INTERPRETATION OF A SIMPLE NITROGEN USE EFFICIENCY INDEX FOR INFORMING NITROGEN FERTILISER MANAGEMENT IN THE BURDEKIN

By

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Abstract

OPTIMISING NITROGEN USE efficiency in the Queensland sugar industry will provide profitability (grower focus), productivity (industry focus) and environmental (social license focus) benefits by ensuring that the crop recovers the maximum amount of applied nitrogen (N), thereby minimising off-site N movement. A simple indicator of N use efficiency is the tonnes cane produced per kg applied N (Partial Factor Productivity of N or Apparent Fertiliser N-use Efficiency- $AppNUE_{Fert}$). Data were used from N-responsive sites/seasons in the RP20 Burdekin nitrogen trials (replicated strip trials) to develop interpretation guidelines for $AppNUE_{Fert}$ in the Burdekin Delta and Burdekin River Irrigation Area. Case studies of partial N budgets illustrated how $AppNUE_{Fert}$ was affected by both applied N recovery by the crop (dependent on the magnitude of N losses) and also by the ability of the crop to convert in-crop N to yield (determined by soil constraints, management practices and seasonal conditions). Particular attention is paid to $AppNUE_{Fert}$ interpretation for low yielding sites and inferences that can be drawn from $AppNUE_{Fert}$ for the management of these sites.

Introduction

The inputs of nitrogen (N) from anthropogenic sources into the waters of the Great Barrier Reef (GBR) lagoon have increased several-fold since European settlement and are linked to increased dissolved inorganic N (DIN) in the GBR lagoon (Brodie *et al.*, 2013). Elevated DIN levels have been linked to increased outbreaks of Crown of Thorns starfish and consequent damage to the GBR (De'ath *et al.*, 2012).

The agricultural land uses contributing DIN to the GBR are sugarcane, horticulture, grains and grazing (Brodie *et al.*, 2013). In 2013, approximately 59 000 tonnes of N were applied to Queensland sugarcane land with an average annual application rate of 162 kg N/ha (Incitec Pivot Ltd, unpubl. data).

Given the high annual rainfall in tropical-subtropical Queensland and its strong seasonal distribution, managing N inputs is challenging because of the mobility of N, particularly in the nitrate form. Nitrate-N has a propensity for off-site movement in runoff, deep drainage or gaseous loss via denitrification, depending on the hydrological characteristics of the site. Minimising N loss depends on synchronising N supply with crop demand so that the crop captures as much of the available mineral N (ammonium-N and nitrate-N) as possible.

Benchmarking and monitoring N-use efficiency is essential for informing N-fertiliser management, and maximising N use efficiency will enhance productivity (viz. optimum yield of harvested product), profitability (viz. optimum financial return from N fertiliser application) and environmental outcomes (viz. minimum off-site N loss).

A simple indicator of N use efficiency that is used in the Queensland sugar industry is the tonnes of cane/kg applied N. In the agronomy literature, this indicator is termed 'Partial Factor Productivity of Nitrogen' (Ladha *et al.*, 2005) because it does not take account of the yield that would have been produced if no fertiliser N had been applied.

For the purpose of this paper, we term this indicator as 'Apparent Fertiliser N-use Efficiency' ($AppNUE_{Fert}$), but note that the units of $AppNUE_{Fert}$ (tonnes FW cane/kg applied N) are the reciprocal of the units of the N multiplier (kg applied N/tonne cane) used in the SIX EASY STEPS for calculating crop N requirements.

A low $AppNUE_{Fert}$ will occur if:

a) the crop captures much of the applied N but is unable to convert this N to biomass because of seasonal conditions (e.g., limited solar radiation; plant available water limitations) or impaired metabolic functioning within the crop (e.g., effects of salinity/sodicity/acidity reducing maximum yield potential);

b) there is limited crop uptake of the applied N because of high environmental losses of the applied N.

Consequently, $AppNUE_{Fert}$ separates N-use efficient from N-use inefficient sites, but is not instructive about the reasons for these efficiency differences. This discrimination is possible if $AppNUE_{Fert}$ is disaggregated into its two component indices: Fertiliser N Uptake Efficiency ($NUpE_{Fert}$) (kg crop N/kg applied N) and N Utilisation Efficiency (NUtE) (t cane/kg crop N). The former index, $NUpE_{Fert}$, is a measure of the efficiency of nutrient management whereas the latter index, NUtE, is a measure of the capacity of the crop to convert N uptake into biomass (and millable cane).

