ON-GROUND TESTING AND MODELLING OF THE EFFECTIVENESS OF ENHANCED EFFICIENCY FERTILISERS IN THE WET TROPICS CATCHMENTS OF THE GREAT BARRIER REEF

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ABSTRACT

In 2020 the Great Barrier Reef Foundation contracted SRA to undertake the project 'On-ground testing and modelling of the effectiveness of Enhanced Efficiency fertilisers in the Wet Tropics catchments of the Great Barrier Reef'. To achieve this SRA and the Queensland Department of Agriculture and Fisheries (DAF) continued a limited number of field trials in the Wet Tropics which were previously established as part of the 'Cane Farmer Trials of Enhanced Efficiency Fertilisers (EEFs) in the Catchments of the Great Barrier Reef: EEF60', which was funded by the Australian Government through Reef Trust. These extensive trials were established across all regions of the Great Barrier Reef catchments and were designed to identify where EEFs could provide agronomic and economic benefits for cane farmers. The additional information collected as part of the GBRF funded project was added to the existing dataset developed as part of EEF60 project and reanalysed, which resulted in an improved understanding of the agronomic and economic effectiveness of EEF's.

CSIRO Agriculture and Food was subcontracted by SRA to undertake the modelling component of the project with the aim of providing information (using APSIM farming systems model) on the expected benefits of EEFs in both time and space to inform when and where using EEFs in place of urea will deliver N loss reductions that can be expected in the Wet Tropics.

The main body of this report contains findings from the work conducted by SRA/DAF and Appendix 1 contains the final report for the modelling work undertaken by CSIRO.

Key findings from both the field trials and modelling work were*:

- Generally, applying urea at 20% less than the SIX EASY STEPS N guidelines results in a small but significant loss in cane yield and industry revenue. Yield losses were more likely in medium and high rainfall conditions and less likely in low rainfall conditions earlier in the season.
- Generally, applying DMPP treated urea at 20% less than the SIX EASY STEPS recommended N rate with urea maintains yield and profitability and improves NUE.
- Generally, applying a CRF blended with urea (20% CRF and 80% urea) at 20% less than the SIX EASY STEPS recommended N rate with urea maintains yield and profitability and improves NUE.
- Crop modelling indicated that the risk of N losses was mostly associated with late season fertiliser application in drier regions and mid-late season fertiliser application in very wet regions of the Wet Tropics.
- Both field trials and modelling showed EEFs were more effective when high loss conditions were experienced, particularly late in the season.
- In-field experiments identified that this was particularly the case on sandy soils, when receiving high rainfall and fertilised late in the season. Whereas crop modelling data in the Wet Tropics suggested EEF application late in the season may potentially have positive yield impacts in some situations due to their ability to reduce N losses.
- Higher than average urea prices improve the cost-competitiveness of using DMPP and blended CRF products (20% CRF 80% Urea) when applied at N rates 20% below the SIX EASY STEPS recommendation.

*Results at individual sites may vary from these general findings

EXECUTIVE SUMMARY

This project which was undertaken by Sugar Research Australia (SRA) and the Queensland Department of Agriculture and Fisheries (DAF) and has built on the work of 'Cane Farmer Trials of Enhanced Efficiency Fertiliser in the Catchments of the Great Barrier Reef: EEF60'. Additional information captured by this project confirms the findings from the EEF60 project and adds to the understanding of how EEFs can provide agronomic and economic benefits to cane farmers.

The project included 17 controlled and replicated field trials located throughout the Wet Tropics, which were previously part of EEF60. Trial data was successfully retrieved from 14 of these sites. At one site located in Babinda, water quality monitoring equipment were reinstalled for detecting leaching and run-off losses of dissolved inorganic nitrogen. These trials contributed valuable information to the existing dataset generated by the EEF60 project.

The trials evaluated the performance of EEFs relative to conventional fertilisers by measuring cane and sugar yield, commercial cane sugar (CCS), grower profitability, nitrogen use efficiency, crop N content, fertiliser N uptake efficiency, post-harvest soil N and water quality (leaching and runoff).

Two main types of EEFs were tested as part of this project, namely controlled release fertilisers (CRFs) and nitrification inhibitors (NIs). The former release urea-N slowly through a protective polymer coating, while the latter are based on the addition of nitrification inhibitors such as DMPP[1] to urea to stabilise the N in ammonium form. The EEFs were tested at N rates below the sugarcane industry's current nitrogen rate recommendations due to their promoted ability to reduce environmental losses through better matching N availability to crop N uptake over the growing season, and their higher costs in comparison to urea.

Four treatments were kept consistent across nine of the fourteen harvested fourth ratoon trial sites. These included two urea treatments and two EEF treatments. One of the urea treatments had N applied at the current industry recommended N rate (SIX EASY STEPS (6ES)) (Urea 6ES), while the other were 20% below 6ES (Urea -20%). EEF treatments were all applied at N rates 20% below 6ES. At six sites DMPP (DMPP -20%) was applied as the Wildcard treatment (EEF treatment based on grower choice) whilst at the other three sites blends of 20% CRF with 80% urea (20% CRF -20%) were applied as the Wildcard. At the remaining five sites several different treatments were applied and included:

- One grower who chose to apply the 1/3 DMPP and 2/3 CRF EEF blend at the 6ES recommended N rate as their Wildcard.
- Three growers who chose to apply the EEF's at approximately 30% below 6ES as their Wildcard.
- One Babinda grower who chose to surface apply urea at the 6ES rate as their Wildcard.

The fourth ratoon data collected in 2021 from Wet Tropics sites were added into the EEF60 dataset and reanalysed to investigate the effects of additional data on previously identified outcomes.

A key finding from this reanalysis (and previously identified by the EEF60 project) was urea applied at N rates 20% below 6ES produced significantly lower cane yields than urea applied at the 6ES recommended application rate. While the lower rate of urea maintained grower profitability, widespread adoption would reduce mill revenue (due to lower cane yield) and potentially have a net negative impact on the industry.

It also clearly demonstrated that both DMPP-20% and 20% CRF -20% performed well, highlighting their potential for broader application in ratoon cane. Both of these EEF strategies maintained similar yields and profitability to urea applied at the 6ES recommended N application rate in ratoon crops whilst improving NUE, maintaining crop N content and maintaining or increasing fertiliser N uptake efficiency and post-harvest soil N. Maintaining production and profitability, along with similar fertiliser input costs, will be key factors for achieving widespread uptake by industry. The substantial increases in NUE (and improvements in fertiliser uptake efficiency) are likely to reduce the risk of nitrate-N losses and improve water quality outcomes.

Water quality monitoring was undertaken at one site at Babinda. The movement of dissolved inorganic nitrogen (DIN) through the soil profile was monitored over the 2020/21 wet season. Analysis of soil water samples collected at depth (1m) were combined with samples collected as part of the EEF60 project and reanalysed. The analysis shows that DIN concentrations remained consistently very low over the four years of monitoring and is likely due to the very high organic carbon levels in the soil profile at this site.

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[1] 3,4-Dimethylpyrazole phosphate

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1 INTRODUCTION

The project included 17 replicated commercial scale field trials, conducted over the 2020/21 cropping season. This included two sites in Mossman, four in Cairns, one in Babinda, two in Innisfail, three in Tully and five in the Herbert (Figure 1). The objective was to capture an additional seasons data from ratoon crops in previously established EEF60 trial sites to assess the effectiveness of the EEF's under varied climatic conditions.

The trials were designed to continue to evaluate the performance of EEFs relative to conventional N fertilisers in terms of cane and sugar yield per hectare (TCH and TSH), commercial cane sugar (CCS) and NUE, with the aim of identifying circumstances in which growers can apply EEFs and maintain profitability. At one site in Babinda, water quality monitoring equipment were installed to monitored and compare N losses between treatments via run-off and deep drainage.

The trials were located on commercial farms across the Wet Tropics region, with major soil types included.

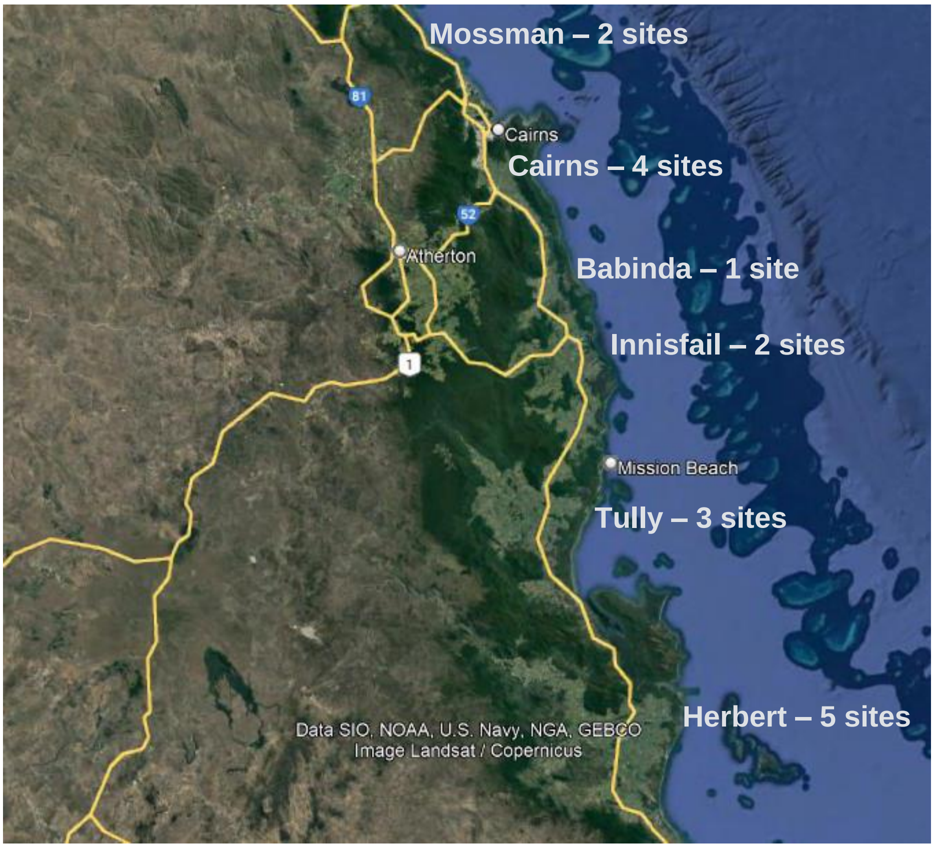

Figure 1: Trial site locations across the Wet Tropics of Queensland.

2 BACKGROUND

The aim of this project was to build on the work of EEF60 by continuing trials in the Wet Tropics for an additional season. Findings have contributed to the development of knowledge of how to best utilise EEF's in the sugarcane farming systems within the Great Barrier Reef catchments.

Two main types of EEFs were tested as part of this project. These were controlled release fertilisers (CRFs) which release N slowly through a polymer coating, and nitrification inhibitors (NIs) which are added to urea to stabilise the N in ammonium form to reduce losses. Both products aim to reduce the amount of nitrate in the soil profile whilst maintaining adequate N supply to meet crop demand.

3 METHOD

3.1 Strip trial site establishment

Protocols developed as part of the EEF60 project were maintained and provided guidelines on research activities to be undertaken. Trial sites were re-established following the completion of the EEF60 project with fertiliser applied 4-6 weeks post- harvest (Figure 2). For each treatment fertiliser boxes were recalibrated to apply the desired rate of product.

Figure 2: Fertiliser box calibration.

Trials were conducted at commercial scale using large, replicated strips. Two forms of EEFs based on urea were used in the trials – Controlled Release Fertilisers (CRFs) and Nitrification Inhibitors (NIs).

Treatments included:

1. Nitrogen at the SIX EASY STEPS® (6ES) rate applied as Urea (Urea 6ES).
2. Nitrogen at 20% less than the 6ES rate applied as Urea (Urea -20%).
3. Nitrogen at 20% less than the 6ES rate applied as a blended product which consisted of 33% nitrification inhibitor treated urea and 67% controlled release fertiliser (DMPP/CRF -20%).
4. Nitrogen at 20% less than the 6ES rate applied as either a blended product which consisted of 80% urea and 20% CRF (20% CRF -20%) or nitrification inhibitor (DMPP -20%), or other product (Other) which was decided based on grower interest (Wildcard).
5. Small plot areas (6 rows x 20 m) with 0 N were included to allow calculation of how much background N was available from the soil.

These treatments were replicated (3 replicates) and randomised at each site.

3.2 Harvest data capture and interpretation

Cane yield and CCS results were supplied by the local sugar mills in each region following the harvest of each trial site (Figure 3). Sugar yield was calculated from these values. The results were analysed to identify if there were any 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 method.

Figure 3: Harvesting a trial site in Gordonvale

3.3 Nitrogen use efficiency indicators

Indicators of NUE were calculated to better understand N dynamics within sugarcane farming systems. Together with productivity, profitability, and environmental data, these inform nutrient management practices. A simple indicator of NUE which is referred to as Partial Factor Productivity of N is calculated using tonnes of cane/kg of applied N. This can be easily calculated using yield data and fertiliser records. Other methods require sampling and processing (Figure 4) of plant samples to estimate crop size and N accumulation. This process was undertaken at all trial sites when crops reached nine months of age. Previous work (Connellan & Deutschenbaur, 2016) demonstrated that biomass and N accumulation in sugarcane peaks by nine months and hence is a suitable time to investigate NUE indicators. Index for Efficiency of Fertiliser N Recovery (NUptEfert) was calculated using estimates of crop N in each treatment along with estimates of crop N in the small areas which did not receive any applied N. NUptEfert is used as an indicator of the efficiency of fertiliser N uptake by the crop.

$$\text{NUpEfert} = \frac{\textit{Total N uptake}_{\textit{fertilised}} - \textit{Total N uptake}_{\textit{0N}}}{\textit{N rate}}$$

Total crop N accumulated in above ground biomass (kg N/ha) was also calculated and compared across treatments, sites, and years.

Figure 4: Weighing plant samples for biomass assessment

3.4 Residual soil mineral nitrogen post-harvest

Soil mineral nitrogen concentration (the sum of concentrations of nitrate nitrogen and ammonium nitrogen) in the top 20 cm of the soil profile was assessed within 1 to 2 days following harvest.

Mineral N (kg/ha) = Concentration (mg/kg) x sampling depth (cm) x bulk density (g/cm^3) x 0.1

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

3.5 Water quality monitoring

At the Babinda water quality monitoring site equipment was installed to monitor DIN concentrations in run-off and leachate. To monitor run-off volume, four SanDimas flumes (Figure 5) were installed, with one deployed in each treatment of a replicate which had the most suitable topography for capturing samples. Each flume contained an Odyssey logger to monitor flow though the flume and a KP sampler (Mark II) to capture water samples for analysis. The KP samplers were triggered via a float switch (turned on when water is present in the furrow) and captured water samples every 20 minutes when triggered. Water samples were collected as soon as possible following a run-off event and in some cases during a run-off event. Samples were then filtered and analysed for NH_4-N and NO_x-N concentrations, with results summed to calculate total DIN concentration.

To capture soil leachate samples, a ceramic pore water sampler was installed at both ends of each plot (strip) (24 ceramic pore water samplers per site). Samplers were buried at 1 m below ground level, directly below the plant row and placed under vacuum with water samples extracted from the soil and delivered to a bottle on the surface via a tube (Figure 6). Water samples were collected on a weekly basis, filtered and then analysed for NH_4-N and NO_x-N concentrations, with results summed to calculate total DIN concentration.

Figure 5: San Dimas flume.

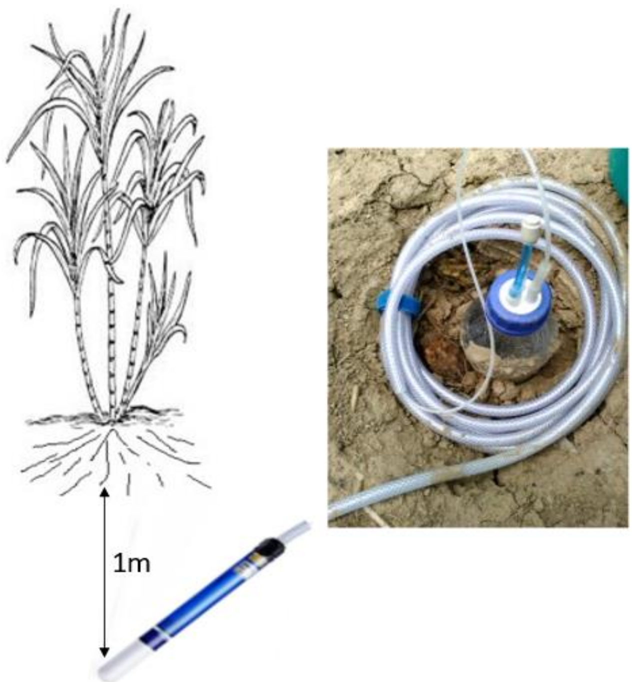

Figure 6: Ceramic pore water sampler and delivery bottle.

3.6 Economic analysis

An important requirement of the economic analysis was to account for all variables that influence the profitability (grower) of each fertiliser treatment including grower revenue, fertiliser costs, harvesting costs and levies. Grower revenue was calculated at the plot (replicate) level by multiplying cane yield by the cane payment formula[2], using relative CCS and the five-year average net sugar price[3] of $421/t to determine grower revenue per tonne of cane.

[2] Cane payment formula = sugar price x 0.009 x (CCS – 4) + mill constant. The mill constant applicable to each mill area was used.
[3] $421 was the five-year average net sugar price for the QSL harvest pool between 2013 and 2017.

Plot level calculations enabled variability to be considered using statistical analysis. Cane yields and relative CCS values were obtained from mill data.

Fertiliser costs were calculated from the average price paid for each product over the courseof the trial. Application costs were also subtracted along with the cost of other nutrients apart from N (e.g. Phosphorus, Potassium and Sulphur). Average harvesting costs were sourced from contractors in each region. The analysis assumes that all other variable growing expenses (irrigation, pest control, etc.) remain the same for each fertiliser treatment. Higher net revenue indicates a higher economic benefit.

To quantify the grower economic benefit, this report applies a method that has been used consistently in past research to calculate the net revenue (or 'partial net return'[4]) from applying different N rates:

Net revenue = gross revenue – fertiliser cost (including application) – harvesting costs – levies (all calculated per hectare).

3.7 Statistical analysis for yield, NUE and economic data

Collected data was added to the existing pool of data collected as part of the EEF60 project and reanalysed to determine if there were any significant changes to EEF60 findings. Given the considerable variation in yields and CCS between different trial sites and regions, the statistical analysis was completed by analysing data for each treatment relative to urea applied at 6ES in each rep, to help isolate the treatment effect. This was achieved by setting the urea applied at 6ES outcome as the benchmark and dividing the outcome of each treatment by the outcome of the 6ES treatment (e.g. 95 tch (Urea -20%)/ 100 tch (Urea 6ES) = Relative yield of 0.95). Following analysis, the relative data was transformed back to its original format (TCH, CCS, TSH, $/ha) and included in figures with the relative data for easy interpretation.

Statistical analyses were conducted on how the treatments affect each of the following traits of interest - TCH, TSH, CCS, Net Revenue, Relative TCH, Crop N content (kg/ha), tc/kg of applied N, NUptEfert, and post-harvest soil N (kg/ha at 0-20 cm)

The nitrogen treatments examined were Urea 6ES, Urea -20%, DMPP/CRF -20% and the Wildcard nitrogen treatment. Treatments in the wildcard mostly consisted of DMPP -20% or 20% CRF -20%. The remaining wildcard types were a mix of other nitrification inhibitors and straight CRFs.

Data were pooled across regions and sites and analysed based on the two forms of data (Relative or Actual).

Trial data were analysed by the common wildcard groupings:

1. All trial sites with wildcard treatments applied at 20% less N;
2. All sites with DMPP wildcard treatment applied at 20% less N;
3. All sites with 20% CRF wildcard treatment applied at 20% less N;

Linear mixed models were fitted to the data using ASReml-R statistical package. The model fitted to the data included the main effects of Product type, Soil type at 0-20 cm, Fertiliser rate, Cumulative rainfall 3 months post application, Harvest (Year) and Region and their 4-way interactions. Plots were nested within replicates and replicates nested within sites with each being fitted as random components of the model.

The traits analysed were TCH, TSH, CCS, Net Revenue, Crop N content (kg N/ha), Partial Factor N Productivity (tc/kg of applied N), NUptEfert, and post-harvest soil N (kg mineral N/ha at 0-20 cm) The significance of the fixed terms was tested using asymptotic Wald statistics. A least significant difference (LSD) multiple comparison test was used to determine which means among a set of treatment means differed from the rest at a significance level of 5%.

The treatment means with confidence interval bars for each analysis were graphed to visually display treatment variability. Letters (a, b, c, etc.) positioned above each bar indicate if means were statistically different from the other bars ($P<0.05$).

[4] For example, Connellan, Thompson, Moody and Arief (2017), Skocaj, Hurney and Schroeder (2012), Schroeder, Hurney, Wood, Moody and Allsopp (2010) and Schroeder, Moody and Wood (2010) used this method to compare the profitability of different nutrient practices.

3.8 Statistical analysis for leaching data

The leaching data from the Babinda were added to data collected from this site during the EEF60 project and were statistically analysed for the effect of the nitrogen treatments on NH_4-N (mg/L), NO_x-N (mg/L) and DIN (mg/L). The nitrogen treatments examined were Urea 6ES, Urea -20%, DMPP/CRF -20% and the Wildcard treatment.

The treatment combinations (DMPP/CRF -20%, Urea -20%, Urea 6ES and Urea 6ES -Surface applied) investigated at the Babinda site were different from other sites in the Wet tropics, consequently the site was analysed separately. At this site the grower chose to surface apply urea at the 6ES recommended rate as his Wildcard treatment.

The significance of the fixed terms was tested using asymptotic Wald statistics. A least significant difference (LSD) multiple comparison test was used to determine which means among a set of treatment means differ from the rest at a significance level of 5%. The treatment means with confidence interval bars for each analysis have been graphed to visually display treatment variability. Letters (a, b, c, etc.) positioned above each column indicates means that are statistically different ($P<0.05$).

3.9 Limitations

While every action was taken to ensure that the highest quality standards were maintained, some aspects of the trials do have limitations. A key limitation of carrying out strip trials on commercial sugarcane farms is the number of plots (or strips) available for the trial. For example, each plot has to be of sufficient size to ensure the mill is able to measure the CCS level of the harvested cane. Depending on the size of the paddock, this may limit the number of plots available across a cane paddock for the trial. Plot availability influences the design of the trial, particularly around the quantity of treatments and replicates available for investigation and subsequent statistical analysis. Given that the quantity of treatments and replicates influences degrees of freedom, care should be taken when interpreting the individual crop statistical results at some of the trial sites. Importantly, degrees of freedom increase when analysing data across multiple harvests and trial sites.

4 TRIAL SITE INFORMATION

4.1 Climate

The Wet Tropics is a region of extremely high rainfall which occurs predominantly over the summer period and encompasses the Mossman, Mulgrave, Innisfail, Tully and Herbert regions. Regional rainfall over the 2020/21 cropping season is presented in Table 1.

Table 1: Actual rainfall over cropping season and long-term averages

Region	Rainfall (mm)	
	July 2020 - June 2021	Average
Mossman	2666	2422
Mulgrave	2285	1912
Babinda	4616	4264
Innisfail	3862	3305
Tully	4939	4068
Herbert	3286	2116

4.2 Soil types

A range of soil types exist across the Wet Tropics catchments of the Great Barrier Reef. The soil name and texture for each region are listed in Table 2.

Table 2: Soil types and number of trial sites in the Wet Tropics

DISTRICT	SOIL NAME*	SOIL TEXTURE (0-20CM)	NUMBER OF TRIAL SITES
Herbert	Cudmore	Loam	1
	Hamleigh	Silty clay loam	1
	Palm	Loam	1
	Toobanna	Loam	1
Tully	Bulgun	Clay loam	1
	Hewitt	Silty clay loam	1
	Lugger / Banyan	Loam	1
Innisfail	Brosnan	Loamy sand	1
	Tully	Silty clay loam	1
Mulgrave/Babinda	Babinda	Loam	1
	Innisfail	Loam	2
	Jarra-Inlet	Loam	1
Mossman	Daintree	Loamy sand	1
	Mossman	Sandy loam	1

*Soil names sourced from the Queensland Government Soils Globe

5 FERTILISER COSTS

Five different types of CRFs were applied in the trials. The price paid for CRFs ranged between $1,292/t and $1,723/t excluding GST but varied depending on CRF type and date of purchase (particularly between years[5]). DMPP was the main NI applied in the trials. DMPP treated urea (marketed as Entec®) cost on average $136 more per tonne than urea (e.g. Urea $643/t + $136 = $779/t), while the inclusion of Nitrapyrin added an average $132 to the price of urea per tonne. Fertiliser costs for each product type were assumed constant across all districts.

The average N costs and cost ranges for each fertiliser treatment, based on the products and rates used in the EEF trials, are shown in Table 3. The cost ranges reflect different N rates applied for each site (as recommended by the 6ES guidelines) and different products (e.g. types of CRFs and NIs). Average N costs for the 2/3 CRF 1/3 NI (80% N) treatment were approximately 50-60% more than Urea applied at 6ES N rates. Average N costs for the main wildcard treatments (NI and 20% CRF applied at 20% less N than 6ES), were generally a similar cost to Urea at 6ES N rates.

Table 3: Average N costs and cost ranges (min-max) for each treatment at the Wet Tropics sites ($/ha)

REGION	T1	T2	T3	WILDCARD	
	UREA 6ES	UREA -20%	DMPP/CRF -20%	DMPP -20%	20% CRF -20%
Wet Tropics	$184 ($140 - $210)	$145 ($112 - $168)	$291 ($231- $349)	$175 ($149 - $203)	$191 ($174 - $217)

[5] The economic results depend on historical average prices, and prices are likely to change in the future (particularly given fluctuations in prices were observed for some fertilisers).

