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Evaluation of enhanced-efficiency fertilisers in Queensland sugarcane

J Connellan[1], M Thompson[2], B Salter[3] and M Olayemi[4]

[1]*Sugar Research Australia Limited, Gordonvale, Qld 4865;* jconnellan@sugarresearch.com.au
[2]*Queensland Department of Agriculture and Fisheries, Townsville, Qld 4814;* matthew.thompson@daf.qld.gov.au
[3]*Sugar Research Australia Limited, Mackay, Qld 4740;* bsalter@sugarresearch.com.au
[4]*Sugar Research Australia Limited, Indooroopilly, Qld 4068;* molayemi@sugarresearch.com.au

Abstract Enhanced-Efficiency Fertilisers (EEFs) are purported to reduce nitrogen (N) losses by better matching N supply to crop demand over the growing season. The EEF60 project was designed to evaluate EEF performance across regions, rainfall conditions, soil types and fertiliser application times. EEFs were tested on 74 sugarcane farms, located between Mossman and Bundaberg, with the lifespan of trial sites ranging from one to three ratoons. Four treatments, including two urea and two EEF treatments, were tested. One urea treatment had N applied at the SIX EASY STEPS Step 4 (6ES) recommended rate (Urea 6ES), while the three other treatments applied 20% less N. Applying urea at 20% less N decreased cane yield in medium and high rainfall conditions but improved profitability in low rainfall conditions. Urea treated with nitrification inhibitor (NI) and blends of 20% controlled release fertilisers (CRF) with 80% urea applied with 20% less N maintained similar productivity and profitability to urea applied at 6ES. Blends with high proportions of CRF applied at 20% less N also maintained productivity but cost more, which generally made them less profitable to apply. Nitrogen-use efficiency indicators, such as crop-N content, partial factor productivity of applied N and N-uptake efficiency, were improved when EEFs were applied at 20% less N. These findings indicate that NI-urea and blends of 20% CRF with 80% urea at N rates 20% less than 6ES can be applied at any time during the season without loss of productivity or profitability in comparison to Urea 6ES. EEFs appeared to obtain higher yields than Urea 6ES in some situations under high rainfall conditions, which corresponds to past EEF research. These findings suggest that the EEF option could be endorsed as a recommended nutrient management strategy, particularly when high rainfall is expected.

Key words Enhanced-efficiency fertiliser, controlled release, nitrification inhibitor, nitrogen, yield, profit

INTRODUCTION

Farmers are under increasing pressure to reduce the risk of nitrogen (N) entering the Great Barrier Reef (GBR) catchments (The State of Queensland 2013). New fertiliser technology, such as enhanced-efficiency fertilisers (EEFs), are an opportunity to improve N-use efficiency (NUE) and reduce losses. Field trials conducted in the Burdekin (Dowie *et al*. 2019) suggested opportunities to use EEFs at N rates below the SIX EASY STEPS Step 4 (6ES) recommendations whilst maintaining productivity and profitability. Those trials also identified that the performance of EEFs on yields was influenced by soil type and fertiliser application timing. A glasshouse experiment in the Herbert (Di Bella *et al.* 2017) tested fertiliser N lost in drainage and as nitrous oxide and found CRFs and NIs to be effective at reducing N losses compared to urea.

While EEFs have been tested in some Australian sugarcane regions, they have not yet had their performance evaluated systematically across different regions, rainfall conditions, soil types and fertiliser application times, which are all known to influence crop production and N responsiveness. The EEF60 project was designed to be the most extensive evaluation of EEFs undertaken in the Australian sugarcane industry. It evaluated the production and profitability implications for commercial sugarcane farms from applying EEFs in place of conventional urea at rates equal to or lower than those in the 6ES recommendations (Step 4 N guidelines). On average sixty trials were conducted annually over three seasons. Sites were in the Wet Tropics (30), Burdekin (15), Mackay-Whitsundays (10) and Bundaberg/Isis (5). The trials were established on different soil types, with fertiliser applied at different application times and under rainfall conditions that varied among sites and crops. Of the total 74 trial sites, 54 had a standardised trial design that allowed data to be investigated based on these characteristics. Two main types of urea-based EEFs were tested. These were a CRF, which releases urea slowly through a polymer coating, and urea coated with a nitrification inhibitor (NI), which stabilises N in ammonium form. Due to their higher unit costs when compared to urea and purported ability to reduce N losses by better matching N supply to crop demand over the growing season, the EEFs were tested at N rates below 6ES.

Here, we report on the agronomic performance and economics of using these products.

METHODS

Trial design

Trial sites were inspected and mapped for electrical conductivity (EC) (Veris 3100 or similar device) to identify changes in soil properties across blocks (Figure 1). Blocks were divided into zones according to soil variation with soil samples collected to a depth of 1 m in each zone. Sub-samples from each 20 cm depth increment were analysed for nutrient status. The 0-20 cm samples were assessed using the SIX EASY STEPS methodology to determine baseline nutrient requirements. Soil samples were analysed for the percentage sand, silt and clay in the top 20 cm of the soil profile. A texture triangle (Hunt & Gilkes 1992) was then used to classify the soil type according to texture (i.e. sandy loam). For statistical analysis, texture classifications were simplified to categories of sand, clay and loam.

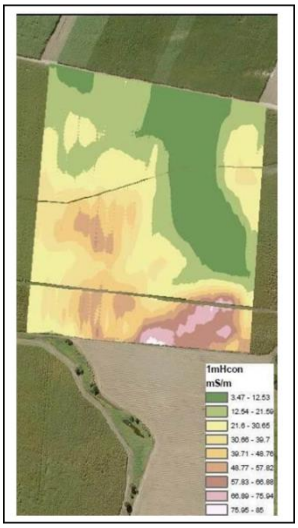

Figure 1. A ‘soil’ map generated from the electrical conductivity measurements.

Trial sites were established in first-ratoon crops with fertiliser applied 4-6 weeks post-harvest. Factors such as crop establishment, irrigation management, and pests and disease management were monitored. Trials were conducted at commercial scale using large, replicated strips with treatments replicated (x3) and randomised. Table 1 provides a description of each treatment in the EEF60 trials.

Table 1. Fertiliser treatments included in the EEF60 trials.

Treatment	N product type	N rate applied	Abbreviation
1	Urea	6ES (Step 4 guideline)	Urea 6ES
2	Urea	20% less than 6ES	Urea -20%
3	1/3 DMPP[E] treated urea + 2/3 CRF (EEF blend)	20% less than 6ES	DMPP/CRF -20%
4: Wildcard[A]	i. DMPP treated urea ii. 20% CRF + 80% urea iii. Other product[B]	20% less than 6ES	i. DMPP -20%, ii. 20% CRF -20% iii. Other
5[D]	None[C]	Zero	0N

[A] Decided based on grower or regional interest.

[B] The other remaining Wildcard product types (iii) were a mix of other nitrification inhibitors (Nitrapyrin) and pure CRFs.

[C] Small-plot areas (6 rows x 20 - 40 m) with 0 N were included to allow calculation of how much background N was available from the soil.

[D] Measured to calculate NUptEfert (results not reported).

[E] 3,4-Dimethylpyrazole phosphate (DMPP).

Cane yield and CCS results were supplied by the local sugar mills with sugar yield calculated from these values. Results were analysed to identify differences in cane and sugar yields which could be attributed to the use of EEFs at N application rates lower than those recommended by the 6ES Step 4 guidelines.

A simple indicator of NUE is Partial Factor Productivity of Applied N (tonnes of cane/kg of applied N) calculated using yield data and fertiliser records. Other indicators require sampling to estimate crop size and N accumulation when crops reached approximately 9 months of age, which has previously been shown by Connellan & Deutschenbaur (2016) to be when crop N accumulation is at its peak. An index for Efficiency of Fertiliser N Recovery (NUptEfert) was calculated using estimates of crop N for each treatment along with estimates of crop N in small areas that did not receive any N. Fertiliser N-Uptake Efficiency is used as an indicator of crop efficiency for capturing fertiliser N. Total crop N accumulated in above ground biomass (kg N/ha) was also calculated.