In this paper, data were used from N-responsive sites/seasons in the Burdekin Delta and Burdekin River Irrigation Area (RP20 Burdekin nitrogen trials) to calculate $AppNUE_{Fert}$, and case studies of partial N budgets are used to illustrate how $AppNUE_{Fert}$ is affected by recovery of applied N by the crop (dependent on the magnitude on N losses) and also by the ability of the crop to convert N uptake into biomass. Interpretation guidelines are developed for $AppNUE_{Fert}$ for the Burdekin District.

Materials and methods

Sites and crop management

During the sugarcane cropping seasons from 2011–12 to 2015–16, replicated and randomised on-farm, large-scale strip trials were established at 22 sites in the Burdekin Delta and BRIA, with cropping cycles ranging from plant crop only to plant crop and up to four ratoons. Strips ranged in length from 300 m to 1 000 m and from 6 to 16 rows wide; crop row spacing ranged from 1.52 m to 1.8 m.

Sites were selected to represent the major sugarcane-growing soils of the district. Surface soil samples (0–20 cm) underwent detailed soil fertility analyses to determine the basal nutrient requirements according to the recommendations of the SIX EASY STEPS decision support package (Schroeder *et al.*, 2010).

For plant crops, basal nutrients (including up to approximately 50 kg N/ha) were banded sub-surface into the soil at each trial site during planting with a calibrated planter box. The bulk of the urea N fertiliser was subsequently banded sub-surface before the crop reached the 'out of hand' growth stage (approximately 120 days after emergence). For ratoon crops, basal nutrients and urea N were banded sub-surface following harvest (generally within 30 days). Fertiliser was applied using a calibrated fertiliser box with load cell technology that allowed a record of the weight of product applied to the plot to be obtained and compared with the calibrated rate. All crops were furrow irrigated according to the irrigation scheduling of the individual farmers. Irrigation water inputs ranged up to approximately 10 ML/ha depending on site and season.

Each trial comprised three or four replicate strips of three or four N rates in a randomised complete block design. One rate corresponded to that calculated by the SIX EASY STEPS methodology based on a District Yield Potential of 180 t (FW) cane/ha and discounted for soil N mineralisation potential (Schroeder *et al.*, 2010). These calculations resulted in sites receiving N rates of 160 or 170 kg N/ha for the plant crops and 200 or 210 kg N/ha for the ratoon crops.

At most sites, an N rate lower than the SIX EASY STEPS rate by 40 kg N/ha comprised the lowest N rate treatment. Two rates higher than the SIX EASY STEPS rate by 40 and 80 kg N/ha, respectively, were used to address industry concerns that the SIX EASY STEPS rate was sub-optimal for maximum cane yield. Consequently, applied N rates were 130, 170, 210 and 250 kg N/ha (sites with four rates) or 170, 210 and 250 kg N/ha (sites with three rates) for the plant crop. Ratoon crops received 170, 210, 250 and 290 kg N/ha (sites with four rates) or 210, 250 and 290 kg N/ha (sites with three rates). It was not possible to include a nil-applied N treatment.

Nitrate concentrations were measured in applied irrigation water. The weights (fresh and dry) and N contents of the components of the above-ground biomass (millable stalk, cabbage, leaves and attached dead leaf) were determined at approximately 9 months after planting/ratooning. Millable stalk weight and N content were measured at harvest (11–17 months after planting or ratooning) following a pre-harvest burn to remove leaf residues. Soil profile (0–100 cm) mineral nitrogen (ammonium-N + nitrate-N) was determined before fertiliser application and after harvest. Cane yield and commercial cane sugar (CCS) content were obtained from the mill processing the harvested cane.

Randomised block statistical analysis was used to assess millable stalk yield and sugar yield responses to applied urea-N. In this paper, only those site/seasons where a significant (P<0.05) cane yield response was obtained to applied urea-N above a lower rate are considered. Seven plant crops and eleven ratoon crops met this criterion. None of these sites gave a significant (P<0.05) response in sugar yield to applied N.