6 RESULTS

6.1 All sites with a DMPP treatment as Wildcard

6.1.1 Yield and net return

This analysis compared how the DMPP applied at N rates 20% lower than 6ES performed relative to the two urea treatments applied at 6ES and 20% below. Figure 7 displays the results of the overarching treatment effects on 25 trial sites in three regions (Wet Tropics, Burdekin and Mackay-Whitsundays) with 65 crops harvested over four ratoons (three ratoons as part of EEF60).

A statistically significant difference (p-value = 0.042) between treatments was identified in the cane yield analysis. Urea 6ES produced significantly more cane (2.1 tch) than the Urea -20% treatment, while both the DMPP/CRF -20% treatment and the DMPP -20% treatment were not significantly different to the Urea 6ES treatment.

Differences in CCS were also significant (p= 0.001), with Urea 6ES producing significantly lower CCS than all the other treatments (0.17, 0.10 and 0.14 units lower than recorded in the Urea -20%, DMPP/CRF -20% and DMPP -20% treatments, respectively). No significant differences in sugar yield between treatments were identified.

Net revenue was also significantly different between the treatments (p= 0.000) with DMPP/CRF -20% delivering significantly lower net revenue than all the other treatments and Urea -20% returning significantly higher grower net revenue than Urea 6ES. The DMPP -20% treatment produced similar net revenue to both urea treatments.

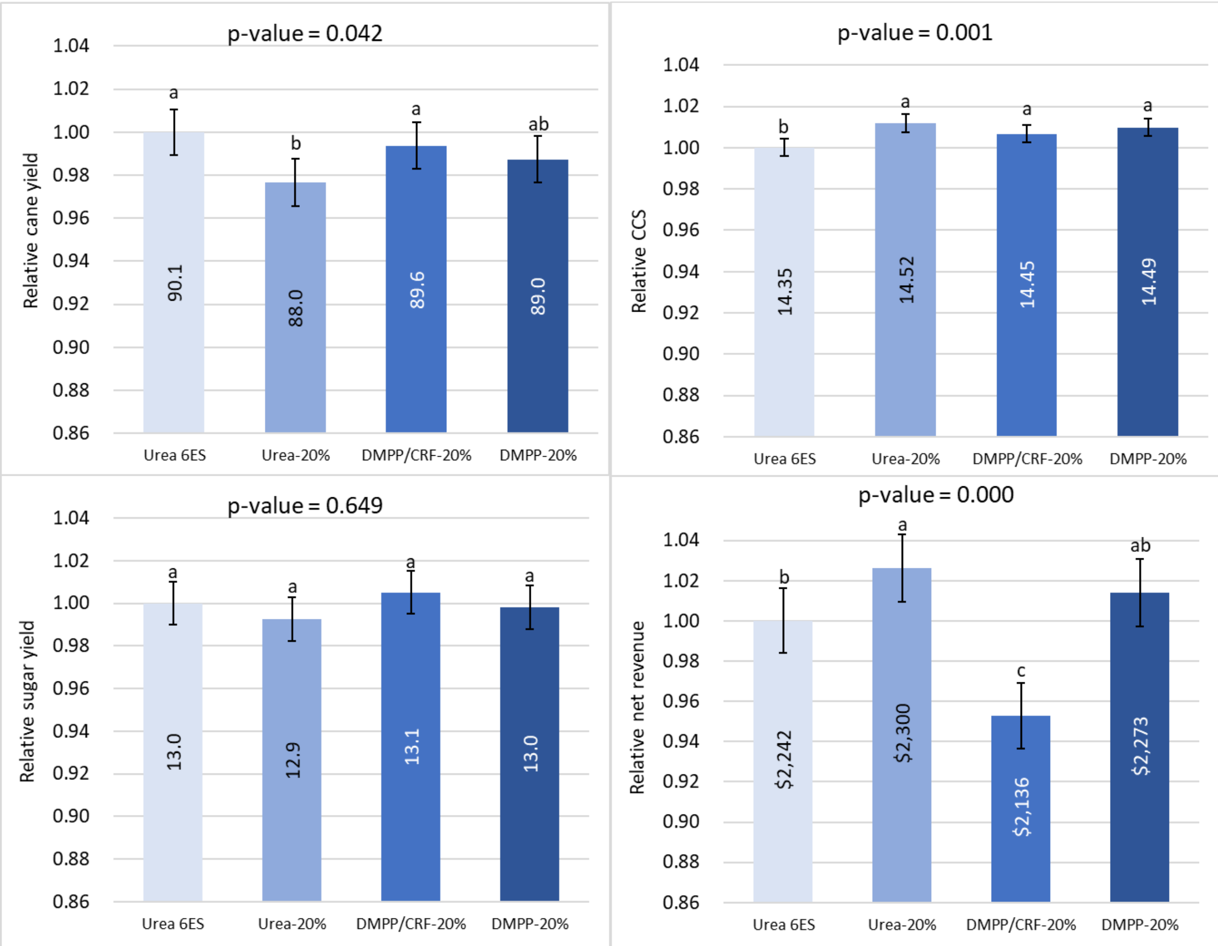

Figure 7: Mean cane yield (tch), CCS, sugar yield (tsh) and net revenue ($/ha) for DMPP sites. Statistical comparisons have been made on a relative basis (y axis), while actual values are shown in text on each column. Error bars indicate the average 95% confidence interval.

6.1.2 NUE indicators and post-harvest soil N -DMPP

The various analyses undertaken to quantify NUE indicators and post-harvest soil N were conducted at 25 sites with 65 sampling events for each of the NUE indicators and post-harvest soil N assessments over four ratoons (three ratoons as part of EEF60). The results of treatment effects across the trial sites in three regions

(Wet Tropics, Burdekin and Mackay-Whitsundays) where DMPP -20% was the chosen Wildcard are presented in Figure 8.

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 (by 0.13, 0.14 and 0.14 t/kg N applied for the Urea -20%, DMPP/CRF – 20% and DMPP – 20% treatments, respectively), 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 (0.014 t/kg applied N lower) although this difference was small. The Urea -20% treatment was not significantly different to the DMPP -20% treatment.

The index for efficiency of fertiliser N recovery (NUptEfert) showed no significant treatment effects. Crop N content was not significantly different between any of the treatments where N was applied and all fertilised treatments containing significantly more N than the unfertilised (0N) treatment.

Post-harvest soil N (kg/ha) calculated for the top 20cm of the soil profile showed no significant differences between any of the treatments.

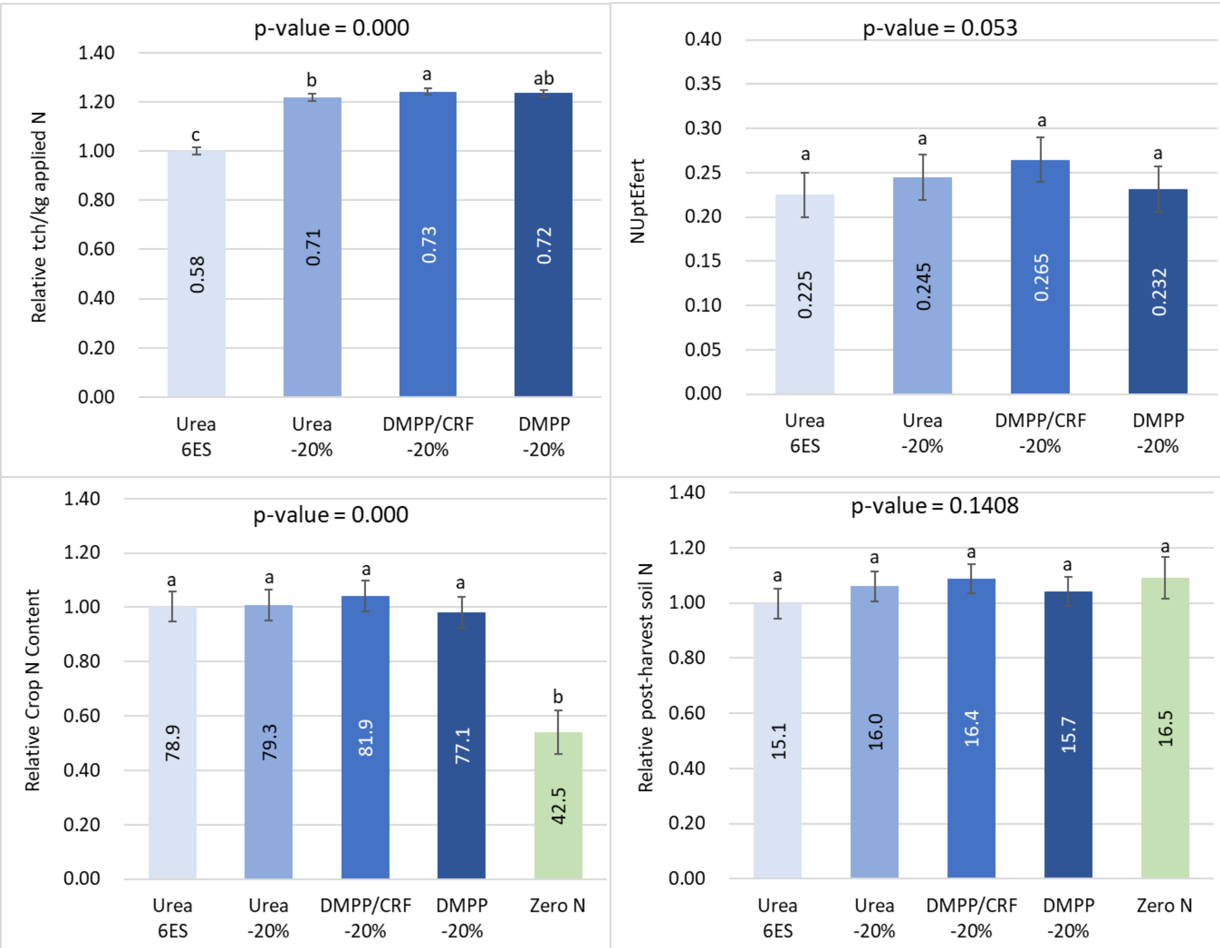

Figure 8: Indices of crop NUE (tc/kg applied N and NUptEfert), Crop N content (kg/ha) and Post-harvest Soil N (kg N/ha in the top 20cm of the soil profile) for all DMPP sites. Statistical comparisons have been made on a relative basis (y axis), while actual values are shown in text on each column. Error bars indicate the average 95% confidence interval.

6.2 All sites with 20% CRF treatment as Wildcard

6.2.1 Yield and net return

This analysis investigated the performance of the 20% CRF blended with 80% urea applied at N rates 20% lower than 6ES compared to the two urea treatments (applied at 6ES and 20% less) and the CRF/DMPP blend applied at 20% less.

Crop productivity data are presented for the overarching treatment effect across the 57 harvested crops over four ratoons (three ratoons as part of EEF60) in Figure 9. The urea treatment at the 6ES N rate produced significantly more cane (2.5 tch) than the Urea -20% treatment, while both the DMPP/CRF -20% treatment and the 20% CRF -

20% treatment were not significantly different to the Urea 6ES treatment. Treatment effects on CCS showed similar trends to the DMPP analysis (relatively lower CCS in the Urea 6ES treatment) but in this analysis was not significantly different. The Urea -20% produced significantly less sugar than the Urea 6ES treatment (0.3 tsh), whilst sugar yields for both EEF's were not significantly different to the Urea 6ES treatment. Net revenue was similar between the 20% CRF -20% and two urea treatments, while DMPP/CRF -20% had significantly lower net revenue (between $162/ha and $178/ha lower).

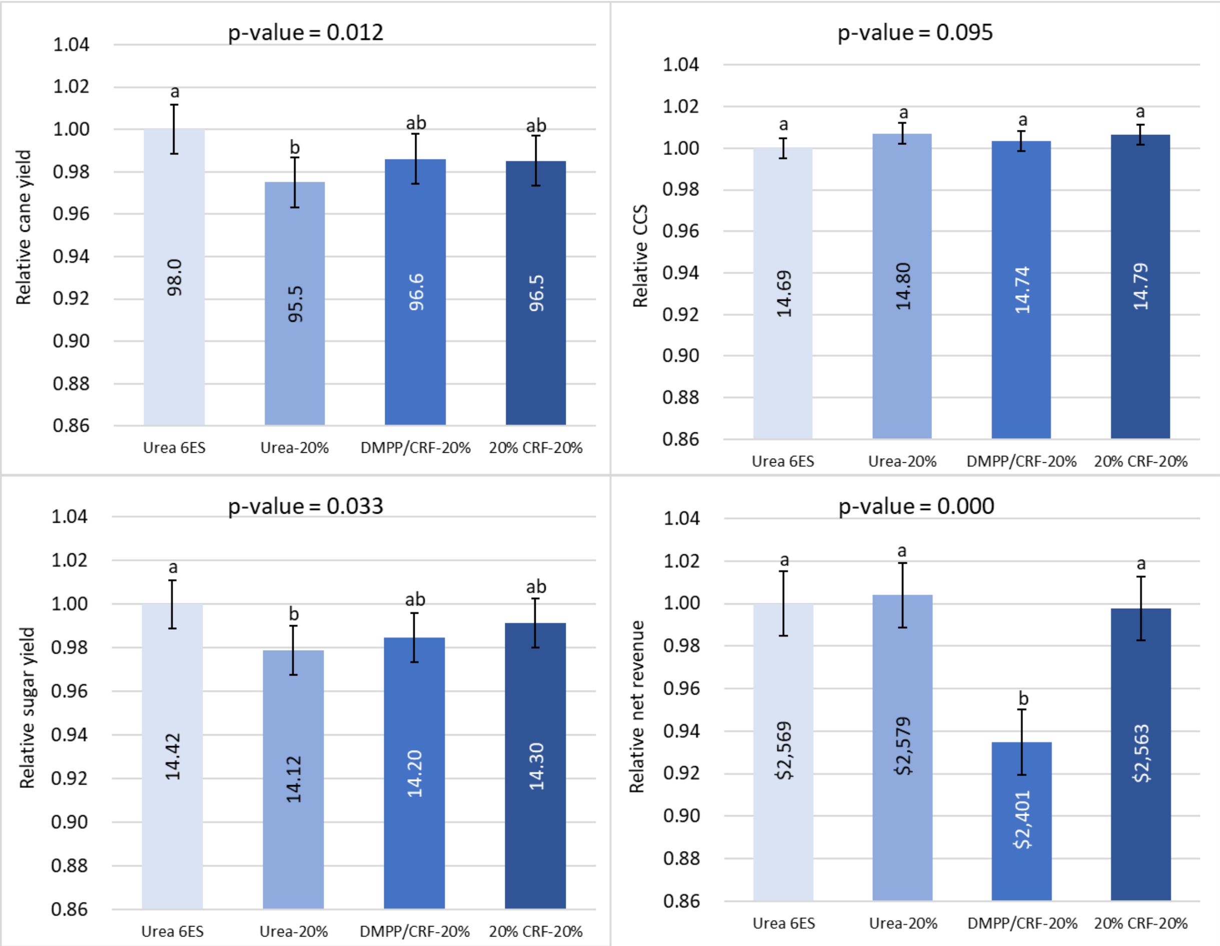

Figure 9: Mean cane yield (tch), CCS, sugar yield (tsh) and net revenue($/ha) for 20% CRF sites. Statistical comparisons have been made on a relative basis (y axis), while actual values are shown in text on each column. Error bars indicate the average 95% confidence interval.

6.2.2 NUE indicators and post-harvest soil N – 20% CRF

The various analyses undertaken to quantify NUE indicators and post-harvest soil N were conducted at 25 sites with 57 sampling events for each of the NUE indicators and post-harvest soil N assessments over four ratoons (three ratoons as part of EEF60). The relative treatment effects across all trial sites in the three regions are presented in Figure 10 for the metrics of partial factor productivity of N (t cane/kg applied N), NUptEfert (kg fertiliser N uptake/kg applied N), crop N content and post-harvest soil N for each treatment.

Partial factor productivity of applied N was significantly lower in the Urea 6ES treatment in comparison to all other treatments (0.13, 0.14 & 0.14 t/kg N applied for the Urea -20%, DMPP/CRF -20% and the 20% CRF -20% treatments, respectively). There was no significant difference between the Urea -20% treatment and either of the EEF treatments.

The index for efficiency of fertiliser N recovery (NUptEfert) for the Urea 6ES treatment was significantly less than all other treatments except the 20% CRF -20% treatment. The Urea -20% and the EEF treatments were not significantly different to each other. Overall fertiliser N capture across treatments ranged from as low as 27% in the Urea 6ES treatment to as high as 35% in the DMPP/CRF -20% treatment.

Crop N content data showed that crops grown with DMPP/CRF -20% captured significantly more N than all other treatments. There was no significant difference in crop N content between the 20% CRF -20%, the Urea -20% and the Urea 6ES treatments. Where no fertiliser was applied (Zero N) crop N was significantly lower than all other treatments and reflected by poor growth in these areas.

Post-harvest soil N (kg/ha) calculated for the top 20cm of the soil profile showed no significant differences between treatments, with no evidence of additional residual mineral N compared to the Zero N reference.

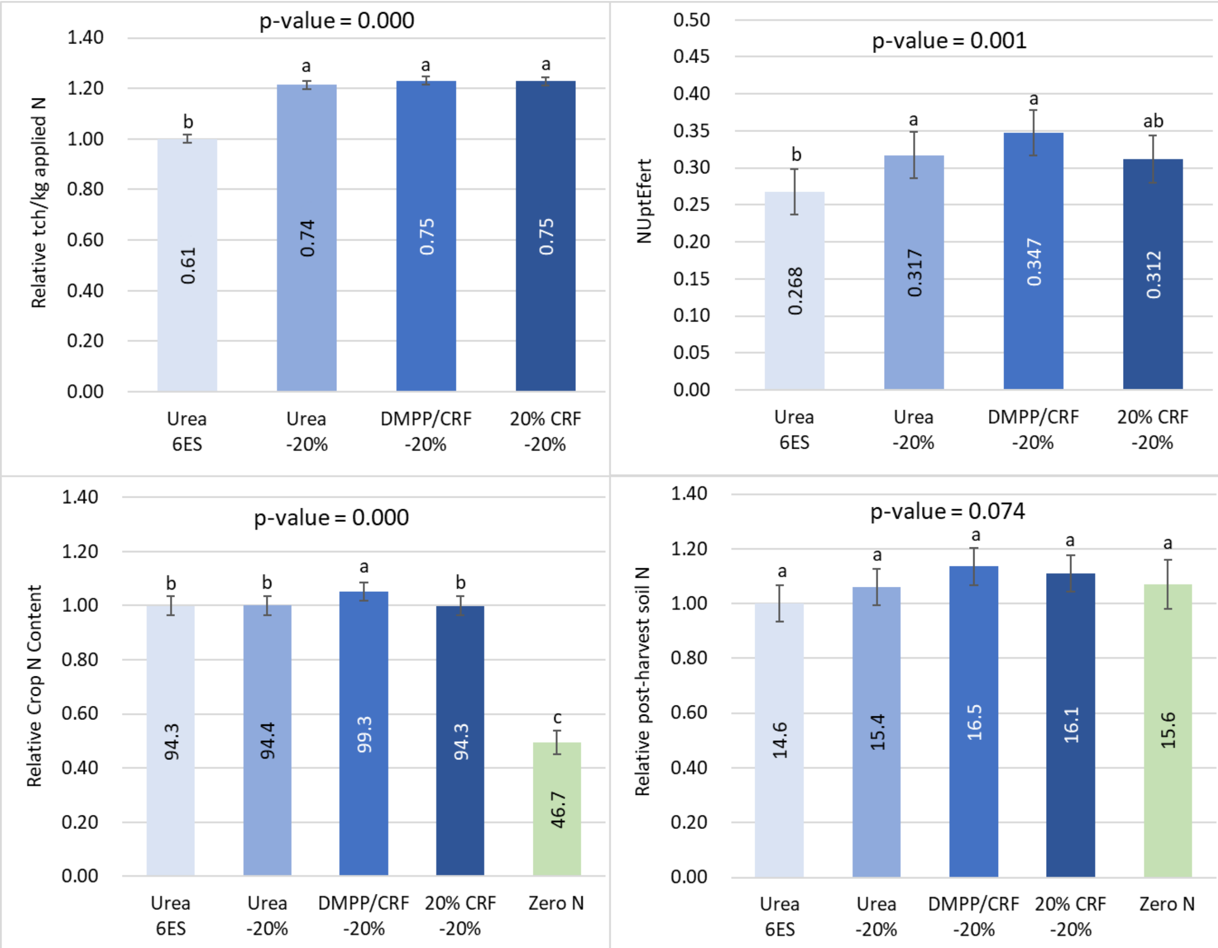

Figure 10: Indices of crop NUE (tc/kg applied N and NUptEfert), Crop N content (kg/ha) and Post-harvest Soil N (kg N/ha in the top 20cm of the soil profile) for 20% CRF sites. Statistical comparisons have been made on a relative basis (y axis), while actual values are shown in text on each column. Error bars indicate the average 95% confidence interval.

6.3 All sites with Wildcards

6.3.1 Yield and net return

This analysis aims to provide an understanding of how EEF treatments (DMPP/CRF -20% and Wildcard -20%) applied at N rates 20% lower than 6ES performed relative to the two urea treatments (applied at 6ES and 20% below).

Figure 11 displays the results for the overarching treatment effect across 54 trial sites in three regions (Wet Tropics, Burdekin and Mackay-Whitsundays) with 137 crops harvested over four ratoons (three ratoons as part of EEF60).

Mean cane yield for Urea -20% was significantly (p-value = 0.000) lower than Urea 6ES and the DMPP/CRF - 20% (2.3 & 1.5 tch respectively). Mean CCS was significantly (p-value = 0.00) lower for Urea 6ES and DMPP/CRF -20% in comparison to the Urea -20% (0.14 and 0.08 CCS lower), while CCS for Urea 6ES was significantly lower than Wildcard -20% (0.11 CCS). Mean sugar yield was significantly (p-value = 0.016) lower for Urea -20% in comparison to Urea 6ES (0.20 tsh), while DMPP/CRF - 20% and Wildcard -20% were not significantly different to Urea 6ES.

For net revenue, the mean differences between the treatments were found to be statistically significant (p-value = 0.000). The Wildcard-20% maintained similar profitability to both urea treatments, while the DMPP/CRF -20% treatment was significantly less profitable than the other three treatments by $135/ha (Urea 6ES), $168/ha (Urea -20%) and $135/ha (Wildcard -20%). While the Urea -20% treatment had slightly higher average net revenue than

6ES urea (although not statistically significant), the significantly lower cane yield would reduce mill revenue. Including revenue from both sugar and molasses, mill revenue would decrease by around $53/ha[6].

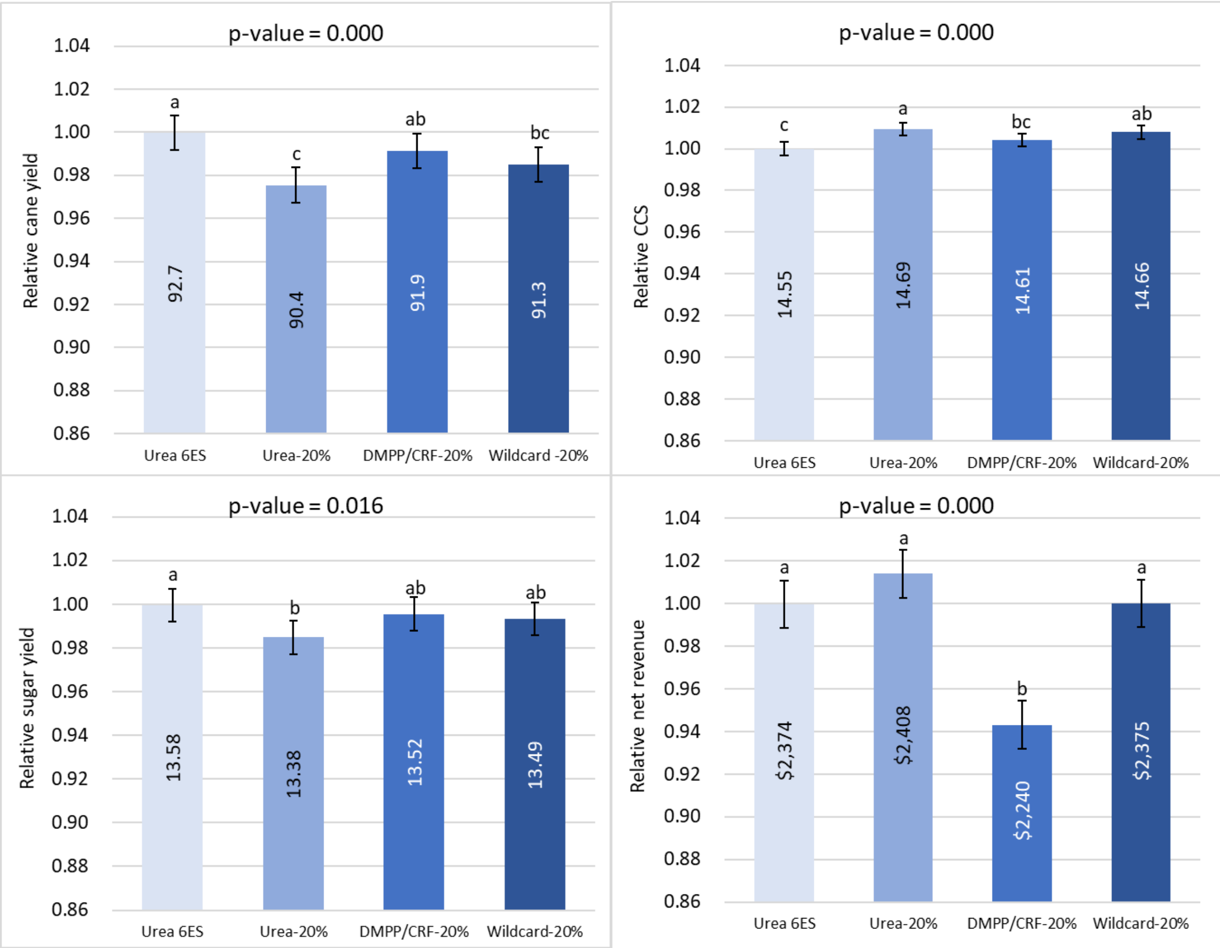

Figure 11: Mean cane yield (tch), CCS, sugar yield (tsh) and net revenue ($/ha) for Wildcard sites. Statistical comparisons have been made on a relative basis (y axis), while actual values are shown in text on each column. Error bars indicate the average 95% confidence interval.

