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Final Report

Improved Water Quality Outcomes from On-Farm Nitrogen Management

Michael J Bell, Anthony J Webster, Danielle M Skocaj, Bronwyn Masters, Jayson Dowie, Nick Hill, Philip W Moody

The University of Queensland Australia

Improved Water Quality Outcomes from On-Farm Nitrogen Management

Michael J Bell[1], Anthony J Webster[2], Danielle M Skocaj[3], Bronwyn Masters[4], Jayson Dowie[5], Nick Hill[6] and the late Philip W Moody[7]

[1] School of Agriculture and Food Science, University of Queensland;
[2] CSIRO Agriculture and Food, Cairns;
[3] Sugar Research Australia, Tully;
[4] Queensland Department of Natural Resources, Mines & Energy, Mareeba;
[5] Farmacist, Ayr;
[6] Farmacist, Mackay;
[7] Queensland Department of Environment and Science, Dutton Park

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Cover photographs: (front) Applying fertiliser N to ratoon cane in the Burdekin using a stool splitter. Image: Jayson Dowie and Heidi Hatch, Farmacist, Ayr. (back) Overview of the Silkwood trial site showing treatment strips and runoff monitoring stations. Image: Bronwyn Masters, NRM&E, Mareeba.

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ACRONYMS

6ES .... SIX EASY STEPS^{TM} nutrient management program
DIN................ Dissolved inorganic nitrogen
DYP............... District Yield Potential
EEF .... Enhanced Efficiency Fertiliser
ET .... Evapo-transpiration
GBR .... Great Barrier Reef
NESP .... National Environmental Science Program
NI .... Nitrification inhibitor
NUpE .... Nitrogen Uptake Efficiency
PCU .... Polymer coated urea
PZYP............. Productivity Zone Yield Potential
RRRC............ Reef and Rainforest Research Centre Limited
UI .... Urease inhibitor

ABBREVIATIONS

CCS .... commercial cane sugar (%)
g N m^{-1} .... grams of nitrogen per metre
kg/ha............. kilograms per hectare
kg N ha^{-1} .... kilogram of nitrogen per hectare
N .... Nitrogen
N/ha .... nitrogen per hectare
NH_4-N........... Ammonium-N
NO_3-N........... Nitrate-N
t cane/ha....... tonnes of cane per hectare
t/ha................ tonnes per hectare

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EXECUTIVE SUMMARY

Total nitrogen (N) loads entering the Great Barrier Reef lagoon have increased greatly in response to land management changes, with the extensive grazing and sugarcane industries identified as major contributors. The dominant form of N lost from the sugarcane industry is via surface runoff and deep drainage of dissolved inorganic nitrogen (DIN) derived from fertiliser applications, with this form of N representing an immediate risk to marine ecosystem health. *Minimising* these losses will require a combination of management strategies that collectively maximise crop recovery of applied N and minimise the risk of loss in runoff or deep drainage. The large N requirement of sugarcane, coupled with an extended period of crop N uptake that can coincide with the monsoonal wet-season in northern Australia, makes this challenging.

This project tested whether a number of inter-related strategies could maintain sugarcane productivity while improving fertiliser N use efficiency and *minimising* N loss in runoff and drainage. It is based on combining improved N fertiliser technology (using Enhanced Efficiency Fertilisers – EEF's) with fertiliser N rate reductions that better match the N applied to the crop demand in a productivity zone, which can range in scale from intra-block, several blocks or a whole farm. The performance of different EEF technologies have been benchmarked against conventional urea fertiliser under conditions consistent with applications in sugarcane fields (i.e. concentrated sub-surface fertiliser bands) in both laboratory and field experiments.

Combinations of the best available EEF products were tested at eight field sites from Mackay to Cairns, using application rates that match the productivity zone yield potential (PZYP – the yield potential of the individual block/zone based on historical mill records) of the blocks in which they were tested. These practices were benchmarked against urea applied at rates calculated using the district yield potentials (DYP) defined in the SIX EASY STEPS^{TM} (6ES) nutrient management program (which represents current industry best management practice), and a treatment that received no fertiliser N. Each site grew a series of consecutive ratoon crops that were harvested in the middle or late harvest rounds, to increase the risk of fertiliser N loss. The lower yields recorded at some of the sites (Silkwood, Freshwater) were a consequence of these later harvests. Traditional crop performance indicators were collected (cane yield, CCS and sugar yield), in addition to crop biomass samplings and analyses that allowed quantification of apparent fertiliser N recovery and the efficiency of fertiliser N use. Runoff losses were quantified at the Freshwater and Silkwood sites, while the concentrations of DIN in deep drainage were also measured at Silkwood. This report presents findings from three (Silkwood and the Burdekin) or four (Tully, Freshwater) consecutive ratoon crops, with the Mackay sites running for three ratoons at the initial location, and then two ratoons at a second location established after termination of the crop cycle at the original site.

Results showed that yields at most sites responded to the application of N fertiliser. Nil N treatments at all sites received no fresh fertiliser for the crop year monitored, but otherwise had a history of the local fertiliser rate (typically the 6ES-DYP rate). These Nil N treatments served to measure the relative and absolute response to applied fertiliser. The cumulative cane production across 3 or 4 consecutive ratoons from these unfertilised treatments represented 65-75% of yields with the recommended fertiliser application rate calculated using DYP. In absolute terms, the cane yield response to applied urea-N at DYP rates averaged from 30-35 t/ha/year in sites at Tully and the Burdekin, to as low as 15-25 t/ha/year at Mackay. At these application rates the apparent crop recovery of urea-N was generally poor, averaging 22% in

the sites in the wet tropics, 19% in the Burdekin and 9-18% at Mackay. The average agronomic efficiency of urea-N across the crop cycle varied substantially between sites, typically ranging from 3-18 kg N applied/t additional cane yield but occasionally as high as 60 kg N/t cane in poor yielding zones in a field at Mackay.

At sites where PZYP < DYP, reduction of the urea N application rate to match the lower productivity resulted in small but not statistically significant decreases in cane yields (3-8%) averaged over 3-4 consecutive ratoon crops. This had no significant impact on either improving fertiliser N recovery or the agronomic efficiency of fertiliser N use. The combination of reduced N rates and use of the EEF blend resulted in improved crop N recovery at most sites (an average of 30% in Wet Tropics sites, 26% in the Burdekin and 15-26% at Mackay), but there were no consistent crop yield increases associated with this extra fertiliser N uptake except for the Silkwood site. As a result, improvements in agronomic efficiency of fertiliser N use (reductions in fertiliser N applied/t cane yield increase) with the EEF blend at the PZYP rate were due primarily to the reduced rate of application rather than any increase in crop yields.

The dynamics of N runoff (Freshwater and Silkwood sites) and drainage (Silkwood) varied substantially with soil type and management, seasonal climatic conditions and fertiliser N treatment. Reduced N rates had the greatest effect on reducing runoff losses of total N at both sites (by 25% at Freshwater and by 60% at Silkwood), but the impact of changing to EEF's was minimal on average, and highly variable between rates and sites. Similar effects of reduced rate and changing to EEF's were also evident for DIN losses at Silkwood. A major contributing factor to the inconsistent effects of EEF's on runoff losses, especially at higher application rates, was the prolonged period over which losses occurred. This most likely reflected the controlled release component of the EEF blend that released N which rapidly transformed into nitrate-N (NO_3-N) throughout the wet season. These effects were especially evident at Silkwood, where persistent high water tables and limited crop N uptake during the wet season increased the chance of elevated concentrations of NO_3-N in the EEF treatments being available for loss in runoff flows.

Laboratory and field studies were undertaken as part of an associated PhD program to look at the implications of applying urea, with or without commercially available coatings or inhibitors used in EEFs, in concentrated bands. Banded applications are almost universally used in commercial cane fields, but the impact of chemical changes that occur in and around the fertiliser band as a result of fertiliser dissolution and urea hydrolysis have not been well documented. It was hypothesized that these changes may impact on the efficacy of EEF technologies and minimise potential productivity and environmental benefits from their use. This work has produced a number of important conclusions. These include (i) The application of fertiliser N in highly concentrated bands typical of those used in the sugar industry does change the dynamics of N transformations in soil and hence the window for crop N acquisition or environmental loss; (ii) The band environment increases the duration of nitrification inhibition and slows the rate of N release from polymer-coated EEF products, both of which can influence the timing of N availability to the crop or prolong the period of vulnerability to environmental loss. These effects are accentuated under drier conditions and in heavier textured soils; (iii) The development of biodegradable materials to replace polymers for coating EEF's will reduce the risk of introducing persistent bioplastics into the environment, but improvements in coat integrity are needed before reliable performance is assured; and (iv) The efficacy of standard urea and the EEF products will vary with soil and seasonal conditions, and so potential agronomic or environmental benefits will likely be site and season-specific.

This project has demonstrated that while N rate reductions will afford water quality benefits, risks of negative productivity impacts remain. Adoption of EEF technology continues to offer promise, particularly in terms of greater fertiliser N recovery by the target crop, but productivity or environmental benefits have not yet been demonstrated on a consistent basis. Given the additional cost/kg fertiliser N applied as EEFs, more extensive testing of agronomic and environmental impacts of different combinations of EEF technologies and fertiliser application strategies (locations, rates and timing) are needed before widespread government or industry investment in these approaches can be justified.

1.0 INTRODUCTION

The latest estimates suggest that anthropogenic activity has more than doubled total catchment nitrogen (N) loads entering the GBR lagoon (from 20,000 to 46,500 t N/year), although the contributions and constituents of those loads vary markedly between regions and between land uses (McCloskey *et al.* 2017). The predominant constituent (48%) of N lost from land used for sugarcane production is dissolved inorganic N (DIN), with this form of N rapidly taken up by pelagic and benthic algae and microbial communities (Alongi and McKinnon 2005), often leading to high levels of organic production and short-lived phytoplankton blooms during the summer season (Furnas *et al.*, 2005, 2011). The high proportion of DIN leaving sugarcane catchments and the rapid bioavailability of this form of aquatic N therefore represents a substantial risk to marine ecosystem health.

The Australian sugar industry operates in challenging environments, with high rainfall and variable soil types collectively producing difficult conditions in which to efficiently manage a mobile nutrient such as N. In addition, the crop demand for available N to support biomass growth and cane yield accumulation occurs over an extended period (typically 6-8 months – Bell *et al.* 2014) that commonly includes the monsoonal wet season. This extended period of crop-N demand, combined with limitations to field access once crop size increases and prolonged wet conditions, increases the risk of loss of labile forms of N via gaseous and aqueous loss pathways, especially if the combination of fertiliser application strategies and soil N transformations result in accumulation of nitrate-N (NO_3-N). While these loss risks vary with soil type, seasonal conditions and the timing of fertiliser application relative to the onset of the monsoonal wet season, their occurrence has resulted in the development of ‘conservative’ N management systems that have typically resulted in the application of N at rates that are in excess of crop N requirements. Current 'best' practice N management is based on the results of a large program of fertiliser N response trials conducted across the industry. It recommends rates that are derived from combinations of target yields (t cane ha^{-1}) assessed at the district level (Schroeder *et al.* 2010), a crop N-requirement factor (kg N t $cane^{-1}$) derived from Keating *et al.* (1997) and a soil-specific N rate adjustment factor that uses soil organic C to estimate the annual N contribution from in-season mineralisation (Schroeder *et al.* 2010). While there are opportunities to refine all three components of this approach (Thorburn *et al.* 2018), there has been considerable attention paid to the use of the district yield potential (DYP) to calculate fertiliser N requirements for fields that are consistently lower-yielding. These situations can result in N supply greatly exceeding crop N demand and may cause the formation of hot-spots for N contaminant export.

Simulation studies (Thorburn *et al.* 2017a) have illustrated the quantum and variability of such off-site N losses from conventionally fertilised sugarcane fields in Tully and Mackay over a 7-year climate sequence. At urea-N application rates of 150 kg N ha^{-1} applied to fine and coarse-textured soils, seasonal total N loss from fertiliser and soil N sources by denitrification and leaching was estimated to range between about 15-110 kg N ha^{-1} at Mackay and between 35-200 kg N ha^{-1} at Tully, with soil type influencing both the quantum of loss and the likely loss pathway. The extent of this variability adds considerable uncertainty to the calculation of an optimal N-fertiliser rate.

There is considerable evidence that at least part of the ‘lost’ fertiliser-N from sugarcane systems is entering the marine environment in the Great Barrier Reef lagoon, with adverse impacts on water quality and the health of the marine ecosystem (Bell *et al.* 2016; McCloskey *et al.* 2016). There is, therefore, an imperative to reduce the quantum of fertiliser-N loss from sugarcane fields, but attempts to do this through a simplistic approach such as reducing N rates in lower yielding fields without changing other aspects of agronomic or fertiliser-N management has been shown to introduce risks to crop productivity (Thorburn *et al.* 2017b, 2018). Similarly, despite recent machinery advances that allow split N applications to be made later in the crop season, there are suggestions that this strategy used with conventional urea alone will still prove relatively ineffective at reducing fertiliser-N requirement and improving N use efficiency (NUE; Thorburn *et al.* 2015).

Enhanced efficiency fertilisers (EEF) attempt to modify fertiliser-N release rates or control the rate of N transformations in and around the fertiliser band to better synchronize labile-N availability with crop-N demand. While different strategies have proved more or less effective in varying soil types (Di Bella *et al.* 2017), their ability to increase cane yield or allow reduced fertiliser-N rates has been variable (Bell *et al.*, 2019; Verburg *et al.* 2017, 2018) and the higher cost of these products/kg N applied has typically resulted in a reduction in profitability, even when applied as blends with conventional urea (Kandulu *et al.* 2017). There has been no work quantifying the impact of EEF use on off-site N losses.

We have conducted field studies that compare the standard approach to fertiliser-N (urea) management currently documented within Step 4 of the SIX EASY STEPS™ (6ES) framework (Schroeder *et al.* 2014) with one in which fertiliser-N rates are based on the productivity potential of the individual block/zone, and the fertiliser is applied as either urea or the most effective blend of EEF products commercially available. The efficacy of these different strategies was assessed on the basis of productivity, profitability, fertiliser NUE and runoff water quality.

This work was supported by more fundamental studies on the performance of conventional and EEF-types of N fertilisers currently being evaluated in the sugar industry, as part of a PhD program completed by Dr Chelsea Janke. This work focused on the chemical reactions that occur in and around a concentrated band of N fertiliser typical of that applied in sugarcane cropping systems, to determine whether the band environment impacts on the effectiveness of different EEF technologies.

2.0 MATERIALS AND METHODS

2.1 Field trial program

2.1.1 Field sites and fertiliser application rates

We established seven field sites after the 2016 crop harvest (Table 1), with an additional site established to replace a block damaged by cyclone Debbie that was ploughed out after the 2018 harvest. All experiments were initiated in 2016 after harvesting the first (1R) or second (2R) ratoon crop, with the exception of the Freshwater site north of Cairns (fifth ratoon – 5R). The new site established at Homebush, near Mackay, was after harvest of the fourth ratoon (4R). Selected site details are shown in Table 1, but it is worth noting that the poor yielding zones in the North Eton (Site 1) and Homebush (Site 2) locations were the result of differences in sodicity (Site 1) or soil texture (Site 2).

The experimental design and plot size varied with site, with experiments at each site typically consisting of at least five treatments with varying replications. In Silkwood, Freshwater and the Burdekin, plots were large-scale strips six to eight cane rows wide and the length of the cane block, with yield (and in the case of Silkwood and Freshwater, runoff water quality) collected from the entire treated strip. Due to the extensive water-quality monitoring equipment requirements at Freshwater and Silkwood the treatments were not replicated at those sites, but the Burdekin trial contained three replicate strips of each treatment. The treated areas at Mackay were also large replicated strips, with treatments deployed in high and low yielding areas of the same block, although the harvested area in each replicate of each treatment was a 30 m length of harvested cane row. At Tully, both sites consisted of smaller plot, replicated experiments in a randomized block design. Plot size was six cane rows wide and 30 m long, and all treatments were replicated four times except for the Nil N plot, which had two 'new' replicate plots in each growing season.

Treatments consisted of combinations of N application rates and fertiliser N products. Each site hosted a Nil N treatment each year (fertiliser-N was withheld for that growing season), but these plots/strips were moved to new plot/strip locations within the trial site annually. Having the Nil N treatment always located on a plot with a history of fertiliser-N application provided a realistic assessment of the soil N supply which the fertiliser-N application was designed to augment in each field. The basis of N fertiliser rates in treated plots was either the District Yield Potential (DYP, currently used to determine the fertiliser-N rates in 6ES) or the Productivity Zone Yield Potential (PZYP, used to determine N rates aligned to a site-specific yield target based on past performance), with those targets shown for each site in Table 1. The PZYP was calculated from the mean yield of the block from mill or satellite records over two or more crop cycles, plus 2 times the standard error of that mean. As all sites were established in ratoon crops, plant-crop yields were generally excluded from this calculation, especially where those yields were markedly higher than yields of the ratoons.

Each site also included a discretionary treatment that was typically applied at a rate that differed to the DYP or PZYP calculation. In the Burdekin, this reflected a rate based on a lower DYP target (i.e. 150 t/ha rather than 180 t/ha). In sites where large variation in yields occurred between La Niña and normal or drier seasons (e.g. in parts of the wet tropics), separate PZYP targets were calculated to reflect the expected seasonal forecast (i.e. lower PZYP targets in forecast La Niña conditions), with the discretionary N rate varied accordingly. There was substantial variation in soil organic carbon (C) among sites (1.0-5.6% C), which modifies the fertiliser-N guideline in 6ES. However, there are recognized situations where the in-season soil-N mineralisation adjustment (which is based on soil organic-C content) is uncertain (e.g., sites occupying low landscape positions and with elevated C, such as the Silkwood site). Given this, the discretionary N rate at the Silkwood, Tully and the first Mackay site were used to compare rates with and without adjustment for the soil-N mineralisation.

Crop harvest and fertiliser application were conducted as per the grower's normal practice at each location, although in both years at all sites there were no crops harvested in the first round (i.e. the first third of the harvest window). This was considered desirable, as it was expected that the best chance to assess the risks of reduced N rates and the efficacy of EEFs would be under conditions where fertiliser-N losses were more likely to occur (i.e. where the onset of the monsoonal wet season occurred before the crop had finished the majority of biomass-N accumulation).

2.1.2 Fertiliser-N sources

The same fertiliser-N sources were used at all sites. The fertiliser-N standard was taken as granular urea, which was applied during the month following harvest of the preceding ratoon. This was compared to an EEF blend consisting of one-third by weight of the urea coated with the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP, marketed commercially as Entec®-urea) and two-thirds of a polymer-coated urea with a reported 90-day release period. The latter product was originally provided by Everris Pty Ltd (Agromaster Tropical®), but in some seasons and locations a shortage of supply resulted in substitution with another polymer coated product with a similar release period supplied by Kingenta Australia (N90).

This blend was chosen as the best possible combination of products that would protect fertiliser-N from risk of loss – initially by retaining the N in the ammonium (NH_4-N) form via the urea coated with DMPP, and then subsequently by slowly releasing urea-N into the soil solution from the coated product where it was hydrolysed and converted rapidly to NO_3-N. The proportions of each product were chosen on the basis of reportedly limited activity of the DMPP nitrification inhibition beyond 5-8 weeks under field conditions and the prolonged crop N uptake period in sugarcane crops (6-7 months – Bell *et al.* 2014). Both products were applied using either stool-split (Burdekin, Mackay, Freshwater and Silkwood) or subsurface side-dress (Tully) fertiliser applicators.

The initial 2015/16 season at the Mackay 1 site hosted an initial exploratory study in which a single EEF product (Entec®-urea) was compared to granular urea, but treatments were adjusted to the EEF blend in subsequent years.