Nitrogen use efficiency indicators

The calculation of NUE indicators followed the procedures detailed by Ladha *et al.* (2005) for grain crops, although some of the terminology has been changed to suit the sugarcane cropping system. The NUE indicators were calculated for the N rate where no further significant (P<0.05) cane yield responses were obtained to applied urea: this is referred to as the 'optimum' urea-N rate.

'Apparent Fertiliser N-use Efficiency' ($AppNUE_{Fert}$) = cane yield (tonnes cane/ha)/optimum urea-N rate (kg N/ha)

'Agronomic Efficiency of Nitrogen' (AE_N) = Δ cane yield (tonnes cane/ha)/Δ urea-N rate (kg N/ha)

where cane yield increment (Δ) is calculated as the difference between the cane yield at the optimum urea-N rate and that at the N rate lower than the optimum; Δ urea-N is therefore 40 kg N/ha.

'Fertiliser N Uptake Efficiency' ($NUpE_{Fert}$) = Δ total crop N uptake (kg N/ha)/Δ applied urea-N (kg/ha)

where total crop N uptake is calculated as (1.15 × above-ground biomass N at 9 months) to allow for the contribution of stool and root N to total crop N (Connellan and Deutschenbaur, 2016), and the crop N uptake increment is calculated as the difference between the total crop N uptake at the optimum urea-N rate and that at the N rate lower than the optimum; consequently Δ applied urea-N is 40 kg N/ha.

'N Utilisation Efficiency' (NUtE) = Δ total crop biomass (tonnes DW/ha)/Δ total crop N uptake (kg N/ha)

AE_N is related to $NUpE_{Fert}$ and NUtE by the equation:

$AE_N = NUpE_{Fert} \times NUtE$

Partial nitrogen budgets

For site/seasons where case studies where undertaken, estimated N losses were calculated from a partial N budget using the following parameters:

Available fertiliser N: 0.6 × (Fertiliser N) (Moody and Schroeder, 2014) where Fertiliser N is the optimum urea-N rate;

In-season soil N mineralisation: 0.2 × (Fertiliser N);

Total crop N uptake: 1.15 × (Above-ground crop N uptake at 9 months) (Connellan and Deutschenbaur, 2016);

Δ *Soil profile mineral N:* [Soil profile (0–100 cm) mineral N at planting or post-harvest previous crop harvest – Soil profile (0–100 cm) mineral N at harvest];

N exported to mill: (Commercial cane yield) × (%N millable stalk at harvest); and

Unaccounted N = Available fertiliser N + In-season soil N mineralisation + Δ Soil profile mineral N - Total crop N uptake

where all units are kg N/ha. N input from irrigation water was ignored because these sites were irrigated with channel water at <0.05 mg N/L.

Results

Nitrogen use efficiency indicators

$AppNUE_{Fert}$ decreases as N-unlimited cane yield decreases (Figure 1) suggesting that more applied N is necessary to produce 1 tonne cane when the site/season yield potential is low.