6.3.2 NUE indicators and post-harvest soil N for Wildcard

The various analyses undertaken to investigate NUE and post-harvest soil N aim to provide an understanding of how the EEF treatments (DMPP/CRF -20% and Wildcard -20%) performed relative to the two urea treatments (applied at 6ES and 20% below). Data has been captured from 54 sites with 137 harvests of data captured over four ratoons (three ratoons as part of EEF60) is included in this analysis. The Wildcard treatment included either a DMPP urea or a CRF blended with urea.

NUE indicators (t cane/kg applied N and NUptEfert), crop N content and post-harvest soil mineral N in the fertilised soil layer (0-20cm) are presented as averages across each of the three trial regions (WetTropics, Burdekin and Mackay-Whitsundays) in Figure 12.

The partial factor productivity metrics (t cane/kg applied N) were significantly lower in the Urea 6ES treatment in comparison to all other treatments (0.13, 0.14 & 0.14 t/kg applied N lower than the Urea -20%, DMPP/CRF -20% and Wildcard -20%, respectively). This is due to the higher rate of N applied in this treatment, with very limited evidence of 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 very small.

The efficiency of fertiliser recovery (NUptEfert) shows that the proportion of fertiliser taken up in the Urea 6ES treatment was significantly less than all other treatments - due primarily to the higher N rate applied. The Urea -20%

[6] Revenue received by the mill was calculated assuming: sugar price = $421/t, mill constant = $0.60, CoW = 1.00, CCS = 13.79 and molasses revenue of $3 per tonne of cane (2012-19 average across Australia, https://asmc.com.au/policy-advocacy/sugar-industry-overview/statistics/)

and the EEFs were not significantly different to each other. DMPP/CRF -20% had the highest mean NUptEfert (0.31kg N uptake/kg fertiliser N applied) however it was not significantly different to Urea -20% or the Wildcard -20%.

Crop N content varied across treatments, DMPP/CRF -20% accumulated significantly more crop N than Urea 6ES, Wildcard -20% and the Zero N areas (4.2 kg N/ha, 4.6 kg N/ha and 46.5 kg N/ha, respectively), but was not significantly different to Urea -20%.

Post-harvest soil N was lowest in Urea 6ES relative to all other treatments however significant differences were not large and suggest that residual fertiliser N in the top soil was negligible across all regions in the top 20cm of the soil profile.

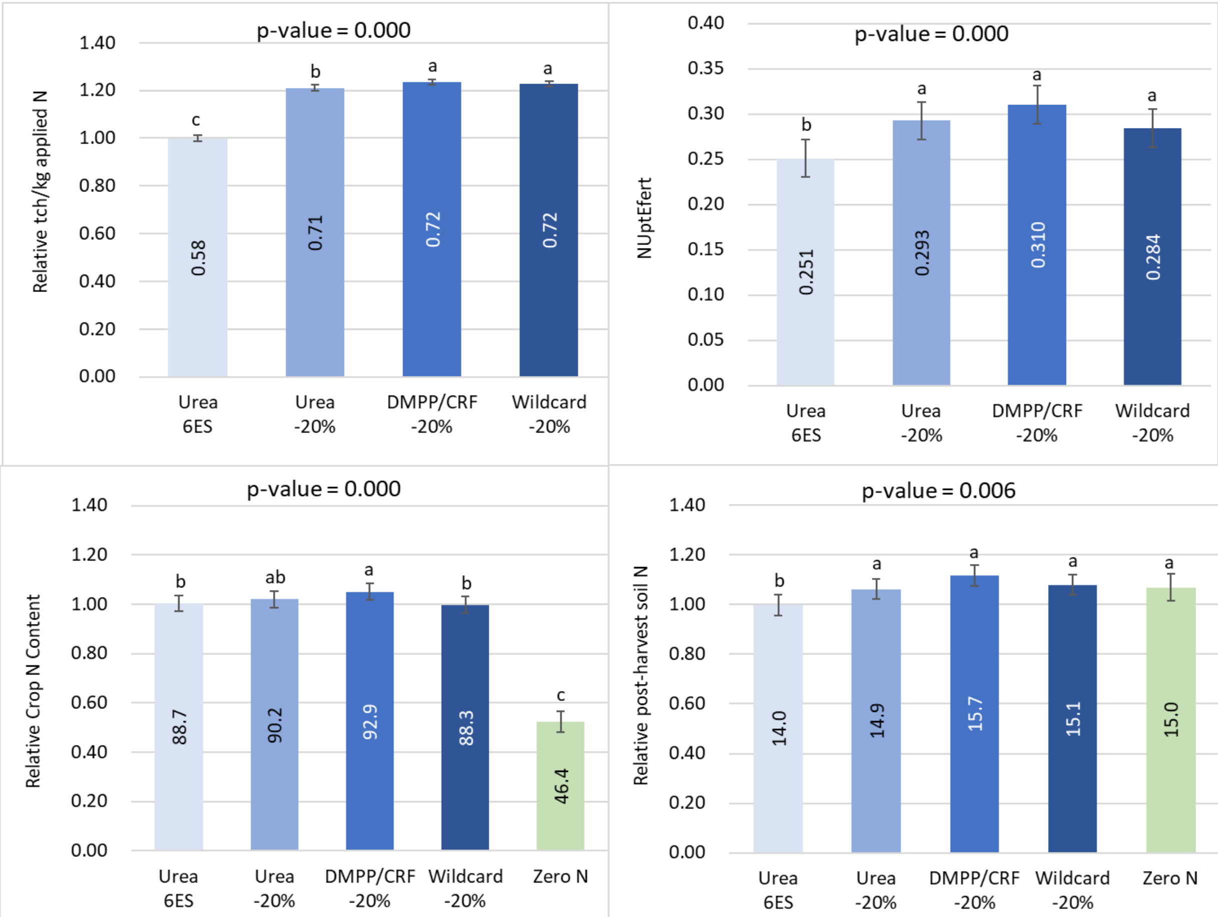

Figure 12: Indices of crop NUE (tc/kg applied N and NUptEfer)t, Crop N content (kg/ha) and Post-harvest Soil N (kg N/ha in the top 20cm of the soil profile) for Wildcard sites. Statistical comparisons have been made on a relative basis (y axis), while actual values are shown in text on each column. Error bars indicate the average 95% confidence interval

6.4 Water quality data for the Babinda trial site

The Babinda water quality site was monitored over four ratoons (three ratoons as part of EEF60). The site was unique compared to other (EEF60) water quality sites due to the extremely high organic carbon content (11.1%) of the soil, which can be described as a peat soil. At this site the grower's preferred practice was to surface apply fertiliser onto the plant bed (whilst avoiding the interrow area) at the 6ES recommended rates.

6.4.1 Leaching data

The movement of dissolved inorganic N (DIN) through the soil profile was monitored by ceramic pore water samplers positioned directly below the crop row at a depth of 1 meter. Soil water samples were extracted under vacuum and were collected on a weekly basis. Twenty-four samplers were positioned across the trial site (2 in each replicate of each treatment), allowing for statistical analysis of data captured.

The average DIN concentrations over 4 ratoons are presented in Figure 13. Data from the first three ratoons captured as part of the EEF60 project were included in this analysis.

Mean differences between the treatments were found to be statistically significant (p-value = 0.04). Monitored DIN concentrations (mg/L) over four seasons were very low compared to other sites monitored as part of the EEF60 project.

Losses of DIN at this site from leaching events were found to be negligible over four seasons of monitoring. Some differences across treatments were observed, however no clear trends could be identified. The most likely explanation for the very low level of DIN concentrations is likely related to the high organic carbon levels in the soil profile at this site.

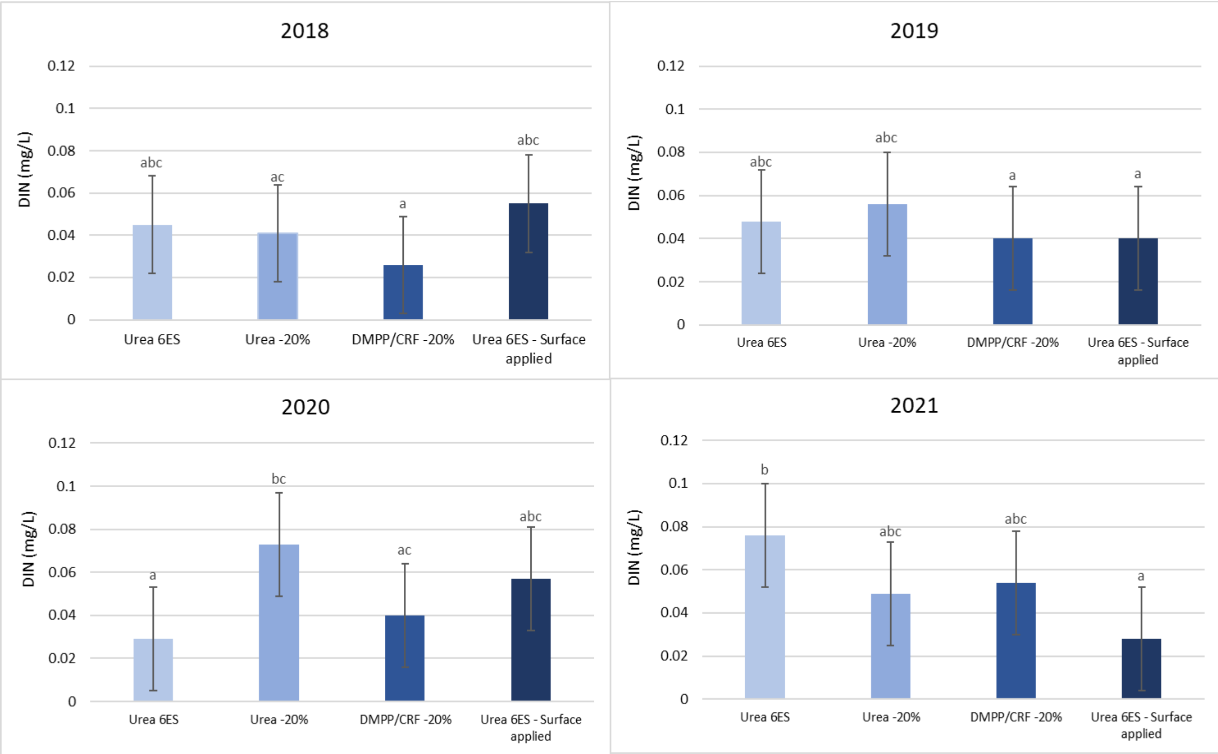

Figure 13: Mean DIN (mg/L) in soil water at 1m below the crop row over four ratoons for the Babinda site.

6.4.2 Run-off data

Surface flow of water at the Babinda site and the export of DIN (mg/L) from each treatment was monitored over a period of four and a half months (October 2020 to March 2021). The aim was to gain an understanding of run-off losses from the EEF treatments in comparison to the two urea treatments. Data in Figure 14 shows the volume of rainfall and run-off (mm) and the concentration of DIN in runoff. Water samples from run-off events were captured by KP samplers and delivered to storage bottles. Samples were collected from the site as soon as possible, however due to limited access in wet conditions samples remained at the site for up to two days following run-off events.

Following the application of fertiliser at this site on the 14th of October 2020, KP samplers were installed in the unlikely event that there was a significant rainfall event prior to the installation of flumes and Odyssey loggers. Within several days of fertilising a rainfall event occurred which resulted in a small runoff event. Rainfall and water sample concentration data is presented for this event however no run-off volumes could be calculated (see Figure 14) DIN concentrations in the first runoff event were highest in the Urea at 6ES - surface applied treatment (3.03 mg/L) followed by the 6ES Urea (subsurface) treatment (1.61 mg/L). Following a minor flood event in early January 2021 there was a second spike in DIN concentrations from the 6ES Urea (subsurface) treatment (2.42 mg/L) and the EEF (DMPP/CRF -20%) treatment (2.06 mg/L).

Water sampling equipment (KP samplers) employed at this site for water quality monitoring were found to be inadequate for collecting representative water samples across the duration of extended flow events, even though runoff volumes were recorded. This means that total DIN loads could not be calculated, only DIN concentrations and total runoff volumes have been presented in this report. Visual comparisons can be made but no meaningful statistical comparisons can be made using this data.

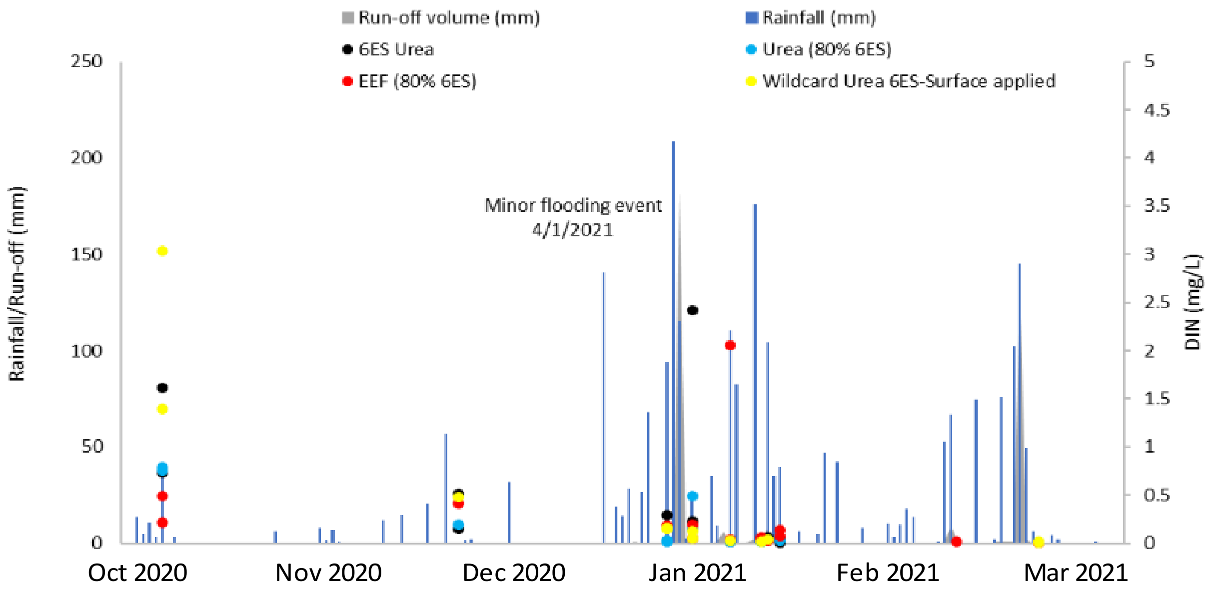

Figure 14: Rainfall (mm) and run-off volumes (mm) with the concentration of DIN (mg/L) for the Babinda site 2020/21.

7 Discussion

Seventeen EEF60 trial sites in the Wet tropics were continued for a fourth ratoon. Protocols used in the EEF60 project were followed to re-establish sites and collect all relevant information. Data was successfully collected from fourteen sites and combined with the EEF60 dataset and reanalysed to re-evaluate the effects of treatment on cane and sugar yield, net revenue, NUE and post-harvest soil N.

The Wildcard treatments represented existing commercial products or blends that were already available in the marketplace. Growers participating in the EEF60 project were given a choice of EEFs to trial as their wildcard, this was continued in the fourth ratoons sites. The majority of wildcards maintained were DMPP and blends of CRF (20%) with urea (80%) at N rates 20% below 6ES. Both choices applied at rates supplying 20% less N than Urea 6ES generally had similar N fertiliser costs to Urea 6ES.

Comparisons between the two most popular wildcard options (ie. DMPP -20% vs 20% CRF -20%) were to some extent constrained by the lower numbers of site-years available to each option, and the fact that each option was tested in a different subset of the experimental locations. However, the additional year of data when added to the EEF60 dataset provided some interesting outcomes, especially for DMPP -20%.

DMPP -20% was the chosen wildcard at 25 sites with data captured from 65 harvests over four ratoons, whilst at another 25 sites growers chose to utilise the 20% CRF -20% blend as their wildcard, with data captured from 57 harvests over four ratoons. Analysis of data from the 25 sites where DMPP -20% was chosen as the wildcard showed that the Urea -20% treatment yielded significantly less cane (p-value = 0.042) than the Urea 6ES treatment (-2.1 tch), whilst EEF treatments were able maintain similar yields to the Urea 6ES treatment. CCS was significantly lower in the Urea 6ES treatment in comparison to all other treatments however sugar yields between treatments were not significantly different. Applying DMPP treated urea at 20% less N than 6ES was found to produce similar grower profitability to applying urea at either 6ES rates or 20% below.

Investigation of indices of crop NUE for DMPP -20% sites, showed Urea 6ES had significantly lower partial factor productivity of applied N (tonnes of cane/kg applied N) compared to both EEFs demonstrating that the additional N applied at the 6ES recommend rate did not result in significantly improved yield. The Urea -20% treatment also had a significantly lower partial factor productivity of applied N in comparison to the DMPP/CRF -20% treatment indicating that the lower rate of urea suffered a yield loss. No significant differences crop N content between urea treatments and EEFs were identified, and no differences were found in crop recovery of applied N fertiliser (NUptEfert). Post-harvest soil sampling showed no significant differences between treatments in soil mineral N in the top 20cm of the soil profile.

Analysis of data from the 25 sites where 20% CRF -20% was chosen as the wildcard showed similar outcomes to those which chose DMPP-20% as their wildcard. The Urea -20% treatment yielded significantly less cane (p-value = 0.012) than the Urea 6ES treatment (-2.5 tch), whilst EEF treatments were able maintain similar yields to the Urea 6ES treatment. CCS was not significantly different between treatments however sugar yields were found to be impacted, Urea -20% treatments yielded significantly less (p-value = 0.033) sugar (-0.3 tsh) than the Urea 6ES treatment. EEF treatments maintained similar sugar yields to the Urea 6ES treatment. Similarly to DMPP -20% applying 20% CRF blended with 80% urea at rates 20% less N than 6ES was found to produce similar grower profitability to applying urea at either 6ES rates or 20% below.

Indices of crop NUE, for sites with 20% CRF -20% showed Urea 6ES had significantly lower partial factor productivity of applied N (tonnes of cane/kg applied N) compared to the Urea -20% and both EEF treatments demonstrating that the additional N applied at the 6ES recommend rate did not result in improved yield. The EEF blend of DMPP/CRF -20% attained a significantly higher crop N content than all other treatments. No significant differences in crop N content between urea treatments and 20% CRF -20% were identified. Recovery of applied N fertiliser (NUptEfert) showed that there were significant differences in the percentage of applied fertiliser recovered by the crop across treatments with the Urea 6ES treatments recovering 27% of the applied N whilst the EEF DMPP/CRF -20% treatment recovered 35% of the applied N. Post- harvest soil sampling showed no significant differences between treatments in soil mineral N in the top 20cm of the soil profile.

A total of 54 trial sites had at least one Wildcard -20% with 137 crops harvested over four ratoons. Most sites trialled were either the DMPP-20% or 20% CRF -20% (47% and 42% of sites respectively) with a small number of sites (11%) which utilised other commercially available nitrification inhibitors or straight CRF's which were not blended with urea. Data from these 137 harvests were analysed and showed very similar outcomes to what was described in the EEF60 final report (Connellan et.al. 2022) and can be summarised as follows:

- Urea -20% had significantly lower cane yield than Urea 6ES and DMPP/CRF -20% (2.3 tch and 1.5 tch respectively).
- Urea 6ES and DMPP/CRF-20% CCS results were significantly lower than Urea -20% (0.14 and 0.08 units respectively).
- Urea -20% sugar yields were significantly less (0.2 tsh) than Urea 6ES, however DMPP/CRF -20% and Wildcard -20% performed equally as well as Urea 6ES.
- Wildcards -20% maintained similar profitability to both urea treatments, however DMPP/CRF -20% significantly decreased grower profitability compared to all other treatments due to its high cost.
- Wildcards -20%, DMPP/CRF -20% and Urea -20% had significantly higher partial factor productivity of applied N than Urea 6ES, however both EEFs had higher partial factor productivity of applied N than Urea -20%, which suggests that EEFs were able to keep more N in the soil profile for crop use compared to Urea -20%.
- Sugarcane grown in DMPP/CRF -20% treatment accumulated significantly more crop N than sugarcane grown in the Urea 6ES and Wildcard -20% treatments, however this did not result in significantly improved yields.
- The efficiency of fertiliser recovery (NUptEfert) was significantly poorer in the Urea 6ES treatment compared to all other treatments demonstrating limited additional N uptake with higher rates of applied N with urea.

Overall, the findings from an analysis of data of all sites as Wildcards -20% is consistent with findings from the analysis of data from sites with DMPP -20% and sites with 20% CRF -20% and reconfirms the opportunities for the broader application of these EEF strategies in ratoon cane at N rates 20% below 6ES.

Modelling performed by CSIRO to investigate when and where EEF's provide water quality benefits found that using urea at N rates at 20 kg/ha less than 6ES could lead to very small cane yield reductions however if an EEF was utilised in place of urea this small yield reduction could often be mitigated (Webster *et.al* 2022).

Water quality monitoring which was continued at the Babinda site for a fourth ratoon demonstrated that DIN concentrations in soil water at 1m below the soil surface (directly below the plant row) were extremely low throughout the four ratoon crops. Significant differences in treatments were found in 2020 and 2021 however no clear trends were identified in either year. The most important finding at this site was the consistently low DIN levels. The most likely reason for this outcome was the very high soil organic carbon levels (approx. 11.1%), however further investigation would be required to provide a clear explanation.

Run-off data was also collected from this site during the fourth ratoon. Information from this dataset was limited to comparison of DIN concentrations in specific runoff events, due to an inability to collect weighted runoff samples across the hydrograph, and so calculate realistic DIN loads in runoff.

Runoff data from the Babinda site collected during 2020/21 indicated that DIN concentrations in run-off peaked in the Urea 6ES-surface applied treatment (3 mg/L) in October 2020 during rainfall. Following this peak DIN concentrations declined until January 2021 at which point minor flooding occurred. Following this event DIN concentrations again peaked in the stool split Urea 6ES treatment followed by the EEF treatment (DMPP/CRF-20% also stool split), though levels were not as high as those detected in October 2020. Observations from the data at this site suggested that early rainfall which resulted in runoff posed a greater risk of N losses where urea was surface applied in comparison to subsurface applications.

8 Conclusion

The objective of this project was to continue a number of EEF60 trial sites in the Wet Tropics for an extra season in order to collect additional data to be included in the EEF60 data set and then reanalyse data to provide more clarity around existing findings or provide new information.

The project confirmed EEF60 findings and clearly demonstrated that when urea was applied at N rates 20% below 6ES a small but significant loss in cane yield was detected. While grower profitability was maintained (at N rates 20% less than 6ES), substantial adoption of this practice would reduce mill revenue, potentially making the net impact to industry negative.

DMPP treated urea and blends of CRF (20%) with urea (80%) applied at N rates 20% below 6ES were able to maintain similar productivity and profitability to Urea 6ES. NUE was improved significantly, and both products were able to maintain a similar crop N content even though 20% less N was applied. Fertiliser N uptake efficiency was maintained or improved in comparison to urea applied at the 6ES rate. Little difference in post-harvest soil N was observed throughout the project.

Leaching data from the Babinda site showed that DIN concentrations remained very low over all years of monitoring and suggested that leaching losses were not a major loss pathway at this site. The reason for this may be due to the very high soil organic carbon levels, however further research would be required to develop an understanding of where and how the N is being lost from this system.

Data presented in this report confirms findings presented in the EEF60 final report. By using EEF's at an N application rate 20% less than recommended by the 6ES method, growers can maintain similar levels of productivity and profitability to urea applied at the 6ES recommended rate. Maintaining production and profit will be crucial to achieving broader uptake of EEF's (applied at lower N rates) by industry and substantial increases in NUE (and improvements in fertiliser uptake efficiency) are likely to reduce the risk of DIN losses and improve water quality outcomes.

9 Acknowledgements

The On-ground testing and modelling of the effectiveness of enhanced efficiency fertilisers in the Wet Tropics catchments of the Great Barrier Reef project was funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation with support from a collaborative partnership between Sugar Research Australia, Department of Agriculture and Fisheries, CSIRO, CANEGROWERS, productivity services and cane farmers.

The final report was prepared with the assistance of Mr Matthew Thompson, Senior Agricultural Economist, Department of Agriculture and Fisheries, Queensland. Mr Thompson provided the economic analysis for this report and contributed to the development of the statistical analysis of the data presented, he also provided general advice and guidance in the development of this report.

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APPENDIX 1

Final Report: Modelling outputs identifying when and where EEFs provide water quality benefits

Final EEF modelling report to the Great Barrier Reef Foundation

December 2022

by Tony Webster, Kirsten Verburg, Jody Biggs, Peter Thorburn CSIRO Agriculture and Food

Contents

Executive Summary

Agricultural land use in Great Barrier Reef (GBR) catchments are discharging sediment, pesticide and nitrogen (N) pollutants at a rate that is too high to sustain a healthy reef ecosystem (GBR Scientific Consensus Statement, 2017). In the Wet Tropics, sugarcane is the dominant agricultural land use and N fertiliser applied to sugarcane the dominant driver of N discharged. Thus, to reduce N entering the GBR lagoon from Wet Tropics catchments N fertiliser management of sugarcane crops needs to be changed (Reef 2050 Water Quality Improvement Plan, 2018).