2.1.3 Fertiliser-N recovery, crop yield and indices of fertiliser NUE

A number of indicators of crop performance were used to assess the agronomic effectiveness of the different fertiliser strategies, with a focus on crop yield responses (cane and sugar yield and CCS), N accumulation in crop biomass and the incremental yield and crop N responses to fertiliser N application (i.e. fertiliser N recovery – kg additional crop N uptake/kg fertiliser N applied), and agronomic efficiency (kg N applied to produce an additional t of cane yield). The data set was also suitable to develop benchmarks of crop N utilisation efficiency (NUtE - kg crop N uptake/t cane produced) that were independent of the source of crop N. The latter measure was useful for benchmarking crop performance between locations, and between treatments at a location, in terms of the extent and severity of N availability as a constraint to productivity.

Fresh and dry biomass and crop-N content were determined from hand-cut biomass samples collected from 7-10 months after fertiliser application on the assumption that at this stage, the crop-N content would be at a maximum, and most relevant to the yield-determining processes (Bell *et al.* 2015). Cane and sugar yields were determined by commercial harvest in the case of the large strip plots, with the bins collected from each strip weighed and CCS determined at the mill. In the case of the small plot trials, yields were determined from small-plot hand harvesting and CCS was determined by near infrared spectroscopy (Berding *et al.* 2003).

2.1.4 Runoff and drainage losses of N

Surface water runoff was monitored in four of the fertiliser rate treatments at Freshwater and Silkwood in three seasons, with the Nil N treatment also monitored at Freshwater. Strategic sampling in the farm drain around the block was also undertaken at Silkwood, while drainage losses of N below the root zone (1 m depth) were also quantified at this site using barrel lysimeters installed in each block in which runoff monitoring was conducted. The lack of reliable drainage volume estimates prevented calculation of N loads from this loss pathway. It should be noted that particularly at the Freshwater site, extreme rainfall events occasionally overwhelmed runoff flumes and so data for runoff N cannot be used as a total annual runoff estimate. We therefore have focussed on relative treatment effects in this report.

Runoff water samples were collected by automated samplers at both sites, although load calculations were estimated differently. At Silkwood, each water sample represented an integrated composite (flow weighted) of runoff from individual events across the hydrograph (event mean concentration) while at Freshwater, discrete flow-weighted samples were collected across the hydrograph. Runoff samples were analysed for sediment, total N, urea-N, ammonium-N, and oxidised-N (NO_3-N and nitrite-N). Drainage samples were analysed for nitrate-N and ammonium-N concentrations at Silkwood only.

Table 1. Details of the experimental sites and fertiliser-N rate treatments.

Location	Soil type	Soil organic C (%)	District yield potential (and 6ES N rate)	Productivity zone yield potential (and N rate)	Discretionary treatment (N rate)	Variety and initial crop stage
Burdekin (Mulgrave region)	Loam over sodic clay (Sodosol)	1.0	180 t ha-^{1} (200 kg N ha^{-1})	130 t ha-^{1} (150 kg N ha^{-1})	Urea rate for a DYP of 150 t ha^{-1} (170 kg N ha^{-1})	Q240^{A} (1R)
Tully 1 (well drained)	Well-drained silty light clay (Tully series)	1.0	120 t ha-^{1} (140 kg N ha^{-1})	130 t ha-^{1} (150 kg N ha^{-1})	(i) PZYP without mineralisation discount (170 kg N ha^{-1}, urea) (ii) Wet season exploratory (120 kg N ha^{-1}, EEF)*	Q208^{A} (2R)
Tully 2 (poorly drained)	Poorly drained silty clay loam (Timara series)	2.3	120 t ha-^{1} (110 kg N ha^{-1})	130 t ha-^{1} (120 kg N ha^{-1})	(i) PZYP without mineralisation discount (170 kg N ha^{-1}, urea) (ii) Wet season exploratory (90 kg N ha^{-1}, EEF)*	Q208^{A} (2R)
Silkwood**	Bulgun series (Hydrosol)	5.6	120 t ha-^{1} (160 kg N ha^{-1}*)	80 t ha-^{1} (100 kg N ha^{-1}*)	(i) Long-term Nil N subplot	Q183^{A} (2R)
Freshwater (Mulgrave)	Well drained clay on alluvium (Innisfail series)	0.8	120 t ha-^{1} (150 kg N ha^{-1})	97 t ha-^{1} (110 kg N ha^{-1})	(i) DYP N rate as EEF blend (ii) Small plot N rate trial, urea/EEF blend	Q208 ^{A} (5R)
Mackay 1 Nth Eton (high yield)	Gravelly yellow sodic duplex (Pindi series)	1.0	130 t ha-^{1} (150 kg N ha^{-1})	130 t ha-^{1} (150 kg N ha^{-1})	(i) PZYP without mineralisation discount (170 kg N ha^{-1}, urea) (ii) Exploratory EEF at 80% DYP, no mineralisation discount (130 kg N ha^{-1})	Q208^{A} (2R)

Mackay 1 Nth Eton (low yield)	Gravelly yellow sodic duplex (Pindi series)	0.7	130 t ha-1 (160 kg N ha-1)	90 t ha-1 (130N kg N ha-1)	(i) EEF at 80% PZYP without mineralisation discount (105 kg N ha-1)	Q208A (2R)
Mackay 2 Homebush (high yield)	Loamy yellow duplex (Sandiford)	0.6	130 t ha-1 (160 kg N ha-1)	130 t ha-1 (150 kg N ha-1)	(i) Exploratory EEF at 80% of DYP rate	Q138A (2R)
Mackay 2 – Home bush (low yield)	Sandy yellow duplex (Sandiford)	0.6	130 t ha-1 (160 kg N ha-1)	90 t ha-1 (130 kg N ha-1)	(i) Exploratory EEF at 60% of DYP rate	Q138A (2R)

* Based on adjusting fertiliser-N rates in response to seasonal climate forecasts (Skocaj 2015).

** The mineralisation index on this high-C Hydrosol overestimates background N mineralisation; the 6ES rates, therefore, do not include the mineralisation rate discount, and were applied as urea or the EEF blend

2.2 PHD PROGRAM - BANDING STUDIES

A series of laboratory studies were conducted to explore the environment created by a concentrated fertiliser band typical of those applied in the sugar industry, and the 1-dimensional movement of N species and inhibitor chemicals from a band into surrounding soil. This laboratory work was complimented by a field study (without plants) in a Vertosol soil at Gatton, where 3-dimensional movement of N species in response to concentration gradients and seasonal rainfall was quantified. Granular urea was used as a reference product against which the performance of different EEFs were benchmarked in each study.

2.2.1 Fertosphere chemistry – sealed containers

The objective of this study was to determine the effectiveness of EEF technologies within the fertosphere (soil within 2.5 cm of the fertiliser band) at field capacity in a range of soils with a history of sugarcane production – including from the Silkwood field site used in this study. Urea and EEF granules were applied to achieve fertosphere conditions that were consistent with an in-band concentration equivalent to that experienced when 150 kg N ha^{-1} is applied in the field in bands 1.8 m apart (i.e. 27 g N m^{-1} of fertiliser band). This is typical of application practices in the Queensland sugar industry. Details of the incubation procedures are provided in detail in the publication by Janke *et al.* (2019).

Measurements consisted of: (i) establishing the key chemical effects and N-transformation activity within the fertosphere, and (ii) contrasting these findings with nitrification inhibitor (NI) coated urea and a controlled release polymer coated urea (PCU). The incubations were conducted under static conditions over a 112- day incubation period, to cover the reported release period of the PCU product. Containers were sealed with the exception of small holes to allow aeration, so there was no interaction between the fertosphere soil and unfertilised soil outside the fertosphere, as would occur in a field situation.

2.2.2 Diffusion of N species and inhibitors outwards from the fertosphere

The incubation was conducted in round incubation pots (225 mm diameter PVC end-caps), using sugarcane soils with contrasting physical and chemical properties (a sandy Dermosol and a heavy clay Vertosol). Methods are provided in full detail in Janke, Fujinuma *et al.* (2020). Briefly, fertiliser N treatments were applied into the centre of the pot in a vertical band/column (1 cm diameter) at a rate equivalent to the in-band concentration of fertiliser N applied at 150 kg N ha^{-1} in bands spaced 1.8 m apart. Cotton wicks were inserted vertically in the fertosphere, and in an offset pattern outwards from the fertiliser band to the extremities of the pots at regularly spaced intervals. Soil moisture was maintained at field capacity over incubation periods that ranged from 16 days (urea, and urea-based EEF’s with urease or nitrification inhibitors) to 35 days (urea and PCUs), with unfertilised soils included in each assay.

Destructive sampling of replicated pots of each treatment was conducted at regular intervals during the incubations. Soil in each pot was collected from a 2 cm diameter central core (designated the ‘0 cm’ position), and then in increments moving outwards from that central core designated as the 2 cm, 4 cm, 6 cm, 8 cm and 10 cm samples. Soil samples were used to determine mineral N using standard methods.

Wicks were used to recover representative soil solution at different distances from the fertiliser bands, and were analysed for urea-N and also for the presence of the urease or nitrification inhibitors used in each product.

2.2.3 Three dimensional movement of N species in the field

The field study was conducted on a Vertosol soil at the University of Queensland, Gatton Campus, over the 2017/18 summer season, with full details provided in Janke, Moody *et al*. (2020). Fertiliser treatments were applied in bands at 12.5 cm depth at rates of 50 to 150 kg N ha^{-1}, with each treatment replicated four times. In-band concentrations were chosen to be representative of fertiliser N rates applied in the sugarcane, grains and irrigated cotton industries.

Treatments included an unfertilised treatment, and application rates of 50, 100 and 150 kg N ha^{-1} applied as urea, or urea with the nitrification inhibitor DMPP (Entec®). In addition, other EEF products tested included urea coated with a blend of DMP and succinic acid (Entec 2, Eurochem Pty. Ltd), urea with the urease inhibitor NBPT (Green Urea NV®) and the PCU, Agromaster Tropical®. After fertiliser application, the distribution of urea-N and mineral N species (NH_4-N and NO_3-N) were monitored over a 71 day period, with samplings based on likely duration of EEF efficacy and in response to significant rainfall or irrigation events. Plots were maintained free of plants during this period.

At sampling events, soil monoliths were collected at right angles to the fertiliser band and dissected into zones that allowed quantitation of vertical (both above and below the fertiliser band) and lateral movement of N out of the fertiliser band, in response to both diffusion and mass flow. Samples were collected over a 30 cm vertical distance (12.5 cm above and below a fertosphere 5 cm in diameter), and out to a distance of 12.5 cm horizontally. At all sampling times, chemical conditions in and around the fertiliser band were monitored, along with urea-N and mineral N species.

3.0 PROJECT OVERVIEW

This report represents a synthesis of results from experiments conducted at Freshwater, Tully (2), Silkwood, the Burdekin and Mackay (2 sites, each with 2 paddock zones). Detailed site reports are attached as appendices to this report: Appendix 1 – Silkwood; Appendix 2 – Burdekin; Appendix 3 – Tully; Appendix 4 – Mackay; Appendix 5 – Freshwater). These appendices provide detailed information about the sites, experiment management, seasonal conditions and other relevant information. Key findings from the field studies (Section 3.1) are presented in terms of treatment impacts on crop productivity across all sites (Section 3.1.1 – Productivity impacts) and runoff water quality for the sites at which it was monitored (i.e. Freshwater and Silkwood, Section 3.1.2 – Water quality benefits).

It should be noted that these experiments were deliberately managed in a way that maximised the exposure of fertiliser N to conditions most likely to promote environmental losses, and so do not represent a broad testing of N management strategies across the industry. Similar caveats need to be made regarding the measured runoff losses at Silkwood and Freshwater, while it should also be noted that runoff data from either site does not necessarily represent annual runoff totals. Flumes were occasionally overwhelmed in major events in each growing season, and so the focus is on relative treatment differences.

The field studies were complimented by more controlled experiments exploring the impact of fertiliser banding on the efficacy of different EEF technologies, applied alone or as blends like those used in the field studies. A number of these experiments have already been published, but a short summary of the key findings from each aspect of the work are reported in section 3.2 (Key findings - laboratory studies), with more details provided in Appendix 6.

A list of published papers arising from the field and laboratory programs appears in the References – Published papers.

3.1 Key findings - Field studies

Seasonal conditions were variable across sites and seasons, both in terms of the amount of wet season rainfall but also the timing of rainfall relative to fertiliser application, which was typically undertaken 1-2 months after crop harvest. This information is presented in each of the detailed site reports, but an example is shown for the four crop seasons from the SRA sites at Tully (Figure 1). This data illustrates the very contrasting conditions into which fertilisers were applied and that fertiliser N released into the soil experienced in the months following application. For example, soil profiles were mostly quite dry when fertilisers were applied, with the 3R crop being the exception; the 2R crop experienced heavy rainfall and flooding within 6 weeks of fertiliser application, while this did not occur until 5 months after fertilising the 3R crop and was never experienced in the 5R crop; spring-summer rainfall totals represented nearly wet (2R and 3R crops), wet (4R) and dry (5R) years, using the classification system reported by Skocaj (2015). These differences in seasonal rainfall distribution and soil moisture dynamics influenced fertiliser N dynamics and crop yields, and are discussed in section 3.1.1.

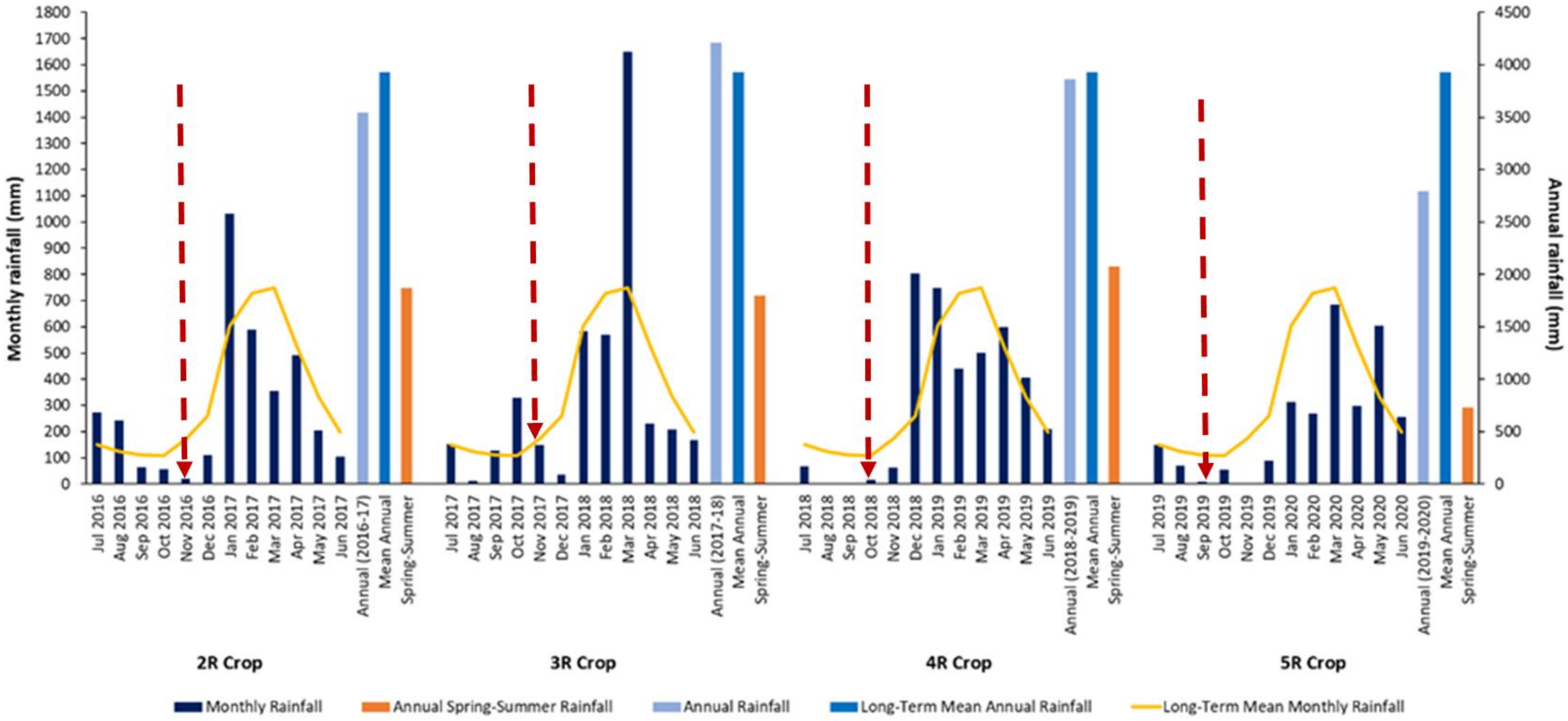


Figure 1. Monthly and annual rainfall recorded at the Tully Sugar Limited Bureau of Meteorology station (32042) pertaining to the 2R, 3R, 4R and 5R crops. Dates of fertiliser application are indicated by red dashed arrows for each season.

3.1.1 Crop productivity

Productivity results have been benchmarked against that of crops receiving urea-N at rates determined using the 6ES methodology – the current industry best management standard. Aside from the unfertilised treatments in some instances (i.e. the Burdekin in Appendix 2), there were no statistically significant effects of fertiliser N rate or N product on CCS, and so sugar yields from the different treatments reflect differences in fresh weight cane yields at each location. Results for individual seasons are presented in the detailed reports for each site (Appendices 1-5). Here we have considered treatment effects in terms of either (a) cumulative cane production over the duration of the monitoring period for all sites, or (b) a repeated measures analysis of productivity data collected from the same replicate plots each year for the duration of the study. The former analysis was conducted for all sites, and represented cumulative cane yields from two (the first and second Mackay sites), three (Silkwood, Freshwater and the Burdekin) and four (the two Tully sites) successive ratoon crops. The latter was only able to be conducted in the fully replicated trials in the Burdekin (three successive ratoons) and Tully (four successive ratoons at both the well-drained and poorly-drained sites).

3.1.1.1 Cumulative cane production

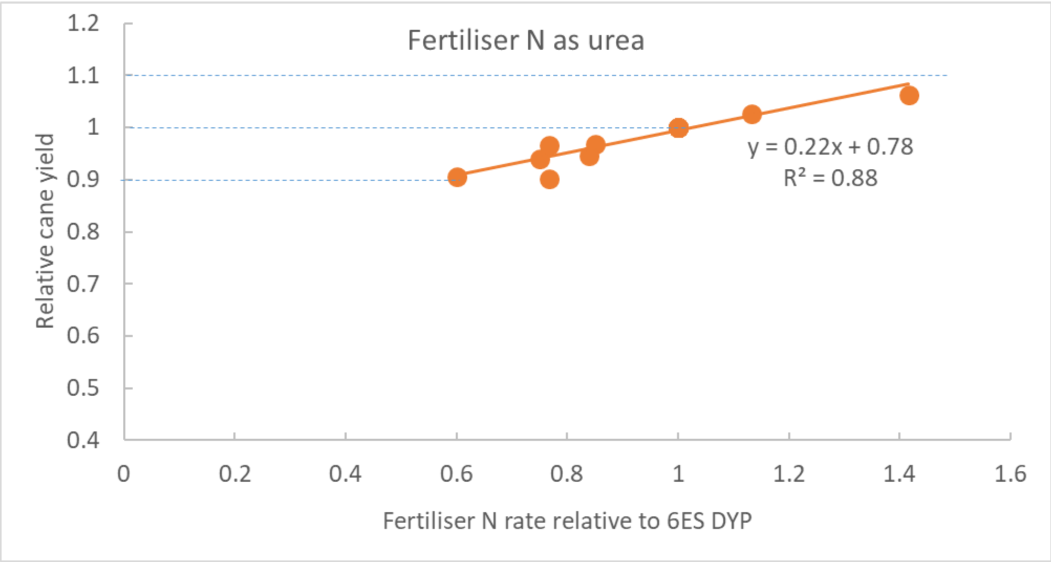
(i) Reduced fertiliser N rate applied as urea

The productivity response to changing the rate of fertiliser N applied as urea (Figure 2a) was linear, but the rate of productivity response was relatively slow. Yield reductions of 10% relative to that recorded from the DYP-derived urea N rate were only recorded in the low yielding zone at Mackay site 2 (Homebush) with a 22% N rate reduction, and at the Silkwood site when there was a 40% reduction in fertiliser N rate. Yields did appear to trend upwards as urea rates increased above the DYP-rate, but effects were small. There was a 4% increase in production with a 13% fertiliser rate increase at the well-drained Tully site and a 6% increase with a 42% increase in urea-N rate in the poorly drained site at the same location. The collective data set suggests that reducing urea-N rates by 20% would result in only a 5-6% reduction in block productivity. However, the size of this rate reduction was in some cases equivalent to the N mineralisation discount, and so responses may reflect either a reduction of the fertiliser N surplus, an underestimation of the soil N mineralisation or some combination of both.