Soil mineral nitrogen (nitrate nitrogen and ammonium nitrogen) in the top 20 cm of the soil profile was assessed at 1-2 days after harvest with samples collected from the shoulder of the bed. Mineral N was calculated using the following equation:

Mineral N (kg/ha) = Concentration (mg/kg) x sampling depth (cm) x bulk density (g/cm3) x 0.1

An assumed bulk density value of 1.2 was used for all samples to calculate mineral N in all regions.

Economics

The economic analysis accounts for all factors that influence grower profitability through a calculation of net revenue, which is grower revenue net of fertiliser costs (including application), harvesting costs and levies (all $/ha; used in past research to compare different N-management practices, for example, Connellan *et al.* (2017), Skocaj *et al.* (2012) and Schroeder *et al.* (2010)). Higher net revenue indicates greater profitability. Grower revenue was calculated by multiplying cane yield by the cane payment formula, using relative CCS and the five-year average net sugar price of $421/t (cane payment formula = sugar price x 0.009 x (CCS – 4) + mill constant. The mill constant applicable to each mill area was used. The Mackay formula recently changed due to new mill ownership and now aligns with other regions. $421 was the five-year average net sugar price for the QSL harvest pool between 2013 and 2017). Fertiliser costs were the average price paid and harvesting costs were sourced from local contractors.

Five types of CRFs were applied in the trials with prices ranging between $1,292/t and $1,723/t (ex. GST). DMPP was the main NI applied, while Nitrapyrin was applied at only a few sites. DMPP-treated urea was on average $136/t more expensive than urea (e.g. $643/t + $136/t = $779/t), while Nitrapyrin added an average $132/t to the price of urea. Average N costs and cost ranges are shown in Table 2. Cost ranges reflect different N rates and products. Costs for DMPP/CRF -20% were approximately 50-60% more than Urea 6ES given the large proportion of CRF (1/3 DMPP and 2/3 CRF). Costs for the main wildcard treatments, DMPP -20% and 20% CRF -20%, were generally similar or slightly lower than Urea 6ES.

Table 2. Average N costs ($/ha) and cost ranges (minimum-maximum).

Region	Urea 6ES	Urea -20%	DMPP/CRF -20%	Wildcard	
				DMPP -20%	20% CRF -20%
Wet Tropics	$184 (140-210)	$145 (112-168)	$291 (231-349)	$175 (149-203)	$191 (174-217)
Burdekin	$256 (202-275)	$199 (155-216)	$400 (291-453)	$246 (227-259)	$256 (230-273)
Mackay-Whitsundays	$184 (145-207)	$142 (108-167)	$279 (217-337)	$174 (131-203)	$175 (147-193)

Statistics

Linear mixed models were fitted to the data using ASReml-R. Table 3 outlines attributes of the modelling including key traits analysed, fixed and random components, and the types of data pooled together based on wildcard product/s applied. Interactions were examined to determine in which environments EEFs performed better or worse (e.g. high rainfall versus low, sand versus clay) and what application times are most or least suitable (e.g. applied late versus early in the season). Interactions of main effects were fitted up to four-way combinations, with significance of fixed terms tested using asymptotic Wald statistics. In addition, trial data was pooled together with the first analysis examining all sites with wildcard treatments applied at 20% less N (100% of data) to explore how all wildcard products performed with different combinations of main effects (e.g. sandy soil with high rainfall). The second and third analyses pooled data from sites where only DMPP (46% of data) or 20% CRF (42% of data) was applied to isolate how these products performed.

Multiple comparison tests were undertaken to determine differences (LSDs) among treatment means ($p<0.05$). The analyses tested data for each fertiliser treatment relative to Urea 6ES (with values for each treatment expressed as a fraction of that obtained from the Urea 6ES treatment – benchmarked at replicate level) to isolate the treatment effect (given the considerable variation in yields and CCS among different trial sites and regions). Following analysis, the relative data was transformed back and displayed in columns within the graphs, for ease of interpretation, together with the relative data. Graphs also display confidence intervals (error bars) and significance letters (a/b/c), where different letters indicate a statistically significant difference.

Table 3. Key traits, fixed and random components of model and types of data pooled together.

Traits	*Yield/Profit*: cane yield, CCS, sugar yield and net revenue. *NUE*: t cane/kg applied N, NUptEfert, Crop N content and post-harvest soil N.
Fixed effects	Fertiliser product and rate, soil type, rainfall, fertiliser application time, harvest year & region.
Random effects	Plots nested within replicates and replicates nested within sites.
Pooled trial data	(1) All wildcard products[A], (2) DMPP wildcards only, and (3) 20% CRF wildcards only.

[A] Including DMPP, 20% CRF and other remaining products.

Rainfall

Table 4 shows rainfall measured in each region for three years of the project as well as the long-term average. In 2018, the Wet Tropics received above average rainfall, while below average rainfall was experienced in 2020. In the Burdekin and Mackay-Whitsundays regions, below average rainfall was received throughout the life of the project.

Table 4. Actual rainfall and long-term averages (July – June) (Source: Bureau of Meteorology 2021).

Region	Rainfall (mm)			
	2018	2019	2020	Average
Mossman	3547	2671	1616	2422
Mulgrave	3378	2230	1554	1921
Innisfail	3903	2963	3048	3823
Tully	4367	3278	3288	4073
Herbert	2784	2525	1943	2117
Burdekin	947	724	997	1043
Mackay	1005	1301	1451	1580

Soil types

A range of soil types exist across the cane-growing areas of the catchments of the Great Barrier Reef. For analysis, soil types were simplified into three categories according to texture (Table 5).

Table 5. Summary of sites by soil type category and region.

Region	Sand	Clay	Loam
Wet Tropics	3	5	16
Burdekin	-	8	10
Mackay-Whitsundays	2	4	6
Total	5 (9%)	17 (32%)	32 (59%)

RESULTS

Results from three separate data analyses are presented. The first analyses data from all trial sites that tested at least one wildcard treatment applied at 20% less N (All Wildcards), while the second and third analyse a subset of data from trial sites that tested either DMPP or 20% CRF only. A total of 128 crops were harvested during the 2018, 2019 and 2020 harvest seasons. Table 6 shows a breakdown of crops harvested by type of wildcard and region.

Table 6. Summary of crops harvested by type of wildcard and region.

Region	DMPP	20% CRF	Other	Total
Wet Tropics	35	17	5*	57
Burdekin	12	21	8	41
Mackay-Whitsundays	12	16	2	30
Total	59 (46%)	54 (42%)	15 (12%)	128

* Includes 3 additional wildcard crops harvested at one site.

All Wildcards

Yield and profitability

Figure 2 displays the results for the overarching treatment effect across 54 trial sites. Of these sites, 46% used DMPP-treated urea as the Wildcard, 42% chose 20% CRFs and 12% chose Wildcards that contained other nitrification inhibitor products or straight CRFs.

Mean cane yield for Urea -20% was significantly lower than Urea 6ES and the DMPP/CRF -20% (2.2 and 1.3 tch, respectively). In contrast, mean CCS for Urea 6ES was significantly lower than all other treatments (between 0.14 and 0.7 CCS lower). Mean sugar yield for Urea -20% was significantly lower than Urea 6ES (0.21 tsh). For net revenue, Wildcard -20% had similar profitability to both urea treatments, while DMPP/CRF -20% was significantly less profitable than the other treatments by between $141/ha and $174/ha. While Urea -20% had slightly higher average net revenue than Urea 6ES urea (although not statistically significant), the significantly lower cane yield would decrease mill revenue by about $46/ha (revenue received by the mill was calculated assuming: sugar price = $421/t, mill constant = $0.60, CoW = 1.00 and CCS = 13.79 (2012-19 average across Australia, https://asmc.com.au/policy-advocacy/sugar-industry-overview/statistics/)).