The use of enhanced-efficiency fertilisers (EEF) has been put forward as one tool sugarcane farmers could use to reduce N losses to the environment (Verburg et al., 2014) and thus N discharges of to the GBR lagoon. Previous experimental research into the use of EEF in sugarcane have focussed on the productivity impacts of using EEF at a lower application rate than urea (e.g., Dowie et al., 2019, Connellan et al., 2022; and an overview of experiments by Verburg et al., 2019a), with the rationale being that the higher cost of the EEF may be off-set by its lower rate. If the lower application rate of EEF would reduce N loss, make more N available to the crop and thereby achieve a similar yield as the higher rate urea, then environmental benefits may be obtained without the risk of productivity losses.

We conducted a broad modelling investigation looking at climate x soil x crop start interactions to identify when and where EEF use could reduce N losses to the environment compared to current industry recommended N rates of urea for ratoon sugarcane crops in the Wet Tropics. We also analysed yield implications of using EEF in place of urea, as understanding N loses concurrently with yield can, after further economic analysis, help determine the likelihood of adoption, as well as any potential need for incentivising adoption.

To help frame the simulation results for understanding how EEF can provide benefits we structured our analyses around a framework for understand the conditions under which use of EEF provides benefits (Verburg et al., 2017, 2022). The framework describes that, firstly, EEF have a 'protection period', which is a period of time after application in which soil N levels are supressed. This protection period is not indefinite. Secondly, for EEF to increase the N available to the crop compared to urea, there must be an 'N loss event' (i.e. a rainfall event sufficient to move nitrate out of the crop root zone) during this 'protection period' – this is the only way EEF can 'save' N from being lost to the environment. Finally, for there to be an agronomic benefit the 'saved' N must be able to be used by the crop to achieve a higher yield. The implications of the framework are that not all situations where EEF is applied will lead to environmental benefits (i.e. when there is no 'N loss event' during the EEF 'protection period'). Additionally, cane yield benefits can only occur when there are environmental benefits (as that is the only way more N is available to the crop), yet cane yield benefits are not guaranteed, only happening when the crop needs the 'saved' N. Therefore, environmental benefits are a subset of all situations where EEF is used, and agronomic

benefits are a subset of situations where environmental benefits occur.

In conducting our investigation, we used the APSIMv7.10 (Holzworth et al., 2014) cropping systems model. Verification of the model for productivity and N loss through runoff was conducted, with the model performing well.

The design of our modelling analysis focussed on ‘virtual N response trials’ representing Wet Tropics sugarcane production, which geographically we divided into ten climate regions. In each climate region we identified the five most common soils used for sugarcane production. We only modelled twelve-month ratoon crops, using crop start (and harvest) dates of 15 July, 15 September and 15 November. In the virtual trials we applied fertiliser in 10 kg N/ha increments between 0 and 240 kg N/ha. We present results for the matrix of 10 climate regions x 5 soils x 3 crop starts. For each scenario of that matrix we analysed results for (1) urea applied at the current industry recommended N rate (Six Easy Steps (6ES), Schroeder et al., 2010), (2) EEF at the 6ES rate, (3) urea at a rate 20 kg N/ha less than 6ES, and (4) EEF at a rate 20 kg N/ha less than 6ES. The 6ES rate was determined from soil organic carbon. We represented EEF in the modelling as a controlled release fertiliser product. However, we also include a summary of how other products may perform (DMPP with a 7- or 28-day half-life, a urea : controlled release fertiliser blend and a urea with DMPP 7-day half-life : controlled-release fertiliser blend). Both blends used the controlled-release fertiliser at 67%.

Our most important findings were that the modelled N loss benefits generated from using EEF at 20 kg N/ha less than 6ES compared to urea at 6ES were highly variable across the climate region x soil x crop start scenarios studied and that the frequency of benefits that would be measurable and statistically significant can be very low depending on climatic, soil and crop start conditions. There was a strong signal that the later the crop start, the greater the frequency and magnitude of N loss benefit from using EEF. For earlier crop starts (July and September), the wetter climate regions showed more N loss benefits than the drier climate regions. Some notable differences between soils within a climate region were observed, meaning N loss benefits are not identical across soils within a climate region.

Most scenarios showed either no or very small yield changes, with the simulated yields for EEF at reduced rate often between those of urea at reduced rate and urea at 6ES rate, although there were some climate region x soil interactions for the November crop starts where EEF generated a yield advantage over urea at 6ES rate.

While this study was limited to modelling, it does provide insights into the possible benefits of EEF over a much wider range of conditions (climate x soil x crop start) than available from experiments. It allows identification of interactions between these factors and broadly when and where benefits from EEF use are more likely to occur. Future research into benefits of EEF use should include a more thorough quantification of N losses via different pathways, as well as more detailed information of crop response to N rates, as the simulations were sensitive to this. The required analysis to generate decision support for providing recommendations from this data was beyond the scope of this work. Our data, insights and analysis could for the basis of such a decision support along with further economic analysis or otherwise help inform the development of policies and/or extension programs to support or encourage adoption of EEF use.

1 Introduction

The Australian sugarcane industry is located primarily along the coastal strip of northeast Australia in catchments of the Great Barrier Reef (GBR). Numerous studies have identified agricultural pollutants draining to GBR catchments pose a threat to the sustainability of that ecosystem (see GBR Scientific Consensus Statement, 2017). As sugarcane, a biomass crop that requires annual nitrogen (N) fertiliser additions, occupies circa 380,000 ha in these catchments, many efforts have been directed at reducing the amount of N that is lost in runoff water from sugarcane farms in GBR catchments. Critically, the sugarcane industry is reluctant to implement interventions that reduce N losses where there is a negative impact on productivity.

The use of enhanced-efficiency fertilisers (EEF) has been identified as one potential intervention that could contribute to lower N losses without affecting productivity (Verburg et al., 2017). Previous research into the use of EEF in sugarcane have compared the productivity of using EEF at a lower rate than urea (see overview of trials in Verburg et al., 2019a), where the cost of EEF and urea may end up being similar given the higher unit cost of EEF. The rationale behind this approach is that where the cost of the fertiliser is the same, and both treatments yield the same, then farmers could apply EEF at a lower rate, with benefits accruing via lower environmental losses of N from EEF use. The assumption that EEF accrues lower environmental N losses has not been thoroughly tested.

Studies into the use of EEF in place of urea has produced variable results in the Australian sugarcane industry, and elsewhere (Verburg et al. 2014, 2016, 2019a). A good example is results of 12 field trials in the Burdekin, where agronomic benefits of EEF application were marginally more likely for late season crops and crops grown on lighter soils (Dowie et al., 2019). Sugarcane farmers would be well served by knowing the situations where the benefits of EEF were more or less likely, so they could better tailor their decision on use of EEF.

An important issue not considered comprehensively in the sugarcane EEF research thus far is the effect of EEF treatments on losses of N to the environment. Nitrous oxide losses were the focus of a number of the earlier field studies (Wang et al. 2016a,b) with variable results. Di Bella et al. (2017) performed a glasshouse study which noted different results between a controlled-release fertiliser and a nitrification inhibitor in relation to N lost in leachate and nitrous oxide loss. A recent study also showed some reductions in runoff N losses from using EEF in place of urea (Bell et al. 2020).

The results presented in this report are from modelling of a large number of climate x soil x management interactions in ‘virtual N response trials’ to identify generalities on where EEF use will provide environmental benefits. These generalities could, in turn, form the basis for recommendations to industry on situations where EEF use is environmentally beneficial. As adoption of EEF is unlikely in situations where sugarcane yield is substantially reduced, we added an analysis of cane yield to understand the magnitude of overlap between situations where both yield and environmental benefits exist.

We use a cropping systems model (APSIM) to provide information on the expected benefits of EEF in both time and space to inform when and where using EEF in place of urea will deliver N loss reductions and when they will not. The study built on the earlier work by Verburg et al. (2019b, 2022) performed for selected soils in the Herbert catchment and extended this to other regions of the Wet Tropics including a wider range of soil types in an attempt to characterise environmental N loss benefits across the Wet Tropics. The report will use a framework of the conditions under which the benefits of EEF arise, described in Section 2, to structure the explanation of results.

2 A framework for understanding how EEF provide benefits

Trial work in the sugarcane industry has shown there are variable agronomic benefits from EEF use. To better understand the drivers affecting these results we utilise a framework adapted from Verburg et al. (2017, 2022) of how EEF provide benefits (Figure 2). EEF act in various ways to reduce the soil N present as nitrate. For example, nitrification inhibitors keep N in the ammonium form, which is much less susceptible to environmental losses than nitrate. Alternatively, controlled-release fertilisers provide a physical barrier around individual fertiliser prills, meaning the fertiliser is 'released' to the soil slowly over time. Both mechanisms keep N in the nitrate form low for some time early in the crop season, which will reduce the risk of N as nitrate loss. In turn, that will make more N available to the crop, which can result in increased yield if the crop can use and respond to the 'saved' N or be used to reduce the N application rate (Figure 2).

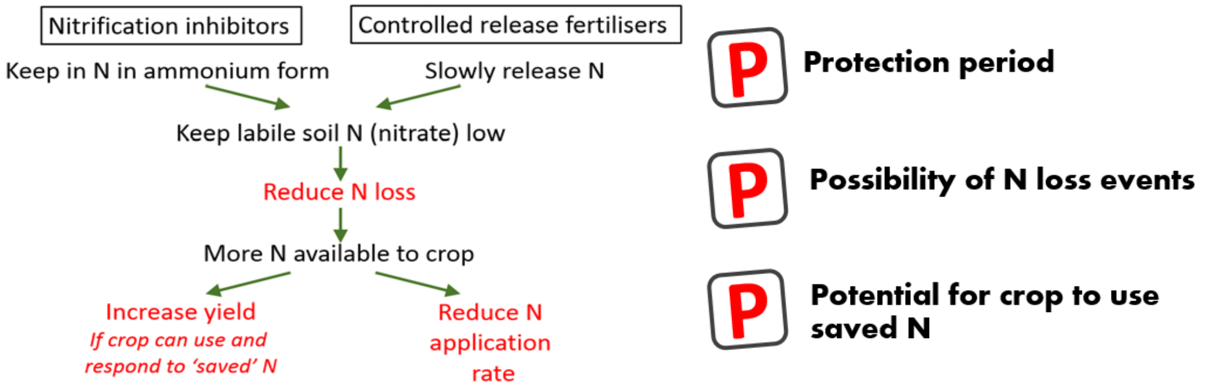


Figure 2: How EEF can provide benefits and prerequisite conditions for benefits from EEF to be realised (adapted from Verburg et al. 2017, 2022).

This understanding of how EEF 'work' highlights there are three prerequisite conditions for obtaining agronomic benefits (Verburg et al. 2022): (1) sufficient longevity of protection of the fertiliser N ('Protection period'), (2) occurrence of a N loss event during this period of protection and before the N is taken up by the crop ('Possibility of N losses'), and (3) the crop being responsive to the fertiliser N ('Potential for crop to use saved N') (Figure 2). Responsiveness to fertiliser N also applies to the option of reducing N application rate. If yield is not affected when the urea N rate is lowered, then EEF do not provide benefit at the equivalent lowered rate, even if some N was 'saved'.

Framework for understanding how EEF can provide benefit:

EEF have a defined (and limited) 'protection period' – which is a period of time after fertiliser application in which losses of N to the environment can be reduced

To get any reduction in N losses, an 'N loss event' must occur during the EEF 'protection period'

To get an agronomic benefit from EEF, the crop must need the additional N available that has been saved from being lost

The implications of this framework for understanding how EEF can provide benefit are that not every situation where EEF are used will lead to environmental loss reduction. Additionally, not every situation where environmental benefits accrue from EEF use will lead to an agronomic benefit. These situations pose economic and policy challenges as it is not clear who would pay for the environmental benefits in the absence of agronomic benefits (Kandulu et al. 2017, 2018).

3 Methods

To understand broadly how EEF may provide benefits across the spatial and temporal variations in the Wet Tropics sugarcane industry a modelling approach was adopted to cover a broad range of interactions between soils, climates and management. This broad approach of using cropping system simulation allows an extraordinary number of 'virtual N response trials' to be run, covering the major soil types and climate regions, and to run those trials over the past 71 years.
The simulations were performed with APSIMv7.10 (Holzworth et al., 2014) configured with the APSIM-Sugar module (Keating et al., 1999; Thorburn et al., 2001; Thorburn et al., 2005; Thorburn et al., 2010). The model configuration also included the APSIM-SoilN model for soil carbon and N dynamics and APSIM-SoilWat for the water balance. Model parameterisation and initialisation were similar to methods used and described by Biggs et al. (2021).

3.1 Model verification

The APSIM-Sugar-SoilN-SoilWat model has an established capability to simulate soil water and N dynamics (Meier et al. 2006; Thorburn et al. 2010, 2011; Biggs et al. 2013), residue decomposition (Thorburn et al. 2001), crop development, growth and N uptake (Keating et al. 1999), including responses to environmental conditions (solar radiation, temperature, water and N stress; Skocaj et al. 2013; Meier and Thorburn 2016; Thorburn et al. 2017; Biggs et al. 2021), and management actions such as irrigation, N fertilisation, planting and harvesting with an option to allow regrowth of the crop for multiple seasons (ratooning).
Verification of the APSIM model has been a 25+ year validation process in which the APSIM model has been continuously exposed to new datasets to "stress test" its performance in new directions (Keating 2020). Indeed, for modelling of sugarcane production systems this has been the case starting with Keating et al., (1999) who verified the model's ability to predict crop development and N uptake, including responses to water and N. Subsequent work further confirmed the crop yield predictions and responses to N (Thorburn et al., 2011a;

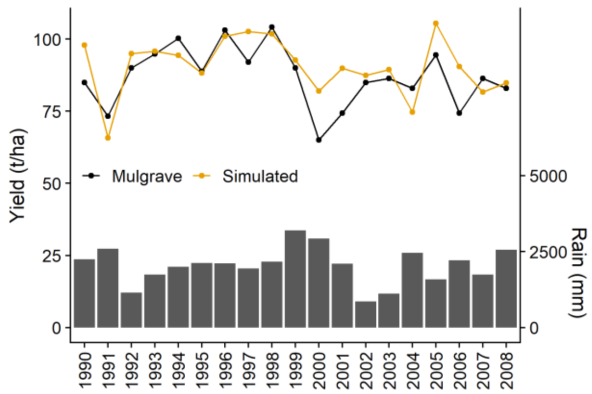
Skocaj et al., 2013; Meier and Thorburn (2016); and Thorburn et al., 2017) drawing on evolving parameterizations for surface residue decomposition (Thorburn et al., 2001), nitrification (Meier et al., 2006), denitrification (Thorburn et al. ,2010), N_2O emission (Thorburn et al., 2010) and N runoff (Biggs et al., 2013). Here, we adopt the lessons from the earlier verification studies, not only in terms of model and soil parameterization, but also scenario design and crop management. However, we also add further verification of APSIM's ability to simulate district yields and of a new model to predict N in runoff (Vilas et al., 2022).

3.1.1 Simulation of crop yield at district level in response to climate variability

Temporal climate variability can lead to variability in the effectiveness of N fertiliser management. So, it is important that to confirm the model is able to represent the effect of climate variability on yield production and N cycling. However, long-term (>3 years) experiments measuring N cycling and/or yield responses are rare. So, we used historical mill yield records from relevant mill regions (Schroeder et al. 2010, "QCANESelect") to verify the model.

Modelling has previously been conducted for a large number of soil types within significant climate of the Wet Tropics at an assumed N rate of 150 kgN/ha (Biggs et al. 2021 and SRA project 2017/009). The simulated yield for all the combinations of climate zone and soil type within each year were aggregated to the region level (weighted by area) and then compared with historical mill yield records. The parameterisation of the model and the area-weighted aggregation followed the methodology described by Biggs et al. (2021).

The model performed well considering the number of assumptions regarding crop length, start and end dates (Figure 3). Processes not represented in the model such as disease, severe cyclone damage, flood affecting harvesting and stand-over cane explain the poor predictions in some regions for 2000 - 2001 (Orange rust outbreak) and 2011 (Cyclone Yasi).



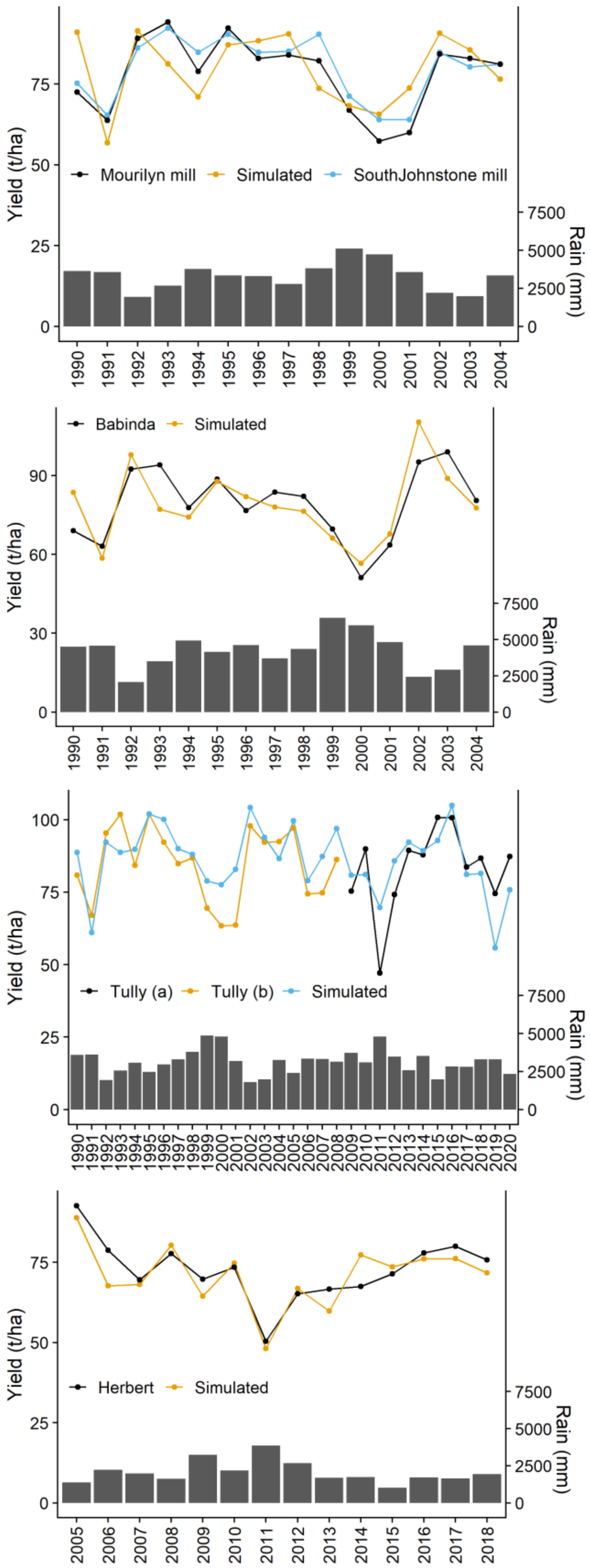


Figure 3: Comparison of simulated and observed regional average yields

3.1.2 Simulation of environmental N losses

To verify the model's ability to simulate runoff volumes and DIN lost via runoff, the model was compared with two experiments. The first experiment (Mossman) (Thorburn et al., 2011a; Webster et al., 2012), was located on a Mossman soil type and the nearest met-station was located at the Mossman Central Mill. The second experiment (Kamerunga) (Bel et al., 2020), was located on an Innisfail soil type and the nearest meteorological station was located at the Cairns Aero.

Soil parameters required by the model were based on local soil survey reports (Murtha 1989, Murtha et al., 1992) and determined using the method described by Biggs et al. (2021) (Table 1) and in Section 3.2.6. Denitrification algorithms in the model are impacted by the rate of gas diffusivity at field capacity which in turn is affected by the soil texture. This parameter, called dnit_k1, was set to 10.05 and 25.1 for the Innisfail and Mossman soil, respectively. In the APSIM-SoilWat module, runoff is determined based on the curve number approach where the texture class of the soil surface was used to estimate this curve number (Dalgliesh et al. 2016). For the Mossman (Silty clay loam) and Innisfail (Clay) soils the curve number was set to 79 and 84, respectively.

The model requires complete daily climate records for maximum temperature, minimum temperature, solar radiation, and rainfall. This data was sourced from the SILO daily meteorological database (https://www.longpaddock.qld.gov.au/silo/) and then modified to use on-site rainfall records preferentially. Data from the Mossman Mill (31044) was retrieved on the 2021-11-03 and from the Cairns Aero (31011) on the 2022-05-25.

Non-default model parameters based on recent advancements are presented in Figure 4 including parameters to represent reduced growth phenomenon (Dias et al. 2019). Also, the denitrification coefficient was set to 0.001379 and the proportion of nitrified N lost as nitrous oxide was set to 0.002 (Thorburn et al. 2010).

Dissolved inorganic N (DIN) lost via runoff was simulated using the algorithm developed by Vilas et al. (2022). Within this algorithm the extraction coefficient required recalibration due to the deeper first soil layer used here. The new value was set to 0.219215 (previously 0.25).

Details of the block management prior to the experiment (Table 2 and Table 3) was used to ‘spin-up’ the model to ensure initial conditions were sensible for the crop class in which the experiment was commenced.

The performance of model was quantified for yields, runoff volume and DIN in runoff using regression analysis, Nash-Sutcliffe Efficiency (NSE) and Root Mean Squared Error (RMSE). It was also assessed using data visualisations. At the Mossman site there were several runoff events triggered by rainfall totals > 400 mm. In these events it was likely that the on-site flumes and/or cane rows were over-topped resulting in an under estimation of the runoff volume. These events were excluded before comparison with the model output.

Table 1: Soil parameters used to model the two experiments (Mossman = Mossman soil and Kamerunga = Innisfail soil).

Exp.	Layer (cm)	SAT (mm/mm)	DUL (mm/mm)	LL (mm/ mm)	SWCON	BD (g/cm3)	Ksat (mm/d)	OC (%)	pH	fbiom	finert	NO3 (kgN/ha)	NH4 (kgN/ha)	SW
Mossman	0-15	0.50	0.36	0.18	0.5	1.27	293	1.46	5.80	0.097	0.40	16.8	15.6	0.270
Mossman	15-30	0.48	0.35	0.18	0.5	1.31	255	0.75	5.73	0.049	0.94	6.2	7.4	0.310
Mossman	30-60	0.46	0.34	0.19	0.5	1.36	234	0.47	5.63	0.066	0.93	11.3	2.7	0.330
Mossman	60-90	0.45	0.33	0.18	0.5	1.39	266	0.29	5.52	0.074	0.88	5.9	2.7	0.310
Mossman	90-120	0.44	0.31	0.18	0.5	1.42	305	0.17	5.39	0.074	0.93	na	na	0.230
Mossman	120-150	0.43	0.30	0.17	0.5	1.45	344	0.11	5.32	0.049	0.97	na	na	0.200
Kamerunga	0-15	0.51	0.39	0.23	0.3	1.24	233	1.72	5.18	0.099	0.48	0.66	0.44	0.341
Kamerunga	15-30	0.49	0.39	0.23	0.3	1.27	177	0.96	5.23	0.043	0.93	0.42	0.04	0.334
Kamerunga	30-60	0.48	0.36	0.22	0.3	1.32	177	0.65	5.35	0.063	0.95	0.64	0.04	0.301
Kamerunga	60-90	0.44	0.30	0.15	0.5	1.41	347	0.23	5.58	0.082	0.82	0.58	0.05	0.268
Kamerunga	90-120	0.43	0.27	0.13	0.5	1.45	444	0.23	5.50	0.063	0.95	0.40	0.01	0.252
Kamerunga	120-150	0.43	0.26	0.13	0.5	1.46	499	0.15	5.43	0.166	1.00	0.28	0	0.244

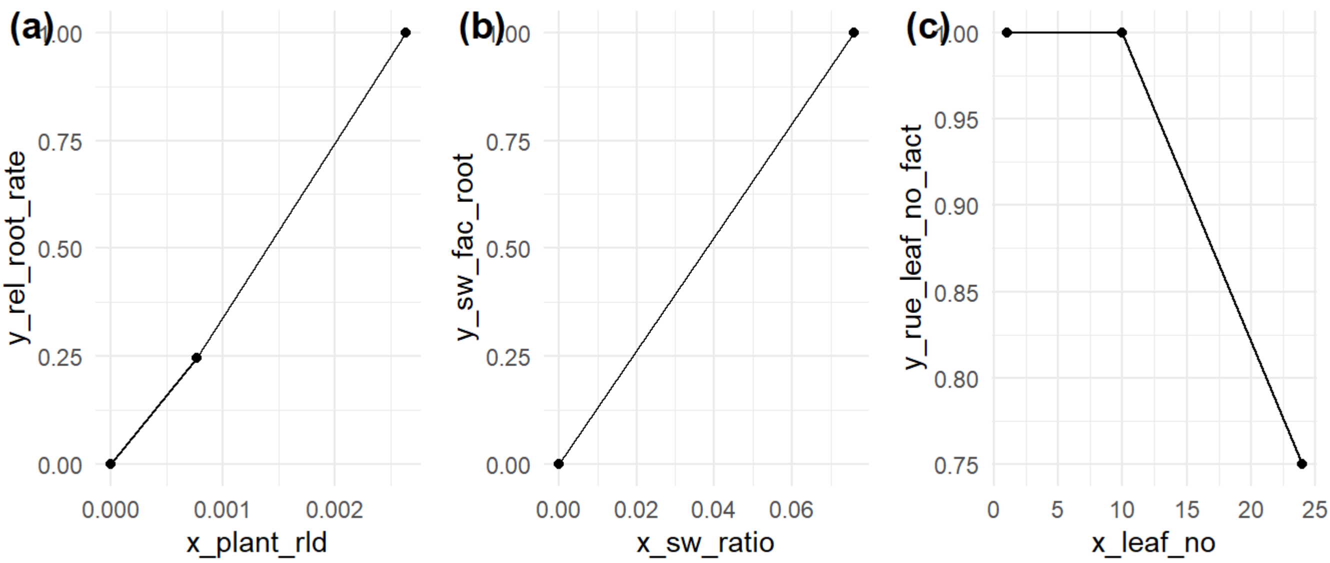


Figure 4: Non-default APSIM parameters used to represent (a) root branching, (b) impact of soil water on root advancement, and (c) growth slow-down phenomenon as per Dias et al., 2019

Table 2: Block management diary for Mossman experiment used in model. Included are the approximate harvest dates and fertiliser rates prior to the commencement of the experiment on 2003-10-28.

