass and plant N uptake in the fertilised treatments were 59–68 Mg ha^{-1} and 161–177 kg N ha^{-1}, respectively at the Burdekin site and 45–54 Mg ha^{-1} and 124–141 kg N ha^{-1}, respectively at the Mackay site. Fertiliser N recovered in the plant increased in response to N rates, ranging from 39 to 65 kg N ha^{-1} and 20 to 46 kg N ha^{-1} at the Burdekin and Mackay site, respectively (Figure 1). The proportion of plant N derived from fertiliser was consistent across the two sites, ranging from 16 to 33% and increasing with higher N rates. The majority of plant N uptake (67–86%) was derived from the native soil N pool, demonstrating a substantial contribution of native soil N to plant N uptake even at high N rates. Plant N derived from native soil N was higher in fertilised plots than in the control plot at the Burdekin site. This "added nitrogen interaction (ANI)" (Liu et al. 2017) can be explained by stimulation of N mineralisation, substitution of native soil N pool with fertiliser N and/or promoted crop growth with expanded roots, resulting in larger accessibility to native soil N at the Burdekin site. There was no significant ANI at the Mackay site, partly explained by the smaller response of plant total N uptake to N rates.

Overall, apparent NUpE was 46–67% and 18–35% at the Burdekin and Mackay site, respectively and significantly higher ($P < 0.001$) than the observed ^{15}NUpE, showing up to 26% of applied N taken up by the plant. The discrepancy between apparent and ^{15}N-based NUpE indicates an inaccuracy of non-isotope methods when evaluating the efficiency of N fertiliser, as the apparent NUpE does not account for the ANI. The observed ^{15}NUpE is at the lower end of the previously reported range (Chapman et al. 1994; Prasertsak et al. 2002; Vallis et al. 1996) across N rates. These findings, together with the lack of response in sugar yield, discourage over-application of N fertiliser.

Fertiliser N remaining in the soil

At harvest, the majority of fertiliser N in the soil was recovered in the top 20 cm of the soil profile around the fertiliser band and only a small amount of fertiliser N was recovered in the deeper soil. The stool split application at the Mackay site resulted in higher fertiliser N concentrations around the fertiliser band compared to the Burdekin site with the two-sided banding of N fertiliser. These results indicate that this fraction N fertiliser may be immobilised and/or adsorbed to surfaces of clay or organic matter, limiting its mobility within the soil profile, but also its availability for plant uptake and loss from the system. The amount of fertiliser N remaining in the soil ranged from 36 to 39 kg N ha^{-1} and 30 to 61 kg N ha^{-1} and accounted for 15–26% and 24–36% of the N applied in the Burdekin and Mackay site, respectively (Figure 1). Fertiliser N remaining in the soil was higher at rates ≥ 150 kg N ha^{-1} at the Mackay site compared to the Burdekin site, suggesting that GCTB may have enhanced immobilisation due to the high C:N ratio of the cane trash, which likely provides long-term benefits for soil N retention (Meier and Thorburn 2016). Importantly, there was no response of N fertiliser remaining in the soil in fertilised plots to N rates ≥ 150 kg N ha^{-1} at both sites. These findings denote that sugarcane soils have only a certain capacity to retain fertiliser N and that increasing N rates do not contribute to higher N retention, highlighting the inefficiency of additional N fertiliser to replenish the soil N taken up by the plant.

Fertiliser N losses in response to N rates and N surplus

Fertiliser N loss ranged from 72 to 149 kg N ha^{-1} and 50 to 143 kg N ha^{-1} at the Burdekin and Mackay site, respectively, accounting for 48–60% and 47–57% of the applied N (Figure 1). Recommended N fertiliser rates resulted in a loss of 50% of the applied N into the environment at both sites. Fertiliser N losses as proportions of the applied N increased at higher N rates ($P = 0.02$). Nitrogen fertiliser losses were significantly correlated with N surplus (Figure 2, $P < 0.001$, $R^2 = 0.51$), calculated as the difference between the N fertiliser rate and plant N uptake. This indicates that N inputs in surplus of the crop N demand are easily lost to the environment. Substantial fertiliser N loss even at low N surplus further emphasises the need to synchronise N fertiliser supply with crop N uptake patterns.