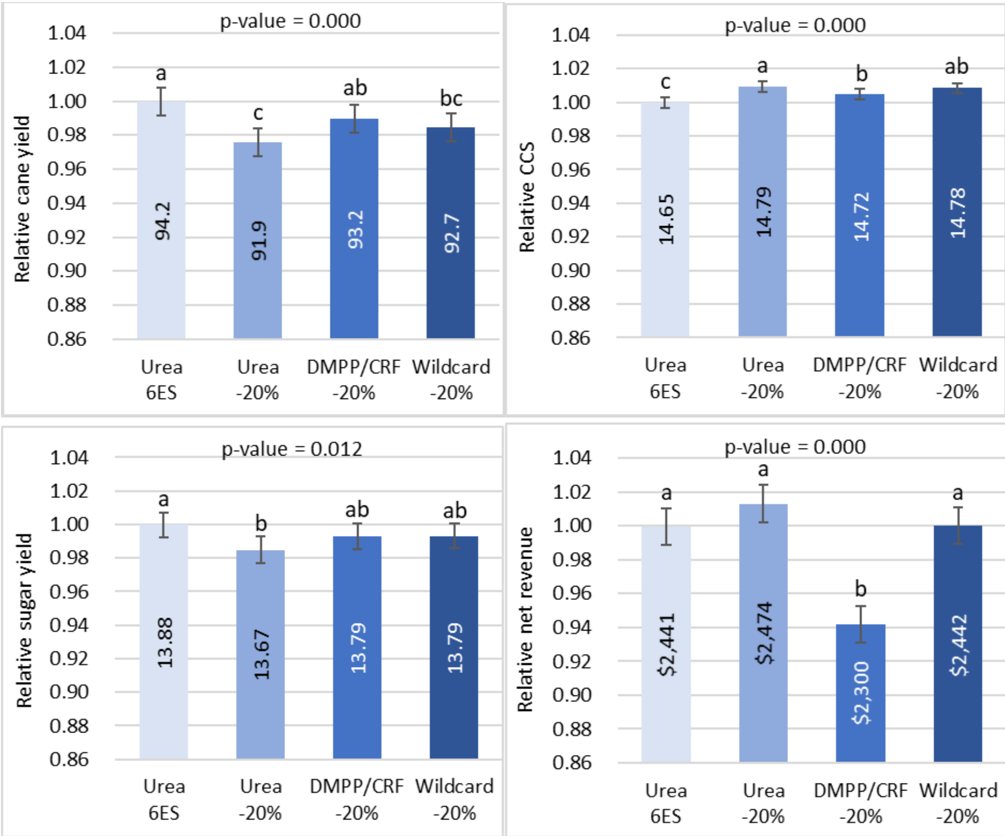

Figure 2. Mean relative and absolute cane yield (tch), CCS, sugar yield (tsh) and net revenue ($/ha) for all Wildcard -20% sites.

Treatment x seasonal rainfall interaction

Rainfall data (irrigations excluded) from Bureau of Meteorology sites was used to determine the influence of rainfall on the performance of the EEFs. Cumulative rainfall was calculated over the 3 months post-fertiliser application and categorised into low, medium or high rainfall according to regional averages (Table 7). Of all observations, 47% were classified as low rainfall, 37% medium and 16% high.

Table 7. Rainfall categories by region.

Region	Rainfall category		
	Low	Medium	High
Wet Tropics	<500 (15)	500-1000 (25)	>1000 (17)
Burdekin	<100 (26)	100-300 (12)	>300 (3)
Mackay-Whitsundays	<300 (19)	300-500 (10)	>500 (1)
Total	60 (47%)	47 (37%)	21 (16%)

Results indicate that rainfall influenced fertiliser performance with significant interactions identified for CCS (p= 0.076, Figure 3; statistical analyses were also completed excluding wildcard treatment data and for this interaction, p=0.044) and net revenue (p= 0.009, Figure 4). No significant differences in CCS were identified under high rainfall conditions. In contrast, CCS was significantly lower for Urea 6ES under medium and low rainfall conditions, whilst DMPP/CRF -20% CCS was only significantly lower in low rainfall conditions. For net revenue, DMPP/CRF -20% delivered significantly lower net revenue than the other treatments in all rainfall conditions (between $110/ha and $171/ha lower than Urea 6ES). In contrast, the Wildcard -20% treatment obtained similar net revenue to 6ES urea in all rainfall conditions and appeared to perform well in high rainfall (although not significantly different to the two urea treatments). The Urea -20% treatment obtained significantly higher net revenue than all treatments in low rainfall conditions ($64/ha higher than Urea 6ES). While Urea -20% achieved similar net revenue to Urea 6ES in medium and high rainfall, factoring in lower mill revenue of $46/ha due to lower cane yield (as previously mentioned) could make the overall net industry impact negative if marginal milling costs are low.

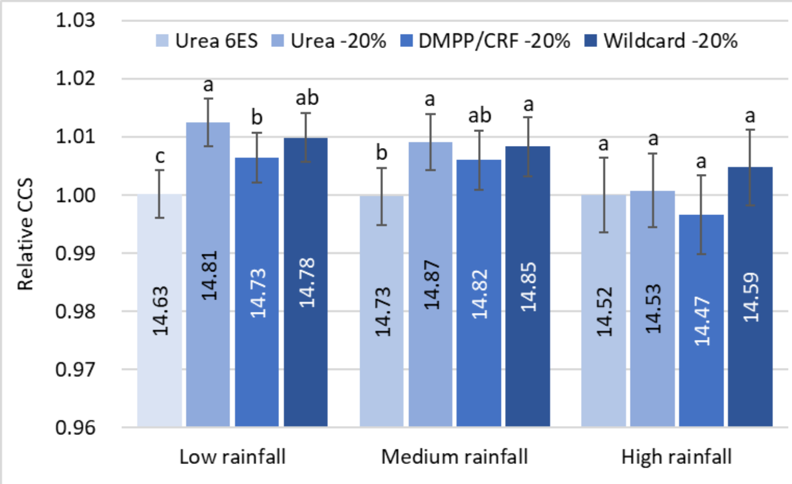

Figure 3. Mean relative and absolute CCS for each rainfall category. Significance letters are only comparable among treatments for each rainfall combination (letters do not compare among rainfall categories).

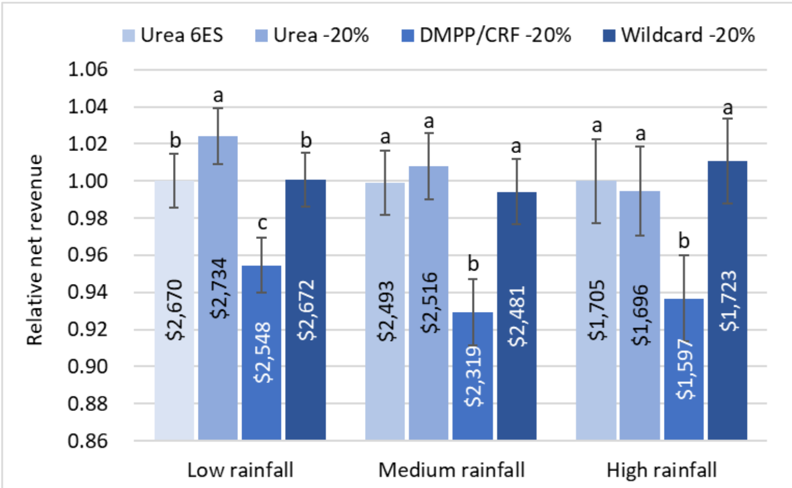

Figure 4. Mean relative and absolute net revenue ($/ha) for all Wildcard -20% sites in each rainfall category.

Treatment x fertiliser application time x rainfall x soil type interaction

The most common soil texture was loam, which comprised 62% of observations followed by clay and then sand (28% and 10%, respectively). Timing of fertiliser application varied among regions with categories (Table 8). Most sites were fertilised mid-season (54% of observations), followed by late season and a small number of early season applications (43% and 3%, respectively).

Table 8. Timing of fertiliser application in each region.

Application time	Wet Tropics	Burdekin	Mackay-Whitsundays
Early-season	-	July	-
Mid-season	August-October	August-September	August-September
Late-season	November-December	October-November	October-November

Results indicate that fertiliser treatment, fertiliser application time, rainfall and soil type interact to influence cane yield (p= 0.031, Figure 5) and net revenue (p= 0.034, Figure 6). No other significant interactions were found. Results from interactions that were significant provide a more insightful analysis than results from the analysis of main effects or lower-level interactions (e.g. results in Figure 5 explain the data better that those in Figure 2).