Date	Operation
2000-08-01	planted
2000-10-09	fertiliser applied 139 (kg/ha)
2001-09-04	sugar harvest (approximate)
2001-10-28	fertiliser applied 185.5 (kg/ha)
2002-09-04	sugar harvest (approximate)
2002-10-28	fertiliser applied 185.5 (kg/ha)
2003-09-04	sugar harvest
2003-10-27	soil mineral N and water content measured
2003-10-28	fertiliser applied; NFarm = 185.5 kgN/ha; NRepl = 102.4 kgN/ha
2004-08-12	sugar harvest
2004-09-27	fertiliser applied; NFarm = 179 kgN/ha; NRepl = 85.7 kgN/ha
2005-01-21	sugar lodge
2005-10-05	sugar harvest
2005-11-10	fertiliser applied; NFarm = 165 kg/ha; NRepl = 96 kgN/ha
2006-08-03	sugar harvest

Table 3: Block management diary for the Kamerunga experiment used in model including harvest dates and fertiliser rates for the current cropcycle prior to the commencement of the experiment on 2019-10-17. Although not shown here, detail of the block history was available back to 1997 so the model was set up to run from this date. N application rates varied by fertiliser type and rate (F1 = 0; UREA_F2 = 78; EEF_F2 = 77; EEF_F3 = 118; UREA_F3 = 116; EEF_F4 = 155; UREA_F4 = 151 kgN/ha).

Crop start month	Date	Operation
Nov	2016-12-01	planted
Nov	2016-12-01	fertiliser applied 120 kg/ha
Nov	2017-08-03	sugar harvest
Nov	2017-09-03	fertiliser applied 150 kg/ha
Nov	2018-09-15	sugar harvest
Nov	2018-10-15	fertiliser applied 150 kg/ha
Nov	2019-11-11	sugar harvest
Nov	2019-12-12	fertiliser treatments applied
Nov	2020-11-25	sugar harvest
Nov	2020-12-16	fertiliser treatments applied
Nov	2021-10-08	sugar harvest
Oct	2016-12-01	Planted
Oct	2016-12-01	fertiliser applied 120 kg/ha
Oct	2017-08-03	sugar harvest
Oct	2017-09-03	fertiliser applied 150 kg/ha
Oct	2018-09-15	sugar harvest
Oct	2018-10-15	fertiliser applied 150 kg/ha
Oct	2019-10-14	sugar harvest
Oct	2019-11-25	fertiliser treatments applied
Oct	2020-10-26	sugar harvest
Oct	2020-11-24	fertiliser treatments applied
Oct	2021-10-08	sugar harvest
Sep	2016-12-01	Planted
Sep	2016-12-01	fertiliser applied 120 kg/ha
Sep	2017-08-03	sugar harvest
Sep	2017-09-03	fertiliser applied 150 kg/ha
Sep	2018-09-15	sugar harvest
Sep	2018-10-15	fertiliser applied 150 kg/ha
Sep	2019-09-07	sugar harvest
Sep	2019-10-17	fertiliser treatments applied
Sep	2020-09-21	sugar harvest
Sep	2020-11-05	fertiliser treatments applied
Sep	2021-10-08	sugar harvest

110.1. Verification Mossman Experiment

Two soil parameters (curve number and rooting depth) were modified to improve the model predictions relative to the experimental data. The fact that these were the only changes required to the standard Mossman soil parameterisation is an important verification of the parameter development methods (Biggs et al. 2021).

The model was able to predict the yields well (Figure 5a; RMSE = 7.95; NSE = 0.44; R^2 = 0.94;

Slope = 1.48; Intercept = -27.97) including the small decline in yields measured in the 2006 crop due to the lower N application rate. The model was also able to replicate the lower yields across both treatments in the 2006 harvested crop.

Runoff volumes for individual events was reasonably predicted (Figure 5b; RMSE = 38.22; NSE = -0.56; R^2 = 0.35; Slope = 0.89; Intercept = 10.45). These results are pleasing given the uncertainty created by APSIM using a daily timestep whereas actual event start and end times are defined accurately to the minute. When aggregated across all measured periods the model was able to replicate the pattern seen from year to year, although the model over predicted the events during the 2006 harvested crop. Interestingly, the model was suggesting that the different N application rates were resulting in different runoff volumes. In the model this result is likely to be due to soil mineral N concentrations in the surface affecting residue decomposition rates. Differences in the amount of surface residues would result in different levels of ground cover which would result in different runoff volumes. Measurements of the effect of fertiliser treatments on runoff volumes were not made and therefore cannot verify this modelled behaviour.

Both the measured and simulated total DIN lost via runoff were small (< 5 kg N ha^{-1}), in line with previous experiments (Webster et al., 2012). However, individual events were not well predicted (RMSE = 0.21; NSE = -0.15; R^2 = 0.14; Slope = 0.32; Intercept = 0.07), a pattern that has been found in previous simulations of runoff (Thorburn et al., 2011b). However, when comparing the total DIN in runoff, across all events, the model was able to predict the relative differences between years and treatments in total runoff DIN losses across all events. Reasons for the poorer performance when comparing individual events versus totals could include uncertainty of duration, start and end dates of the record of the event, or the model's daily time step limiting the ability to replicate shorter term variation in rainfall intensity and hence runoff. Both reasons become less of an issue as the data is aggregated over a whole crop season.

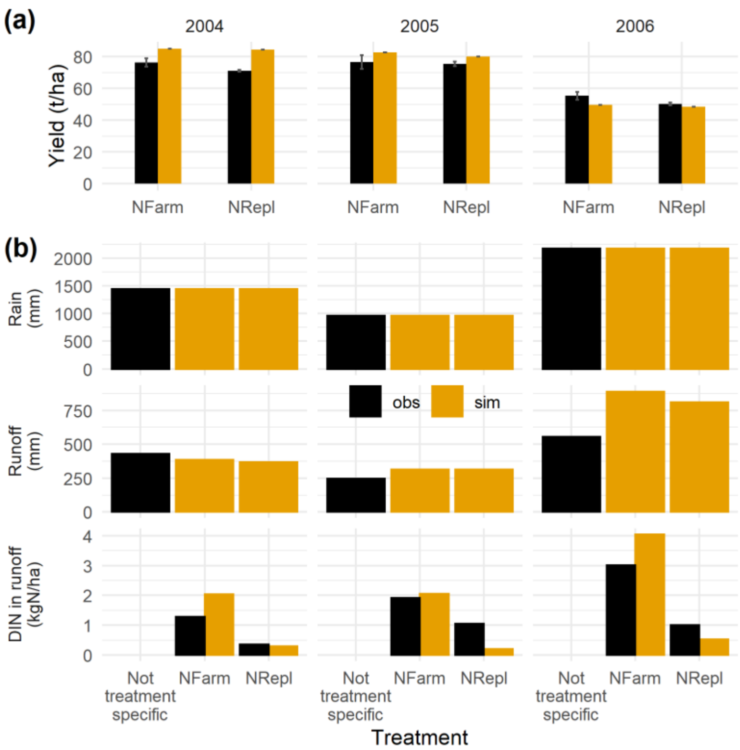


Figure 5: Comparison of simulated and observed (a) yields and (b) rainfall, runoff volume and DIN in runoff for the Mossman experiment. The experiment included a higher rate based on the traditional practices on the site (NFarm) and a lower rate based on the N replacement concept (NRepl). Observed runoff was not separated by treatment.

210.1. Verification Kamerunga Experiment

No additional changes were needed to the initial parameterisation of the Innisfail soil to achieve the good predictions for this site, further validating the methods used to generate the parameters (Biggs et al. 2021).

All the 2021 harvested crops were harvested on the same day resulting in different durations of crop growth for each of the crop start treatments (i.e., Sep =13 mths, Oct = 11 months, and Nov = 10.4 months). Initially the model was predicting large differences in yield between the three crop start treatments (i.e., Nov = low yield & Sep = high yield). However, it is known that the dry matter content (DMC) of stem can vary with crop age (Inman-Bamber 204). So instead of assuming a DMF of 0.3 for the 2021 harvested crop, it was varied according to crop length (i.e., 10.4 months = 0.25; 11 months = 0.275; 13 months = 0.325). Across all years and treatments, the model predicted the yields well (Figure 6; RMSE = 7.33; NSE = 0.51; R^2 = 0.64; Slope = 0.64; Intercept = 27.14). In some specific cases the model appears to over predict the yield at the lowest N application rates (e.g., Sep-2020). Further details of the initial soil conditions may help understand and improve the model prediction.

In contrast to the Mossman experiment runoff volume was well predicted for most of the individual events (Figure 7; RMSE = 49.13; NSE = 0.5; R^2 = 0.78; Slope = 1.25; Intercept = -21.16), with the only exceptions being the two largest and consecutive events (Events I and J during the 2021 harvest crop). As with the Mossman events this can be explained by the model's daily time step limiting the ability to replicate shorter term variation in rainfall intensity and hence runoff. This is compounded by consecutive events where the end time of the first event and the start time of the second event fall on the same date.

The model's ability to predict the DIN lost via runoff was good (Figure 8; RMSE = 0.43; NSE = 0.01; R^2 = 0.5; Slope = 0.99; Intercept = -0.02). This achievement is considerable considering the small amounts of DIN lost within each event (< 12 kg N ha^{-1}). Measured DIN losses for the 2021 harvested crop were not available in time to be included in the model verification.

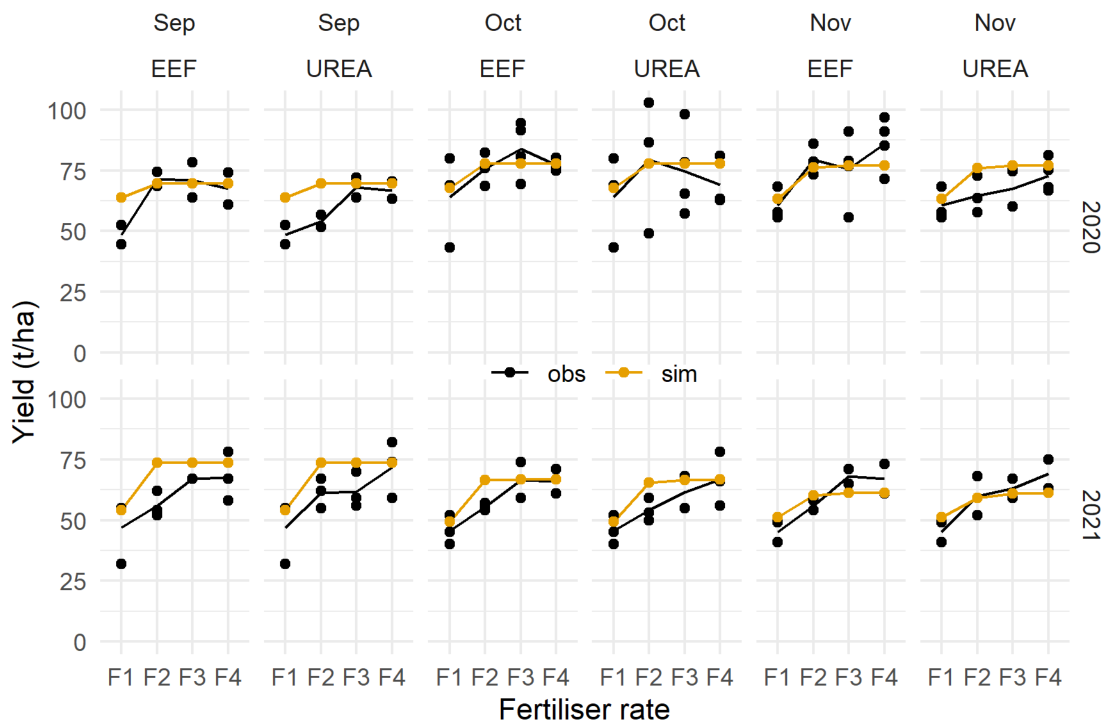


Figure 6: Comparison of simulated (orange) and observed (black) yield responses to fertiliser N for two fertiliser types (EEF and UREA), three crop start dates (Sep, Oct, and Nov), and for two consecutive crops harvested in 2020 and 2021. Individual observed replicates are shown as black

points along with the average observed yield shown as a black line. F1 = 0 kg N/ha, F2 Urea = 78 kg N/ha, F2 EEF = 77 kg N/ha, F3 Urea = 116 kg N/ha, F3 EEF = 118 kg N/ha, F4 Urea = 151 kg N/ha, F4 EEF = 155 kg N/ha.

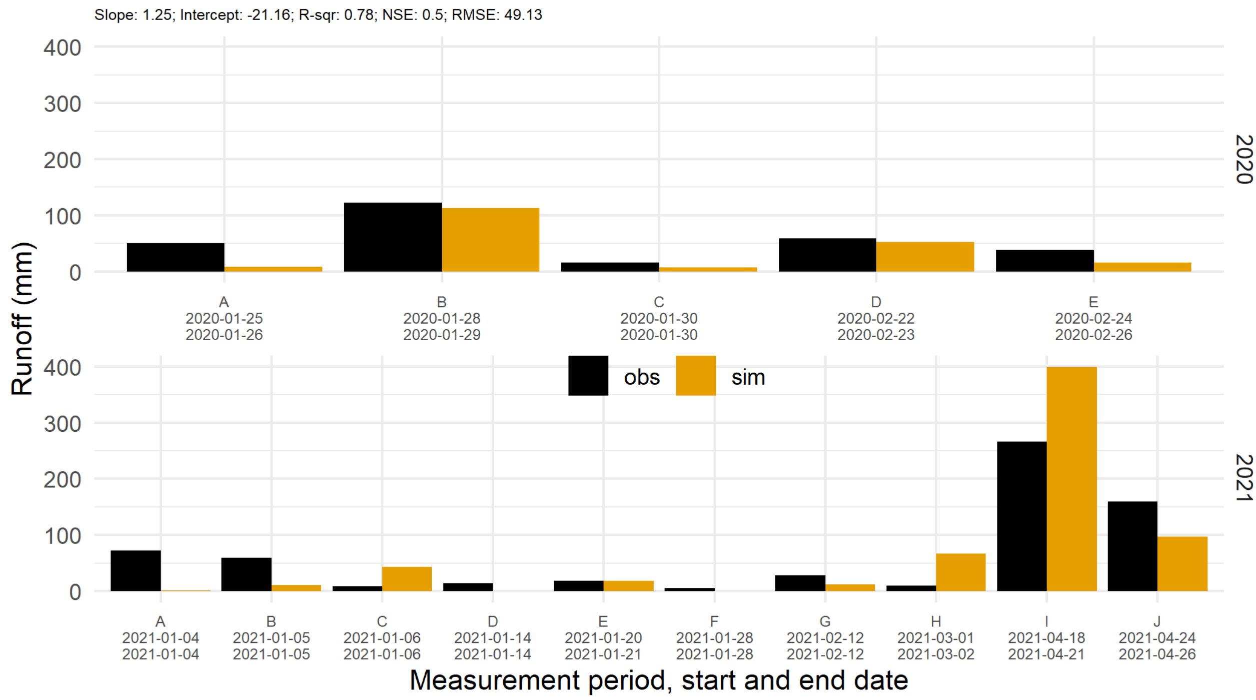


Figure 7: Comparison of simulated (orange) and observed (black) runoff volume for specific event periods (labelled as A, B, C, etc) for both the 2020 and 2021 harvested crops. The start and end date of each measurement period is included.

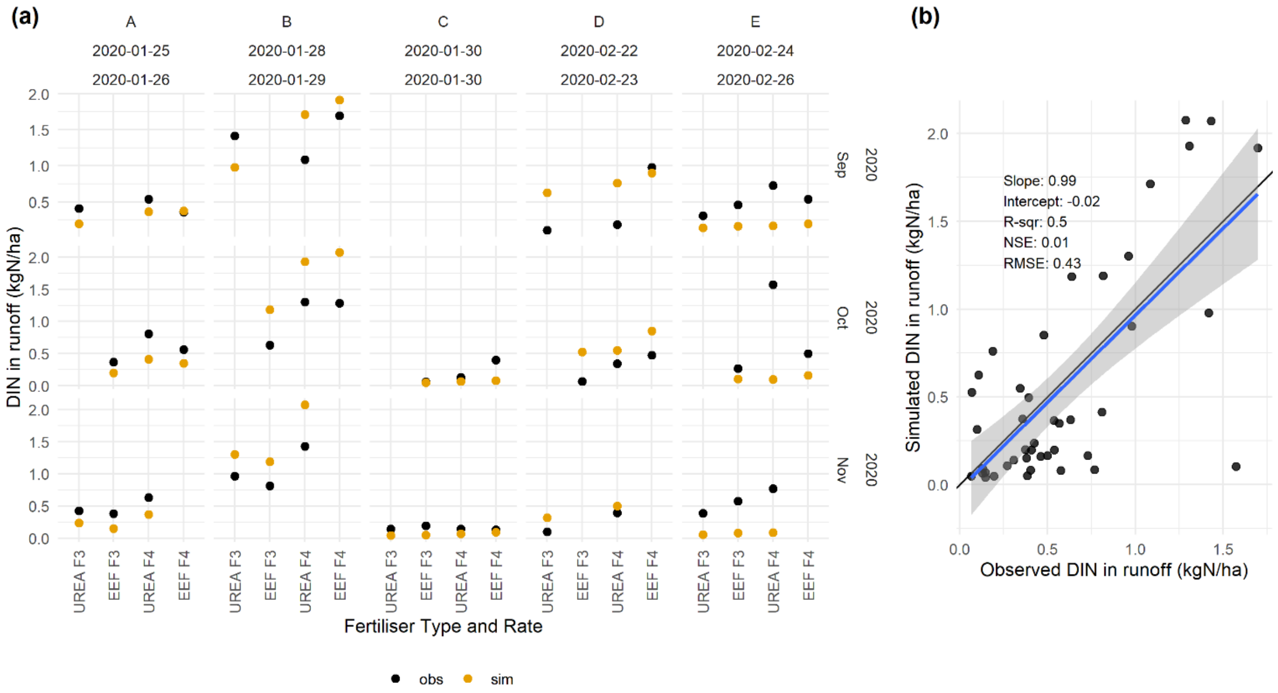


Figure 8: Comparison of simulated (orange) and observed (black) DIN lost shown for five events (labelled as A, B, C, etc) during the 2020 harvested crop and (b) a regression plot including statistical goodness of fit measures. Results for the two highest N rates (F3 and F4) for both EEF and urea fertiliser types are shown. The start and end dates for the observed periods are included. F3 Urea = 116 kg N/ha, F3 EEF = 118 kg N/ha, F4 Urea = 151 kg N/ha, F4 EEF = 155 kg N/ha.

3.1.3 Model verification implications for simulated scenarios

The favourable verification of the model against the historical mill yield records (Section 3.1.1) and the Mossman and Kamerunga (Section 3.1.2) runoff experiments gives confidence in both the soil parameter development methods and the relatively new DIN in runoff algorithm proposed by Vilas et al. (2022), both of which are important to the outcome of the scenario simulations conducted in this project.

3.2 Simulation scenario analysis design

3.2.1 Simulation design

Simulations were for 12-month ratoon crops where the initialisation of the model was reset at the beginning of each of the modelled seasons to ensure that in each crop season the only variable was fertiliser type and/or rate. The full set of simulations included 71 seasons of climate data, three crop start dates (15 July, 15 September and 15 November), 25 N rates (0-240 kg N/ha) and 6 fertiliser types. The latter included *urea*, a 100% controlled-release urea fertiliser (*crf*), a blend of 33% urea and 67% controlled-release urea fertiliser *(ureacrf*), two fertilisers consisting of urea plus a nitrification inhibitor (*dmpp7* and *dmpp28*), and the urea-controlled-release fertiliser blend with nitrification inhibitor (*dmpp7crf*).

3.2.2 Simulated fertilisers

The simulated controlled-release fertilisers were based on a Meister10 product parameterised by Verburg et al. (2022). Its release is similar to Agromaster Tropical, the product used in several EEF experiments within the sugarcane industry. The nitrification inhibitors represented a DMPP-like product, which temporarily prevented nitrification of ammonium in the layer of fertiliser application. Longevity of nitrification inhibitors, including DMPP, can vary in response to soil properties and temperature Verburg et al. (2014) and this can affect their effectiveness (Vilas et al. 2019a, b). Two inhibitor persistence half-lives of 7 and 28 days were simulated to represent likely lower and upper bounds on longevity. Note that for the *dmpp7crf* blend the initial inhibitor concentration was calculated from 33% of total N applied. The validity of this assumption has not been verified at this stage. It is possible the inhibitor will work more locally and have less or no impact on the nitrification of the CRF component of the blend. In addition, it is possible that the assumption of a 7-day dmpp half-life was shorter than that of the blended product used in the EEF60 trials.
The fertilisers were applied 10 days after the crop starts for September and November crops and 42 days after crop starts for July crops. Fertiliser application was assumed to be subsurface, which is known to limit ammonia volatilisation losses. Hence ammonia volatilisation was ignored in these simulations.

3.2.3 Simulated output variables

The model was designed to report at harvest the following variables: cane yield (fresh weight tonnes/ha/crop) and the total N lost via runoff, deep drainage and denitrification (kg N/ha/crop). Many other variables related to soil water dynamics, crop stresses and soil fertility were also reported to assist with diagnosing the simulated behaviour.

3.2.4 Climate regions

Ten regions were chosen to represent the variation in climate across the Wet Tropics (Figure 9). Each region was represented by one climate station, downloaded from SILO point patch met data or its gridded data resource (https://www.longpaddock.qld.gov.au/silo/). The climate region specifications in the Tully region were based on Sexton et al. (2017) and in the Herbert region on work in SRA project 2017/009.
The average annual rainfall ranged from 1603 mm per year at Stone River region in the south to 4311 mm in the Babinda region in the north. The relative monthly rainfall distributions were similar across the climate regions, with 70 to 82% of rainfall falling during the wet season period December to April (Figure 10).

3.2.5 Crop start

Three crop start dates (15 July, 15 September and 15 November) were used in this analysis. As this analysis is based entirely on ratoon crops, crop start refers to the date the previous crop was harvested, and as the crop is 12 months, also refers to the date of harvest. So, for a crop harvest year of 2011, the 15 September crop start data references the modelling for a ratoon crop that was started on 15 September 2010 and grown for 12 months to be harvested on 15 September 2011. All data for the 2011 year came from this period.

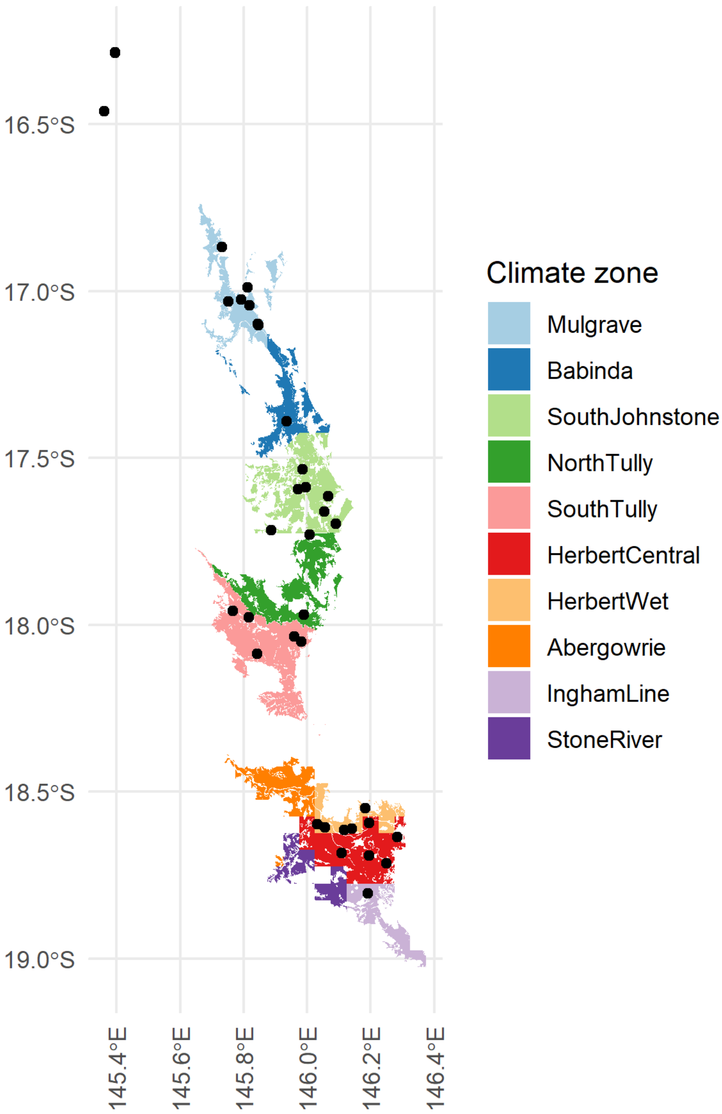


Figure 9: Ten regions used in the factorial simulations. For references, the black circles indicate the locations of EEF60- trial sites within the Wet Tropics (climate region specifications in the Tully region based on Sexton et al. (2017) and in the Herbert region on work in SRA project 2017/009).