(ii) Reduced fertiliser N rate applied as EEF blend

The productivity response to lower N rates with the EEF blend was largely similar to that of urea, with three noticeable exceptions (Figure 2b). These occurred at the unreplicated Freshwater and Silkwood sites, where changing from urea to the EEF blend at the DYP rate increased productivity by 11% and 30%, respectively, while a 14% yield increase was recorded with the EEF blend in the sandy, low yielding zone at the Homebush site – despite N application rates being reduced to only 60% of the DYP rate. These apparently strong relative productivity responses arising from use of the EEF blend all occurred at low yielding sites/zones, and the increases in cane production averaged only 6 (Freshwater and Homebush) – 12 (Silkwood) t ha^{-1} $year^{-1}$. As pointed out in the detailed economic analysis conducted for the Tully sites (Appendix 3), these small productivity increases were rarely enough to compensate for the much higher cost of the EEF blend ($3.30/kg of N applied) compared to urea ($1.23/kg of N applied). The exception was when rate reductions were large (e.g. reduced from 150 kg N/ha (DYP urea) to 90 kg N/ha (60% of DYP) at the Homebush site), and the combination of higher yields (an average of 6 t ha^{-1}) and reduced N rates would have resulted in small increases in profitability.

(a)



(b)

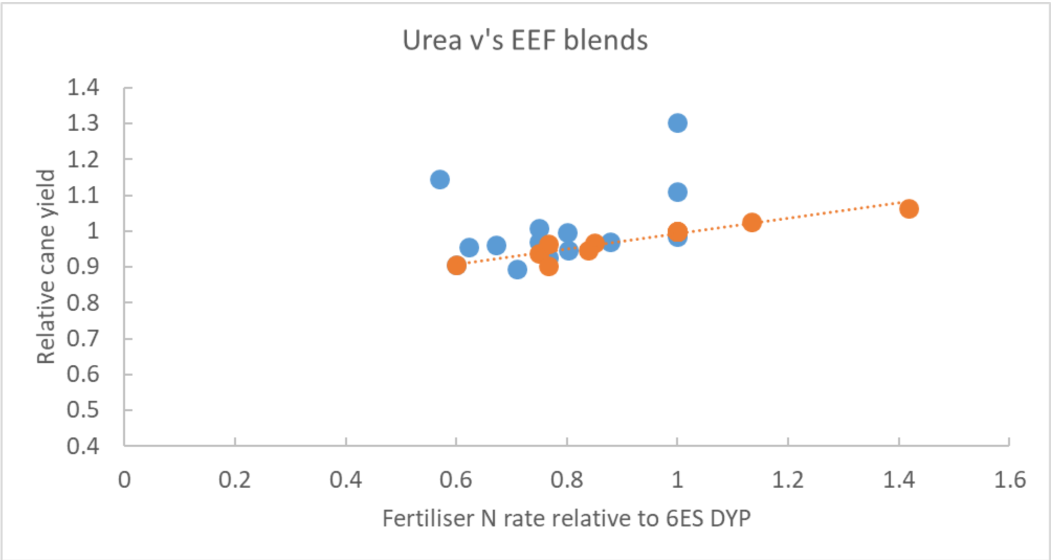


Figure 2. Effects of application of (a) urea-N or (b) urea-N (orange circles) and the EEF blend (blue circles) at different rates on the cumulative cane produced over 2, 3 or 4 consecutive ratoon crops at the field experimental sites. The fertiliser N rates are expressed as a fraction of the rate that was applied based on the 6ES-DYP calculation, while productivity is expressed as a fraction of that produced from plots receiving urea at the 6ES-DYP rate.

3.1.1.2 Seasonal influences on the crop response to N fertiliser product and rate

The four season replicated experiments at Tully (well-drained and poorly-drained sites) and the three season replicated experiment in the Burdekin were subjected to a repeated measures analysis of variance, to test for consistency of responses in relation to differing climatic conditions across the contrasting seasonal conditions (e.g. Figure 1 for the sites at Tully, and in the detailed Burdekin report in Appendix 2). All three experiments returned significant responses to growing season, but no significant effects of N treatment (rate or product) and more importantly, no significant interaction between growing season and N treatment, indicating an encouraging stability of treatment responses. Average cane yields progressively decreased with age of the crop (R1 to R3) and harvest date (mid-August to the end of October) in the Burdekin, falling from 119 t/ha (R1) to 94 t/ha (R3). Yields in the sites at Tully were more variable, related to combinations of seasonal conditions and crop lodging as well as to differences in crop duration/harvest date, and ranged from 118 t/ha (R2) to 102 t/ha (R3) at the well - drained site and 95 t/ha (R2) to 107 t/ha (R3) at the poorly-drained site (see Appendix 3).

While there was no statistically significant interactions between seasons and treatments, the variation in cane yields in response to N rates and products have been presented in Figure 3 for the Burdekin and poorly-drained Tully sites to illustrate the contrasting effects of seasonal conditions in irrigated (Burdekin) and rainfed (Tully 2) farming systems. At the irrigated Burdekin site there was a trend for small yield reductions when the urea rate was reduced by 15%, most noticeably in the 2016/17 season, and increasing the rate reduction to 25% (equivalent to moving to a rate based on PZYP rather than DYP) resulted in a further 5% - 7% yield reduction in all seasons. In contrast, the same 25% rate reduction with the EEF blend showed stable productivity equivalent to that from the full DYP-based rate.

In contrast, the poorly-drained site at Tully showed 10-15% yield increases with a markedly higher rate of urea application in two of the four seasons (2017/18 and 2019/20), but no response in others. However, there were similar productivity increases at much lower N rates with the EEF blend in the 2019/20 season and a slightly smaller response to the EEF blend at the DYP rate in 2017/18. In contrast, treatments receiving the EEF blend performed relatively poorly in both 2016/17 and 2018/19 seasons, regardless of rate. The former season was characterised by an early season flood event and bad crop lodging, while 2018/19 was continuously wet without any major flood events. Variation in crop N accumulation (discussed later) was not consistent with these yield responses.

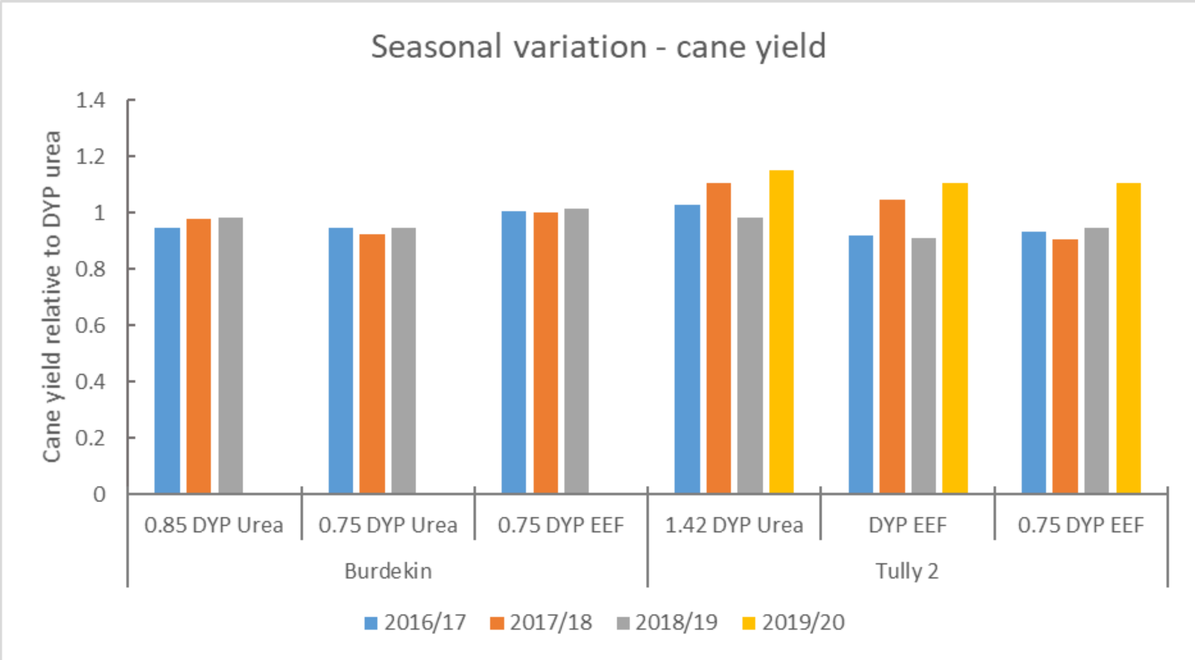


Figure 3. Effects of fertiliser N treatment on the cane produced over three (Burdekin) or four (Tully 2) consecutive growing seasons. The fertiliser N rates are expressed as a fraction of the rate applied using the 6ES-DYP calculation, while productivity is expressed as a fraction of that from plots receiving urea at the 6ES-DYP rate.

3.1.2 Crop N accumulation and use

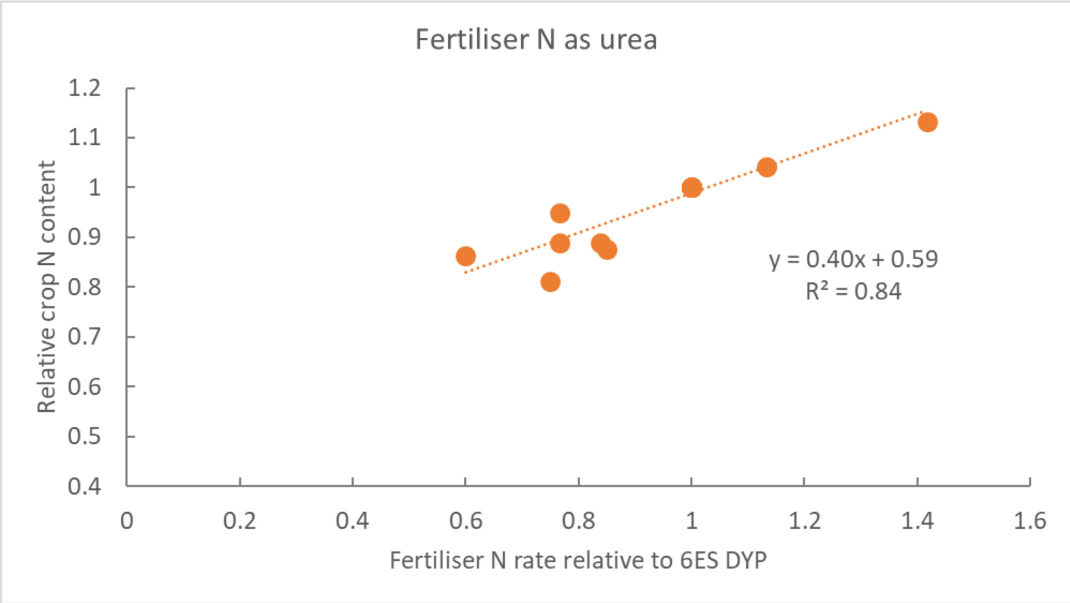
The greatest challenge in reducing fertiliser N rates is ensuring that crops are able to access enough N in a timely manner to maximise crop performance, while minimising the loss of N to the environment via gaseous (denitrification, volatilisation) or aqueous (runoff and deep/lateral drainage) loss pathways. While acknowledging that seasonal conditions and the timing and placement of fertiliser N have key roles in the efficiency of crop N recovery, we have initially considered crop N recovery in these studies as a cumulative total summed across the monitoring period (two to four consecutive growing seasons), before considering seasonal variation at individual case study sites.

3.1.2.1 Total N accumulation

(i) Reduced fertiliser N rate applied as urea

In a similar response to that recorded for cane yields (Fig 2a), there was a linear relationship between the rate of urea-N applied and the produced accumulated in crop biomass across all sites (Figure 4a), with the rate of increase or decrease in crop N content in response to lower or higher rates quite small. This relationship suggests that a 20% reduction in urea-N application rate (relative to the DYP rate) would result in only a 9% reduction in crop N content compared to crops receiving the DYP rate, but rates would have to increase by 28% to result in crop N uptake that was 10% greater than that from the DYP rate. This relationship highlights both the low dependency on fertiliser N for crop N uptake in the year of application, as well as the inefficiency with which crops accumulate N at higher rates of applied N fertiliser.

(a)



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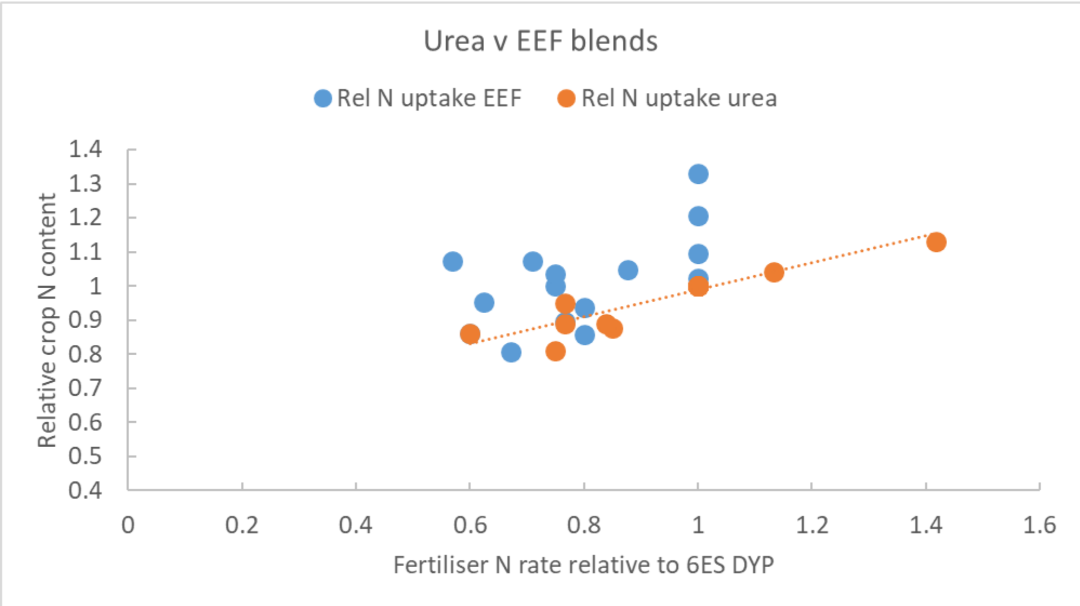

Figure 4. Effects of application of (a) urea-N or (b) urea-N (orange circles) and the EEF blend (blue circles) at different rates on the cumulative crop N accumulation over 2, 3 or 4 consecutive ratoon crops at the field experimental sites. The fertiliser N rates are expressed as a fraction of the rate that was applied based on the 6ES-DYP calculation, while productivity is expressed as a fraction of that produced from plots receiving urea at the 6ES-DYP rate.

(ii) Reduced fertiliser N rate applied as EEF blend

The cumulative crop N uptake response to lower N rates with the EEF blend (Fig 4b) differed a little to that of cane yield (Figure 2b) with the data suggesting a fairly consistent increase in relative N accumulation when the EEF blend was used instead of urea at an equivalent rate. These effects were particularly evident in situations where apparent urea-N recovery at the DYP rate was quite low (e.g. Mackay2 and Silkwood) and the EEF blend effectively doubled apparent fertiliser N recovery, but in less extreme situations (e.g. Burdekin, the poorly drained site at Tully and at Freshwater) the apparent fertiliser recovery increased by nearly 50%.

We have compared the apparent fertiliser N recovery of the EEF blend compared to urea at sites where both products were applied at the same application rate in Figure 5, noting that this does not include the lower rate of urea and EEF applied at the Silkwood site. The latter were excluded because application rates varied from year 1 to year 2, and there was no apparent fertiliser N recovery for either product in the prolonged waterlogged conditions in year 3. This relationship (Figure 5) suggests the strongest improvements in fertiliser N recovery from using the EEF blend were in situations where urea applications were least effective – consistent with conditions of larger environmental losses.

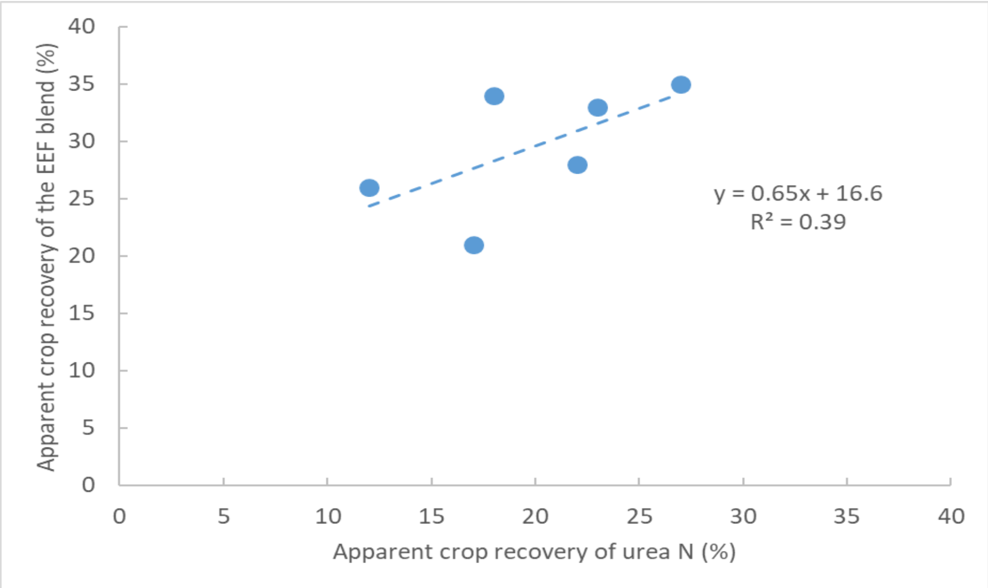

Figure 5. The average apparent fertiliser recovery in crop biomass (% N applied) for urea and EEF treatments applied at the same rate across the experimental sites. These data do not include sites at Mackay (no common EEF and urea N rates), while the average for the well-drained Tully site excludes the heavily lodged R2 crop.

While EEF use tended to increase crop recovery of fertiliser N (Figures 4b and Fig 5), this typically did not result in higher cane yields (Figure 6), which was consistent with the relatively high crop yields in the absence of any applied N for that season (relatively yields of 65-75% of those achieved with the DYP application rate) and the magnitude of the actual crop responses.