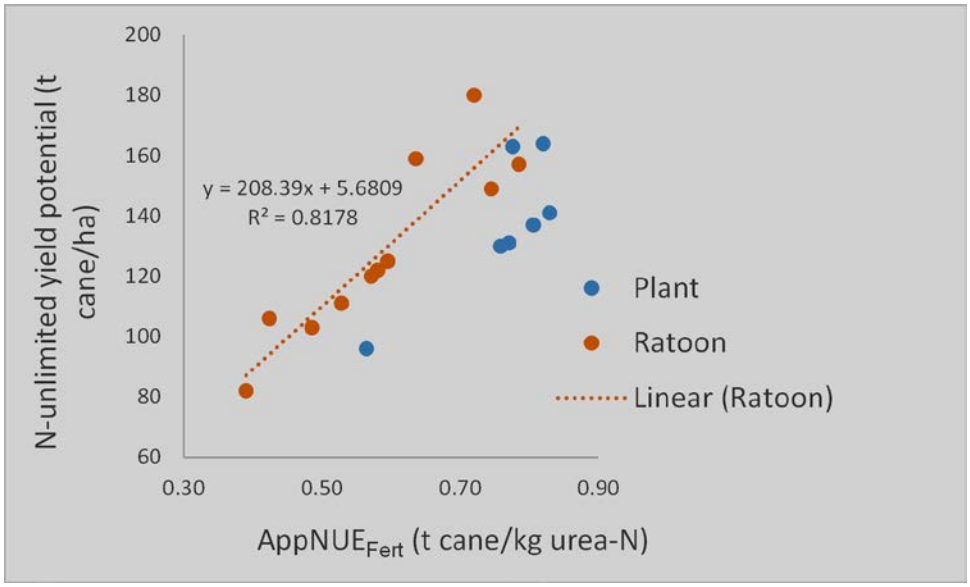

Fig. 1—Plot of apparent fertiliser N-use Efficiency ($AppNUE_{Fert}$) against N-unlimited yield potential for plant and ratoon crops.

This apparent yield effect can be partly attributed to the fact that $AppNUE_{Fert}$ attributes all cane yield production to applied N without accounting for the yield that would have been produced without applied N. This unaccounted yield would constitute a larger proportion of low yield potential sites/seasons than higher yield potential sites/seasons. However, this confounding factor is avoided in the calculation of AE_N, and AE_N is plotted against N-unlimited yield potential in Figure 2.

There is still a strong correlation between AE_N and N-unlimited cane yield potential for ratoon crops, indicating that at sites with low yield potential, less cane is produced per increment of applied urea than for sites/seasons where the yield potential is higher. Plant crops do not show this trend although the range in N-unlimited crop yields is not as wide as for the ratoon crops.

For the ratoon crops, there is a high correlation between final cane yield (t cane/ha) (y) and stalk yield at 9 months (t DW/ha) (x) with the equation of best fit: $y = 75.54e^{0.0246x}$ (R^2=0.57, P<0.01, n=10). Also, since total crop N uptake for ratoon crops at 9 months is around 95% of total N uptake by harvest (Moody and Connellan, 2018), above-ground biomass and total crop N uptake at 9 months are used in this paper to assess the relative importance of fertiliser N recovery ($NUpE_{Fert}$) and N Utilisation Efficiency (NUtE) for determining biomass (and, by inference, cane yield) response to applied N.

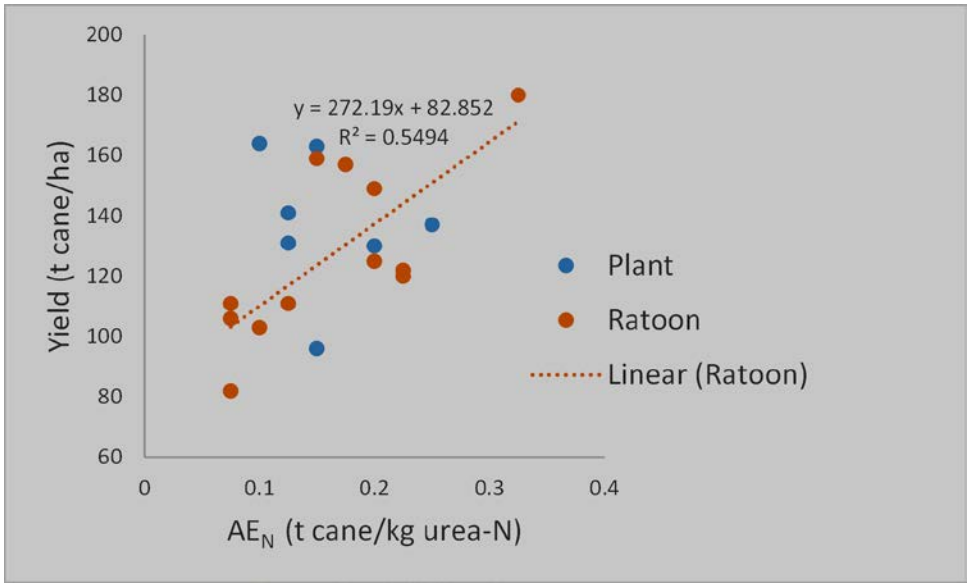

Fig. 2—Plot of agronomic efficiency of nitrogen (AE_N) against N-unlimited yield potential for plant and ratoon crops.