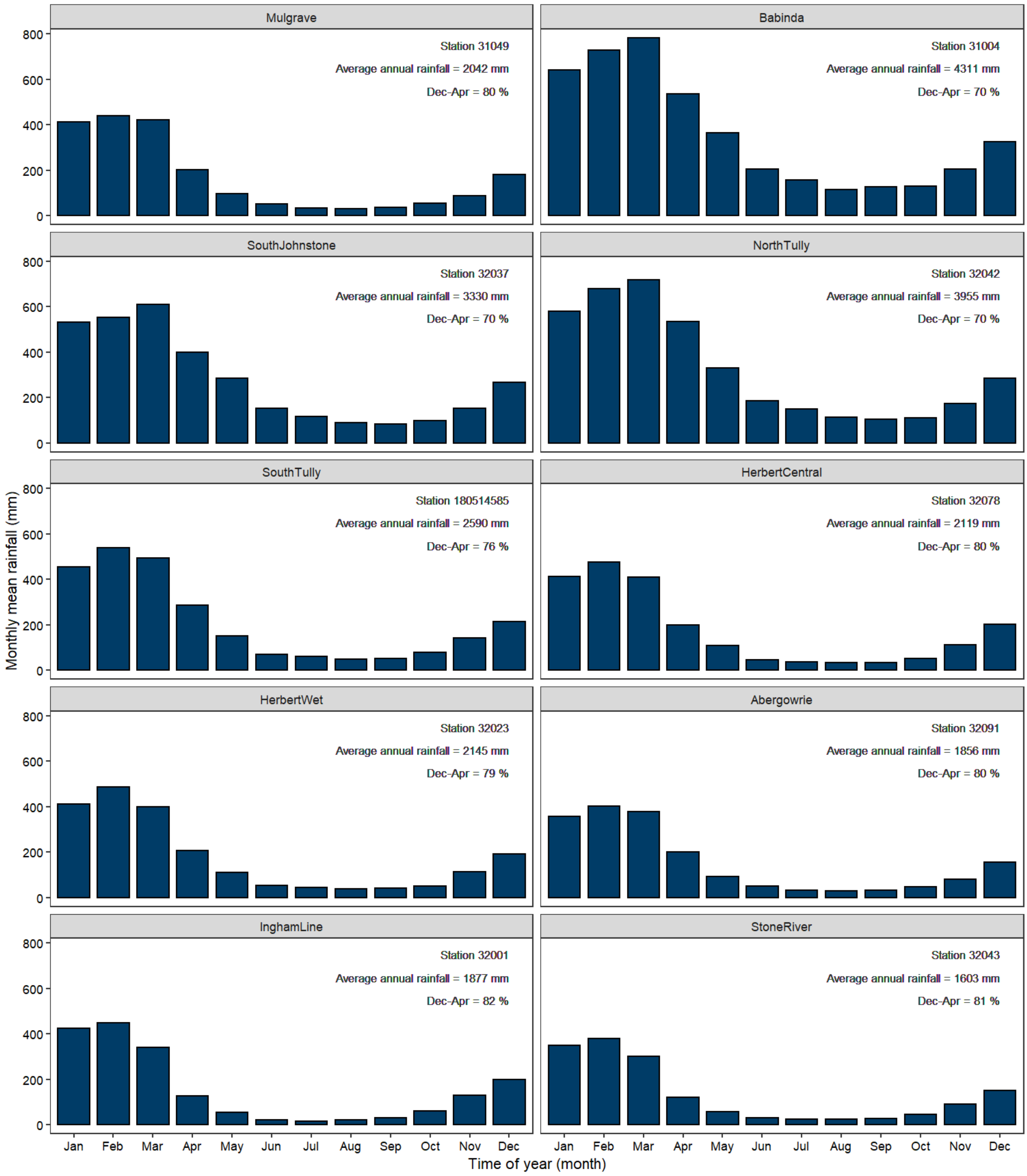


Figure 10. Average (1950-2020) monthly rainfall, average annual rainfall and percentage of rain during the Wet Season (December – April) for the climate station data used to represent the 10 climate regions

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3.2.6 Soils

In each region the most dominant soils were identified based on information from local soil surveys (Cannon et al., 1992; Murtha et al., 1992; Murtha, 1986). In all regions except Babinda the top five soils by area were chosen. In the Babinda region the fourth and fifth soils would have been the Babinda and Nind soils. These soils have been considerably modified over time due to drainage works, so that the original soil descriptions cannot be relied on to develop soil parameterisations. A Hewitt soil was substituted for the Babinda soil and the sixth most common soil Coom was included as fifth soil.

The soils and some key properties of the surface soil (0-20 cm) as well as the 6ES N rate based on parameterised organic carbon levels are included in Table 4. Particle size distributions for the full profiles are shown in Figure 11. It is the texture of the full profile that will affect how easily N is lost and which pathway will dominate.

The properties for the full profile were used to parameterise the soils for the modelling analysis using a methodology described in Biggs et al. (2021). The method involved the application of pedotransfer functions to estimate soil hydraulic properties from the soil survey soil texture and soil carbon measurements, and then developing the parameterisation of organic carbon pools via long-term 'spin-up' simulations to allow these pools to stabilise. This also ensured that these pools and the overall organic carbon levels would reflect conditions under agriculture, rather than the natural conditions under which the soils were sampled for in the soil surveys.

It is important to note that while the parameterised soils each represent a named soil class, there can be considerable variation in soil properties within each soil class. In other words, simulation results for, say, a Coom soil will reflect the representative sample of that soil class as presented in the soil survey, but they will not necessarily predict what will happen in all experiments performed on Coom soils. In the same vein, the same soil name may mean different things in different regions due to different soil resources, e.g., the Coom soils in Babinda and North Tully had quite different particle size distributions (Figure 11). The 6ES N rates included in Table 4 relate to the organic carbon content of the modelled soils. Therefore, for the same reasons, these soils are not necessarily the same as those from experiments performed on soils with the same name.

Table 4. Selected soils for each region and properties of the 0-20 cm layer.

Mulgrave	Mission	1.37	130	20.63	11.61	67.75	Loam
Mulgrave	Liverpool	2.28	110	21.31	13.85	64.84	Loam
Mulgrave	Clifton	1.27	130	15.53	21.05	63.42	Loam
Mulgrave	Virgil	1.49	130	22.85	14.81	62.34	Clay Loam
Mulgrave	Innisfail	1.53	130	40.72	24.89	34.39	Clay
Babinda	Tully	2.18	110	43.38	31.32	25.3	Silty Clay
Babinda	Thorpe	1.99	120	17.74	11	71.27	Loam
Babinda	Timara	3.16	100	34.56	51.79	13.65	Silty Clay Loam
Babinda	Hewitt	7.53	100	32.59	28.24	39.17	Silty Clay Loam
Babinda	Coom	1.63	120	27.77	22.12	50.1	Clay Loam
SouthJohnstone	PinGin	2.39	110	51.63	35.87	12.5	Silty Clay
SouthJohnstone	Galmara	2.95	100	46.74	11.66	41.6	Clay

SouthJohnstone	Innisfail	1.57	130	40.72	24.89	34.39	Clay
SouthJohnstone	Eubenangee	4.08	100	54.65	22.72	22.63	Clay
SouthJohnstone	Liverpool	2.32	110	21.31	13.85	64.84	Loam
NorthTully	Tully	2.08	110	35.09	27.36	37.56	Silty Clay Loam
NorthTully	Galmara	1.2	140	21.2	9.93	68.87	Clay Loam
NorthTully	Thorpe	1.91	120	17.26	11.22	71.52	Loam
NorthTully	Coom	2.19	110	45.31	39.08	15.61	Silty Clay
NorthTully	Tyson	2.34	110	25.65	6.1	68.26	Sandy Clay Loam
SouthTully	Thorpe	1.91	120	17.26	11.22	71.52	Loam
SouthTully	Tully	2.08	110	35.09	27.36	37.56	Silty Clay Loam
SouthTully	Coom	2.19	110	45.31	39.08	15.61	Silty Clay
SouthTully	Lugger	1.75	120	11.71	10.13	78.16	Sandy Loam
SouthTully	Bulgun	3.09	100	46.42	22.16	31.43	Clay
HerbertCentral	Toobanna	1.37	130	19.7	29.93	50.38	Silty Loam
HerbertCentral	Hamleigh	1.9	120	41.05	30.55	28.4	Silty Clay
HerbertCentral	Yuruga	1.01	140	17.62	19.52	62.85	Loam
HerbertCentral	Trebonne	1.46	130	14.93	21.69	63.38	Loam
HerbertCentral	Ashton	1.12	140	11.15	11.11	77.74	Sandy Loam
HerbertWet	Macknade	1.41	130	15.47	15.12	69.41	Loam
HerbertWet	Herbert	1.88	120	24.83	21.32	53.85	Clay Loam
HerbertWet	Hamleigh	1.9	120	41.05	30.55	28.4	Silty Clay
HerbertWet	Toobanna	1.37	130	19.7	29.93	50.38	Silty Loam
HerbertWet	Leach	2.58	100	40.36	35.42	24.22	Silty Clay
Abergowrie	Herbert	1.88	120	24.83	21.32	53.85	Clay Loam
Abergowrie	Abergowrie	1.34	130	15.45	15.67	68.88	Loam
Abergowrie	Manor	1.22	130	33.07	30.97	35.96	Silty Clay Loam
Abergowrie	Bluewater	1.36	130	19.14	18.44	62.42	Loam
Abergowrie	Porter	1.18	140	7.79	30.27	61.94	Silty Loam
InghamLine	Althaus	0.92	140	3.87	17.3	78.84	Loamy Sand
InghamLine	Yuruga	1.01	140	17.62	19.52	62.85	Loam
InghamLine	Byabra	0.8	140	9.72	10.46	79.82	Loamy Sand
InghamLine	Molonga	2.05	110	38.47	32.55	28.98	Silty Clay Loam
InghamLine	Bluewater	1.36	130	19.14	18.44	62.42	Loam
StoneRiver	Yuruga	1.01	140	17.62	19.52	62.85	Loam
StoneRiver	Lugger	0.99	140	8.64	9.16	82.2	Loamy Sand
StoneRiver	Ashton	1.12	140	11.15	11.11	77.74	Sandy Loam
StoneRiver	Hillview	1.32	130	16.68	14.25	69.07	Loam
StoneRiver	Cudmore	1.01	140	4.58	15.45	79.97	Loamy Sand

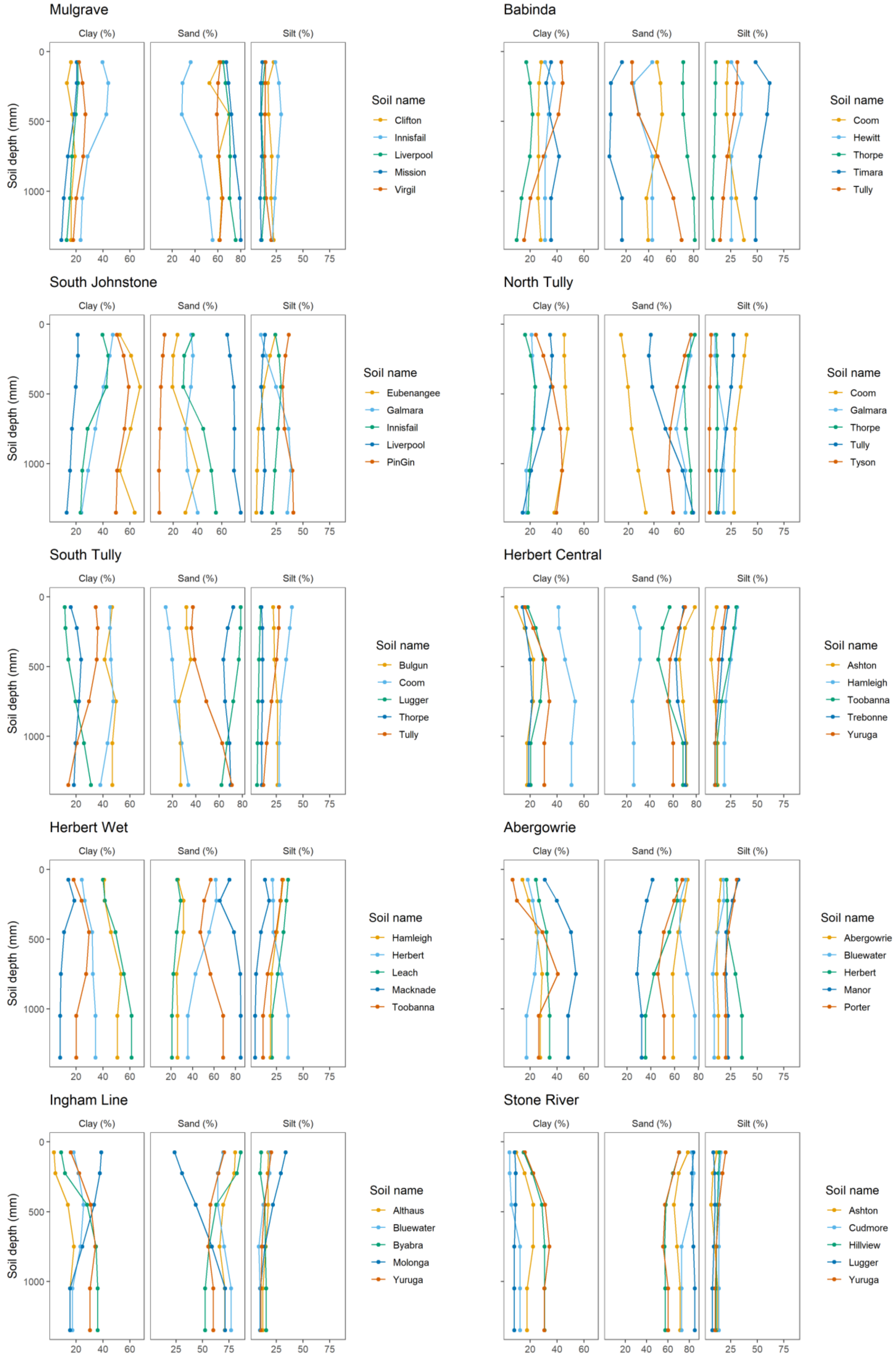

Figure 11. Soil profile particle size distributions for the 5 soils in each region

3.2.7 Simulated treatment analysis

For each scenario (climate region x soil x fertiliser type x year) 25 N rates were simulated (0 – 240 kg N/ha in 10 kg N/ha increments). While this allows N response curves and optimum N rates to be determined, the analysis here was focussed on generating results that may resemble on-farm trial work. Some sugarcane industry trials apply N fertiliser at rates equal to industry guidelines (Six Easy Steps (6ES) – Schroeder et al., 2010), and at a rate around 20% less than 6ES. In our analysis we could choose the N rate best matched to the 6ES rate for each soil based on the soil Organic Carbon in the 0-20cm layer (Table 4). We could not choose a rate that was 20% less than the 6ES rate, so instead chose to conduct our analysis on a rate that was the 6ES rate minus 20 kg N/ha (which was the closest overall rate to 20%). In these results we focus on urea applied at 6ES (U_{6ES}), EEF applied at 6ES (EEF_{6ES}), urea applied at a reduced rate, namely 6ES minus 20 kg N/ha (U_{red}) and EEF applied at 6ES minus 20 kg N/ha (EEF_{red}).

Simulated treatment names used in this analysis:

U_{6ES} = Urea applied at the Six Easy Steps rate (based on OC in Table 4)

EEF_{6ES} = EEF (as 100% controlled-release fertiliser, i.e. *crf*) applied at the Six Easy Steps rate (based on OC in Table 4)

U_{red} = Urea applied at reduced rate, Six Easy Steps rate minus 20 kg N/ha

EEF_{red} = EEF (as 100% controlled-release fertiliser, i.e. *crf*) applied at reduced rate, Six Easy Steps rate minus 20 kg N/ha

4 Results

In this section we first look at the current industry guideline N application rate (Six Easy Steps) and present the simulated N losses for those, looking at climate region x soil x crop start interactions. How these N losses may change by applying EEF (as controlled-release fertiliser) at the Six Easy Steps rate in place of urea are then investigated.
Next, we look at the impact of reducing the N rate for both urea and EEF (as controlled-release fertiliser) by 20 kg N/ha from the Six Easy Steps application rate. This analysis includes results for both N losses and cane yield, as any negative impact on cane yield could discourage farmer adoption, although productivity effects would also depend on CCS.
Finally, we compare EEF types other than controlled-release fertiliser. It is recognised controlled-release fertiliser may be too expensive for farmers to adopt, and the effectiveness of alternative EEF are considered.

4.1 Simulated N losses at current industry recommended N rates using urea

Current sugarcane industry recommended N application rates are determined by the Six Easy Steps guidelines (6ES, Schroeder et al., 2010). Nitrogen may be lost from the cropping system via denitrification, deep drainage and runoff. The mean simulated total N loss in the regions and soils studied here from 12-month ratoon crops receiving N applied as urea at the soil specific current industry recommended N rate (6ES) are presented in Figure 12. The average distribution of N losses between runoff, denitrification and deep drainage are presented in Figure 13.
Total N losses were consistently and markedly affected by crop start, with more N lost by crops starting in November than September or July (Figure 12). Of these earlier two times, more N was generally lost in crops starting in September than July. The box plot distributions in Figure 12 also suggest the variability of total N losses increases when crop start moves from July to September to November. Additionally, there are some variations apparent between climate regions and soils.

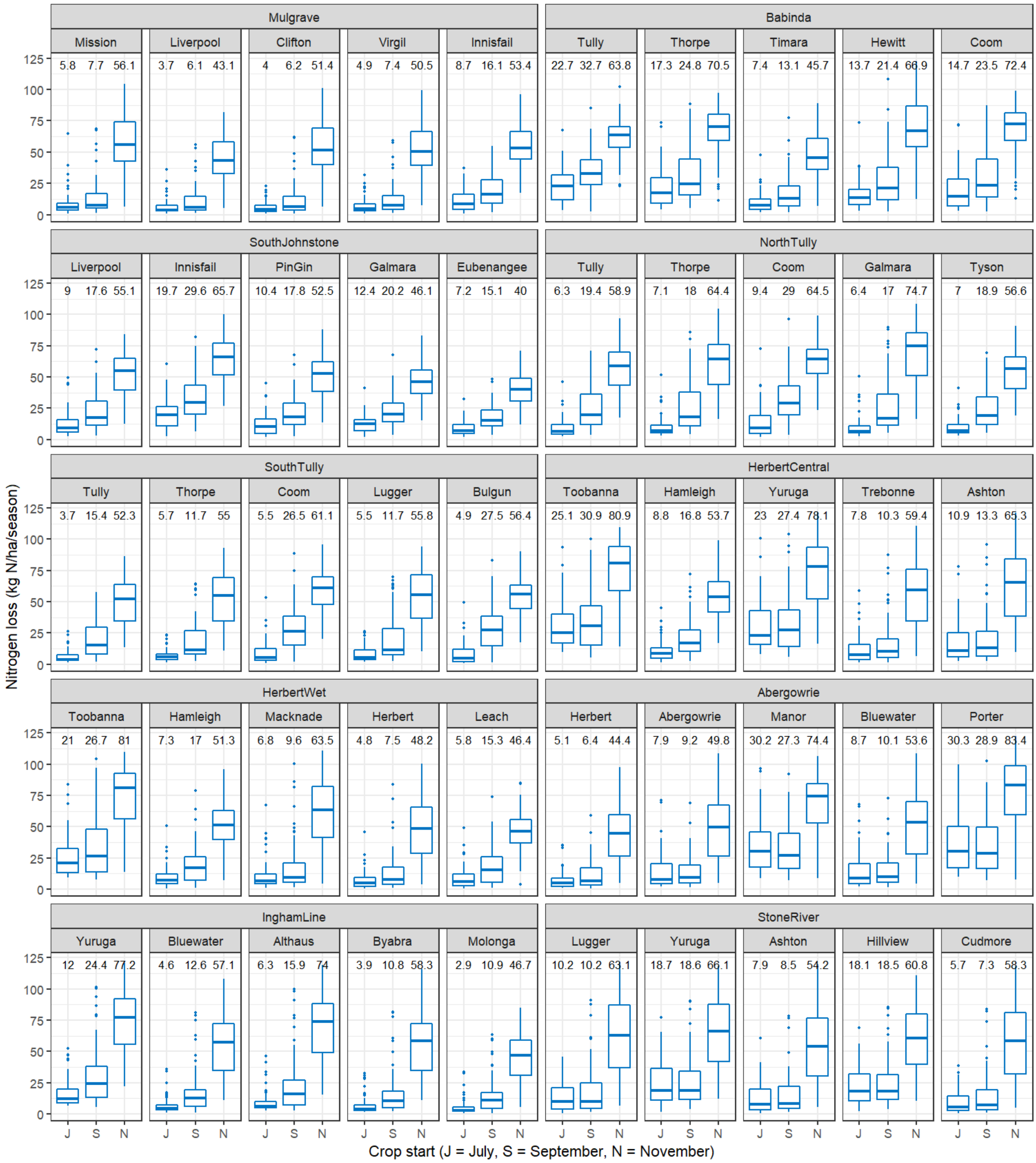

Figure 12: Distribution of simulated total N loss for 12-month ratoon crops using urea at current industry recommended N rate for top 5 soils in each region (numbers give medians by scenario).

4.1.1 N loss pathways

On average (across 71 seasons of crops harvested between 1950 and 2020) the amount of N lost via runoff was a small component of the overall N loss for most soil and climate combinations (Figure 13). There are some climate region x soil combinations where N lost via runoff is much more dominant than others, for example the Timara and Hewitt soils in Babinda. Additionally, the proportion of total N losses that is runoff is highest in the wettest climate regions (Babinda, South Johnstone, North Tully). The overall average simulated N loss in runoff (for a cropping season) was 2.0 kg N/ha, with most scenarios (climate region/soil x crop start time) having simulated median N losses below 5 kg N/ha, or even below 1 kg N/ha for early crops and southern regions.

The bulk of the N losses consist of drainage and denitrification losses. There are major differences between soils as to the dominant form that N is lost as. Soil texture (Figure 11) is the primary driver, with coarser textures soil leading to higher drainage losses, and heavier soil more denitrification. Scenarios with higher runoff are also those heavier textured soils, where water has the chance to accumulate on the soil surface.

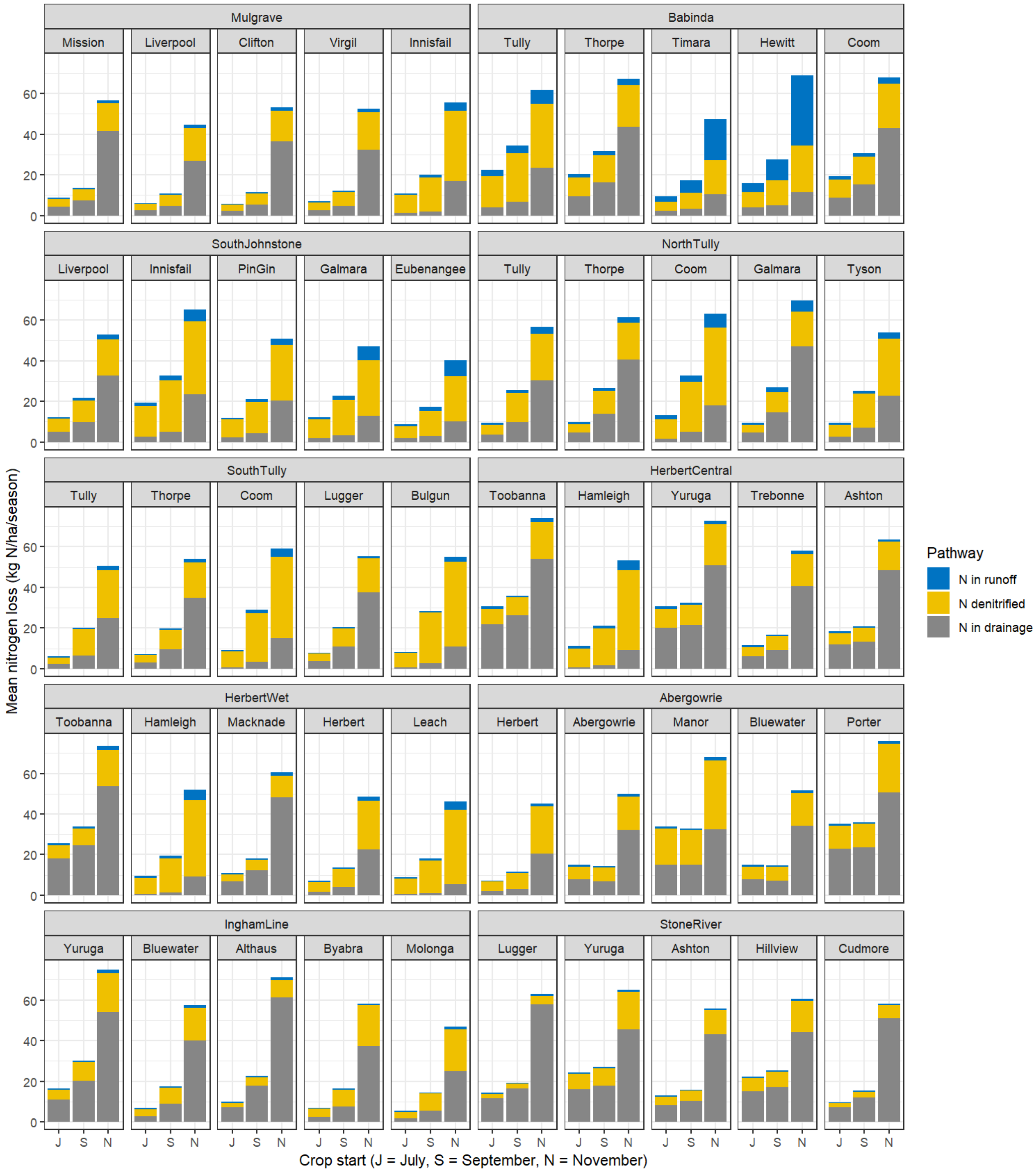

Figure 13. Mean simulated N loss by pathway for 12-month ratoon crops using urea at the soil-specific 6ES N rate for the top 5 soils in each region.

Under current industry guidelines (Six Easy Steps) when applying N as urea, N losses to the environment vary depending on the crop start time. N losses increase as the start of the crop, and fertilising time, gets closer to the Wet Season.