Urea -20% produced significantly lower yields than Urea 6ES in both clay and loam soils (by 2.8 tch and 3.4 tch, respectively) when applied late season and subjected to high rainfall conditions. Similar yield decreases were found in some medium rainfall combinations (loam mid-season and clay late-season), but no significant differences were identified following low rainfall conditions, indicating that the lower N rate with urea was able to maintain yield in drier conditions. In contrast, DMPP/CRF -20% and Wildcard -20% consistently maintained comparable yields to Urea 6ES in all combinations except one (late/clay/medium rainfall). The EEFs appeared to outperform both urea treatments in sandy soils when applied late under high rainfall conditions, although differences were not statistically significant. The EEF treatments also performed well in loam soil when applied late under high rainfall conditions, with DMPP/CRF -20% producing significantly higher yield than Urea -20%. In clay soils when applied late and under high rainfall conditions, the EEFs maintained similar yields to Urea 6ES.

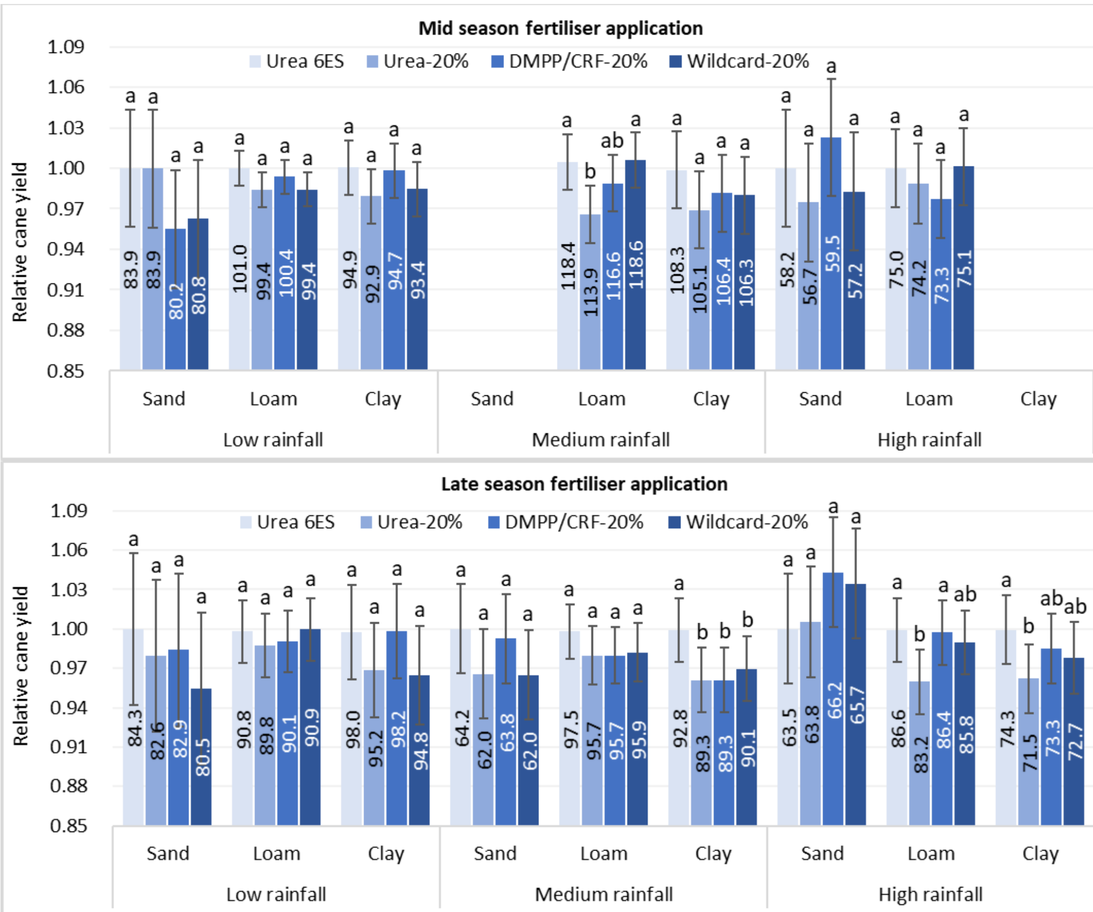

Figure 5. Mean relative and absolute cane yield (tch) for Wildcard sites for each time of fertiliser application, rainfall category and soil type. Significance letters are only comparable among treatments for each soil type and rainfall combination (not among soil types or rainfall conditions).

In terms of net revenue (Figure 6), Wildcard -20% obtained similar net revenue to Urea 6ES in every combination of rainfall, soil type and fertiliser application time. Wildcard -20% performed well in a sand/high rainfall/late season combination, although was not significantly different to the urea treatments. DMPP/CRF -20% had significantly lower net revenue than at least one of the urea treatments in nearly all mid-season fertiliser application combinations (varying between $127/ha and $198/ha lower than Urea 6ES). Exceptions included sandy soils in high rainfall and most late season combinations except sand and loam soils in high rainfall, and sand and clay soils in low rainfall. Urea -20% obtained significantly higher net revenue than Wildcard -20% in low rainfall on sandy soil when fertiliser was applied mid-season.

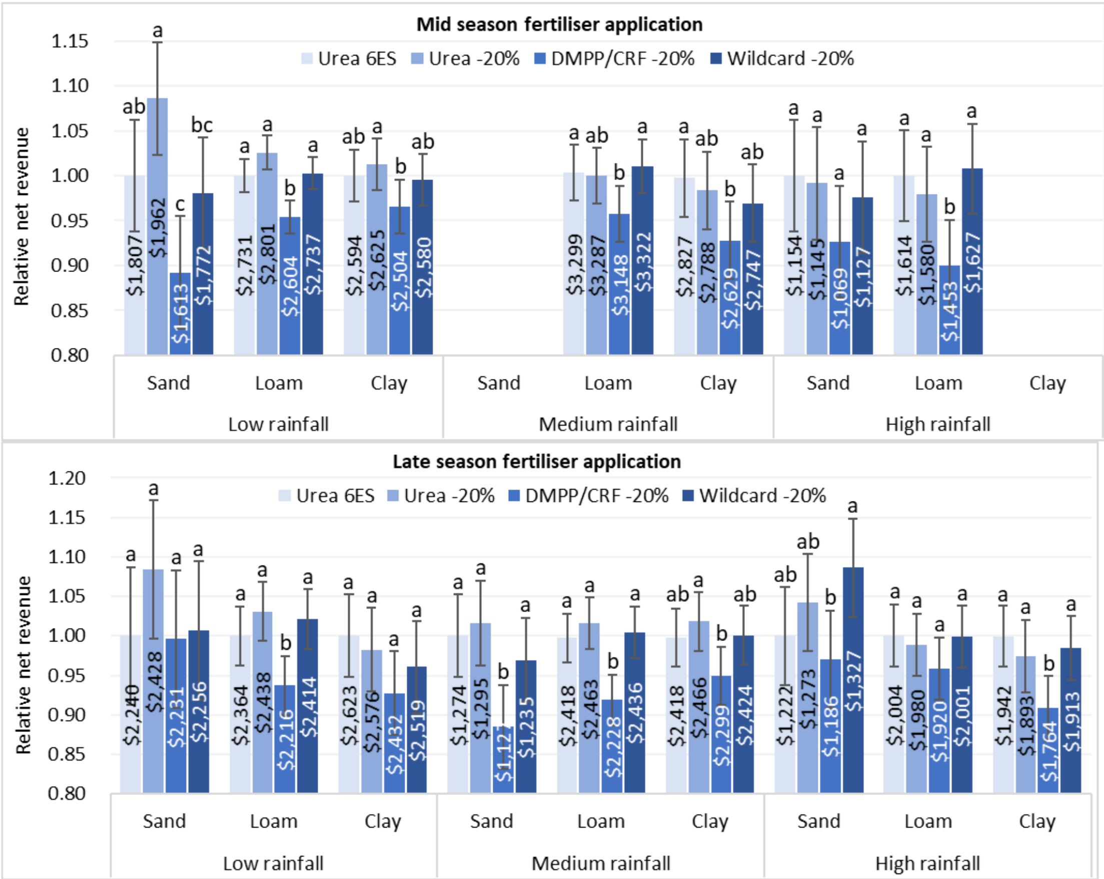

Figure 6. Mean relative and absolute net revenue ($/ha) for all Wildcard -20% sites for each time of fertiliser application, rainfall category and soil type. Missing columns indicate no trials met these criteria.

NUE indicators and post-harvest soil N

The NUE parameters (tc/kg applied N and NUptEfert), crop N content and post-harvest soil mineral N in the fertilised soil layer (0-20 cm) are presented as averages across each of the three trial regions (Wet Tropics, Burdekin and Mackay-Whitsundays) in Figure 7.