For ratoon crops, AE_N was correlated with $NUpE_{Fert}$ ($r=0.69$, $P<0.05$) but not NUtE ($r=-0.368$, ns). Because of the decline in AE_N that occurs as N-unlimited yield potential decreases (Figure 2), it is apparent that improving N fertiliser use efficiency at low-yielding sites will depend on reducing N losses by denitrification, leaching or runoff.

Partial nitrogen budgets

Partial nitrogen budgets are presented for some case study sites/seasons to illustrate the proportionally large losses of applied fertiliser N that are particularly evident for sites/seasons where the N-unlimited yield potential is low. Yield and $AppNUE_{Fert}$ values of the case studies are presented in Table 1 and the partial N budget components are indicated in Table 2.

Table 1—Yield and N efficiency indicators of the case studies in the 2013–14 cropping season.

Site/Soil	Crop class	N-unlimited yield potential (t cane/ha)	$AppNUE_{Fert}$ (t cane/kg applied urea-N)
5- Sodic duplex (6Drc)	R1	132	0.63
10- Vertosol (RUgb)	R2	106	0.49
12- Dermosol (BGnb)	R1	97	0.46

Table 2—Partial N budgets for the case study sites.

Site	Urea-N applied (kg N/ha)	Estimated available fertiliser N (kg N/ha)	Estimated in-season soil N mineralisation (kg N/ha)	Δ Soil profile mineral N	Total crop N uptake (kg N/ha)	Unaccounted N (kg N/ha)	N exported to mill (kg N/ha)	Crop N/ Fertiliser N
5	210	126	42	–5	139	24	72	0.66
10	250	150	50	2	85	117	54	0.34
12	210	126	42	0	123	45	75	0.59

Site 5 had a higher N-unlimited yield potential than either Site 10 or Site 12. In simple relative terms, total crop N uptake at Site 5 was 66% of the urea-N applied, and the estimated N loss was low (24 kg N/ha).

In contrast, Sites 10 and 12 had low N-unlimited yield potentials. Although the N-unlimited yields at both these sites were similar, Site 10 had lower apparent fertiliser N recovery (34%) than Site 12 (59%), and much higher estimated N losses (117 kg N/ha *cf.* 45 kg N/ha).

Field observations made during the cropping season noted that Site 5 had some gaps but weed management was adequate.

In contrast, Site 12 was very weedy and the crop was occasionally water-stressed because of ineffective irrigation management of this sandy soil. The comparatively high percentage recovery of fertiliser N by the crop at this site indicates that competition with weeds and occasional water limitations had caused physiological constraints to crop production, rather than inadequate N uptake.

On the other hand, there were no obvious management issues with the Vertosol clay loam soil at Site 10, yet the crop recovered much less fertiliser N than at Site 10. It is inferred that perhaps denitrification was a major N loss pathway at this site caused by periodic waterlogging of the soil during irrigation. Therefore, two low-yielding sites had low $AppNUE_{Fert}$ caused by different factors.

Interpretation of $AppNUE_{Fert}$

The regression equation for ratoon crops in Figure 1 represents the N-adequate situation when there is no further cane yield increase to urea-N applied above the optimum rate.

Figure 3 reproduces the N-adequate regression line from Figure 1 and also shows the $AppNUE_{Fert}$-yield relationship when the urea-N rate is 40 kg N/ha lower than the optimum rate (*i.e.* N-deficient situation) and 40 kg N/ha higher than the optimum rate (*i.e.*, N-surplus situation).

It is apparent that $AppNUE_{Fert}$ at any particular cane yield can be used to identify whether the crop N status is deficient, adequate or in N-surplus.