4.2 Simulated change in N loss following use of EEF at current industry recommended N rates

Simulations indicated that use of N applied at 6ES rate (EEF_{6ES}) could reduce the amount of N loss in comparison to N applied as urea at 6ES rate (U_{6ES}). Going from urea to an EEF consisting of 100% CRF, the simulated change in total N loss at the soil-specific 6ES N rate ranged from -67 kg N/ha to + 7 kg N/ha. The mean change in total N loss across all seasons and scenarios (climate region x soil x crop start) was a reduction of 9 kg N/ha with only 2% of simulated crop seasons giving an increase in total N loss.

Crop start time had a big effect on N loss reductions from using EEF, with reductions considerably larger for November crop starts than July and September starts (Figure 14). Part of the reason for this is that total N losses for the earlier crop start times were less than for the November crop start (Figure 12), meaning there is less N being loss initially to reduce from.

Climate region appears to be a driver influencing the N loss reductions observed in crop start time. In the wetter climate regions (Babinda, South Johnstone, North Tully and to a lesser extent South Tully, Herbert Central and Herbert Wet), there appears to be more of a reduction in N losses for the July and September crop starts compared to the drier climate regions. This is due in part to the wetter climate regions having greater losses than dry climates for the earlier crop starts, and also because in wet climate regions there are more likely to be ‘N loss events’ during the dry season (Figure 10). Climate region interactions with soil also affected the benefits from EEF relative to urea. These effects were usually smaller and aligned with differences in rainfall amount (Figure 10) and in magnitude of N loss under urea (Figure 13).

Using EEF (controlled-release fertiliser) in place of urea at Six Easy Steps rates reduced N losses to the environment.

In dry climates, N loss reductions from using EEF are largely limited to late starting crops (fertilising close to the wet season). ‘N loss events’ are generally limited to the wet season in dry climates.

In wet climates, N loss reductions from using EEF are realised through the year, and greatest in late starting crops (fertilising close to the wet season). There can be ‘N loss events’ through the year in wet climates, however they are more prevalent during the wet season.

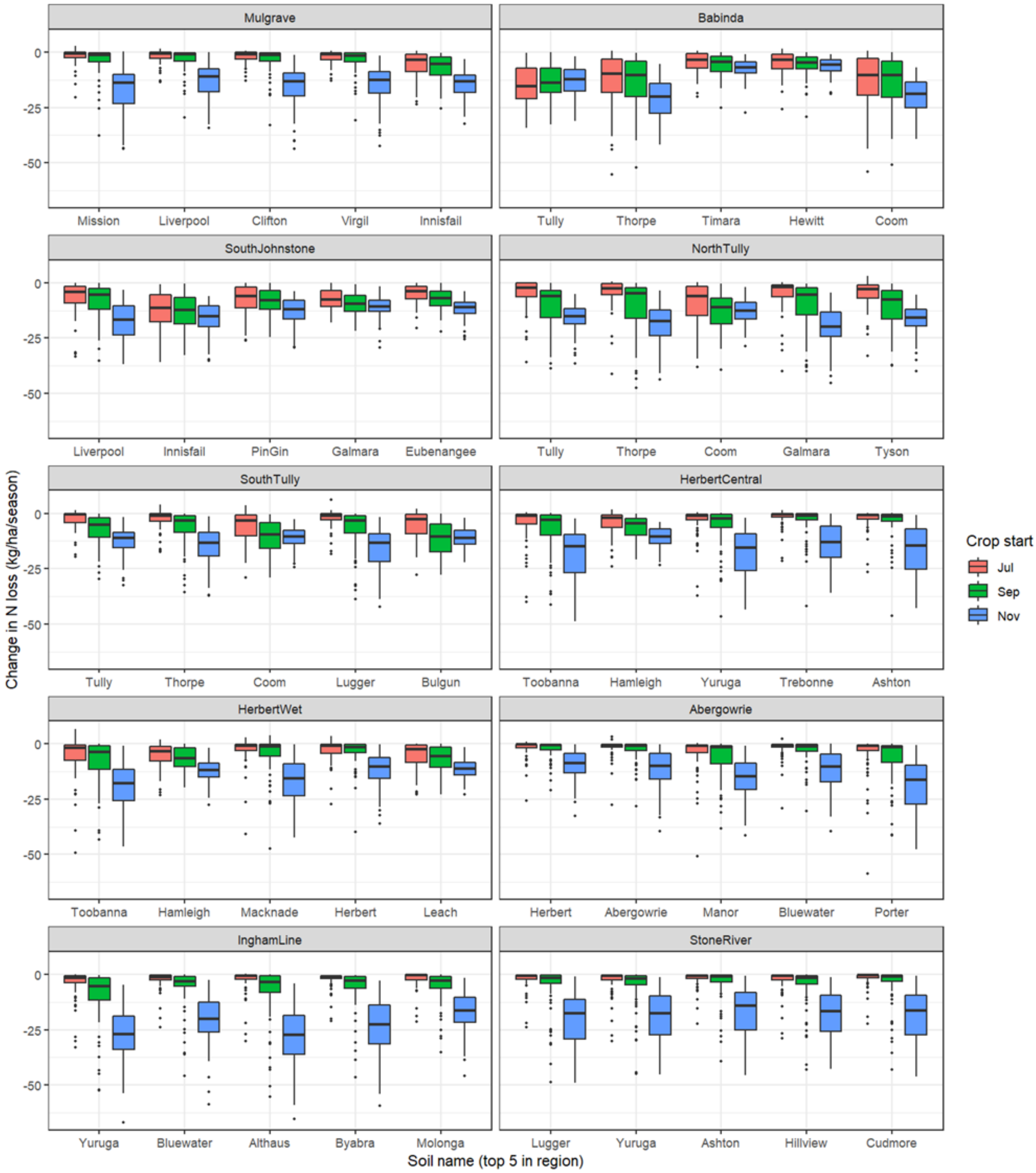

Figure 14. Change in simulated total N loss for 12-month ratoon crops using an EEF consisting of 100% controlled-release fertiliser instead of urea at the soil-specific 6ES N rate.

4.2.1 Runoff

While all N loss pathways can directly or indirectly affect the health of the Great Barrier Reef, the focus is often of N in runoff. The effect of EEF on simulated N in runoff was very small. Across all scenarios, soils and climates the average effect from EEF was a reduction of 0.2 kg N/ha, with 90% of results falling between -2.7 and +1.5 kg N/ha. The EEF outcomes were also more mixed than those for total N loss, with both reductions (41%) and increases (59%) in N loss experienced (Figure 15). However, for the two soils with the highest N in runoff losses (Timara and Hewitt soils in the Babinda region, Figure 13) the N loss reductions due to EEF use were clear with 81% of seasons resulting in a reduction of N in runoff up to a maximum reduction of 30.3 kg N/ha.

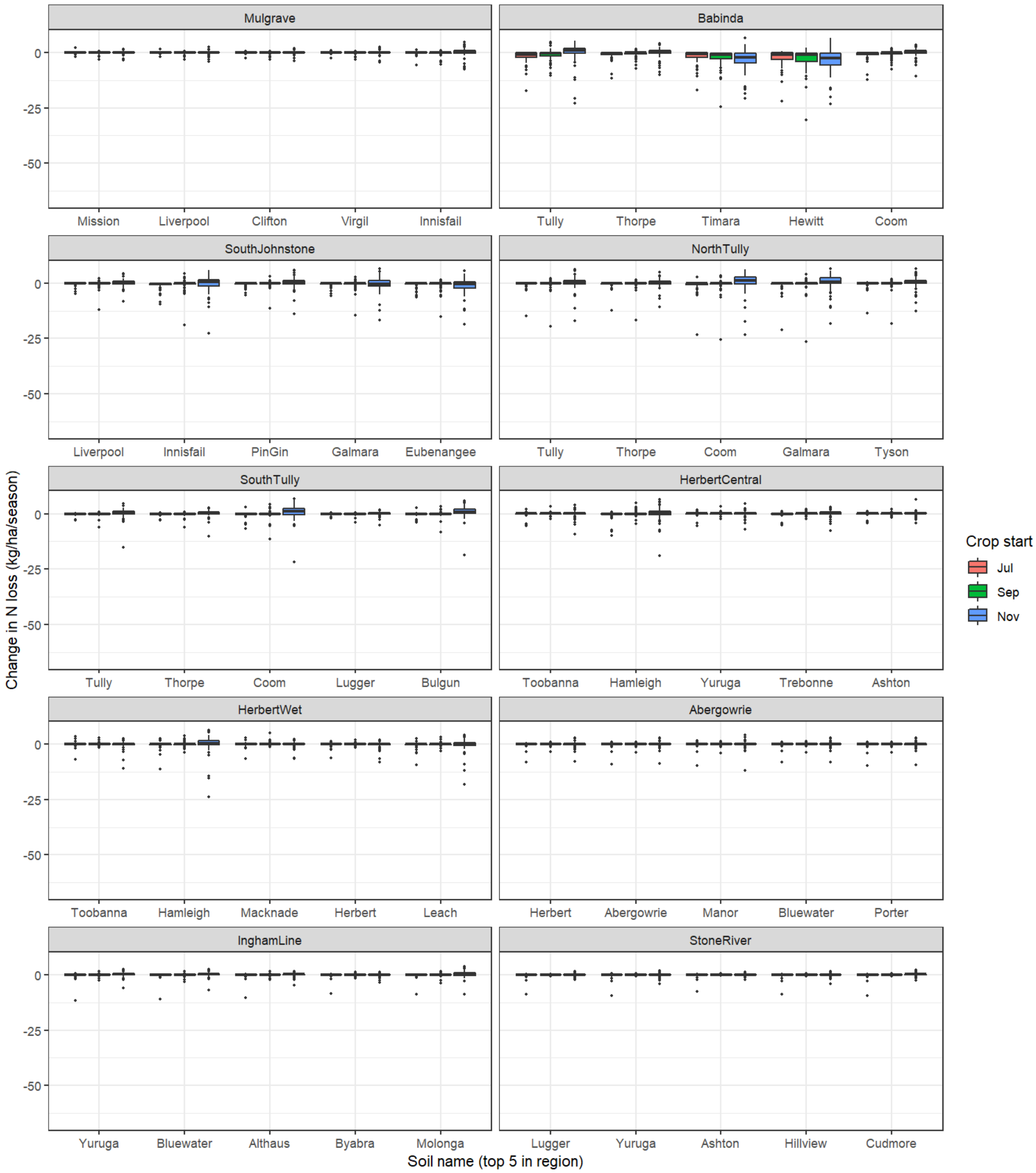

Figure 15. Change in simulated N loss via surface runoff for 12-month ratoon crops using 100% CRF instead of urea at the soil-specific 6ES N rate.

4.3 Simulated change in N losses following use of urea or EEF at reduced rate

Here, we analyse the N loss outputs from the simulations comparing urea at the 6ES application rate (U_{6ES}) with urea (U_{red}) and EEF (EEF_{red}) each applied at a rate equal to 20 kg N/ha less than the 6ES rate. There is an increased cost associated with using EEF, and many trials in the sugarcane industry have looked to offset this additional cost by comparing urea at the current industry recommended N rate with an EEF rate that is approximately 20% less than the urea N application rate (for example the EEF60 trials - Connellan et al. 2022). In our simulations we applied N in 10 kg/ha increments, so could only choose a 20 or 30 kg/ha reduction. On average, a 20% reduction from the recommended application rate was closer to 20 kg than 30, so the 20 kg N/ha reduction was chosen.

Reducing the N rate of urea, reduced the simulated total N losses. The N loss reductions under U_{red} were generally small for July and September crops, with the exception of some soils in the Herbert Central, Abergowrie and Stone River climate regions. In all regions the N loss reductions were largest for November crops.

The use of EEF increased the reductions in N loss for the November crops across all climate regions and for July and September crops for the wetter regions (especially Babinda, South Johnstone and North Tully). The N loss reductions for July and September crops in the Herbert Central, Abergowrie and Stone River climate regions were not or only marginally increased by the use of EEF, indicating that these loss reductions related to loss of unused (surplus) N later in the season.

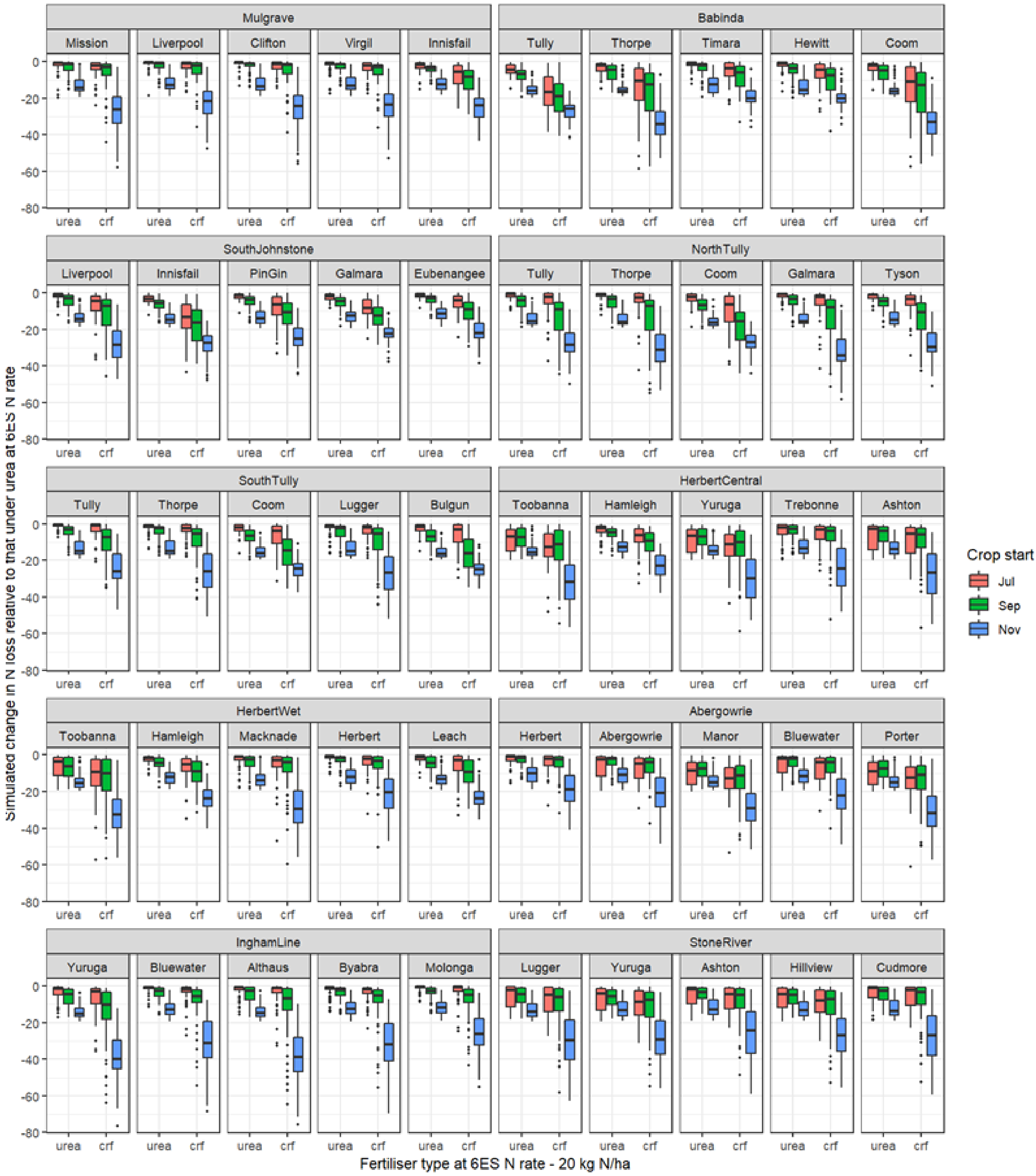

Figure 16. Simulated change in N loss for 12 month ratoon crops from using urea at 20 kg N/ha less than urea at 6ES and EEF at 20 kg N/ha less than urea at 6ES.

The frequency of reductions in N loss accompanying the change from U_{6ES} to U_{red} or EEF_{red} are shown in Figure 17. For both U_{red} and EEF_{red} in place of U_{6ES} the frequency of N loss reductions being greater than 5 kg N/ha were lowest for the July crop start and greatest for the November crop start. The use of EEF_{red} increased the chance of achieving N loss reductions for the July and September crop start compared to using U_{red} (Figure 17).
Using EEF_{red} in place of U_{6ES} in these crop starts increased the frequency of realising N loss reductions to 46% and 66% for the July and September crop starts. However, with the November crop start, the frequency of N loss reductions from using U_{red} was 94%, and for

EEF_{red} 100%.

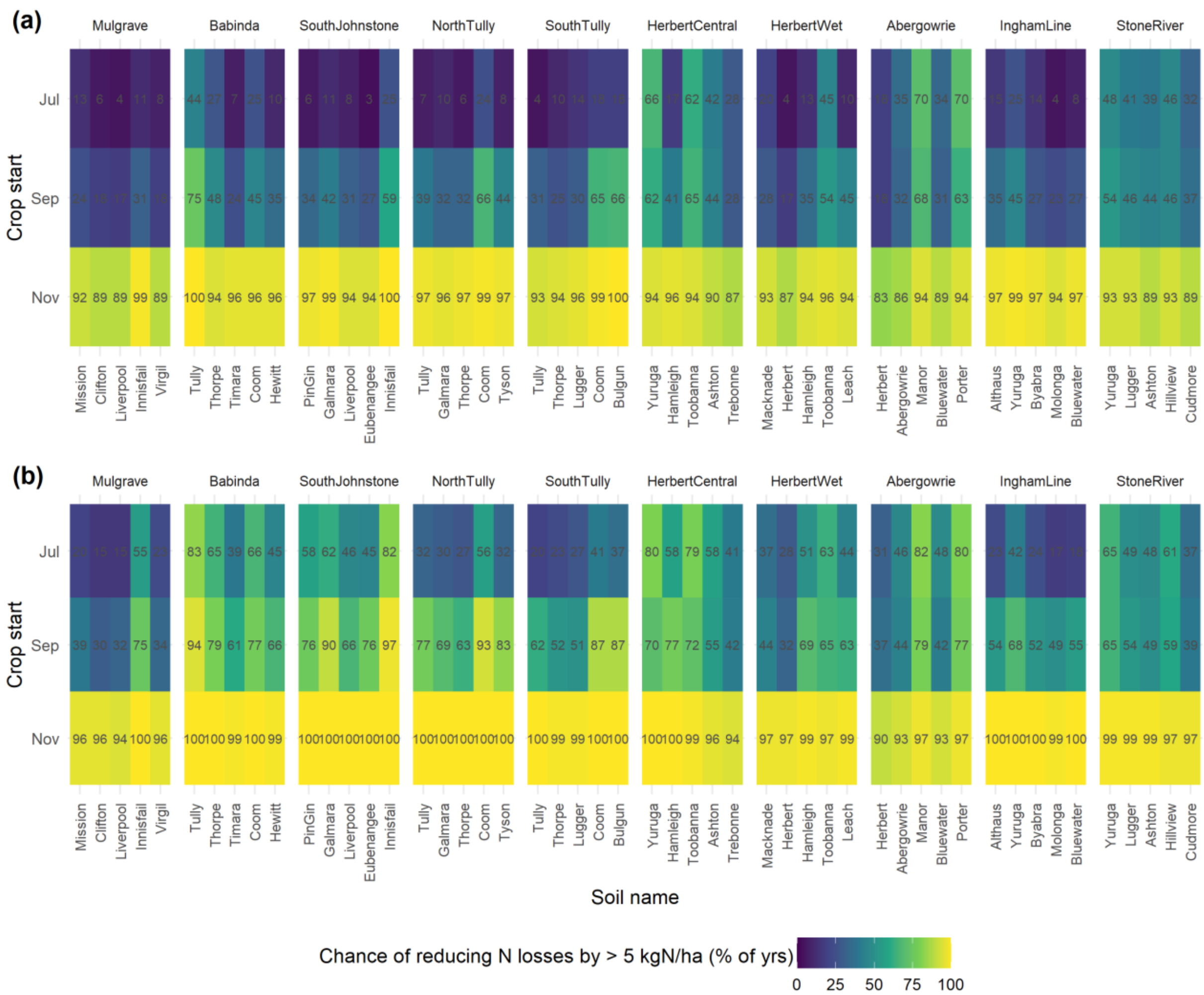

Figure 17: Frequency (as % of seasons) of simulated N loss reductions > 5 kg N/ha in changing from urea N at the soil-specific 6ES N rate (U6ES) to urea N at the reduced N rate of 6 ES – 20 kg N/ha (Ured – (a)) or EEF N at the reduced N rate of 6 ES – 20 kg N/ha (EEFred – (b))

Reduction in N rate can reduce N loss, especially for late crops. EEF enhances that effect, with greater and more consistent N loss reductions.

4.4 Simulated change in cane yield following use of urea or EEF at reduced rate

Figure 18 shows the simulated cane yield change for both U_{red} and EEF_{red} compared to U_{6ES}. The grey bands in Figure 18 indicate yield differences +/- 3 t/ha, a band in which differences may be difficult to identify experimentally due to spatial variability and experimental error. The simulations show a large number of scenarios where the yield change for both U_{red} and EEF_{red} compared to U_{6ES} is within the +/- 3 t/ha band. However, the yield change from U_{red} compared to U_{6ES} was generally negative for all crop starts (yield loss in 82% of simulations; average yield loss of 1.5 t/ha).

In many of the simulated scenarios the yield change from EEF_{red} compared to U_{6ES} was less negative than for U_{red} (yield loss in 53% of simulations), indicating that the EEF could mitigate some of the potential yield reductions from reducing N application rate. While July and September crop starts on average still experienced a yield loss (-1.0 and -0.6 t/ha), the average yield of the EEF_{red} treatment across all scenarios and seasons was equal to that of U_{6ES} treatment. This was in part because the simulations suggested that for some climate region and soil combinations yield gains from the EEF_{red} treatment compared to U_{6ES} were possible for the November crop start. These soils were generally the lighter textured and better drained soils (Table 4).

Note that the cane yield losses referred to are very small and were mostly well within the indicated grey bands, so that these may not be noticeable in the field.

Figure 18: Simulated cane yields for 12-month ratoon crops using U_{red} (urea) or EEF_{red} (100% crf) at a reduced N rate (soil-specific 6ES N rate – 20 kg N/ha) relative to simulated yields obtained for urea at U_{6ES} (the soil-specific 6ES) N rate. Grey band indicates +/- 4%, approximately the range where spatial variability may mask effects.

Using urea at 20 kg N/ha less than 6ES in comparison to urea at 6ES can lead to very small yield reductions. When using EEF at 20 kg N/ha less than 6ES in comparison to urea at 6ES this small yield reduction is often mitigated. In some late crops EEF at 20 kg N/ha less than 6ES in comparison to urea at 6ES can result in yield increases. Overall, EEF at 20 kg N/ha less than 6ES is an intermediatory position between urea at 20 kg N/ha less than 6ES and urea at 6ES.

4.5 Are all EEF equally effective?

Up to now we have shown the simulated benefits for an EEF type that consisted of 100% controlled-release fertiliser (*crf*). Due to their high cost, controlled-release fertilisers are often blended with urea. We, therefore, also simulated a blend with 33% urea and 67% controlled-release fertiliser (*ureacrf*). In addition, we simulated two nitrification inhibitors with different longevities (*dmpp7* and *dmpp28*, with half-lives of dmpp of 7 or 28 days) and a urea-controlled-release fertiliser blend with the shorter longevity nitrification inhibitor added to its urea component (*dmpp7crf*). See Methods Section 3.2.7 for further details.
The differences between the EEF types affect how they provide protection (Figure 2) as well as the duration of the 'protection period'. In the *ureacrf* blend, part of the N was released immediately and not provided any EEF protection (Figure 19). The difference in half-life of the simulated dmpp results in a difference in longevity of nitrification inhibition (Figure 19) ranging from full inhibition for 45 days and part-inhibition for another 100+ days (*dmpp28*) to inhibition reducing to less than 5% in 49 days (*dmpp7*). Longevity of inhibition observed in field experiments has varied widely in response to temperature and soil chemical and biological conditions (Verburg et al. 2014; Vilas et al. 2019b). The *dmpp7* and *dmpp28* were chosen to reflect the possible range in protection period.

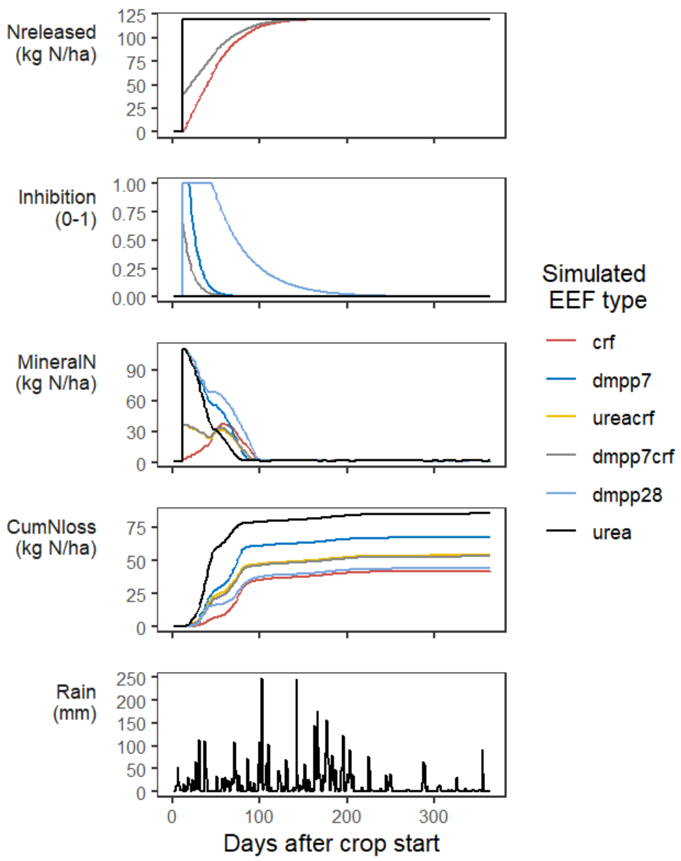

Figure 19: Comparison of release patterns and longevity of inhibition for the scenario of a 12-month ratoon crop harvested September 2011 grown on a Thorpe soil in the North Tully region at the soil specific 6ES rate of 120 kg N/ha fertiliser. Simulated EEF types: crf mimics a 100% controlled-release urea fertiliser, dmpp7 and dmpp28crf represent urea with nitrification inhibitor of different longevity, and ureacrf and dmpp7crf are urea-controlled-release fertiliser blends, where the latter includes nitrification inhibitor for its urea portion. As dmpp7 and dmpp28 do not have slow release their time series for N released is identical to that of urea. Similarly, as crf and ureacrf do not have nitrification inhibitor, their timeseries for Inhibition is identical to that of urea.