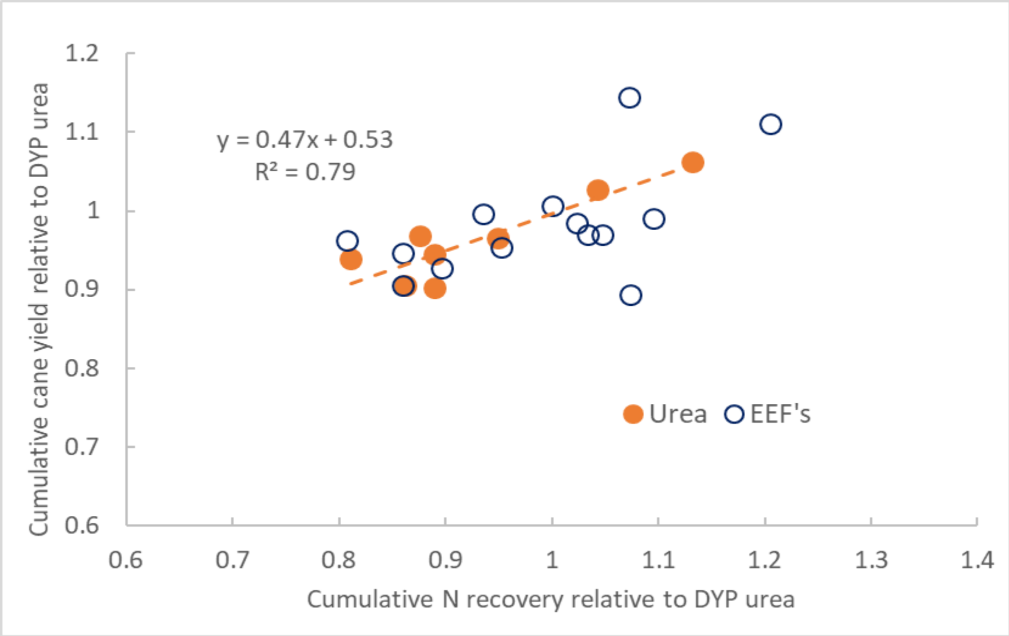

Figure 6. The relationship between recovery of applied fertiliser by the crop and the cane yield response for urea and the EEF blend across all sites. Data reflect the cumulative crop N content and cane yield production for each treatment at each site, but expressed relative to the N recovery and cane production of the DYP urea benchmark.

The agronomic efficiency (AE) of cane yield responses to applied N (the fertiliser N required to produce an additional tonne of cane yield) is documented for each treatment in the site appendices attached to this report. This data generally shows greater variation between sites at the DYP urea rate (from 3.8-4.0 kg N applied/t additional cane produced at the two Tully sites to 19 (Burdekin) – 24 (low yielding zones at the Mackay 1 site) kg N applied/t additional cane produced) than in response to reduced rates or use of EEF's. The greatest impacts of reduced rates or changed products were at the Burdekin, Silkwood and low yielding zones in the Mackay2 sites. In the Burdekin, AE was improved from 19 to 14 kg N applied/t additional cane produced through use of the EEF blend and adoption of reduced rates based on PZYP rather than the 180 t DYP yield target, while a similar combination of much reduced N rates and EEF use improved AE from 10.6 to 4.0 kg N applied/t additional cane produced at Homebush. At Silkwood, AE effectively halved (from 11.7 to 6.2 kg N applied/t additional cane produced) through changing to the EEF blend at the DYP rate. Encouragingly, these improvements in fertiliser NUE were accompanied by increased (at both Silkwood and Homebush) or identical (Burdekin) productivity across the monitoring period. Effects at other sites were more variable, typically resulting in only small changes in AE with either similar or slightly reduced crop production.

Finally, efficiency with which cane crops at the different sites used N accumulated in crop biomass to produce cane yield (iNUE) is shown in a cumulative analysis across all sites in Figure 7. This data set shows that for all sites except Silkwood and the low yielding zone at Homebush (Mackay 2), crops produced ~1 t cane for each kg of N accumulated in crop biomass over the monitoring period. Productivity at the Silkwood site is clearly strongly limited by another factor (presumably seasonal waterlogging, but possibly also low pH) that results in approximately half the productivity response to accumulated N, while the low yielding zone of the field at Homebush was able to use the very limited N it was able to get hold of with effectively double the efficiency of most sites. The latter response is interesting, as it suggests that fertiliser N losses may be a strong driver of productivity in this sandy, low yielding part of the field, and is consistent with the relatively strong crop yields with the EEF blend, despite an application rate that was only 60% of that based on the urea-DYP standard.

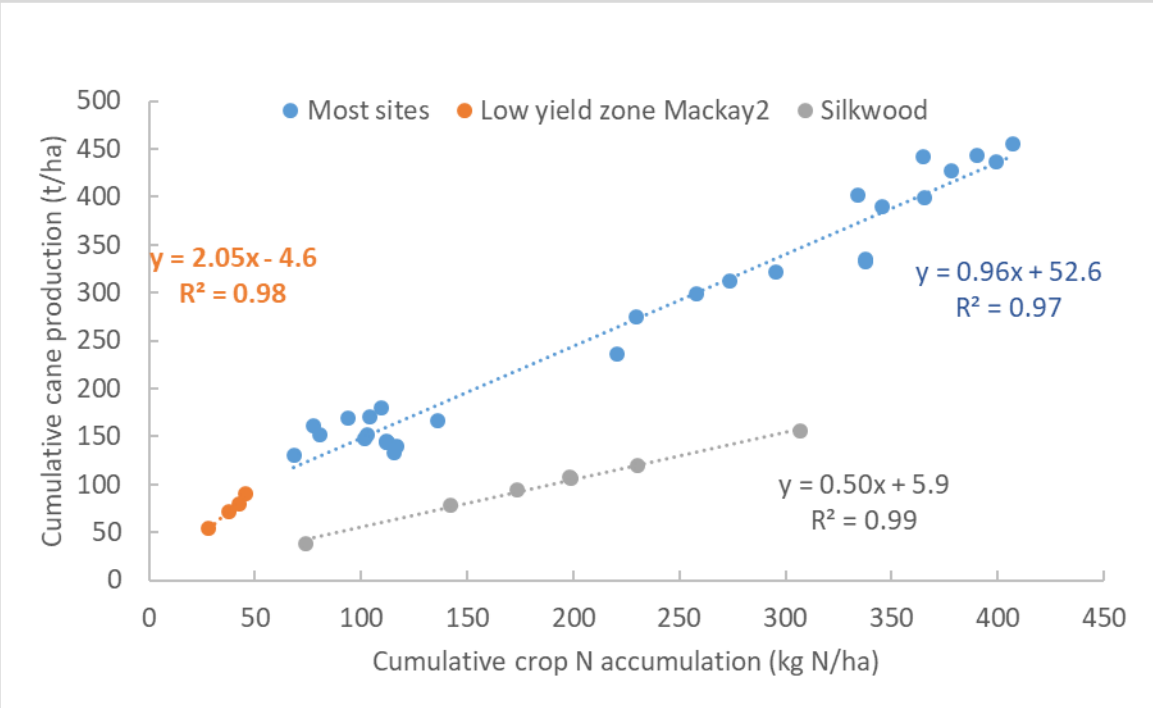

Figure 7. The relationship between cumulative crop N accumulation and cane yield for all sites and treatments in this study. The slope of the respective regressions are indicative of the iNUE of the sugarcane crops at these sites across the monitoring period.

3.1.2.2 Seasonal influences on crop N accumulation in response to N fertiliser product and rate

As with the analysis of cane yields, the variation in crop N accumulation in response to the contrasting seasonal conditions and locations was reflected in statistically significant seasonal effects on fertiliser treatment responses at both Tully sites and in the Burdekin, but without any significant season * treatment interactions. Examples of these seasonal effects are provided in Figure 8, to illustrate the variation present between seasons at the irrigated (Burdekin) and the rainfed (Tully) trial sites that have contrasting landscape positions and propensity to periodic water-logging. The irrigated Burdekin site produced a similar pattern of response in each of the three growing seasons, with small and inconsistent declines in crop N content with urea at rates 15% less than the 180 t DYP standard (i.e. 78-98% of those with DYP urea), but much more consistent declines when rates were reduced by 25% (79-84% of those with 180t DYP urea rate). In contrast, the EEF blend at 25% lower application rates produced crop N contents that were very similar (i.e. 98% to 103%) of those obtained with the DYP standard in all seasons.

The contrasting responses of the two Tully sites in the 2016/17 season illustrates strong benefits of either use of EEFs or significantly higher N rates at the poorly-drained site, but a slight reduction in crop N contents with both strategies at the well-drained site. This season was characterised by an early season flood (Figure 1) and prolonged waterlogging, especially at the poorly-drained site, which may have resulted in substantial losses of N to the environment. Strategies that would have potentially increased the remaining N available to the crop (much higher rates of urea, or use of EEF's) were both effective at increasing crop N accumulation under those conditions. While the reduced N accumulation at the well-drained site with those strategies may seem counter-intuitive, it should be noted that this site lodged badly in this season and it would not be unexpected that crops with higher early season N contents may have lodged earlier, resulting in lower growth and N accumulation later in the growing season.

Other observations were the relatively poor response to the EEF blends at the poorly-drained site in 2018/19, despite similar N uptake at the well-drained site in the same season, and the consistent performance of the EEF blends under very dry conditions in the 2019/20 season at both sites. The latter effect is reassuring, as recent reports have highlighted the importance of prolonged soil moisture to ensure release of N from the coated urea granules (Verburg *et al.* 2020) and the dry seasonal conditions for more than three months after application (Figure 1) would likely have slowed N release into the crop root zone. The lack of any negative effects may have been related to delayed crop growth and N demand commensurate with the dry conditions, so that the EEF blend was still able to release N for more rapid crop growth once the wet season commenced.

The reasons for the relatively poor crop N contents in response to the EEF blends at the poorly-drained site in 2018/19 are not immediately obvious, given the extended wet conditions that occurred from December. A mitigating factor may have been the lack of flooding and what seems to have been apparently greater N availability in the unfertilised plots than previous years – a factor that could reduce the reliance on fertiliser N in the 2018/19 season. Unfortunately, the samples analysed for natural abundance of ^{15}N that may have shed some light on these factors have yet to provide any useful insights, and so effects remain unexplained.

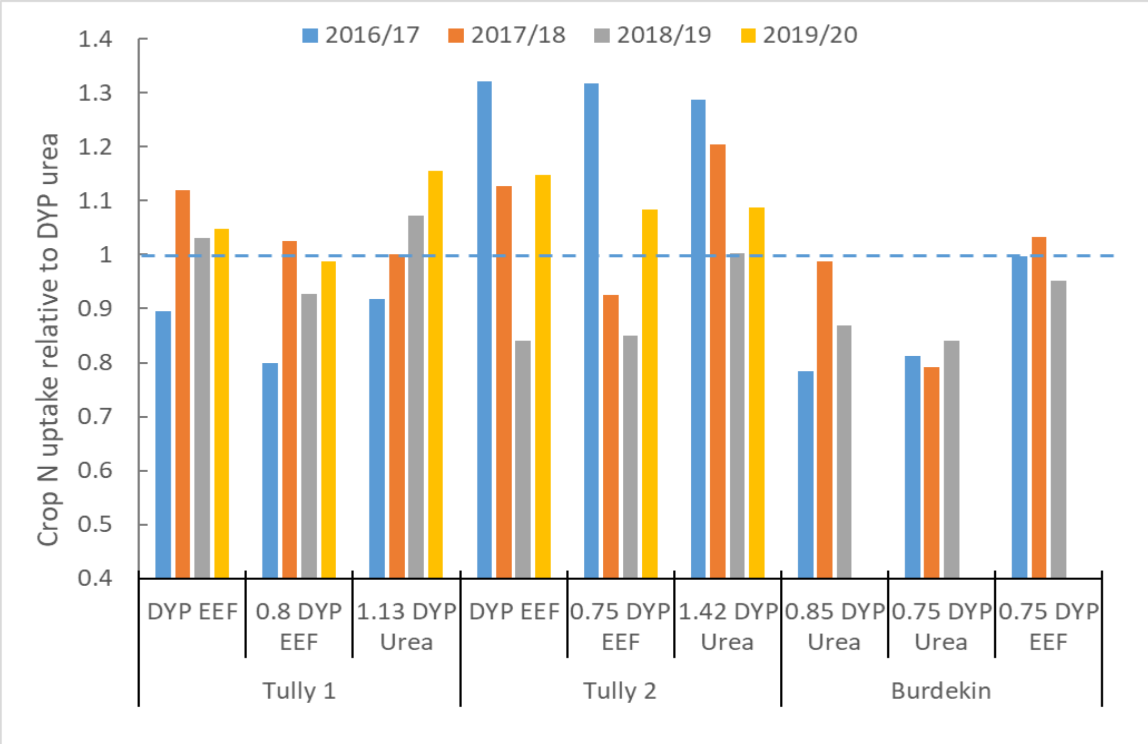

Figure 8. Effects of fertiliser N treatment on the N accumulated in crop biomass over 3 (Burdekin) or 4 (Tully) consecutive growing seasons. The fertiliser N rates are expressed as a fraction of the rate applied using the 6ES-DYP calculation, while crop N accumulation is expressed as a fraction of that from plots receiving urea at the 6ES-DYP rate.

3.1.3 Runoff losses

The seasonal quantities of total N measured in runoff in the 2017, 2018 and 2019 crop seasons are shown in Figure 8, for treatments receiving fertiliser rates determined using either the DYP or PZYP yield target to calculate the fertiliser N rate, and applied as either urea or the blend of EEF technologies specified in 2.1.2. As runoff losses were collected from unreplicated strips at both locations, statistical comparisons cannot be made and results should be considered as indicative only.

The two clear observations that can be made for these data are that: (i) reducing N rates from that derived by DYP to a PZYP rate at Freshwater and Silkwood (24% and 37.5% reductions, respectively) resulted in 20% (Freshwater) - 60% (Silkwood) reductions in total N measured in runoff, while (ii) switching from urea to the EEF blend at the same N rate resulted in much smaller reductions in runoff losses at Freshwater and variable effects at Silkwood.

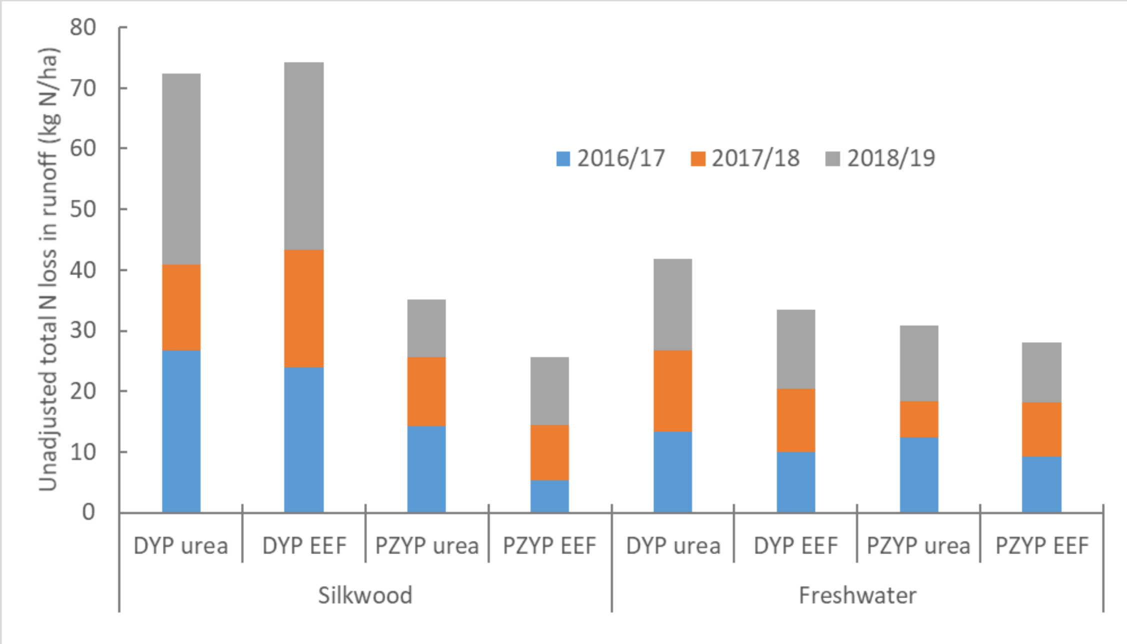

Figure 9. Runoff losses of total N at the Silkwood and Freshwater sites for the 2017 and 2018 and 2019 crop seasons. Losses were recorded for N application rates determined using DYP (industry standard) or PZYP, with each rate applied as either urea or a blend of EEF products. Seasonal totals did not represent total N lost in runoff, as flumes were overwhelmed by flooding events in each season.

A second study was established at Freshwater for the 2019/20 growing season to look at the interaction between application rates (DYP v PZYP), fertiliser form (EEF or urea) and application time (Sept, Oct or Nov) on runoff losses of fertiliser N. The expectation was that the closer the fertiliser application was to the on-set of the wet season, the greater the vulnerability of the fertiliser N to runoff losses and reduced crop N uptake. Unfortunately this study was hampered by relatively dry seasonal conditions in late 2019 such that the first runoff events were not experienced until late January 2020. This resulted in quite small runoff losses of N in all treatment combinations monitored. There was a trend for less N losses with lower application rates in both the later application times, but there were no indications of any effect of fertiliser product.

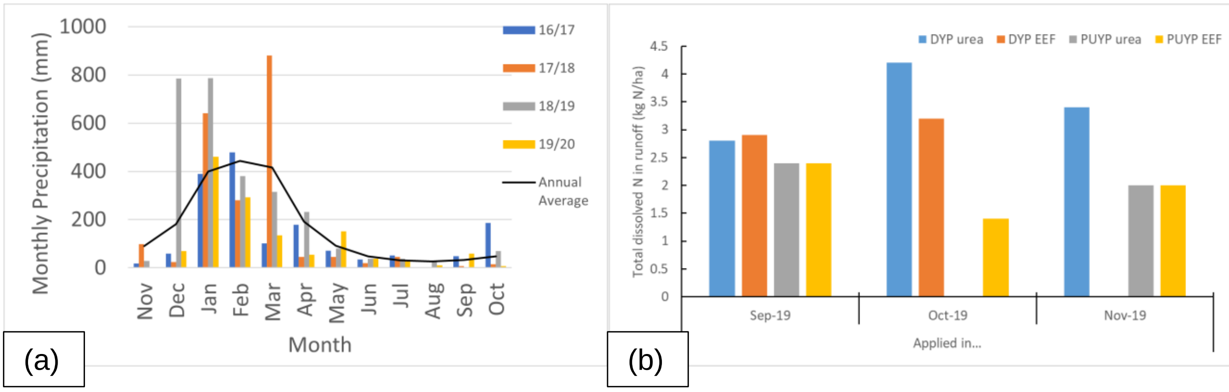

Figure 10. (a) Monthly rainfall totals across the four consecutive crop growing seasons at the Freshwater site and the monthly long term average and (b) dissolved total N in runoff over the 2019/20 wet season from fertiliser N applied in September, October and November 2019. Missing data for October (PZYP urea) and November (DYP EEF) were the result of equipment malfunctions during runoff events.

Unfortunately, runoff losses of DIN were only able to be measured at the Silkwood site. Results (Figure 11) mirror the effects of N rate on runoff losses observed in Figure 9, but there appeared to be a seasonal interaction influencing the relative impact of urea or EEF fertilisers on total DIN loads – particularly at the DYP rate. The EEF blend produced consistently lower DIN loads at both rates in the 2016/17 season, but DIN losses actually increased when EEF's were used at the DYP rate in both 2017/18 and 2018/19, even though differences were small.