The partial factor productivity metric (tc/kg of applied N) was significantly lower in the Urea 6ES treatment in comparison to all other treatments (between 0.13 & 0.14 t/kg applied N lower). This is solely due to the higher rate of N applied in this treatment, as there was very limited evidence of any yield increase in response to the higher N rate. The Urea - 20% treatment was significantly less productive per kg of N applied than the EEF treatments (0.01 tch/kg N applied lower), although this difference was small.

The NUptEfert metric shows that the proportion of fertiliser taken up in the Urea 6ES treatment was significantly less than all other treatments. This was due primarily to the higher N rate applied, as there were only small differences in crop N contents (Figure 7). The DMPP/CRF -20% treatment had the highest mean NUptEfert

(0.31kg N uptake/kg fertiliser N applied) but was not significantly higher than the other treatments with N applied at the same rate.

Crop N content varied significantly with treatment. The DMPP/CRF -20% treatment resulted in significantly more crop N than the Urea 6ES treatment, the Wildcard -20% treatment, and the Zero N areas (4.1 kg N/ha, 4.6 kg N/ha and 46.9 kg N/ha, respectively). There was no difference in crop N content between the Urea 6ES treatment and the Wildcard -20% treatment.

Post-harvest soil mineral N in the top 20cm of the soil profile was lowest in Urea 6ES relative to all other treatments, although differences were not large. The greatest difference was only 1.8 kg N/ha between Urea 6ES and DMPP/CRF -20% treatment.

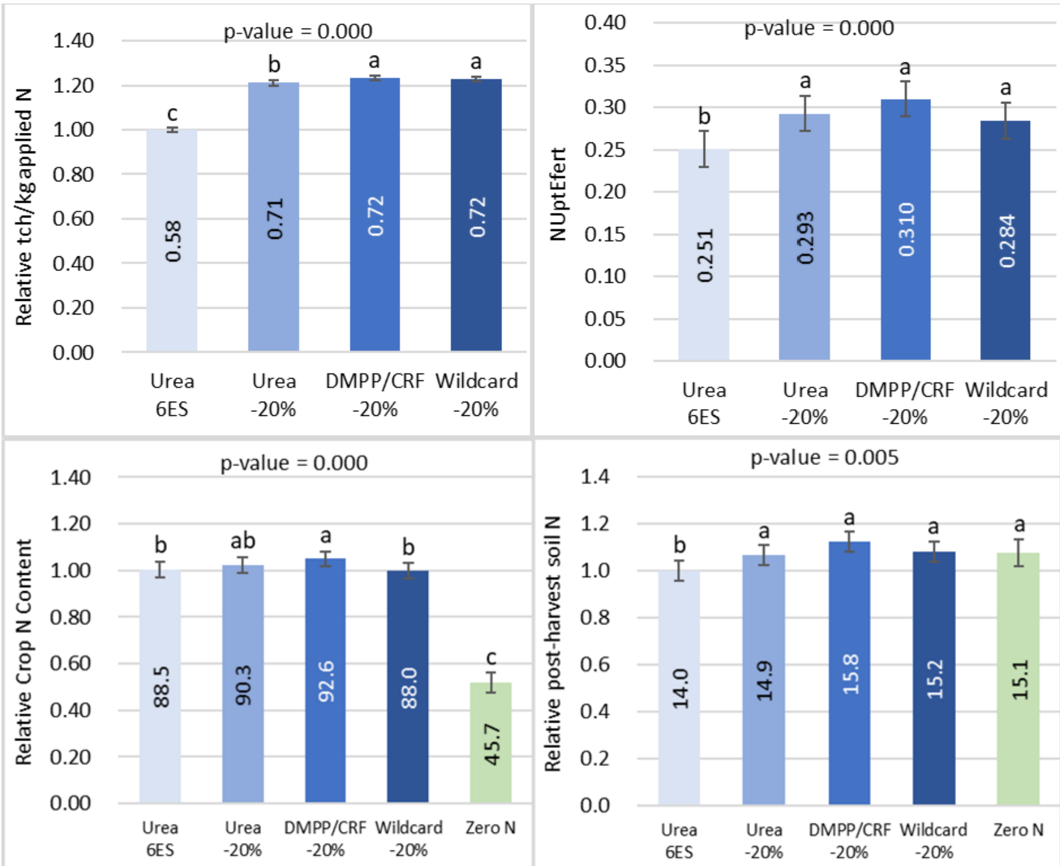

Figure 7. Mean relative and absolute crop NUE (tc/kg applied N and NUptEfert), Crop N content (kg N/ha) and Post-harvest Soil mineral N (kg mineral N/ha in the top 20cm of the soil profile) for all Wildcard -20% sites.

While the relatively lower profitability of the DMPP/CRF -20% treatment would be a strong disincentive to adoption due to a combination of limited, if any, growth responses and much higher fertiliser costs, the performance of the lower cost Wildcard -20% treatment (Figures 5, 6 and 7) supports the potential for broader application of these fertiliser products in the industry. Nitrification inhibitors (such as DMPP) and CRF blends (e.g. 20% CRF) were able to maintain crop N uptake in ratoons at N rates 20% below 6ES. The next section investigates trials where each of these commercially available EEF products were used in isolation.

DMPP wildcards only

Yield and profitability

This analysis compares how the DMPP wildcard with 20% less N performed against the other treatments across 25 sites (59 crop harvests), with the overarching treatment effect shown in Figure 8. Although results show similar trends to the preceding analysis that included all Wildcard -20% products (Figure 2), no significant differences were identified among treatments for cane and sugar yields in this smaller subset of trials. Differences in CCS were still significant (p = 0.002), with Urea 6ES producing significantly lower CCS than all other treatments (between 0.11 and 0.17 units lower). Net revenue was also significantly different (p= 0.000) with DMPP/CRF -20% delivering significantly lower net revenue than all other treatments (between $112/ha and $171/ha lower), while Urea -20% returned significantly higher net revenue than Urea 6ES ($59/ha higher). DMPP -20% produced similar net revenue to both urea treatments.

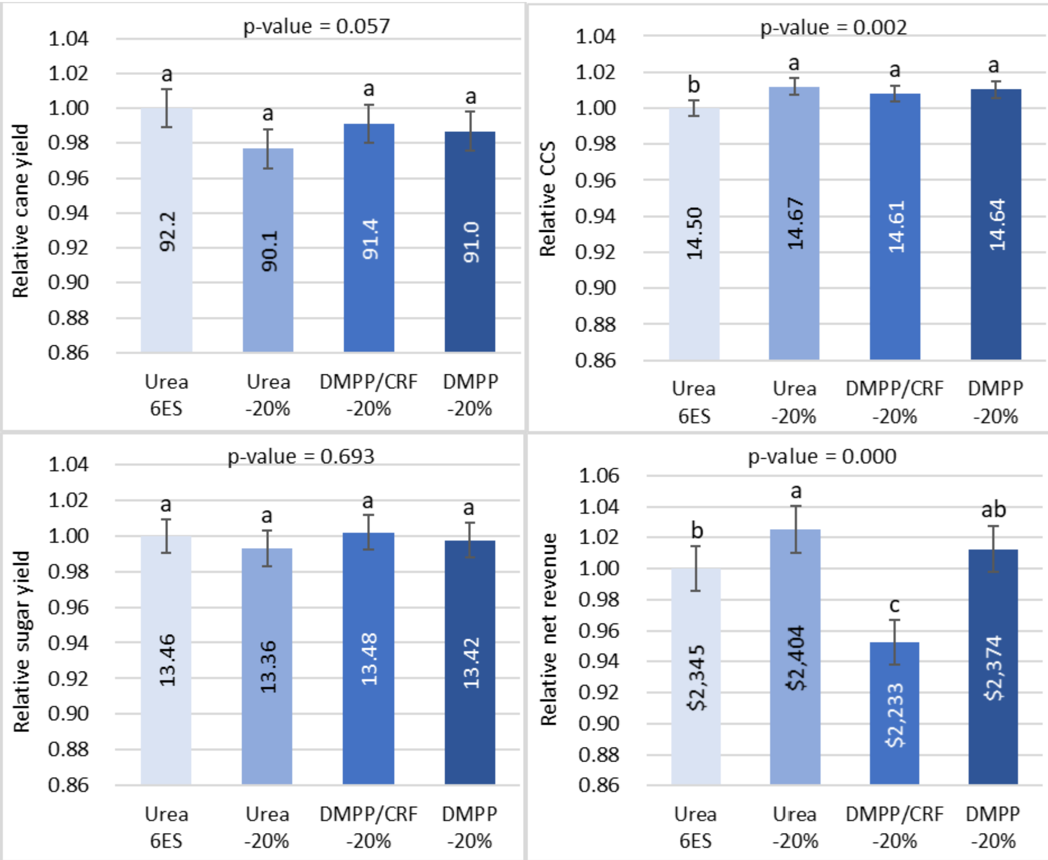

Figure 8. Mean relative and absolute cane yield (tch), CCS, sugar yield (tsh) and net revenue ($/ha) for DMPP sites.