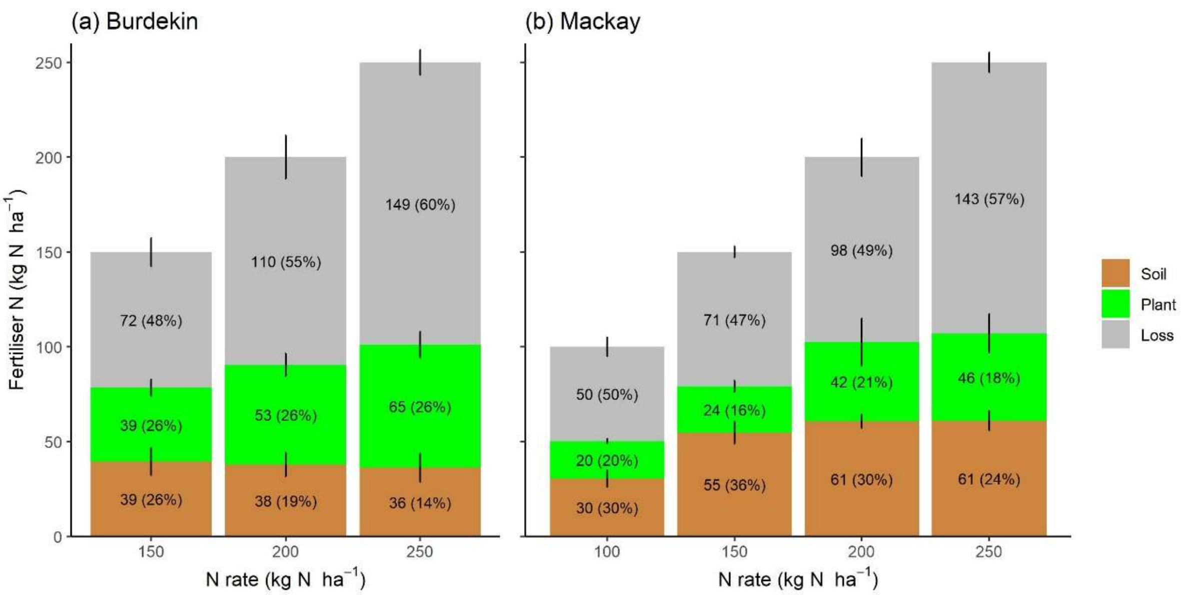

Figure 1. Fertiliser N recoveries in the soil and plant and fertiliser N loss in the 100N, 150N, 200N and 250N treatments at (a) the Burdekin and (b) the Mackay site. The error bars indicate standard errors and the percentages in the columns are proportions of fertiliser N to the applied N rate.

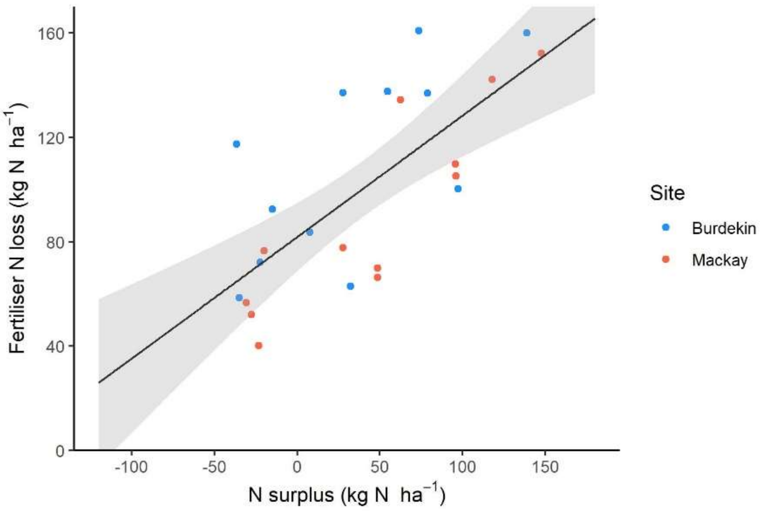

Figure 2. Response of fertiliser N loss to N surplus at the Burdekin (blue) and Mackay (red) sites. The solid line and the shaded area indicate the regression line including both sites and 95% confidence intervals, respectively.

Conclusions

High N application rates in these tropical sugarcane cropping systems did not increase yield nor the retention of N within the soil profile but increased N losses to the environment. Even at the recommended N rates 50% of the N applied was lost, discouraging over-application of N fertiliser in tropical sugarcane crops in QLD. Matching N rates with crop N demand is essential to avoid increases in losses of N fertiliser in response to the N surplus observed in this study. Our findings highlight the urgent need to re-define N fertiliser rate recommendations using isotopic indicators of N fertiliser use efficiency. Extrapolating the results of field-measured ^{15}N recoveries by crop modelling approaches could aid in optimising N rates to minimise N pollution while maintaining crop productivity for different sugarcane growing regions in Australia.

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