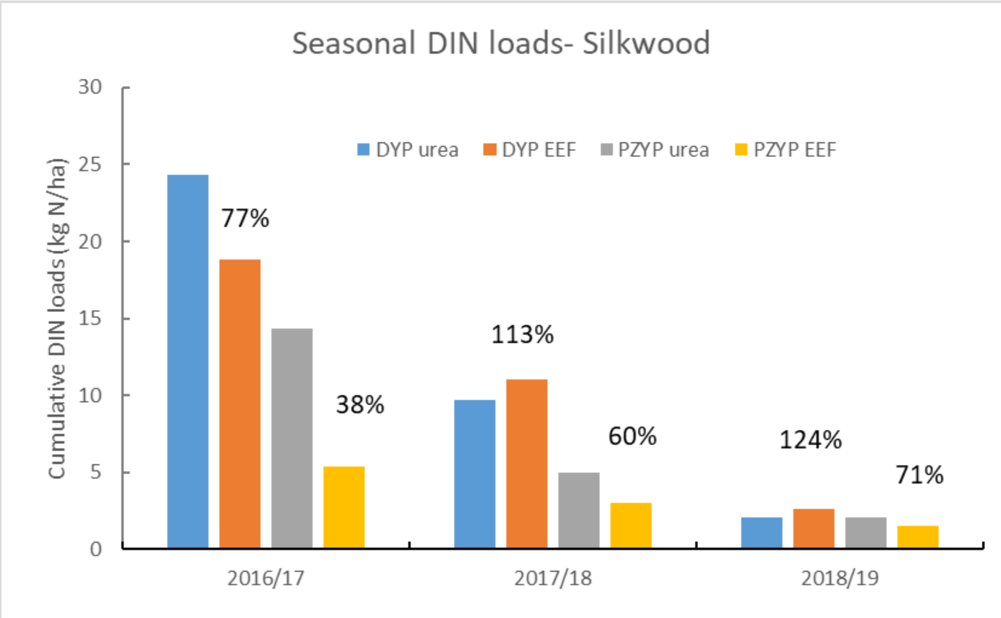

Figure 11. Seasonal runoff losses of DIN in response to differing fertiliser N rates and products at the Silkwood site across three consecutive growing seasons.

These contrasting effects of EEF's on seasonal DIN loads were most probably related to the dynamics of N release from the controlled release (polymer-coated) component of the EEF blend (Figure 12). Nitrate-N concentrations in the top 2.5 cm of soil in the vicinity of the fertiliser band were often elevated for a much longer period each year than for the equivalent rate of urea, especially at the DYP application rate. The high water table and limited root activity during the wet season at this site was likely to be a major contributor to this effect, as the fertiliser N released from the controlled release granules was unable to be accessed efficiently by the crop. This increased the window of runoff loss risk for the EEF blend, so that despite typically higher DIN concentrations in early runoff events shortly after fertiliser application with urea, the EEF blend at DYP provided lower DIN concentrations in runoff but over an extended period, resulting in higher total DIN loss in some seasons.

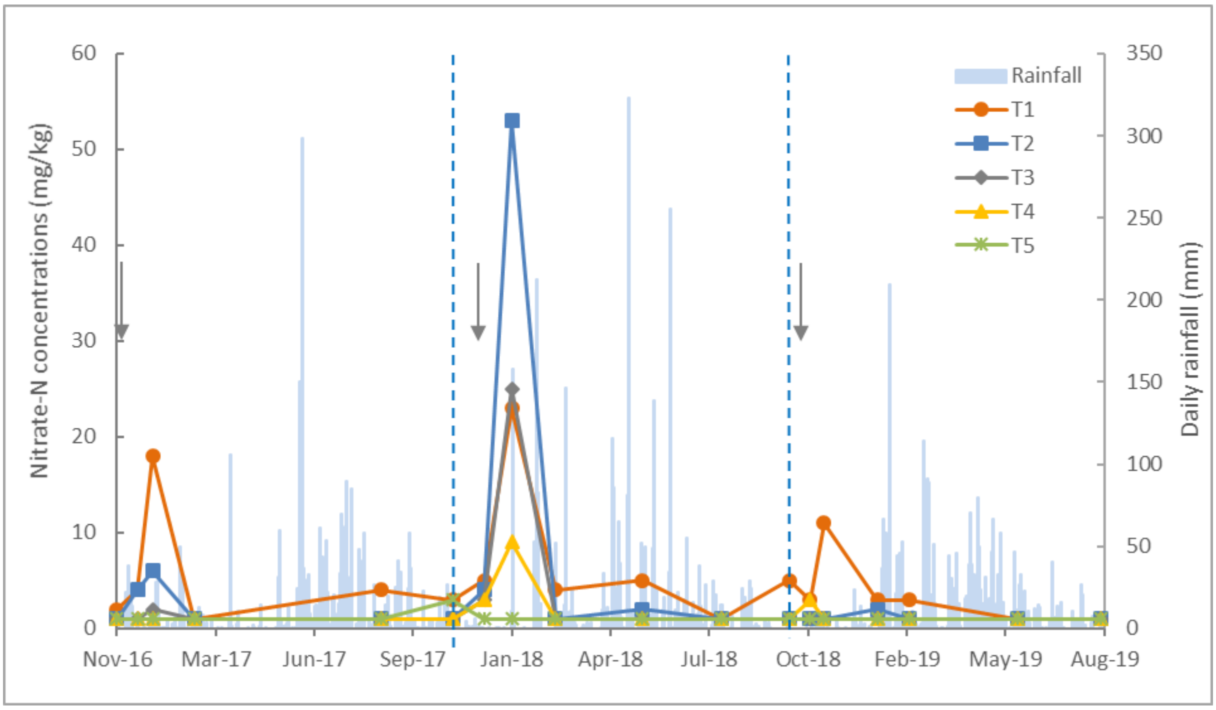

Figure 12. Soil nitrate-N concentration in the row (0–2.5 cm depth) from the Silkwood sugarcane trial site during second (2016–17), third (2017–18) and fourth (2018–19) ratoons. Dashed lines represent harvest date and arrows indicate fertiliser application. Fertiliser rates were 160 kg N ha^{-1} annually in T1, 100 kg N ha^{-1} in year 1 and 160 kg N ha^{-1} in years 2 and 3 in T2, 100 kg N ha^{-1} in T3 and T4 and no applied N in T5. Urea was used in T2 and T3 and the EEF blend in T1 and T4.

3.2 Key finding - laboratory studies

The key findings from the laboratory studies are presented as a series of extracts from the abstracts of technical manuscripts either already published (Appendix B) or currently in review. We have not presented any data in tables or figures, but readers are referred to the full manuscripts which will be uploaded into e-Atlas as they are published.

3.2.1 Initial fertosphere studies in sealed systems

A 112-day incubation experiment was conducted with the EEFs band-applied in three contrasting soils with a history of sugarcane production. In standard urea and NI-urea treated soils, the pH within the fertosphere significantly increased to a maximum of ~pH 9.2–9.3. Alkaline conditions and high ammonium concentrations promoted elevated aqueous ammonia concentrations, resulting in complete nitrification inhibition. The PCU granules released ~40% of total urea-N content within 14 days, followed by significantly slower release rates for the remainder. The initial rapid urea-N release was attributed to damaged polymer coats, while the neighbouring undamaged granules within the band may have contributed to the slow subsequent release phase through reduced concentration gradients that restricted diffusion from granules. Variation between soils suggests that soil properties such as clay content and pH buffer capacity may influence urea hydrolysis, but not nitrification. These results suggest that both nitrification inhibitors (NIs) and controlled-release technology may not have the expected impacts on N transformations and availability when applied in a concentrated band in some soil types, due to the dominant impact of the band environment on either N release or N transformations.

3.2.2 Diffusion of N species and inhibitors outwards from the fertosphere

<u>*Inhibitors*</u>

In a 16-day laboratory incubation, the efficacy of the nitrification inhibitor (NI), 3,4-dimethylpyrazole phosphate (DMPP) and the urease inhibitor (UI), N-(n-butyl) thiophosphoric triamide (NBPT) were investigated by incubating two commercially available urea-based products containing these additives in bands at concentrations equivalent to 150 kg N ha^{-1} (row spacing 1.8 m) in contrasting soil types. Products were assessed relative to a band of granular urea applied at the same rate, but unlike the experiment described in 3.2.1 (fertosphere soil monitored in a sealed system), N species and inhibitors were allowed to freely diffuse outwards from the centrally placed band.

The urea band produced substantial increases in soil pH, EC, and aqueous NH_3 concentration which influenced ureolytic activity and nitrification within the fertosphere and surrounding soil for both soil types. However, key soil physicochemical factors including cation exchange capacity (CEC), impedance (to diffusion) and pH buffering capacity (pHBC) influenced the size and persistence of the impacted zone and resulted in substantial soil-type variation.

The inclusion of DMPP in the urea band did not provide any inhibitory benefits beyond those observed from urea alone, except when the inhibitor was able to diffuse beyond the alkaline zone affected by urea-N hydrolysis, because severe inhibition of nitrification was already occurring. The benefit of the NI was observed in the soil with higher clay, organic matter and pHBC, which restricted the size of the zone in which ureolytic-induced chemical changes and resulting nitrification inhibition occurred. In contrast, the urease inhibitor NBPT provided temporary benefits by slowing the rapid rise in pH, EC and aqueous NH_3 observed in standard urea bands. This resulted in NO_3-N concentrations that were similar to those of untreated urea, despite significantly lower NH_4-N concentrations, suggesting the more benign environment in the fertosphere allowed rapid nitrification to occur, despite effects being short-lived (*ca*. 9 days) in both soils. The benefits of NI and UI technology are likely to vary considerably between soils and application methods when compared to a standard urea band, and these studies are providing a physicochemical approach to determining where and when the benefit of 'stabilising' EEF technology may be realised.

<u>*Polymer-coated urea*</u>
Two additional experiments over 35 and 91-day incubation periods compared the N dynamics of a urea band against a band of PCU granules, with the focus on N release from the band and its subsequent diffusion into unfertilised soil. The same contrasting soil types were used as in the inhibitor studies. In the shorter duration study, PCU granules provided a sustained release of urea-N to the soil solution compared to standard urea, with the lower urea-N concentrations limiting the development of the toxic conditions associated with rapid urea hydrolysis. Differences were observed between soil types, but these were comparatively small. The relatively mild fertosphere conditions for the PCU (compared to standard urea) resulted in relatively greater proportions of PCU-derived mineral N being oxidised to nitrate, potentially increasing N-loss risk.

In the 91-day incubation, the close proximity of PCU granules to each other in a band restricted the diffusion-driven release of urea-N from the granules compared to that when granules were mixed through a Dermosol. This supports earlier hypotheses of fertiliser banding impacting N release dynamics, slowing N release from PCU and impacting the availability of N for crop uptake. Soil moisture content and mass flow are therefore likely to be strong drivers of N release from bands of PCU, through their impact on the maintenance of strong concentration gradients between the banded PCU granules and the surrounding soil.

3.2.3 Three dimensional movement of N species in the field

This study took a mechanistic approach to investigating the potential of banded nitrification inhibitors (NIs), a urease inhibitor (UI) and a controlled release polymer-coated urea (PCU) for improving NUE under field conditions. A 71-day field trial was conducted at Gatton, Australia, with fertiliser treatments banded at rates of 50, 100, 150 kg N ha^{-1} at a band spacing of 1.8 m. Excavation of soil profile cross sections allowed quantification of urea- and mineral N species in the fertosphere and surrounding soil at set sampling intervals.

There was evidence of strong nitrification inhibition in and around a band of granular urea, as in the laboratory studies, but these effects decreased with distance from the band and over time. The addition of NIs extended the inhibition already observed in a standard urea band by up to 50 days longer, although the duration of NI-conferred inhibition was dependant on the rate of NI-urea application. The UI preserved urea-N at a concentration which was 16-fold higher *cf*. standard urea over 7 days, but no urea-N was detected after 21 days. This suggests that the NUE benefits of UIs are at best transient when applied in sub-surface bands. Slow release of urea-N from banded PCU resulted in lower concentrations of N in the soil solution. This reduced N dispersal by *ca.* 50 mm *cf.* urea, resulting in a N-enriched zone which was considerably smaller. Relatively benign chemical conditions around PCU bands enabled rates of nitrification (NH_4–N:NO_3–N ratio of 46%) which were similar to urea. Collectively, these results demonstrate the relative efficacy and risks of the different EEF technologies, when applied in fertiliser bands. This knowledge supports the effective utilization of band-applied EEFs for improved NUE in agricultural systems.

3.2.4 Fate of nitrification inhibitors in soil

A 7-day incubation of the NI DMPP applied at a range of concentrations was conducted in three soils of varying physicochemical properties, with or without sterilization by gamma radiation in order to determine the relative contributions of inhibitor sorption or microbial digestion to inhibitor loss. The impact of urea on the fate of DMPP in soil was also investigated by either including or excluding granular urea in incubations, but the experiment was not designed to explore the impact of treatments on inhibitor efficacy.

Both microbial activity and soil characteristics had a significant effect on the concentration of DMPP in the soil solution, which is considered to be the active fraction of inhibitor when applied in soil. The relative importance of inhibitor sorption and microbial degradation on the fate of DMPP varied with soil type, with inhibitor sorption increasingly dominant as clay content and/or variable charge characteristics increased. The high cation exchange capacity (CEC) in the Vertosol resulted in rapid sorption of DMPP to the soil matrix with little desorption over 7 days after application. The variably charged Ferrosol demonstrated increased sorption of DMPP to the soil matrix when urea was applied, as a result of the increased alkalinity in response to the ureolytic process. Soils with little matrix-DMPP interaction (i.e., the Dermosol, with low clay content, low CEC and no variable charge) showed the least inhibitor sorption. The combination of low inhibitor sorption capacity and low microbial activity (even in the unsterilized Dermosol) may allow DMPP to persist in soil solution at higher concentrations for longer periods, but the impact of this on N transformations will be dependent on maintaining coincidence of the inhibitor and the NH_4-N substrate.

Collectively, these findings suggest the efficacy of DMPP will vary considerably with soils and co-application of other constituents (i.e., urea), and more detailed research is needed to better understand these interactions and their impact on product efficacy.

3.2.5 Diffusion study of EEF blends in fertiliser bands

In a 60-day laboratory incubation, the efficacy of blended DMPP-urea and PCU at varying ratios (1:2, 2:1) and a commercially available biodegradable CRF (plant oil coated urea; POCU) were investigated by incubating in two soils of differing physicochemical characteristics (a Vertosol and a Dermosol). These products were assessed relative to bands of pure granular urea, DMPP-urea, and PCU, with all N-fertilisers applied in bands at concentrations equivalent to 150 kg N ha^{-1} (row spacing 1.8 m).

Blends of DMPP-urea and PCU typically resulted in N concentrations and distributions of NH_4-N and NO_3-N that were intermediate to that of DMPP-urea or PCU alone, within each soil. The combination of coarse texture and poor chemical buffering (i.e., low CEC and pHBC) in the Dermosol meant that there were only small differences between urea, PCU, NI-urea and blends in NO_3-N formation , in that soil. In this soil, the initial inhibitory effect of urea hydrolysis on nitrification in the urea and DMPP-urea treatments dissipates over time and mineral N species in soil solution diffuse away from the fertiliser band and any residual DMPP, limiting the extent of DMPP-mediated inhibition of nitrification. In contrast, the PCU delivers a controlled supply of urea to the soil solution which rapidly hydrolyses and is oxidised to NO_3-N, resulting in similar NO3-N production to the other fertiliser treatments over the incubation period.

In contrast, the greater impedance to solute (mineral N species) diffusion in the Vertosol contributed to a significant inhibitory effect of DMPP on nitrification, reducing overall NO_3-N production in both pure and blended DMPP-urea treatments *cf*. standard urea. Using NO3-N production over the 60d incubation period as a benchmark for the risk of environmental losses, the efficacy of fertiliser treatments in this soil was DMPP-urea-PCU blends (higher ratio of PCU may offer small but insignificant benefit) > DMPP-urea = PCU > urea.

When compared to PCU, POCU may initially release more N as a result of a higher prevalence of ‘burst’ granules. However, the overall dynamics and proportions of N in soil solution were similar to that of PCU, suggesting this technology may be a suitable option for managing the competing requirements of (i) a predictable N supply and (ii) mitigating polymer persistence in the environment.

The results provide a mechanistic understanding of fertiliser-blend dynamics which may be used to predict and / or assist in interpretations of EEF-blend efficacy in the field. Further, preliminary evidence demonstrates the potential of biodegradable CRFs to replace existing PCU CRFs in order to address concerns of polymer persistence in the environment.

4.0 RECOMMENDATIONS AND CONCLUSION

Controlled experiments in the laboratory and field demonstrated that the key factor determining effective NI was coincidence of the inhibitor and the target mineral N species (NH_4-N) in and around the fertosphere of banded applications. This is most likely to occur in heavier textured soils, as evidenced with the field study in the Vertosol, and can result in commercially available NI products being effective for longer than expected in those situations. However, in lighter textured soils that coincidence of inhibitor and NH_4-N was less pronounced due to more rapid diffusion of mineral N away from the band, so under the added influence of leaching conditions, NI products may prove less effective.

Release of N from the PCU products can be delayed when applied in concentrated bands, and during periods when soil in the fertosphere is dry, contributing to possible delays in N supply at critical crop growth stages. The more benign fertosphere environment arising from the slower N release from CRF granules does allow rapid nitrification to occur in and around the band. The prolonged release period of CRF products, combined with the rapid nitrification upon release, widens the potential environmental loss window and means that released N needs to be rapidly assimilated by a crop if environmental benefits are to accrue.

We chose to use commercially available NI and PCU products in this project on the basis that the combination of technologies was most likely to provide a crop N supply that was better synchronised to crop demand, allowing improved NUE. This was particularly important given the sugarcane N uptake period is typically six months or longer. The combination of band dynamics and fluctuating seasonal rainfall in the contrasting soils and seasonal conditions are likely to have contributed to the large benefits from EEF use in some situations and the lack of any effects in others. The availability and efficacy of these EEF products continues to evolve, as evidenced by the emergence of biodegradable replacements for PCU's, but the principles developed for their effective use in sugarcane cropping systems in this project will be relevant and a useful guide to farmers, advisors and fertiliser manufacturers.

The project was unable to demonstrate any significant yield increases through the use of EEF technologies, even in situations where fertiliser applications were made at a time that maximised the risks of environmental losses of N when applied as urea. However, it was able to demonstrate relatively consistent increases in the proportion of fertiliser N recovered in crop biomass, compared to urea. The failure to convert that additional crop N into higher yields reflects the relatively small proportion of the sugarcane crop N that was estimated to be derived from fresh fertiliser applications (i.e. only 20-25%) and the existence of other yield constraints at some sites (i.e. lodging, dry seasonal conditions).

The project has shown relatively small falls in crop yield in response to a reduction in urea-N application rates to match the individual block or zonal productivity, with those responses reduced further, or eliminated, when that application rate reduction was matched with adoption of EEF technologies that deliver improved crop N recovery. These findings have significant implications for improved water quality, as the factor that had the greatest impact on N loads in runoff (as DIN or total N) was fertiliser application rate. While the use of EEF technologies on their own did not provide substantial benefits in runoff water quality, and could actually cause greater N runoff losses than urea when applied at high rates, their use did allow a reduction in application rates with a lower productivity risk. The concurrence of these project findings, albeit from a limited number of sites and seasonal conditions, with preliminary results emerging from a broader evaluation of these approaches in the Reef Trust 4/EEF60 project is therefore very encouraging. The latter project is an example of the broader evaluation that is needed before this combination of management approaches can be confidently promoted to stakeholders as a reliable and low risk approach to the win-win of maintaining productivity and improving water quality through improved fertiliser NUE. However, further testing is needed to provide clearer guidelines to fertiliser manufacturers, industry and Natural Resource Management bodies on which EEF technologies are most effective, which soil types and application times are most likely to deliver benefits from EEF use, the likely size of water quality benefits and the extent to which fertiliser application rates can be reduced.