Treatment x Rainfall

At sites with the DMPP -20% wildcard, 44% of observations were classified as low rainfall, 32% medium and 24% high rainfall. Results indicate that rainfall influenced the performance of fertiliser treatments, with significant interactions identified for sugar yield (p= 0.059) and net revenue (p= 0.003). The Urea -20% treatment produced significantly lower sugar yield than all other treatments under high rainfall conditions but was not significantly different following low or medium rainfall (Figure 9).

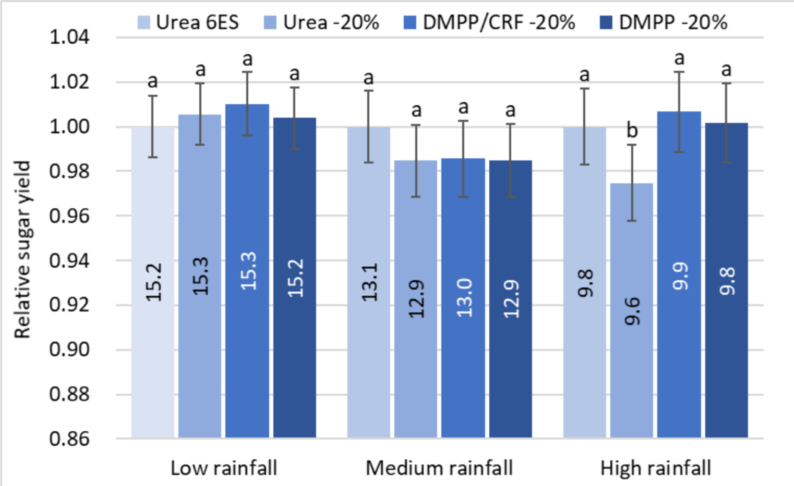

Figure 9. Mean relative and absolute sugar yield (tsh) for DMPP sites in each rainfall category. Significance letters are only comparable among treatments for each rainfall combination (not among rainfall conditions).

For net revenue (Figure 10), DMPP/CRF -20% generated significantly lower net revenue than all other treatments in all rainfall conditions except Urea 6ES in low rainfall. The DMPP -20% treatment obtained similar net revenue to 6ES urea in all rainfall conditions but performed particularly well in high and low rainfall (although not significantly different to the two urea treatments). The lower N urea treatment obtained significantly higher net revenue than Urea 6ES in low rainfall conditions ($122/ha) due to relatively better CCS and lower fertiliser costs.

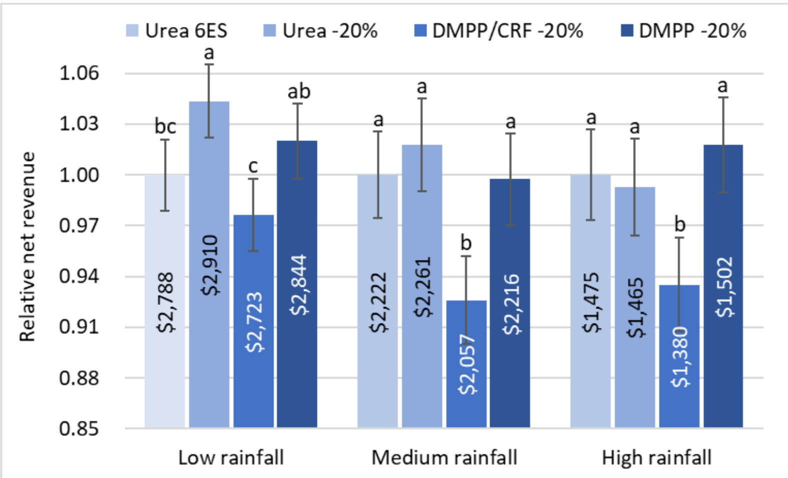

Figure 10. Mean relative and absolute net revenue ($/ha) for sites hosting the DMPP 20% wildcard treatment in each rainfall category.

NUE indicators and post-harvest soil N

Data from 25 sites (59 crop harvests) were used in this analysis (Figure 11). The partial factor productivity of applied N (t cane/kg applied N) was significantly lower in the Urea 6ES treatment in comparison to all other treatments (between 0.129 and 0.142 lower) due to the higher rate of N applied without any corresponding productivity increase. The Urea -20% treatment was significantly less productive per kg of applied N than the DMPP/CRF -20% treatment (0.013 t/kg applied N lower), although this difference was small.

The index for efficiency of fertiliser N recovery (NUptEfert) showed no significant treatment effects, although similar to the combined product analysis in Figure 7, with the highest mean value n the DMPP/CRF -20% treatment. Crop N content was also not significantly different between any of the treatments where N was applied, with all fertilised treatments containing more N than the unfertilised (0N) treatment. Post-harvest soil N (kg/ha) showed no significant differences among any of the treatments, with no evidence of additional residual mineral N in any of the fertilised treatments compared to the 0N reference.

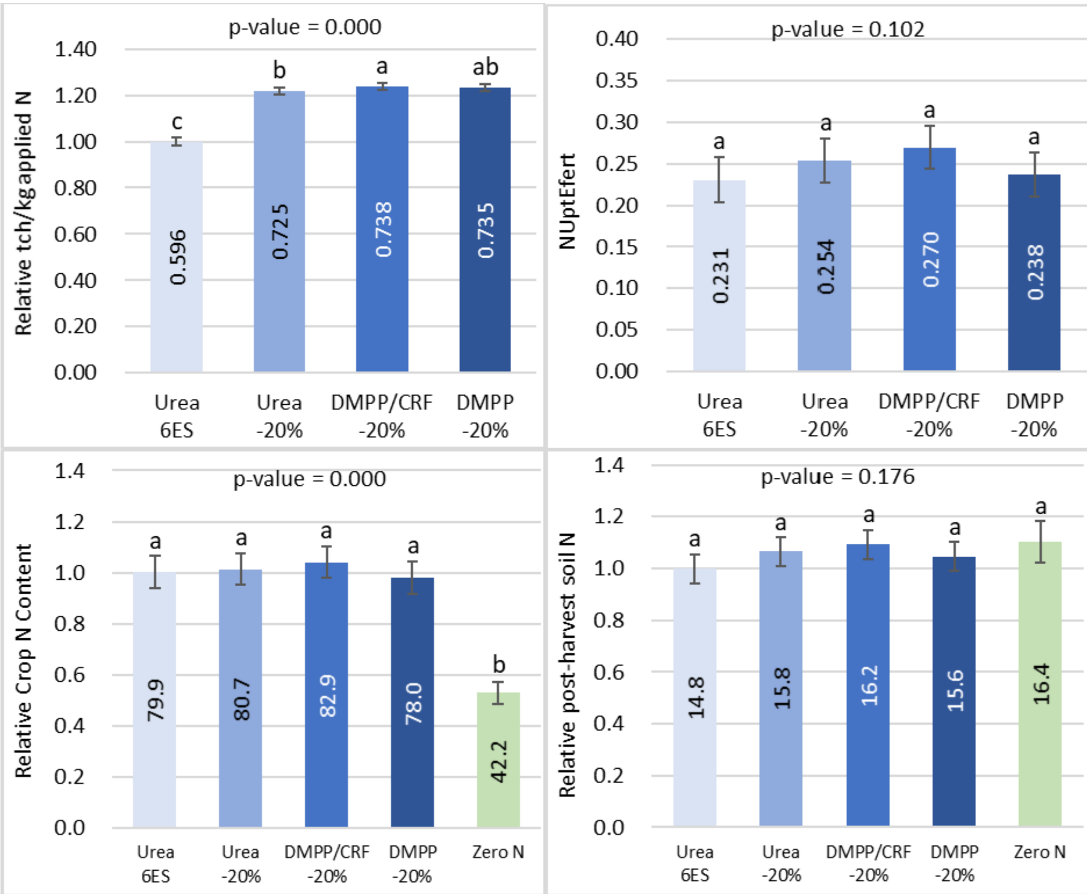

Figure 11. Mean relative and absolute crop NUE (tc/kg applied N and NUptEfert), Crop N content (kg/ha) and Post-harvest Soil N (kg N/ha in the top 20 cm of the soil profile) for DMPP sites in response to fertiliser treatment.