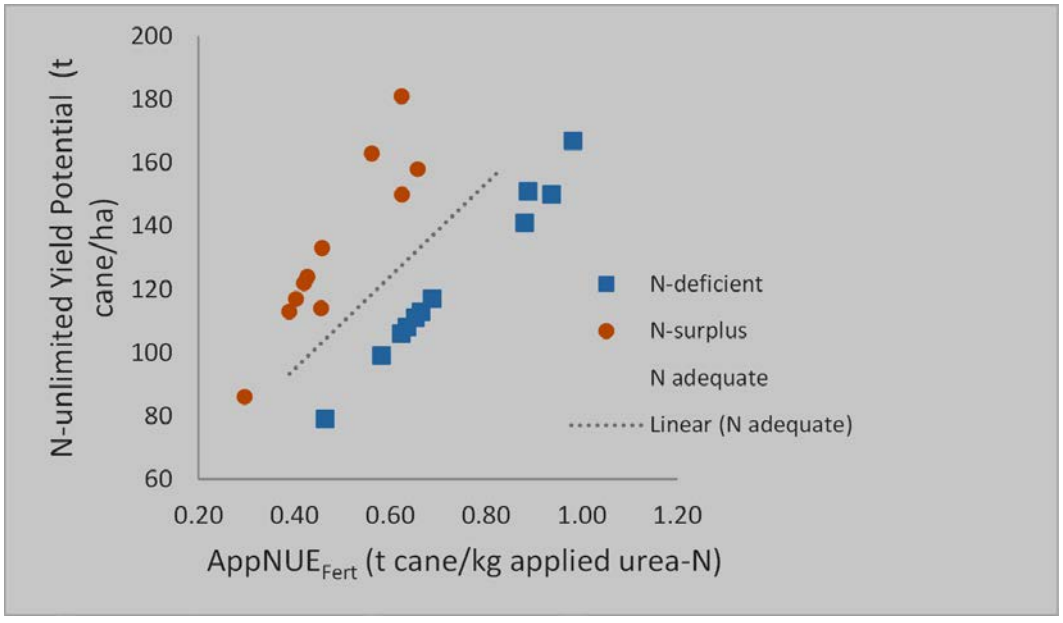

Fig. 3—Plot of apparent fertiliser N-use Efficiency ($AppNUE_{Fert}$) against yield of ratoon crops. Regression line is for $AppNUE_{Fert}$ – yield data at optimum urea-N rate.

Confidence intervals (P=0.05) for the N-adequate regression line allow interpretive guidelines to be developed for $AppNUE_{Fert}$ (Table 3).

Table 3—Interpretation of Apparent Fertiliser N-use Efficiency' ($AppNUE_{Fert}$) values (t cane/kg applied urea-N) for irrigated ratoon crops in the Burdekin District.

Yield (t cane/ha)	N-deficient	N-adequate	N-surplus
80	>0.48	0.31–0.48	<0.31
100	>0.53	0.42–0.53	<0.42
120	>0.59	0.50–0.59	<0.50
150	>0.71	0.63–0.71	<0.63
180	>0.91	0.71–0.91	<0.71

Discussion

Apparent Fertiliser N-use Efficiency ($AppNUE_{Fert}$) (t cane/kg applied N) is a simple indicator of nitrogen fertiliser use efficiency that can be used to benchmark efficiency and to discriminate between N-efficient and N-inefficient sites. Ratoon crop data from the Burdekin show that this indicator is positively correlated with N-unlimited yield potential when N is applied as urea.

This finding is supported by case studies of partial N budgets that show high losses of N can occur when urea is applied to sites where N-unlimited yield potential is low. As illustrated in the case studies, low yield potentials are indicative of one or more of the following causes: soil constraints, such as compaction or sodicity that limit yield potential through physiological effects on the crop; weed pressure or ineffective irrigation management causing crop stress; and low crop recovery of applied urea-N due to large off-site N losses.

The two former causes are likely to be reflected in low NUtE, and, if addressed by management strategies such as amelioration of sodicity or improved irrigation management, would likely increase $AppNUE_{Fert}$ by increasing the N-unlimited yield potential. However, where low $AppNUE_{Fert}$ is caused by low $NUpE_{Fert}$, then mitigation of N loss pathways by management *(*e.g., raised beds and improved drainage to mitigate denitrification) and/or the use of enhanced efficiency fertiliser products (e.g., nitrification inhibitors; controlled release fertilisers) to improve synchrony between nitrogen release and crop demand is indicated.

If the magnitude of off-site N losses can be reduced, then it is quite feasible that N fertiliser inputs could also be reduced without impacting productivity because the crop will be able to recover sufficient N to meet its yield potential. Current field trials being undertaken in the National Environmental Science Program (NESP) and Reef Trust Phase 4 Program are testing this principle.

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