A major issue slowing the adoption of new fertiliser technology by industry will be the increased price/kg of fertiliser N applied that is currently incurred by using EEF's – especially the controlled release/coated products. The research in this project has suggested that, at least in some situations, the additional cost associated with these expensive coated products may not provide much additional benefit to that delivered by the (relatively) cheaper stabilised technologies (particularly the NI-coated urea products). However, the extent to which this conclusion can be extended across soil types and production environments needs broader testing. Regardless, substitution of a higher priced fertiliser product used at lower rates than urea will be difficult to promote to industry at all levels. Growers will need to be assured the productivity risk is minimal, and fertiliser resellers will need to see a change in the commission structure to assure them of income stability.

In conclusion, this project has found evidence to support our hypothesis that the combination of EEF technologies and reduced fertiliser N application rates can minimise the risk of productivity loss while delivering reduced runoff losses of N and improved water quality. The fact that these reduced rates were able to be maintained through up to four consecutive ratoon crops without any apparent rundown in N available to the crop was also encouraging. The on-going investment by industry and the Reef Trust program to more extensively test this combination of management approaches in different soils, climatic zones and management windows will deliver greater confidence in these approaches from a productivity perspective. However, the limited investment to quantify the runoff water quality impacts of these approaches in this project, and more broadly, represents a missed opportunity that should be addressed urgently. It is only with more extensive water quality data that government and environmental agencies can be confident that investing in practice change will bring the environmental benefits needed to improve the health of the Great Barrier Reef ecosystem.

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APPENDIX 1: SILKWOOD SITE

Paddock-scale water quality monitoring of nitrogen fertiliser management practices in sugarcane: 2016–2019 Wet Tropics region

Author: B. Masters, J. Fries and N. Tahir
Affiliations: Queensland Department of Natural Resources, Mines and Energy, Mareeba, QLD 4880

INTRODUCTION

This project aimed to compare nitrogen (N) loss and yield from a sugarcane paddock trialling different N fertiliser rates and forms. Nitrogen rates were determined within the SIX EASY STEPS framework and were derived using either the district yield potential (DYP) or the productivity unit yield potential (PUYP), with or without the soil mineralisation index (soil carbon discount). Fertiliser was applied as either standard granular urea, or as an enhanced efficiency fertiliser (EEF) blend consisting of the nitrification inhibitor 3, 4-dimethylpyrazole phosphate (DMPP, by ENTEC®) and a polymer coated urea (Agromaster Tropical, by Everris). Nitrogen loss was monitored in surface water runoff, deep drainage (leaching), soil, and crop uptake during the second to fourth ratoons. Additionally, an assessment of N use efficiency (NUE) and the construction of N mass balance (budget) were also conducted. This report summaries the surface water runoff and deep drainage N results. The full results (water quality, soil, plant, N mass balance, and NUE) are detailed in a corresponding technical publication (Tahir *et al.*, in prep). Water quality monitoring conducted in the plant and first ratoon stages of the crop were presented in Masters *et al.* (2017).

METHODS

The methods used in this study are described below in summary. Detailed methods relating data collection and analyses for this study are published in the corresponding technical report (Tahir *et al.*, in prep).

Site details and treatments

The trial site is located near Silkwood approximately 30 km south of Innisfail, in the Wet Tropics region of north Queensland (17°44'44.72"S 146° 2'58.76"E; Figure 13). The region is characterised by a wet tropical climate with the majority of rainfall occurring over the summer period between January and March. The site is situated on an alluvium floodplain deposit within the South Johnstone drainage sub-basin. The soil is classified as a Hydrosol (Isbell, 2002) and locally described as Bulgun series (Murtha, 1986). Sugarcane beds were formed into rows spaced 2 m apart before the planting of cane (variety Q183) in dual-rows (0.7 m apart). The site was not irrigated. Previous sugarcane yields have ranged between 35–80 TCPH (Commercial Cane Sugar 11.9–13.9). Further details of soil classification and characteristics of the site are provided in Masters *et al.* (2017).

This trial included the second, third and fourth ratoon phases (2016–2019) of a sugarcane crop. The treatments compared standard granular urea and the EEF blend at N rates established by SIX EASY STEPS framework DYP (120 TCPH) and the site-specific PUYP (80 TCPH), with and without a soil N mineralisation discount (60 kg N/ha; Table 2). The EEF blend consisted of 66% polymer coated granular urea (controlled-release) and 33% nitrification inhibitor (DMPP) treated granular urea. The treatments (1–4) were established by dividing the paddock into four strip plots, each consisting of 12 cane rows and instrumented to monitor water quality. An additional strip of 11 rows divided into three plots (T5-T7) was included to monitor natural soil N mineralisation and plant N uptake with nil fertiliser applied, or nil fertiliser alternating with fertiliser (Table 2). All other cultivation and weed management practices were kept uniform across all treatments. Details of the individual treatment rates and forms are summarised in Table 2.

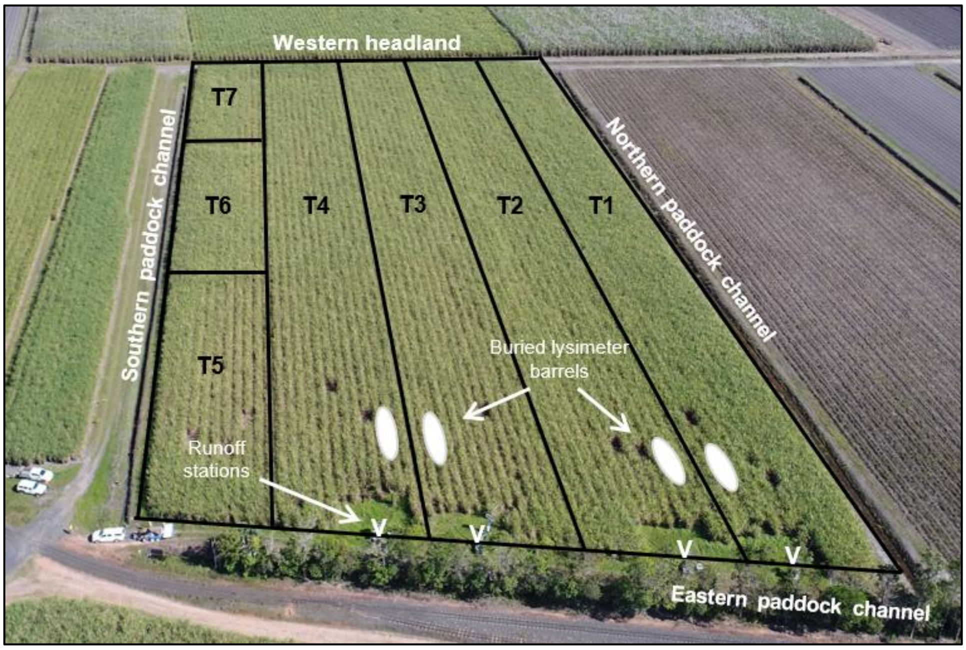

Figure 13: Silkwood sugarcane trial site with seven nitrogen treatment plots and water quality monitoring stations, North Queensland. Note: Treatments 1–4 were monitored for water quality, biomass, yield and soil N. Treatments 5–7 were only monitored for yields, biomass and soil N. Missing cane sections indicate recent biomass sample collection sites.

Table 2. Nitrogen treatment details for the Silkwood sugarcane trial site.

Product	EEF mix#	Standard urea	Standard urea	EEF mix	N/A	Standard Urea
Second ratoon (2016–17)						
Rate (kg N/ha)	160	100	52	52	nil	T6 – 160 T7 – 160
Details	Harvested 25 November 2016, fertilised on 6 December 2016					
Third ratoon (2017–18)						
Rate (kg N/ha)	160	160	100	100	nil	T6 – 160 T7 – nil
Details	Harvested 2 November 2017, fertilised on 28 November 2017					
Fourth ratoon (2018–19)						
Rate (kg N/ha)	160	160	100	100	nil	T6 – nil T7 – 160
Details	Harvested 9 October 2018, fertilised on 22 October 2018					

Notes: Fertiliser was applied via sub-surface banded application (centre-bed). Potassium (100 kg/ha) as Muriate of potash was applied annually. No water quality monitoring occurred for Treatments 5 to 7. #EEF (Enhanced efficiency fertiliser) mix = 66% Controlled-release N fertiliser; 33% Nitrification inhibitor treated urea fertiliser (2016–2017) = Everris Agromaster Tropical (44% N), Nitrification inhibitor (DMPP) = ENTEC (46% N), Standard urea = 46% N.

Data collection and analysis

Four monitoring stations fitted with Parshall flumes and depth loggers (pressure transducers) to direct and measure surface water runoff from each treatment (Figure 14). Automated refrigerated samplers were used to collect water samples during runoff events, and two tipping bucket rain-gauges were used to collect rainfall data throughout the study. Runoff samples were collected in flow-integrated pulses (1–6 mm intervals) (Harmel and King, 2005), subsequently composited and filtered prior to analyses. This method produced a composite sample of surface water, stratified over the course of a runoff event, resulting in an event mean concentration (EMC) for the constituents of interest (generally referred in this report as a ‘concentration(s)’). In the absence of an automated sample, grab samples were collected from surface water within the flume during actively occurring runoff events. Nutrient concentrations in deep drainage (i.e. water that has drained through the soil below the root zone) were measured using a suction barrel lysimeter system installed at 1 m depth below the crop (November 2013). Each treatment was instrumented with five barrels allowing for variability to be assessed, noting that some barrels ceased functioning during the study. Runoff water samples were analysed for all N species, total suspended solids (TSS) and other cations. Primarily results for dissolved inorganic N (DIN: ammonium-N + oxidised N), urea-N and total N (TN) are presented in this report. Deep drainage water samples were analysed for DIN only. All sample analyses were conducted by the Chemistry Centre (NATA Accredited Laboratory), Queensland Department of Environment and Science at Dutton Park, Brisbane.

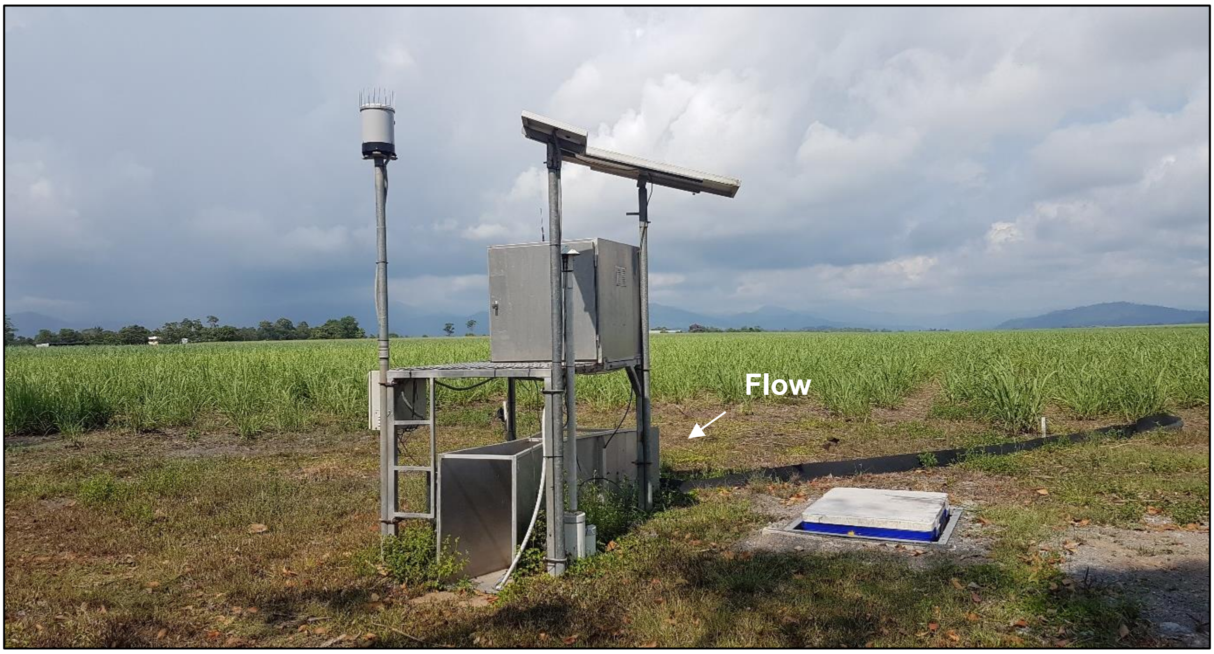

Figure 14. Monitoring station at Silkwood sugarcane trial site.

Surface water discharge volume was determined by multiplying flow rate (calculated using the Parshall flume equation) and time interval. Nitrogen loads in runoff for each treatment were then calculated with cumulative discharge and constituent concentrations (mg/L) using the area under the curve method (numerical integration) (Jurasinski *et al.*, 2014). Nitrogen loads in deep drainage were not calculated for this report due to drainage volume uncertainty. Modelling of drainage volumes in the future may allow for calculation of these loads. However, rainfall and runoff data were used to construct a water balance to assess the relative importance of each hydrologic component.

Crop yield from each treatment was measured at harvest by separating treatments across bins and recording weights at the mill.

RESULTS

Overview of hydrology

Overall, each ratoon received similar total rainfall (<3,000 mm; Table 3), but the distribution and amount of rainfall, and subsequently runoff following fertiliser application was distinctly different each year (Figure 15). The second ratoon was defined by low rainfall prior to and following fertiliser application, receiving a total of 60 mm before the first runoff event 32 days later, after receiving substantial 273 mm rainfall event (“dry” start). The start of the third ratoon was characterised by above average rainfall during the months of October–November (686 mm), with a following 130 mm in the week prior to fertiliser application. A minor runoff event was then experienced 3 days after fertilising (“wet” start), from only 23 mm rainfall. In the fourth ratoon, the first runoff event occurred 49 days after the application of fertiliser from a 79 mm rainfall event, following rainfall of 126 mm over a seven-day period (“delayed” start).

Table 3. Water balance for the sugarcane crop-soil system at the Silkwood sugarcane trial site during second (2016–17), third (2017–18) and fourth (2018–19) ratoons.

Year	Total rainfall (mm)	Runoff (mm)	Drainage and ET (mm)	Runoff (%)	Drainage and ET (%)
2016–17	2,969	636	2,333	26	74
2017–18	2,916	1,404	1,512	48	52
2018–19	3,154	1,810	1,344	57	43

Note: Runoff presented as average of each treatment. Annual rainfall totals for cropping year, calculated from harvest to harvest for each ratoon (second ratoon 25/11/2016– 2/11/2017, third ratoon 2/11/2017– 22/10/2018, fourth ratoon 9/10/2018 - 9/10/2019). Rainfall and runoff measured on site, evapotranspiration (ET) and drainage volumes calculated by difference.

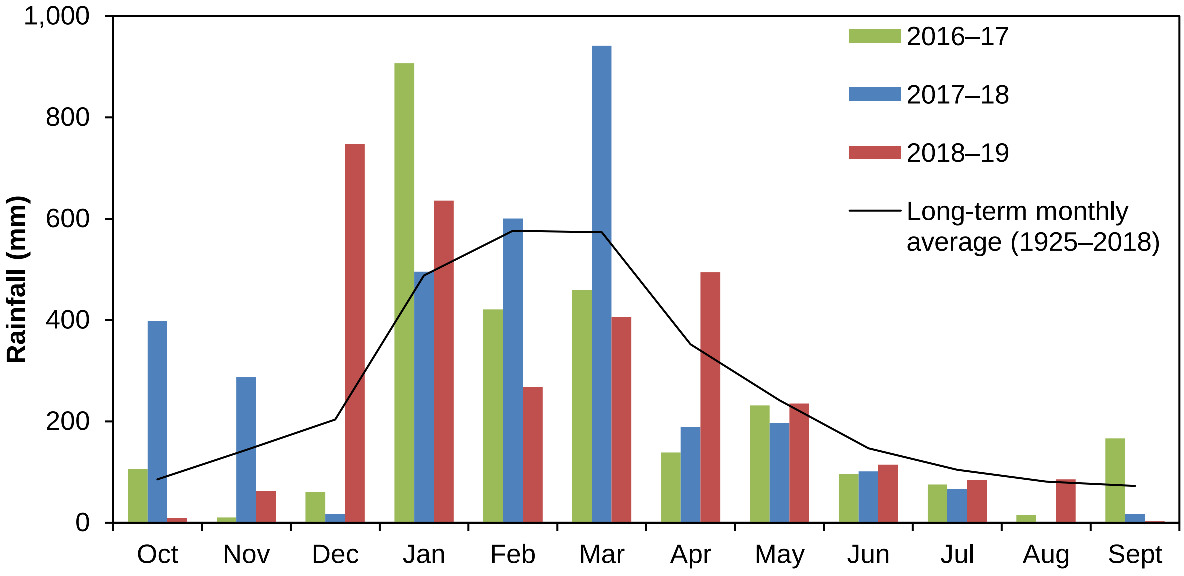

Figure 15. Monthly rainfall totals at the Silkwood sugarcane trial vs. the long-term monthly average. Long term average provided by Bureau of Meteorology, Bingal Bay Station No. 032009 (1925–2018).

DIN and urea-N in runoff

Dissolved inorganic N concentrations in runoff consisted of varying proportions of oxidised-N and ammonium-N, depending on treatment and timing of runoff. Differences in oxidised-N and ammonium-N concentrations between treatments were most prominent in the first runoff events following fertiliser application (Figure 16, Figure 17). Treatment 2 (high N urea) had the highest concentrations in all three years, peaking at 10.9 mg/L and 4.5 mg/L for oxidised-N and ammonium-N, respectively. Treatment 4 (low N EEF) consistently exhibited lower concentrations, with a peak of 3.3 mg/L (oxidised-N) and 1.4 mg/L (ammonium-N). Concentrations from T2–4 declined rapidly to <1.0 mg/L following the initial 1–3 runoff events post fertiliser application. However, concentrations in T1 (high N EEF) exhibited sustained elevated concentrations in subsequent events, compared to the other treatments (Figure 16, Figure 17). This was most evident in the second year. Furthermore, these comparatively higher DIN concentrations in T1 were occurring mid wet season during periods of high rainfall and large runoff volumes (Figure 16, Figure 17). Concentrations in all treatments declined to <0.1 mg/L by early March each year (Figure 16, Figure 17).

Overall, oxidised-N was the primary constituent of DIN, however, ammonium-N concentrations were considerable in the initial runoff events after fertiliser application (Figure 16, Figure 17). Treatments 2 and 3 (urea) had the highest oxidised-N losses in initial events of the second and third ratoon, with the highest concentrations occurring in T2 (7.8 and 10.9 mg/L). However, in the fourth ratoon oxidised-N concentrations were highest in T1 (4.4 mg/L), with the peak occurring in the first runoff event. Following initial events, the greatest concentrations of oxidised-N were in T1 across all years, which contributed to the elevated DIN concentrations mid-wet season. Ammonium-N concentrations were consistently highest in T2 (peak of 4.5 mg/L) (Figure 17). Ammonium-N concentrations were generally lower in the EEF treatments each year.

The highest urea-N concentrations in runoff occurred in the third ratoon, when runoff occurred shortly after fertiliser application (Figure 18). The highest concentrations were measured in the urea treatments (T2 = 8.9 mg/L, T3 = 2.4 mg/L), whereas urea-N concentrations from both EEF treatments were <1.0 mg/L. Concentrations then declined to <0.2 mg/L for all treatments by the third runoff event. In the second ratoon and fourth ratoon, concentrations were 0.001–0.128 mg/L and 0.002–0.774 mg/L for all treatments, respectively.