20% CRF wildcards only

Yield and profitability

This analysis compares how the 20% CRF (80% Urea, 20% CRF) wildcard with 20% less N than Urea 6ES performed against the other treatments across 25 sites (54 crop harvests). Crop productivity data for this smaller subset of Wildcard sites are presented for the treatment effect only in Figure 12. Urea 6ES produced significantly more cane (2.6 tch) than Urea -20%, while both DMPP/CRF -20% and 20% CRF -20% were not significantly different to Urea 6ES. Treatment effects on CCS showed similar trends to the combined Wildcard and DMPP analyses (lower CCS in the Urea 6ES and DMPP/CRF -20% treatments) but no significant differences were identified here. Both Urea -20% and DMPP/CRF -20% produced significantly less sugar than Urea 6ES (0.19 and 0.24 tsh, respectively), while sugar yield was not significantly different between Urea 6ES and 20% CRF -20%. Net revenue was similar between 20% CRF -20% and the two urea treatments, while DMPP/CRF -20% had significantly lower net revenue (between $156/ha and $180/ha lower).

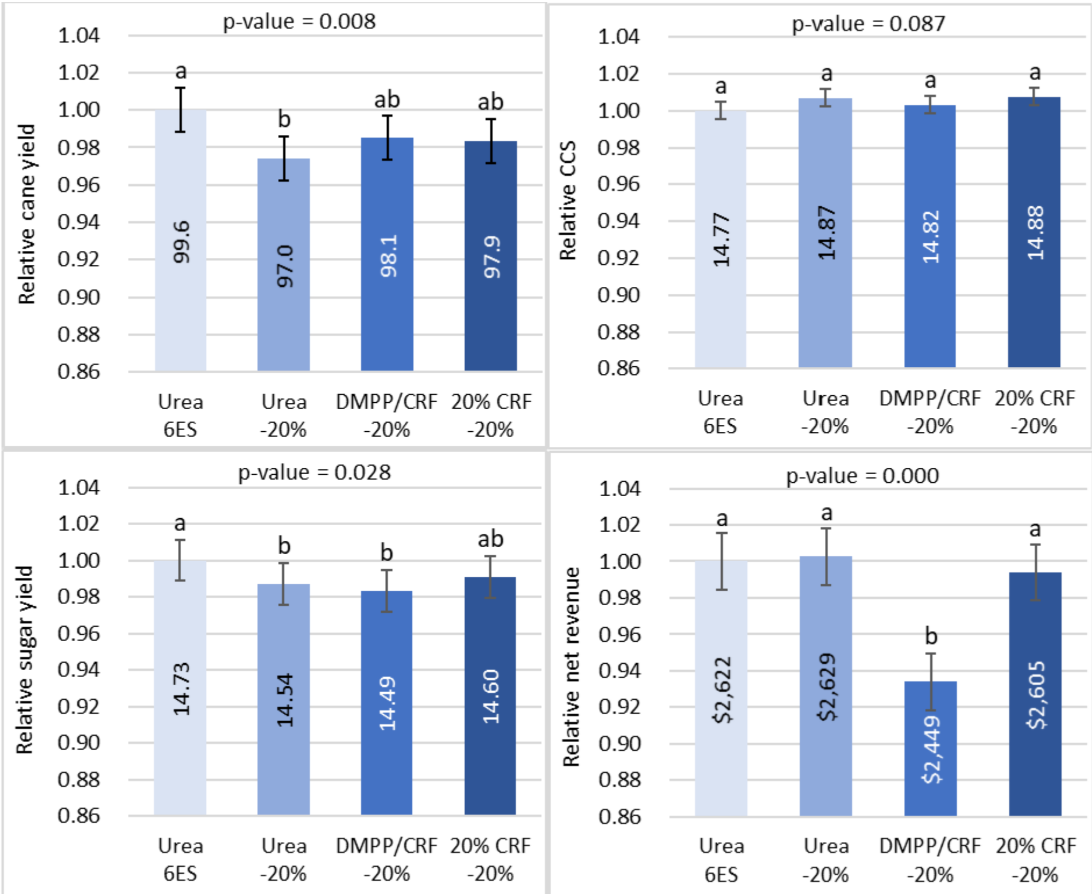

Figure 12. Mean relative and absolute cane yield (tch), CCS, sugar yield (tsh) and net revenue ($/ha) for sites hosting the 20% CRF treatment.

NUE indicators and post-harvest soil N

Data from 25 sites (54 crop harvests) were used in this analysis (Figure 13). The mass of cane produced/kg of applied N was significantly lower in the Urea 6ES treatment in comparison to all other treatments (between 0.13 and 0.14 t/kg N lower). NUptEfert for the Urea 6ES treatment was significantly less than all other treatments due to the higher rate of N applied in this treatment for no additional crop N uptake.

Crop-N content data showed that the DMPP/CRF -20% treatment captured significantly more N than the Urea -20% treatment, the 20% CRF -20% treatment and the Zero N treatment (4.7 kg/ha, 4.8 kg/ha and 53.3kg/ha higher, respectively). There was no significant difference in crop N content between the 20% CRF -20%, the Urea -20% and the Urea 6ES treatments. Post-harvest soil N (kg/ha) showed no significant differences among any of the treatments, with no evidence of additional residual mineral N in any of the fertilised treatments compared to the 0N reference.

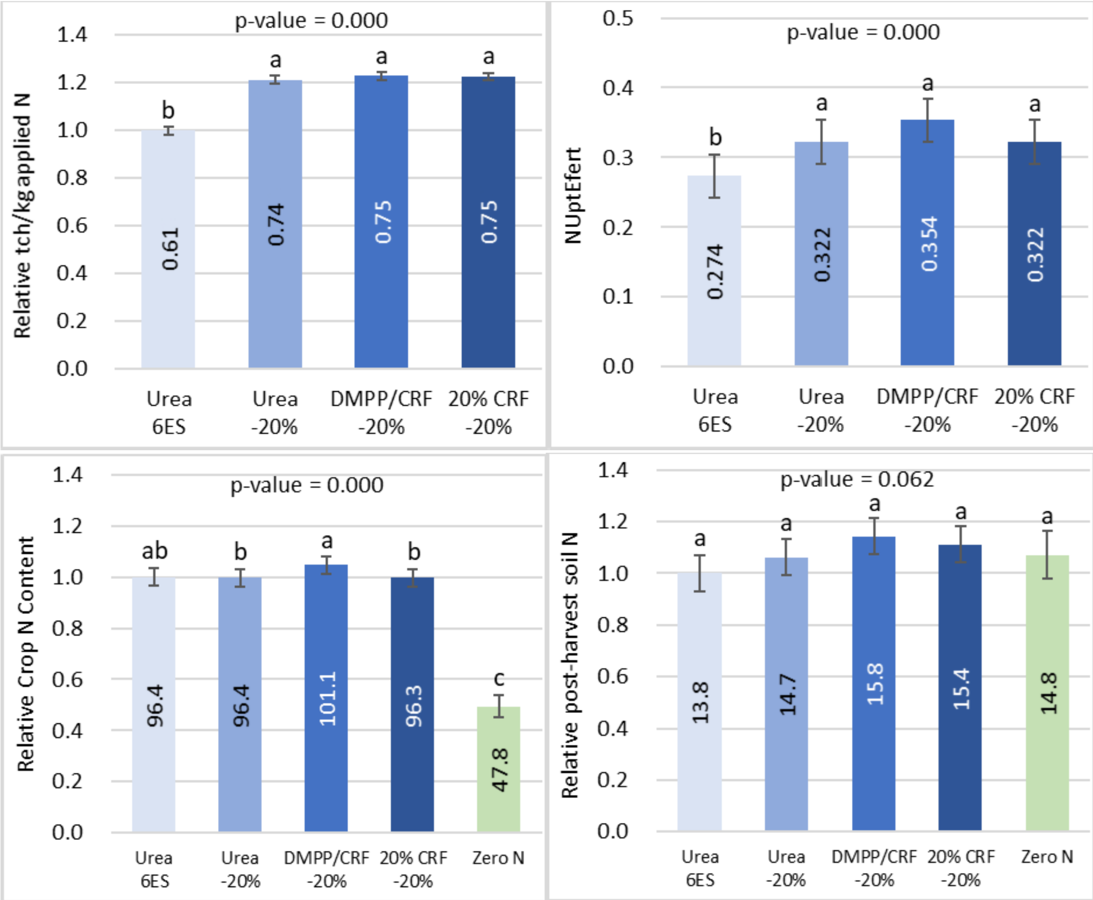

Figure 13. Mean relative and absolute NUE (tc/kg applied N), NUptEfert, Crop N content (kg/ha) and Post-harvest Soil N (kg/ha) for sites hosting the 20% CRF wildcard treatment.