The differences in protection period affect the simulated dynamics of mineral N, which can in turn affect the simulated N loss as shown in Figure 17. The presence and magnitude of differences in N loss between the EEF types depends on the timing of rainfall and the timing

and magnitude of crop N uptake in response to seasonal conditions.
The mean N loss reductions realised for each EEF product over all the simulated scenarios and seasons showed *dmpp7* achieved on average 29% of the N loss reduction of *crf* (range 13 to 50%), *ureacrf* and *dmpp7crf* achieved on average 68 and 71% of the reductions of crf, respectively (range 60 to 83%) and *dmpp28* achieved N loss reductions that could be higher than *crf* (on average 106%) (Figure 20). *Dmpp28* also showed the most variation of response compared to *crf* (range 56 to 154%). Blending the controlled-release fertiliser with urea is hence less effective for reducing N losses and the effectiveness of nitrification inhibitors is very sensitive to the longevity of protection.

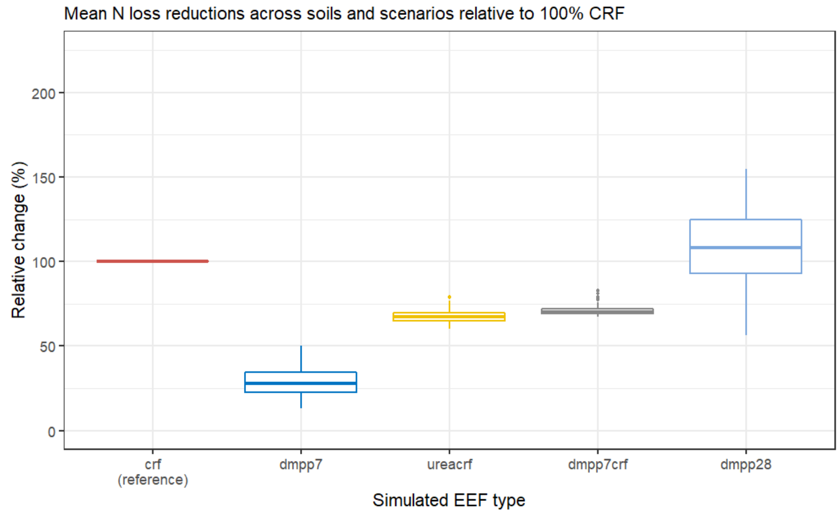

Figure 20: N loss reductions achieved by different simulated EEF types relative to 100% CRF. Simulated EEF types: crf mimics a 100% controlled-release urea fertiliser, dmpp7 and dmpp28crf represent urea with nitrification inhibitor of different longevity (7- and 28-day half-life respectively), ureacrf a urea-controlled-release fertiliser blend, and dmpp7crf a urea with nitrification inhibitor blended with controlled-release fertiliser.

To investigate whether there are any climate region x soil x crop start interactions in the relative effectiveness of the EEF types, Figure 21 shows the mean N loss reduction for all the EEF blends at EEF_{6ES} compared to U_{6ES}. November crop starts show greater N loss reductions for all EEF blends, and July crop start shows the smallest N loss reductions. The relative effectiveness of each EEF blend varied. However, the order in which the blends achieved N loss reductions was consistent.

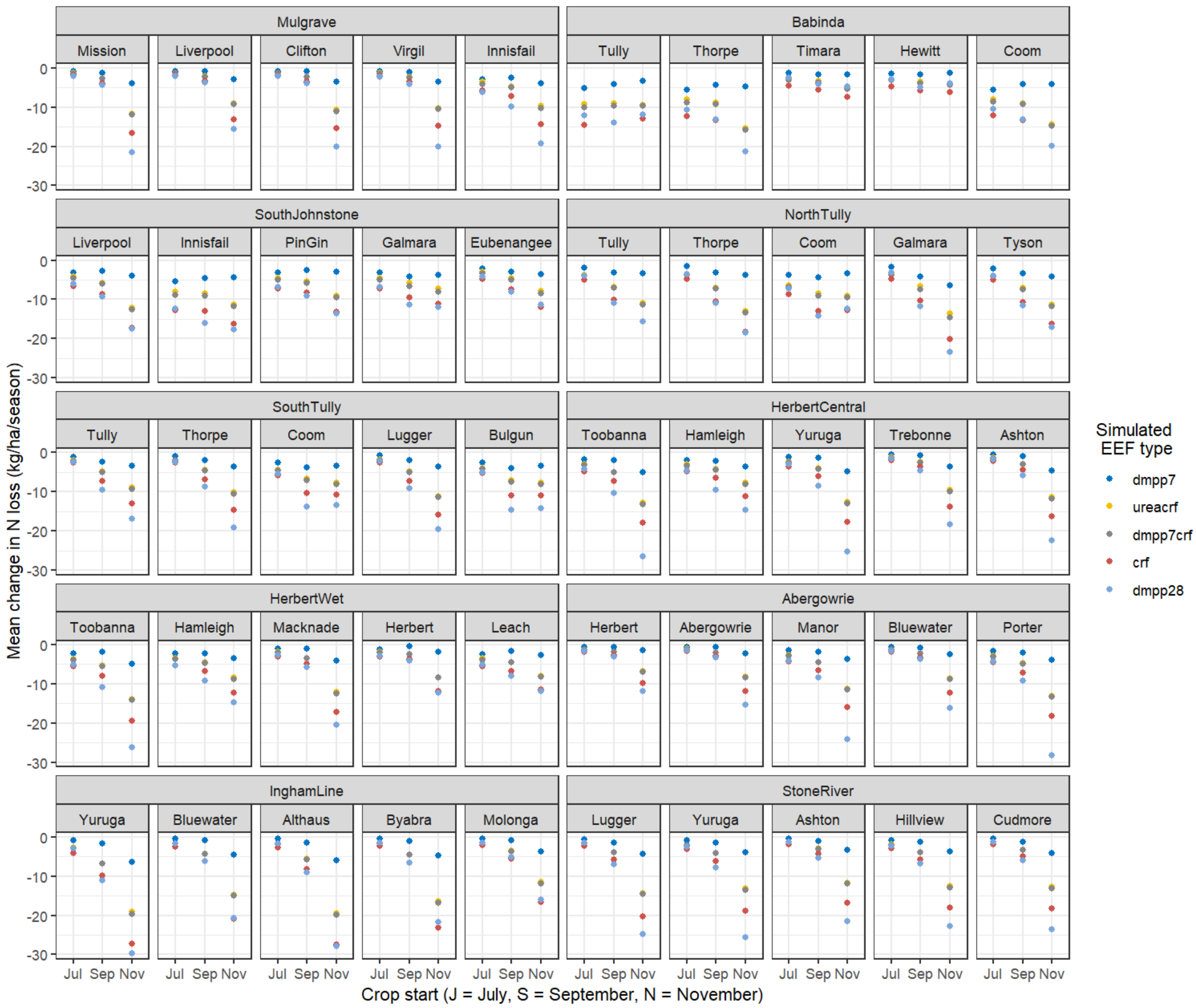

Figure 21: Comparison of simulated mean reductions in total N loss relative to urea achieved by different EEF at the soil-specific 6ES N rate. Simulated EEF types: crf mimics a 100% controlled-release urea fertiliser, dmpp7 and dmpp28crf represent urea with nitrification inhibitor of different longevity (7- and 28-day half-life respectively), ureacrf a urea-controlled-release fertiliser blend, and dmpp7crf a urea with nitrification inhibitor blended with controlled-release fertiliser.

All EEF act to decrease N susceptible to be lost compared to urea. The longevity of the EEF 'protection period' influences the degree to which N losses can be reduced. DMPP with long (28 days) half-life and 100% controlled-release fertiliser products have the longest protection periods and are most effective in reducing N losses compared to urea.

5 Discussion

The virtual N response trials modelled here provided an opportunity to analyse the effects of EEF use in sugarcane production systems in the wet tropics of Queensland, Australia across many scenarios (10 climate regions x 5 soils x 3 crop starts x 71 seasons). The results indicate that there is considerable potential for EEF to reduce N losses to the environment. Our simulations show N loss reductions from using EEF in place of urea tend to be more consistent, and of greater magnitude, for the late crop start (November) compared to the early (July) and mid (September) crop starts. However, the wetter regions, especially Babinda, South Johnstone and North Tully, showed simulated N loss reductions can be achieved with the earlier crop starts too.

It is difficult to indicate exactly the expected magnitude of the N loss reduction from EEF use. The simulation results show that the N loss reductions will not only depend on climate region, soil type and management factors such as crop start, but also on the type of EEF (which affects the duration of the 'protection period'). In addition, the season-to-season variability is very high, both in terms of N loss from urea application at current industry recommended N rates, and in terms of N loss reductions that could be realised from EEF use. At the current industry recommended N rate across the simulated scenarios and seasons, the simulation results suggest that using EEF in place of urea could achieve a maximum reduction in total N loss of 67 kg N/ha. The median N loss reductions for all simulations were between <1 and 15 kg N/ha for July and September crop starts, and between 5 and 27 for kg N/ha November crop starts. Increases in total N loss were possible, but infrequent (2% of all scenarios and seasons involving the simulated 100% controlled-release EEF). An implication of the large season-to-season variability is that benefits that would be measurable and statistically significant may only occur in a subset of seasons for the early and mid-season crops, especially in the drier climates.

While the simulations, nevertheless, indicate a potential for EEF use to reduce total N loss, only a small proportion of the total N loss was simulated to be lost in runoff (on average 7%) with absolute amounts mostly below 5 kg N/ha, except for two poorly drained soils in the wet Babinda region. The effectiveness of EEF in reducing N loss in runoff was also lower than that for the denitrification and deep drainage pathways, with a higher incidence of increases following use of the controlled-release EEF. The small N loss reductions simulated from runoff relative to drainage and denitrification losses could still be significant in helping achieve the N loss targets set in the Reef 2050 Water Quality Improvement Plan (2018).

The simulations often predicted small cane yield losses when reducing the rate of urea (going from current industry recommended N rate to a rate 20 kg N/ha lower). In many cases those yield losses were predicted to be within 3 t/ha (the approximate range of significant detection experimentally), but this depended on region and soil type. EEF application at 20 kg N/ha less than current industry recommended N rates was found to mitigate this yield loss to a greater or lesser extent, and sometimes even increase yield. On average across all scenarios and seasons, the EEF_{red} treatment achieved the same yield as the U_{6ES} treatment, but for the majority of July and September crop starts yields were between those of the U_{6ES} and U_{red} treatments. The exact yields depended on crop start, soil and climatic conditions with EEF yield benefits more likely in situations where N loss during the early season was likely and N loss was a limiting yield factor.

The modelling findings align well with the framework of three prerequisite conditions for getting environmental and agronomic benefits from EEF use (Figure 1). The 'protection period' of the EEF is not indefinite, but the longer this period, the higher the chance that the N is still protected during an 'N loss event' (a rainfall event large enough to cause N loss). Simulations with different EEF types confirmed that longer protection periods, whether through a higher proportion of controlled-release fertiliser or a longer longevity of nitrification inhibition, increased the potential for N loss reductions. A consequence of this first prerequisite condition is that urea-EEF blends, particularly those with low percentages of EEF, will have reduced efficacy. This introduces a trade-off between cost and potential benefits from using EEF.

The second prerequisite condition of an 'N loss event' event happening during the protection period and before crop uptake implies that not all situations where EEF is applied will lead to environmental benefits. The simulation results indicate that the likelihood of N loss reductions is higher for later crop starts than for earlier crop start due to the summer dominant rainfall distribution. The exceptions are the wetter regions such as Babinda, South Johnston and North Tully, where the annual rainfall is higher, and N loss events are also experienced earlier in the season for July and September crops.

The third prerequisite condition, that agronomic benefits require the crop to be responsive to saved N, explains why yields with EEF_{red} are often between those with U_{6ES} and U_{red}. Where the yield loss going from U_{6ES} to U_{red} is a consequence of a suboptimal N rate and not affected by N loss early in the season, the use of EEF_{red} will similarly have a reduced yield and not be able to mitigate the yield loss. Where N loss happens early in the season during the protection period of the EEF and constrains the N supply to the crop, the reduced yield of U_{red} can be mitigated by use of EEF_{red}. The EEF_{red} can then potentially achieve the same yield as U_{6ES} or yield even higher if the yield of U_{6ES} was also limited by N loss and the EEF was effective in reducing N loss. The simulation suggested that the latter situations mainly occurred for late crops grown on lighter soils, where yield potential was less affected by other factors such as water logging. Earlier simulation studies by Verburg et al. (2018, 2022) demonstrated how late crops grown on heavy clay soils were susceptible to prolonged waterlogging and could have limited N response, which limited the benefits of EEF.

The simulated cane yield effects are similar to the combined results from the EEF60 field trials (Connellan et al., 2022). The combined results over 4 years from all the EEF60 sites showed that reduction of the urea N rate by 20% resulted in a significant reduction in cane yield. When specific subsets of the data were analysed, the same trend was seen, but it was not always statistically significant. Analysis of the cane yield results for all EEF products together or separate typically showed EEF at the reduced N rate achieved an average yield between, but usually not statistically significant from the urea at 6ES and reduced rates. This result can be explained by the effects differing in the individual trials which involved different crop starts, climates and soil types.

Further analysis of the experimental results by time of fertilisation (mid, late), rainfall in the first three months (low, medium, high) and soil texture (sand, loam, clay) suggested that cane yield benefits from EEF were more likely for late season fertiliser applications under wetter conditions (Connellan et al. 2022). While not statistically significant due to the smaller number of experimental results in each category, the analysis also obtained cane yield increases relative to urea at 6ES for late season crops on sandy soils in high rainfall seasons. Dowie et al. (2019) obtained a similar result in trials involving a 50% blend CRF for late crops and sandy soils.

The consistency between the modelling and experimental results increases confidence in the findings (i.e., risk of very small cane yield losses under reduced urea rate, mitigation by EEF, especially under wetter conditions, and possibility of yield increases for late crops under wet conditions on lighter soils). While the modelling did not include simulation of Commercial Cane Sugar (CCS) and resulting sugar yield, the experimental findings of Connellan et al. (2022) for sugar yield often mirrored those of cane yield with the reduced rate EEF usually achieving an intermediate average sugar yield between the two urea rates.

Where it was difficult to obtain statistically significant results experimentally to explore interactions between treatments, time of fertiliser application, rainfall and soil type, the modelling could test more climate x soil x management scenarios and a wider range of seasonal conditions. It also allowed the cane yield effects to be related to N loss reduction benefits. As such simulations help to interpret experimental findings when these become uncertain due to spatial variability, measurement uncertainty and the limited set of climatic conditions sampled.

Modelling a complex system like the sugarcane production systems is, of course, not without uncertainties either. Appendix 1 provides further comment on this. The care taken in using a validated model and the focus on relative effects and their likelihoods rather than absolute magnitudes of predicted effects reduces the impact of model uncertainty and makes the findings more robust. The consistency of the modelling findings with the prerequisite framework and with the experimental findings also strengthens the confidence that the results can be drawn upon for assessment of the role that EEF can play providing environmental and agronomic benefits. Future research identified in Appendix 1 includes a more thorough quantification of N losses via different pathways, as well as more detailed information of crop response to N rates, as the simulations were sensitive to this.

The variable efficacy of EEF use, affected by climate, soil and seasonal conditions, needs to be considered when developing policies and/or extension programs to support or encourage adoption of EEF use. The benefits, environmental or agronomic, will not be the same everywhere across the Wet Tropics. The reason why effects may not be observable in every season also warrants communication in order to manage expectations.

The analysis here needs to be complemented by economic analysis as separate effects on CCS could negate some effects and the cost of the EEF needs to be considered too. The study by Connellan et al. (2022) present some of these results in relation to experimental findings. The finding that environmental benefits from EEF use (reduction of N loss) will occur more frequently than agronomic benefits poses a challenge for driving adoption of EEF: how to enable their use to reduce environmental effects where agronomic benefits may not cover their cost. Economic risk analyses incorporating environmental trade-offs and so-called ‘social net returns’ (e.g., Kandulu et al. 2017, 2018) may need to be explored and external incentives considered (e.g., reef credits, credits for fertiliser companies to reduce the cost of EEF).

6 Conclusions

The most important contribution of this report is the identification of specific interactions between climate regions, soil and crop start that generate differing environmental and agronomic benefits from use of EEF compared with urea. These insights have implications for providing EEF recommendations for N management by the Wet Tropics sugarcane industry. The simulations indicate that application of EEF instead of urea in the sugarcane industry can generate N loss benefits and increase yield, but that the magnitude of these benefits is highly variable and the frequency of measurable benefits can be very low depending on climatic, soil and crop start conditions.

The key insight from this analysis is that crop start has a major effect on environmental N losses. Therefore, the later the crop start, the more likely EEF will provide N loss reductions compared to urea. In turn, this affects the ability of EEF to provide yield benefits. Further climate region x soil x crop start interactions lead to differing magnitudes and frequency of N loss and yield benefits from EEF use. By using the framework presented in Figure 2, we can understand why the studied interactions are generating differing benefits. The key notion of the framework that EEF only generate environmental benefits when there is an ‘N loss event’ during the EEF ‘protection period’ is a simple way of explaining and identifying scenarios where EEF could provide environmental benefits.

Our results clearly identify when crop start occurs later in the season, it will be more likely that EEF will provide N loss reductions over urea use, and the larger that benefit will be. This result can be explained using our framework, as the late crop start is closer to the wet season, where heavy rainfall generates ‘N loss events’. The EEF ‘protection period’ is time limited, with different EEF products providing protection for different lengths of time. Nitrogen loss reductions from using EEF in place of urea are more prevalent in the wetter climate regions we investigated compared to the drier regions. Again, this can be explained using our framework, as ‘N loss events’ are more likely during the dry season in the wetter climates. Finally, as a consequence of crop responsiveness to N, yield benefits are only obtained when the crop requires the N ‘saved’ from N loss. This favours high yielding crops and fertiliser rates that are close to the optimum N, corroborating the experimental results of clearer yield benefits on lighter, permeable soils. The interplay between these prerequisite conditions explains the predicted differences in effects from EEF use in different regions and on different soil types – a variable efficacy that should be considered when advising the industry on EEF use or developing policies to encourage adoption.

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Appendix 1. Comment on modelling uncertainties and future research needs

Modelling a complex system like the sugarcane production system is not without uncertainties. We took care to use a model that over the years has been verified in a wide variety of circumstances with specific attention to different processes (see Methods section). Additional model verification was included in the current study to improve the modelling of N responsiveness via adjustments to the model 'spin-up' process and to try a new method of modelling of N in runoff (Vilas et al. 2022) against data from two experimental trials. In addition, we included a repeat verification against district yields across years in the various regions following these model and parameterisation changes. This was in addition to the verification work previously reported in this project () where we used EEF60 data to verify the model.

The presented results – N loss reductions and cane yield increases following application of EEF – are sensitive to the prediction of soil mineralisation. The simulated soil mineralisation determines the soil N supply and hence affects the responsiveness of the crop to fertiliser N. This is less of a concern when comparing relative effects (e.g., climate regions, soils, and crop start times) of urea and EEF at the same N rate to determine when and where EEF may be more or less effective and what drives the effectiveness. However, the quantitative results of comparisons between urea at the soil-specific 6ES rate and a reduced N rate of urea or EEF are more sensitive and hence need to be interpreted with care. This includes the predicted reductions in cane yield, although these are already mostly within measurement error.

Our parameterisation methods included 'spin-up' runs to stabilise the model's organic carbon pools. These 'spin-up' runs drew on historical soil survey data, which was collected mostly from soils in natural conditions, due to the absence of equivalent, contemporary soil information to depth for sugarcane soils. The 'spin-up' runs therefore also served to simulate the changes in soil organic carbon levels following years of sugarcane production, including changes in trash management from the 1990s. We have found this the most reliable approach to parameterising a wide range of soils, correctly reflecting soil differences and relative district yields where this has been verified (e.g., Tully; Biggs et al. 2021). However, the soil mineralisation levels and resulting optimum N rates remain an estimate, and further verification similar to that in Tully would be useful for the other regions. Especially for the soils in the Ingham Line region where we predicted optimum N values above the 6ES N rates (affecting the magnitude of simulated yield losses) and for some of the high organic carbon soils.

For use of the simulation results as a guide to farmers, it is important to note that there is considerable variation in soil properties even within the named soil types (see Methods section). Therefore, farmers may want to verify the N responses on their soils using test strips to establish N response curves. These tests strips do not necessarily have to be replicated if measuring responses at multiple N rates (at least 5-6 across the likely optimum N range). However, as response curves can vary from year to year, especially for the later ratoon crops, it would be useful to repeat these over multiple years to build up an understanding of the crop N responses on a given soil.

Most of the EEF simulation results presented in this report related to the 100% controlled-release urea fertiliser type. While not many farmers use a 100% controlled-release fertiliser product on account of its cost, it provides a useful reference of the N loss reductions and yield increases that could be obtained. In addition, we were most confident with this EEF type in the model. Its release pattern has been tested against field data and following its release, the urea would behave similar to regular urea, apart from possible minor differences in within-band chemistry (Janke et al. 2020). For comparison, we did simulate the other EEF product types used in the EEF60 experiments.

While the simulations for the urea-controlled-release fertiliser blend would be similarly reliable, there is more uncertainty in our simulation of the nitrification inhibitors. The longevity of nitrification inhibitors in response to temperature and soil chemistry is not well understood and was, therefore, not reflected in our simulated products. Instead, we simulated two contrasting nitrification inhibitor longevities. The longevities of commercial products available are likely to be somewhere in between.

The modelling of nitrification inhibitors introduces another challenge of correctly simulating the relative preference and rates of uptake of ammonium and nitrate. While the new uptake model used for this purpose was verified against the original data in Keating et al. (1999) (Verburg et al., 2017), further testing would be warranted. It is, therefore, difficult to compare the relative effectiveness of the different EEF. However, it is clear that longevity of inhibition will be key to the efficacy of nitrification inhibitors and that short half-times of 7 days are likely to be insufficient to make a measurable difference to crop performance or total N loss.

While the original aim for this work was to clarify the effects of EEF on N losses in runoff, this is the N loss pathway that we probably have least confidence in. The N in runoff model (Vilas et al. 2022) is relatively new and there are not many datasets available for testing, two of which were included in this study and only one of which included the effect of EEF. In the big scheme of things, the N in runoff losses are predicted to only form a small proportion of the total N losses. The available data do confirm that the simulated amounts are reasonable. For example, Fraser et al. (2017) present a compilation of data from several studies, including the Webster et al. (2012) data and the early data from the Mackay field trial used by Vilas et al. (2022). Their reported average dissolved inorganic N (DIN) load was 2.3 kg N/ha with a median of 1.3 kg N/ha. Considering only the ratoon crops from their table, these values change to 1.2 and 1.5 kg N/ha, respectively. Maximum reported DIN load under ratoon crops was 6.3 kg N/ha. However, in view of the more immediate impact of N in runoff for the Great Barrier Reef and some of the higher values predicted for two of the Babinda region soils, further testing and hence more experimental data would be warranted. The current model only considers N in the surface layer to be available for runoff. It is, therefore, sensitive to simulated N concentrations in this layer. Hence why the responses to controlled-release EEF were more variable. It would be good to evaluate these assumptions further, e.g., in a controlled environment experiment.

Despite the above uncertainties, the modelling provides a means to extend the sparse experimental data to give an indication when, where and why EEF will provide environmental and agronomic benefits or not. The high variability introduced by variable seasonal conditions, differences in mineralisation and N loss pathways of different soil types, as well as complex system interactions make it impossible to draw firm conclusions from experimental data alone.

In view of the above, future research needs include:

- Verification of crop N responses on different soil types, e.g. like the modified Delphi approach used in Biggs et al. (2021) where simulated N responses were assessed by an advisory panel and other local agronomists against relevant experiments and their general experience. These more informal experience-based verifications would be complementary to other verification work, as they can be biased by the nature of the soils used in the experiments, which may differ from the 'typical' profiles modelled.
- Further testing of modelling of nitrification inhibitors drawing on more detailed experimental data and analysis of their subtly different responses in different soils compared with controlled-release EEF.
- Confirmation and quantification of the sensitivity of sugarcane crops to N stress in the earliest stages.
- Further experimentation and testing of effects of EEF on N losses via different pathways including N in runoff.

The soil differences in the current simulations could also be analysed further in terms of soil properties instead of relying on soil classification, given the considerable variability within soil name classes. It would be useful to explore through user experience analysis how the soil information could be best conveyed to farmers as there would be a trade-off between knowledge of local soil properties (including below the top 10 cm) and judging soil type from landscape position, which was the basis for many of the soil classifications in the region.
In addition, we see an opportunity to draw on these simulation analyses to develop prediction of EEF benefit for specific seasons. We presented a macro analysis where the frequency of benefit could be identified for crop start x soil x climate region interactions, and this analysis could form the basis for a more detailed analysis of data to identify and codify the drivers of benefit. Progressing this analysis to codify these scenarios into a decision support was beyond the scope of this work. In addition, such decision support would need to draw on economic analyses.

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