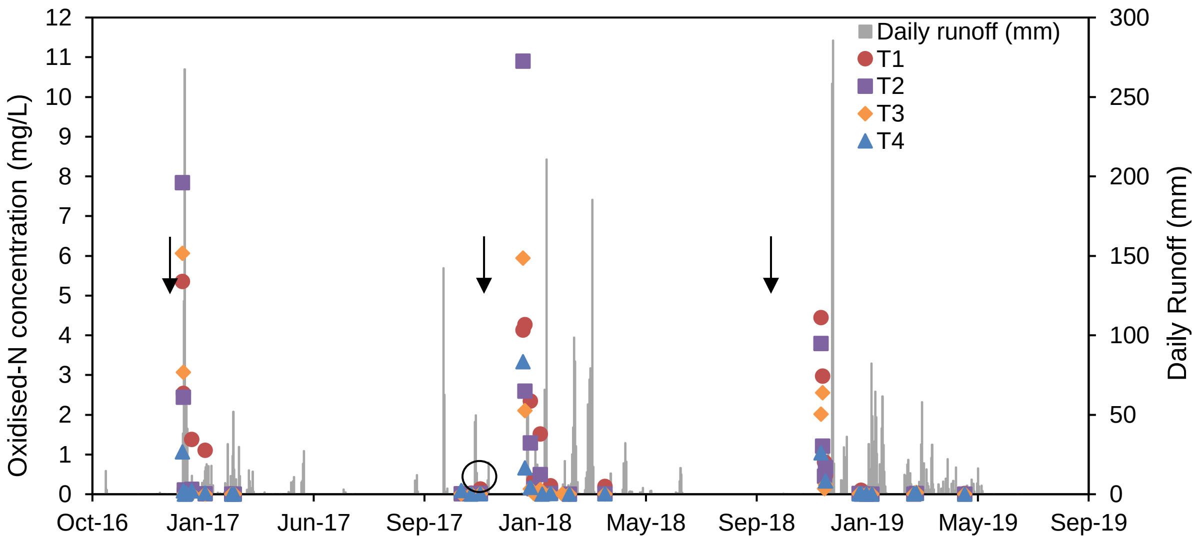

Figure 16. Oxidised-N event mean concentrations in surface water runoff from the Silkwood sugarcane trial site during second (2016–17), third (2017–18) and fourth (2018–19) ratoons. Runoff presented as the mean of all treatments. Arrows indicate fertiliser application. In the absence of automated samples, grab samples were used for all treatments from 10–12/01/2017 and T1 on 0/11/2018. The open circle marker indicates where a grab sample occurred in T1 only. Refer to Table 1 for treatment details.

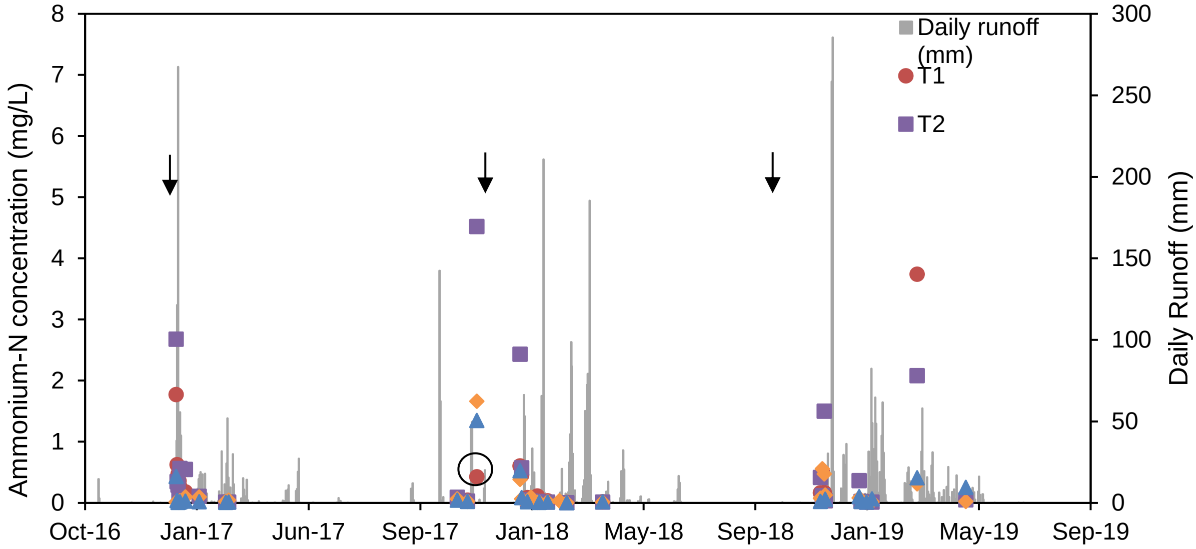

Figure 17. Ammonium-N event mean concentrations in surface water runoff from the Silkwood sugarcane trial site during second (2016–17), third (2017–18) and fourth (2018–19) ratoons. Runoff presented as the mean of all treatments. Arrows indicate fertiliser application. In the absence of automated samples, grab samples used for all treatments from 10–12/01/2017 and T1 on 30/11/2018. The open circle marker indicates where a grab sample occurred in T1 only. Refer to Table 1 for treatment details.

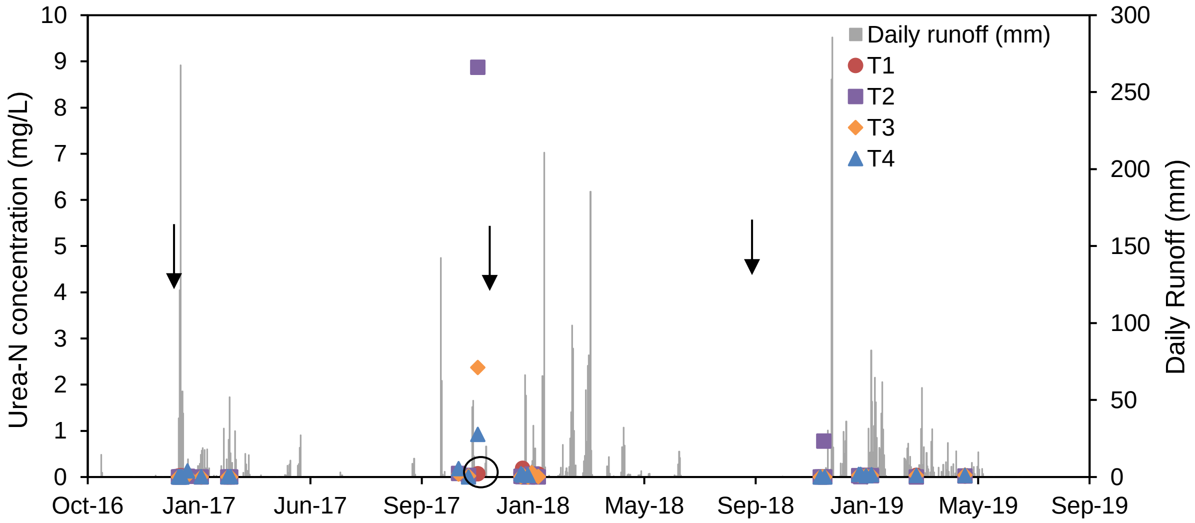

Figure 18. Urea-N event mean concentrations in surface water runoff at the Silkwood sugarcane trial site from second (2016–17), third (2017–18) and fourth (2018–19) ratoons. Runoff presented as the mean of all treatments. Arrows indicate fertiliser application. In the absence of automated samples, grab samples used for all treatments from 10–12/01/2017 and T1 on 30/11/2018. The circle marker indicates where a grab sample occurred in T1 only. Refer to Table 1 for treatment details.

DIN in deep drainage

Dissolved inorganic N concentrations in deep drainage exhibited large increases following fertiliser application and the onset of the wet season in each ratoon (Figure 19). Overall, the greatest concentrations were experienced in the third ratoon ("wet" start). During this season treatments applied with standard urea (T2 and T3) exhibited higher peak concentrations than the EEF applied treatments (T1 and T4). However, in the second and fourth ratoons T1 exhibited higher peak concentrations. In general, concentrations of oxidised-

N were considerably higher than ammonium-N, constituting an average of 78 and 95% of DIN concentrations in the second and third ratoons, respectively (data not shown). However, in ratoon four concentrations of oxidised-N were on average only 41% of DIN (data not shown). Overall, ammonium-N concentrations ranged from 0.001–0.130 mg/L, while oxidised-N ranged from 0.0005–11.2 mg/L throughout the study period. Drainage monitoring ceased when rainfall conditions were low, this occurred from July to October in both ratoons.

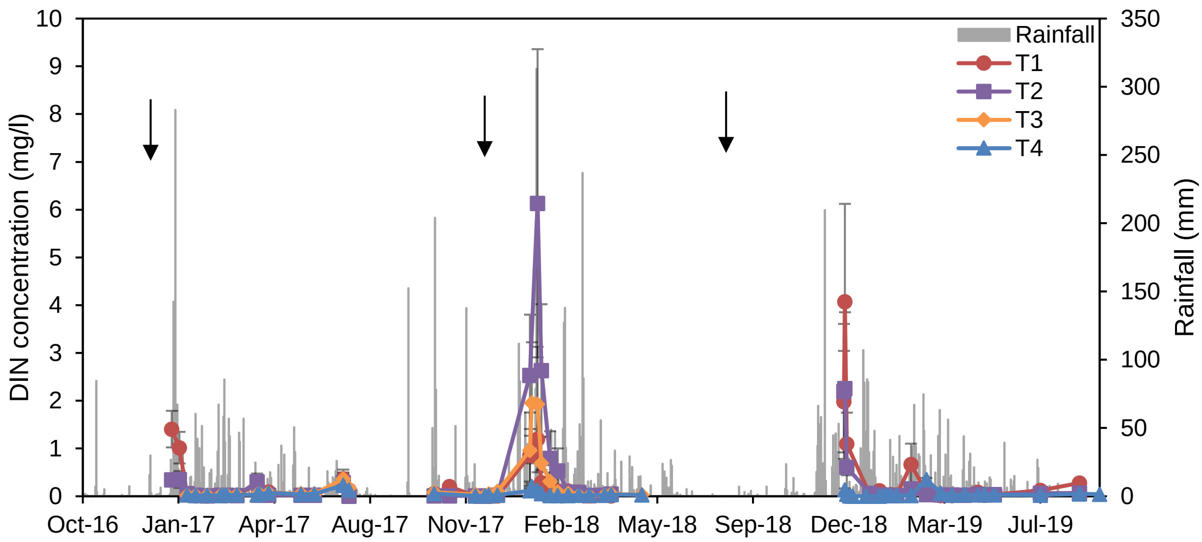

Figure 19. Mean concentrations of DIN in drainage water leaching from treatments at the Silkwood sugarcane trial site during second (2016–17), third (2017–18) and fourth (2018–19) ratoons. Error bars denote +/- 1 standard error. Arrows indicate fertiliser application. Refer to Table 1 for treatment details. Note: no concentration data available during periods of dry soil conditions where systems were not operational.

Nitrogen loads in runoff

Overall, TN loads ranged from 5.4 to 33 kg/ha and consisted primarily of DIN, except in the final year (Figure 20; Table 4). In all years, the greatest TN loads were from T1 and T2. There was a consistent decline on DIN losses over the course of the study. However, no decline in TN losses was evident across ratoons, indicating a shift from DIN dominated losses to predominantly organic N and particulate N.

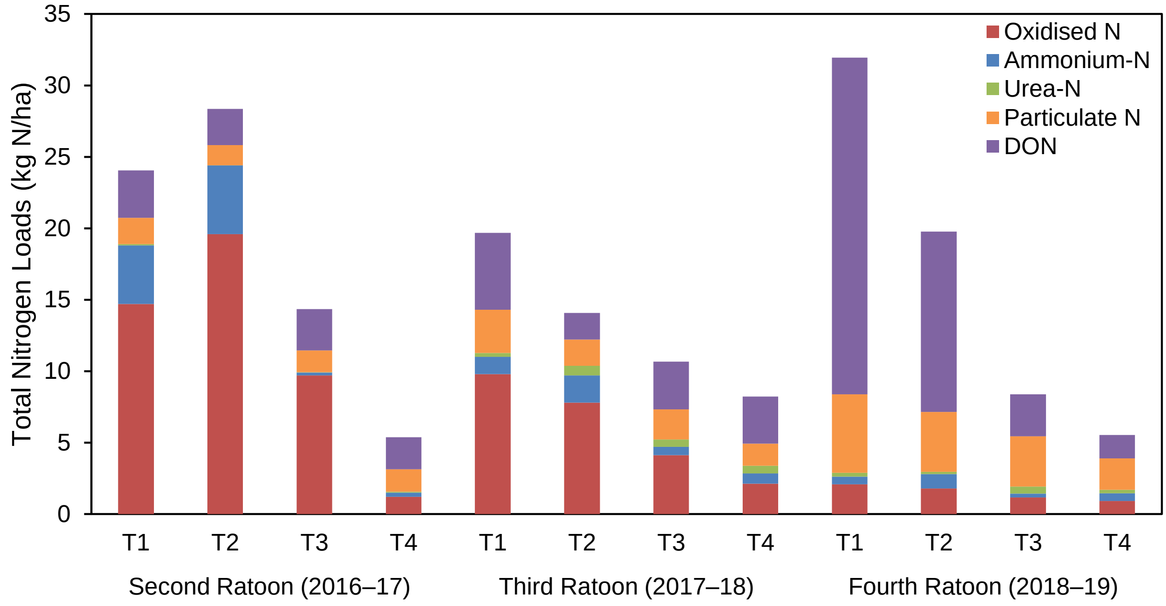

Figure 20. Nitrogen loads as contributing constituents from the Silkwood sugarcane trial site during second, third and fourth ratoon. DIN presented separately as ammonium-N and oxidised-N. DON is presented without urea-N.

Table 4. Runoff N loads from the Silkwood sugarcane trial site during second, third and fourth ratoons.

Year	Second Ratoon (2016–17)				Third Ratoon (2017–18)				Fourth Ratoon (2018–19)			
Treatment	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
N load (kg/ha)												
N rate (kg N/ha)	160	100	52	52	160	160	100	100	160	160	100	100
TN	24.0	26.8	14.3	5.4	19.4	14.1	11.3	9.1	32.9	19.0	9.0	6.8
DIN	*18.8*	*24.3*	*9.9*	*1.5*	*11.0*	*9.7*	*5.0*	*3.0*	*2.6*	*2.1*	*2.1*	*1.5*
Urea-N	0.09	0.02	0.02	0.07	0.28	0.68	0.43	0.24	0.26	0.15	0.49	0.25
Ammonium-N	4.1	4.8	0.2	0.3	1.2	1.9	0.6	0.7	0.5	0.3	0.9	0.5
Oxidised-N	14.7	19.6	9.7	1.2	9.8	7.8	4.4	2.3	2.1	1.8	1.2	0.9
DON-N*	3.3	2.5	2.9	2.2	5.4	1.9	3.4	3.3	23.5	12.6	2.9	1.6
Particulate N	1.8	1.4	1.5	1.6	3.0	1.8	2.1	1.5	5.5	4.2	3.5	2.2

*DON is presented without urea-N.

The amount of oxidised-N and ammonium-N in DIN varied between treatments and each ratoon (Figure 20, Table 4). The oxidised-N load ranged between 1.2–19.6 kg/ha in the second ratoon, 2.3–9.8 kg/ha in the third, and 0.9–2.1 kg/ha in the fourth ratoon (Figure 20, Table 4). The greatest DIN loads were from T1–T3. Ammonium-N loads ranged between 0.2–4.8 kg/ha over the course of the study and generally contributed 20% (on average) of total DIN losses. Ammonium-N loads were greatest from T1 and T2 in the second and third ratoon and greatest from T3 in the fourth ratoon.

Urea-N loads contributed less than 5% of N to the TN load in runoff in all years and did not exceed 0.7 kg/ha. Urea-N loads were greater in the third and fourth ratoon than the second ratoon (Figure 20, Table 4). The greatest losses of urea-N in runoff occurred during the third ratoon from treatment T2 where standard granular urea was applied. N losses from other organic forms of N (DON, TDN and TSN) increased in the fourth ratoon (Figure 20, Table 4), with the greatest loads occurring in T1, particularly as DON (23.5 kg/ha). DON loads ranged between ~2–5 kg/ha in the second and third ratoon and increased to 1.6–23.5 kg/ha in the fourth ratoon.

Agronomic

Crop yields were generally proportional to fertiliser N rate, with yields increasing as N rate increased (Table 5). In most instances there was also a slight increase in yield between EEF treatments when compared to the same N rate applied as urea (Table 5). Although these differences were marginal (i.e. the EEF treatments were 2–3 TCPH higher than the corresponding urea treatments) and it is important to note these results are not replicated. Treatment 1 (high rate EEF treatment), which retained the same application rate all three years, yielded slightly lower in the third ratoon (53 vs. 61 TCPH), and had considerably lower yields in the fourth ratoon (39 TCPH). However, other treatments where N rates were increased had higher yields, proportional to application rate. Yields from all treatments were lowest in the fourth and final ratoon of the study.

Table 5. Crop yields from four treatments at the Silkwood sugarcane trial site during second, third and fourth ratoons.

Crop/year	Agronomic	T1	T2	T3	T4
Ratoon 2 (2016–17)	**Fertiliser rate (kg N/ha)**	160	100	52	52
	Product	EEF mix	Urea	Urea	EEF mix
	TCPH	61	38	31	33
	CCS	11.9	--	--	--
Ratoon 3 (2017–18)	**Fertiliser rate (kg N/ha)**	160	160	100	100
	Product	EEF mix	Urea	Urea	EEF mix
	TCPH	53	50	42	44
	CCS	14.3	14.4	--	14.6
Ratoon 4 (2018–19)	**Fertiliser rate (kg N/ha)**	160	160	100	100
	Product	EEF mix	Urea	Urea	EEF mix
	TCPH	39	34	31	30
	CCS	12.9	--	--	--

Note: Yields and CCS obtained from South Johnston MSF sugar mill, CCS values not measured for low-yielding treatments.

DISCUSSION

Water quality

The impact of N rate and N form on DIN loads in runoff differed substantially across years and was strongly influenced by the amount and distribution of rainfall. In the EEF treatments, when runoff occurred less than 32 days after fertiliser application DIN concentrations were considerably lower than the conventional urea treatments (Figure 16, Figure 17). The conditions experienced in the first month (i.e. “wet” or “dry” start) strongly influenced the critical N loss pathways (i.e. runoff or deep drainage). In contrast, when the initial runoff event followed a comparatively “delayed” start, in this case 49 days, treatment differences were less pronounced with lower DIN in runoff and drainage. This indicated that the EEF blend tested in this study may be more effective at reducing N concentrations available for loss when N application coincides close to higher risk periods. In the context of wet tropics sugar production, higher risk is due to late harvested blocks or predicted La Nina years, when the an early onset to the wet season may occur (Skocaj, 2015).

A majority of the annual DIN loss is determined by the first few runoff events (85–95%; Masters *et al* 2017a). Therefore, in addition to the form and rate of fertiliser applied, the size and timing of these initial events can have a substantial leverage on the total annual loads. In this study, the second ratoon experienced the greatest DIN losses in surface water runoff. This was primarily a result of minimal rainfall occurring between fertiliser application and the first runoff event, hence there was little opportunity for infiltration and crop uptake of the available N pool prior to the runoff occurring. The first event occurred in a relatively short period after fertilising (32 days) and it is likely the pool of highly mobile fertiliser N was still largely intact. This would have reduced the opportunity for plant uptake, hence increasing the pool of soil mineral N available for off-site loss at the time of the runoff event. In comparison, in the fourth ratoon more rainfall occurred between fertilising and the first runoff event (49 days), facilitating better growing conditions, reducing the soil mineral N pool, and hence resulting in lower DIN loss. These differences in DIN loss were further exacerbated by the size of the first events, with the second ratoon experiencing a larger initial rainfall event (273 mm) compared to the fourth ratoon (79 mm). These comparative large runoff volumes in the second ratoon, coupled with high DIN concentrations, resulted in greater DIN loads early in the season.