DISCUSSION

EEFs were tested at N rates below the 6ES Step 4 guidelines due to their promoted ability to better match crop N uptake over the growing season, and to minimise the impact of their higher costs relative to urea. A complementary benefit from improving NUE is a reduction in risk of N losses, which has benefits for water-quality outcomes. Given the tight margins experienced by sugarcane growers and millers, together with heightened risks experienced by farming businesses (climate, price volatility, disease, etc.), it is vital that improvements in NUE are not perceived to come at the cost of industry profitability. Likewise, management practices are less likely to be widely adopted where there are perceived risks to the longer-term sustainability and resilience of the industry. Consequently, a key emphasis of the project was placed on interpreting results in terms of their collective impact on production, profitability and NUE.

The combined analysis of data across all 54 trial sites with a standardised trial design indicated that applying urea at N rates 20% below 6ES would result in lower cane yields than with urea at 6ES on clay and loamy soils under high rainfall conditions when fertiliser was applied late in the season (2.8 and 3.4 tch lower, respectively). Similar cane yield losses were also recorded in some medium rainfall situations. In contrast, urea with 20% less N delivered higher CCS than Urea 6ES in low and medium rainfall conditions (0.18 and 0.14 units higher, respectively) but not under high rainfall conditions. Given yields were maintained and CCS improved in low rainfall conditions along with lower fertiliser costs, urea with 20% less N delivered higher grower profitability ($64/ha higher) than 6ES Urea in low rainfall conditions. Compared to Urea 6ES, urea applied at rates 20% lower resulted in 21% greater NUE and 17% higher fertiliser uptake efficiency, while crop N content and post-harvest soil N were maintained.

While grower profitability was similar between the two urea options in medium and high rainfall conditions, substantial adoption of urea with 20% less N would reduce mill revenue given the structure of the cane payment formula (e.g. less tonnes of cane reduces mill revenue, while higher CCS adds relatively lower revenue). For example, if 20% of the Australian sugarcane harvested area (74,639 ha) had reduced yield of 2.8 to 3.4 tch, mill revenue could potentially decrease by $4.3 to $5.2 million per year. While targeting low rainfall conditions to apply urea with 20% less N could be effective at maintaining yield and increasing profitability, the current accuracy of seasonal climate forecasts make this strategy risky for growers (e.g. accuracy diminishes when forecasts are >2 weeks).

DMPP/CRF -20% had fertiliser costs that averaged 50-60% higher than Urea 6ES, even though 20% less N was applied. Across all 54 trial sites, DMPP/CRF -20% produced similar cane yield to Urea 6ES in most situations and higher CCS in low rainfall conditions. While not significantly different, DMPP/CRF -20% appeared to yield best in sandy soils that experienced high rainfall conditions after fertiliser application, particularly when fertiliser was applied closer to the onset of the wet season, which corresponds to findings from past EEF trials conducted in the Burdekin (Dowie *et al.*2019). The higher N fertiliser costs generally made DMPP/CRF -20% less profitable than Urea 6ES except for a few situations such as in sand and loamy soils that experienced high rainfall conditions after late season fertiliser application. Compared to Urea 6ES, DMPP/CRF -20% improved NUE by 23%, fertiliser uptake efficiency by 24% and post-harvest soil N by 12%, while maintaining crop N content.

Growers in the project were given a choice of EEFs to trial for the Wildcard treatment, with many deciding to test either urea treated with DMPP or low proportion blends of CRF (20%) with urea (80%) at N rates 20% below 6ES. Both choices generally had similar N fertiliser costs to Urea 6ES. These Wildcard treatments performed well across all 54 trial sites, producing similar cane yield to Urea 6ES in all situations except one, and higher CCS in low and medium rainfall conditions (0.15 and 0.12 CCS higher, respectively). The Wildcards had similar profitability to Urea 6ES across all soil, rainfall and application time combinations, and like the DMPP/CRF -20% treatment, the Wildcards appeared more profitable in sandy soils with high rainfall after late fertiliser application. Compared to Urea 6ES, the Wildcards with 20% less N improved NUE by 23% and fertiliser uptake efficiency by 13%, while they maintained crop N content (in all regions) and improved post-harvest soil N by 8% despite the lower N application rate. Collectively, these results highlight the potential for broader use of EEFs in ratoon cane at N rates that are 20% less than 6ES.

Comparisons among wildcard options were to some extent constrained by the lower numbers of site-years available to each option, and that each option was tested in a different subset of the experimental locations. At sites where DMPP -20% was the chosen Wildcard treatment, crops achieved higher CCS (0.14 units) than Urea 6ES and similar cane yields and profitability. In addition, DMPP -20% improved NUE by 23% and maintained fertiliser uptake efficiency, crop N content and post-harvest soil N compared to Urea 6ES. Similar analyses for sites where the chosen Wildcard was 20% CRF -20% showed that cane yield, CCS and profitability were similar to that from Urea 6ES. Also, 20% CRF -20% improved NUE by 23% and fertiliser uptake efficiency by 18% compared to Urea 6ES, while maintaining crop N content and post-harvest soil N.

CONCLUSIONS

There is growing pressure on farmers within the GBR catchments to reduce N losses and EEFs may provide an opportunity to substantially reduce them. The EEF60 project was designed to compare the production and profitability of EEFs with conventional urea applied at rates based on the 6ES Step 4 guidelines. Trials were conducted over three seasons testing CRFs (mainly polymer coated urea) and NIs (mostly DMPP) with 54 sites having similar treatments. EEFs were tested at N rates below 6ES due to their higher unit costs and purported ability to better match N supply to crop demand.

Compared to Urea 6ES, applying urea at 20% less N decreased cane yield in medium and high rainfall conditions but under low rainfall conditions CCS improved and higher grower profitability was achieved. Nevertheless, the current accuracy of seasonal climate forecasts makes targeting low rainfall conditions risky – which highlights the opportunity for applying EEFs. EEF blends with high proportions of CRF applied at 20% less N maintained productivity but cost more, which generally made them less profitable to apply. In contrast, the performance of the lower cost EEF options – 'DMPP treated urea' and blends of '20% CRF with 80% urea' – applied with 20% less N supports the potential for broader application of EEFs by growers. Both options were able to maintain crop N uptake and content in ratoons and produced similar productivity and profitability to Urea 6ES, while increasing NUE by 23% and maintaining or improving fertiliser uptake efficiency and post-harvest soil N. Maintaining production and profit will be crucial to achieving broader uptake of EEFs by industry, while large increases in NUE will reduce the risk of N losses and improve environmental outcomes.

Our findings suggest that both DMPP-treated urea and blends of 20% CRF with 80% urea applied at N rates 20% less than 6ES could be promoted to growers as an alternative to their existing nutrient-management strategy. Use of EEFs delivered higher yields than Urea 6ES in some situations under high rainfall conditions, which corresponds to past EEF research. To capitalise on the intrinsic benefits of EEFs (e.g. NUE, and environmental benefits), they could be endorsed as the preferred nutrient-management strategy when high rainfall is expected, particularly when fertiliser is applied close to the onset of the wet season.

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