Although the EEF products provided some reductions in runoff DIN loss under wet conditions, the realised water quality benefit was diminished at high application rates. This was evidenced by consistently high DIN loads from T1 (Figure 20). The nitrification inhibitor contained in the EEF blend trialled in this study aims to inhibit nitrification processes, while the polymer coated urea aims to delay the hydrolysis of urea that occurs in the soil following fertiliser application. However, the higher application rate of these products resulted in elevated oxidised N concentrations in runoff throughout the middle of the wet season (Figure 16), when runoff volumes were typically greatest. This suggests that the EEF blend was effective at delaying the release of N in initial runoff events (Figure 16, Figure 17) and deep drainage (Figure 19). However, the polymer coated urea product at a higher application rate may have potentially increased oxidised N available for loss later in the wet season. Overall, there is potential to utilise EEF products in sugarcane nutrient management in the Wet Topics, although this would require climate forecasting (i.e. planning fertiliser application relative to predicted rainfall), with the most appropriate application targeted to blocks fertilised late in the year and close to the wet season.

Results also showed a substantial urea-N loss in surface water runoff in events occurring soon after the application of standard granular urea. Urea-N remains under reported in water quality research, little is known about its contribution to agricultural runoff (Davis *et al*., 2016). This is important as urea-N loss contributes to eutrophication within waterways due to its ‘un-degraded’ state (Glibert *et al.*, 2006; Solomon *et al.*, 2010; Glibert *et al.*, 2014). Concentrations of urea-N were up to 8 mg/L in initial events when runoff occurred within the week of fertiliser application. These concentrations were only detected in runoff from standard urea treatments, suggesting that the EEF blend used in this study also contributes to reducing urea losses.

Deep drainage during the three ratoons demonstrated how DIN loss can differ between fertiliser forms and rate, and season. The differences were best demonstrated in the third ratoon when fertiliser application occurred in relatively wet conditions. The highest DIN concentrations in the standard urea treatments during this ratoon. The first increase in drainage DIN concentration was observed 50 days after fertiliser application. It is likely that fertiliser application in wet conditions favoured N mobilisation and subsequent drainage N-loss in the urea treatments. In contrast the EEF treatments demonstrated a lower propensity for mobilisation and loss in this situation. However, use of the EEF products at higher rates resulted in the highest concentrations of DIN in drainage during the second and fourth ratoons. Therefore, losses via drainage are likely to have been higher in these instances, therefore it is important to consider application rate when consider product/form.

Yield and site constraints

Determining the most agronomically productive N rate whist reducing off-site N losses proved challenging at the Silkwood trial site. All treatments consistently yielded (30–61 TCPH) well below the DYP (120 TCPH) in the Wet Tropics region, and below the PUYP (80 TCPH). The highest yields were from the higher N rate treatments each ratoon (34–61 TCPH, Table 5), however, these treatments also had the highest measured N losses. When the N rate was applied at the PUYP rate with the soil carbon discount in the second ratoon (i.e. 52 kg N/ha), yields were extremely poor, and would likely be unviable in a commercial setting. The low yields experienced with application of the soil carbon discount also indicate that in-season mineralised N either wasn't efficiently taken up or wasn't utilised by the crop.

In addition to nutrient management practices, environmental factors also play a major role in the productivity of all crops (Skocaj *et al.*, 2013; Skocaj, 2015). During the monitored period, rainfall has varied between 2916 mm and over 3,100 mm per year, with much of this occurring within a few months. These factors were likely to be a primary driver for variance in annual yields from the Silkwood trial site, with the highest yields on record (84–113 TCPH) occurring in a plant crop, during below average rainfall (1,718 mm) in the first year of monitoring (Masters *et al.*, 2017). Since annual changes to practice management on a farm or paddock scale tend to be minimal, years of high rainfall and low yields are indicative of conditions favouring higher N losses to the environment (Skocaj and Everingham, 2014).

CONCLUSIONS

The study conducted at the Silkwood site revealed important N-loss dynamics in low-lying Wet Tropics sugarcane. Poor soil-drainage and highly variable rainfall were distinguishing environmental characteristics that influenced N-loss through runoff and drainage each ratoon. Each year rainfall conditions varied during the critical phase when fertiliser is applied and before the crop N demand has re-established. This resulted in three distinct scenarios ('dry', 'wet' and 'delayed' starts) and three distinct patterns of N-loss in both runoff and drainage. Wet conditions favoured rapid mobilisation of fertiliser N and this was detected in drainage water following extended rainfall. During the study, the proportion of TN lost in runoff in the form of DIN varied between 91% and just 8%. This variation was indicative of the rapid loss of fertiliser N during unfavourable conditions (wet starts), and therefore the increased effectiveness of EEFs in these conditions. The critical management practices that impacted N-loss were application rate, and fertiliser form (product) with further interactions between these factors. Application rate alone clearly increased N-loss in runoff with the highest N rates delivering the highest TN loads (19–31 kg/ha). EEF treatments were effective at reducing DIN concentrations in initial runoff in most cases. However, when application rate was increased, this benefit was diminished, and greater DIN loads were lost from the EEF products.

Overall, the trial site was consistently low yielding and typically well below the DYP (120 TCPH). Increasing N application rates provided marginal improvements in yield, however even at the highest rates applied, yields were low compared to similar sugar cane production systems in the region. There was no notable improvement in yield achieved through use of EEF fertiliser products. The poor performance of the crop-soil system was in large part due to the susceptibility of the site to waterlogging, which is driven by soil type (low permeability and poor drainage) and high rainfall (~3,000 mm/yr).

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APPENDIX 2: BURDEKIN SITE

Author: Mr Jayson Dowie and Ms Heidi Hatch
Affiliation: Farmacist, Burdekin

SITE DETAILS

The Burdekin NESP trial site was located in the Mulgrave area of the BRIA for harvest years 2017-2019. The soil type was classed a 6Drc - sand or loam over sodic clay (Figure 21) and the site was also EC mapped with a Veris 3100 to determine soil variability within the block. The trial was then positioned to minimise soil variation and irrigation effects (Figure 22).

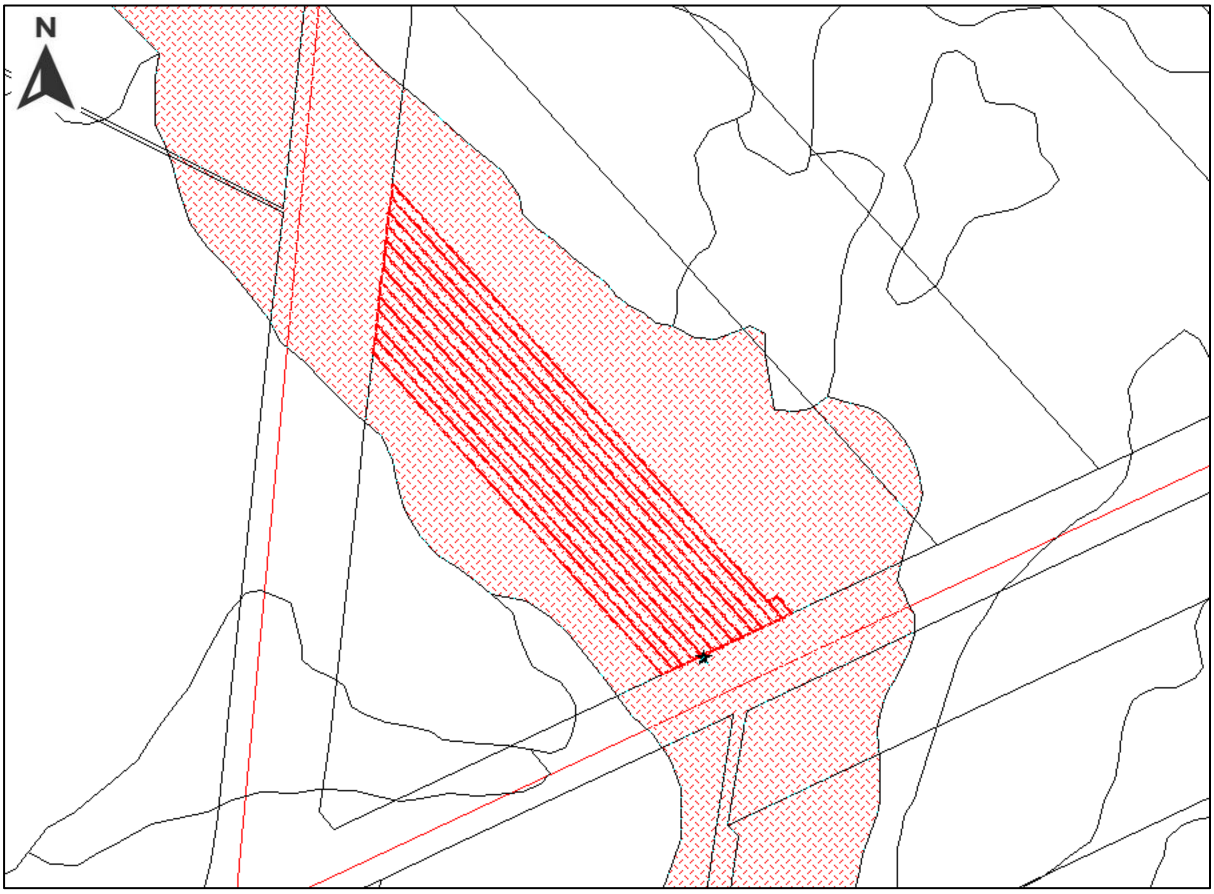


Figure 21. Trial layout with soil zone map overlay. Highlighted zone represented the soil type classed as 6Drc. Scale: 1cm = 0.05747km.

Layer source: Queensland Government 1994, Soil survey of the Burdekin River Irrigation Area, North Queensland, Haughtons area Stages II and III - HTC/HTN, *https://publications.qld.gov.au/hr/dataset/soils-bria-haughtons-north-htn/resource/544e1612-85e3-448f-8ae5-cf19317296e3*.

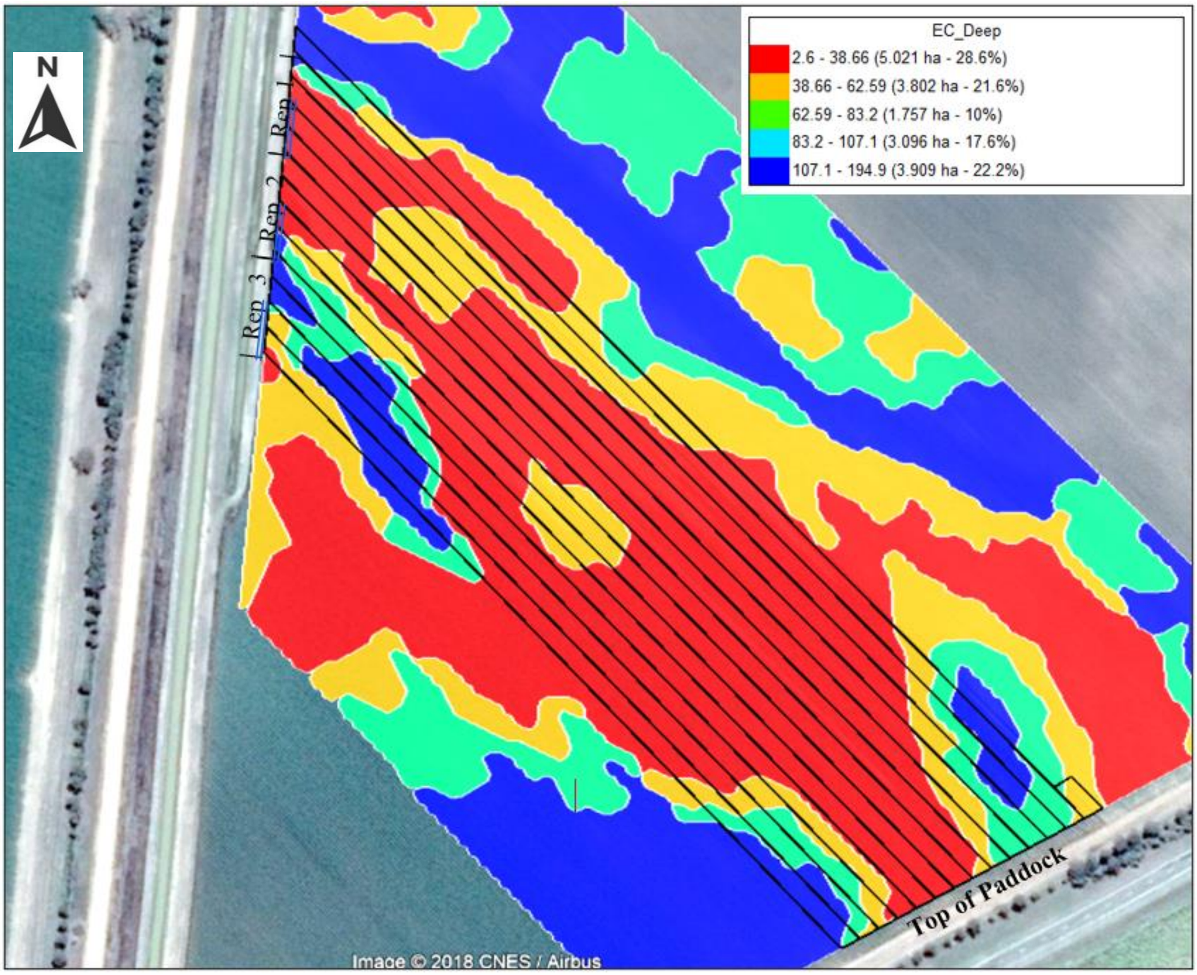


Figure 22. Trial layout with EC map overlay. Scale: 1cm = 0.05747km

Soil analysis results at 0 – 20cm described the soil as a grey clay with a pH of 7.2 (Attachment A). The soil had an organic carbon percentage of 1% and a cation exchange capacity (CEC) of 24.6 cmol/kg. There were no issues with salts or sodium at this depth. Soil N cores in 20cm increments were taken prior to fertilisation from 0 – 100cm from four locations within the trial perimeter. These samples were dried in the ovens at SRA at 40-degree C for a period of seven days. Samples were then sent to DSITI for mineral N analysis. Results are shown in Attachment B.

Irrigation was supplied through the SunWater channel system which is clean water containing no nitrates or salts, and was applied by flood irrigation. The block has no history of mill mud application or legumes in previous years that would impact on N introduction from alternate sources. Rainfall data is provided in Attachment C.

EXPERIMENTAL PROCEDURES

Trial timeline

The trial was conducted over the 2017-2019 harvest seasons, with the trial being plough-out after the 2019 season due to declining yields and the grower's rotation. The time line for key events at the trial site is provided in Table 6 below.

Table 6. Trial activity timeline for the 2017, 2018 and 2019 crop seasons

Project Year	Class	Activity	Date
Year 0	Plant	Harvest	5th August 2016
Year 1	1R	Fertiliser Application	29th August 2016
		Biomass Sampling (224 days after harvest)	17th March 2017
		Pre-Harvest Biomass Sampling	27th July 2017
		Harvest	18th August 2017
Year 2	2R	Fertiliser Application	12th September 2017
		Biomass Sampling (230 days after harvest)	6th April 2018
		Pre-Harvest Biomass Sampling	12th September 2018
		Harvest	2nd -3rd October 2018
Year 3	3R	Fertiliser Application	5th November 2018
		Biomass Sampling (253 days after harvest)*	12th June 2019
		Pre-Harvest Biomass Sampling (Green Cane)	24th September 2019
		Harvest + Biomass Sampling (Burnt cane – stalk only)	24th-25th October 2019

*slight delay due to grower's irrigation schedule

Treatment Details

Fertiliser treatments investigated District Yield Potential (DYP) which forms the basis of the SIX EASY STEPS methodology, and Productivity Unit Yield Potential (PZYP). In the Burdekin there are two DYP rates (150t/ha and 180t/ha) both of which were used in the trial. Historical yield data was captured and used to calculate PZYP (Attachment D). There was also an additional PZYP treatment based on an EFF product which was a blend of one third ENTEC to two-thirds AgroMaster. The blend was mixed at Landmark Ayr. The Burdekin treatments are summarized in the table below.

Three replications of each treatment were applied in plots that were 6 rows wide and extended the entire length of the paddock in a randomised block design (Figure 23). Treatments were applied using a 3-row stool splitter at 1.65m spacing using a John Deere hydraulic rate applicator on RTK guidance. Treatment blends were calibrated before application. The Zero N treatment was confined to a 6-row x 30m sub-plot as requested by the grower, with this area moved each year so that the treatment represented a crop grown on residual fertility from previous fertilised seasons. Single super phosphate was used for this treatment to avoid any N application but provide enough phosphorus (P) to meet crop demands. Due to the small area, the product was hand applied into a slot created by the stool splitter with no fertiliser on board, to ensure fertiliser depth and position were consistent with those in the other treatments (Figure 24a & b). The single super phosphate band was then manually covered with soil.

Table 7. Treatment descriptions and nutrient application rates

Treatment	Description	Product	Rate (kg/ha)	N (kg/ha)	P (kg/ha)	K (kg/ha)	S (kg/ha)
1	Zero N	SS Phosphate	230	0	20	0	25
2	DYP 180t/ha	Nitra-P	495	200	20	0	0
3	PZYP 130t/ha	CB Nesp 345	390	150	20	0	0
4	PZYP 130t/ha EEF	CB Entec /AM	396	150	20	0	0
5	DYP 150t/ha	CB Nesp 345	440	170	23	0	0
Block applied with 1t/ha gypsum prior to trial.							

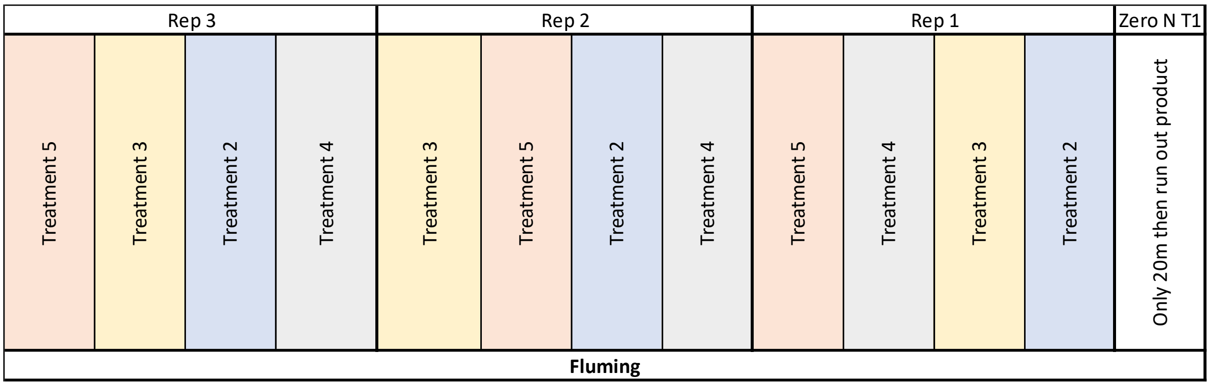


Figure 23. Trial layout (Zero N T1 moved each year from side to side)

Figure 24. a) Applying single super phosphate by hand into b) a pre-existing trench created by the stool splitter

Biomass Sampling

The first biomass sampling event each year was conducted approximately 200 days after fertiliser application, in accordance with the experimental protocol (Attachment E), with the exact sampling dates shown in Table 1. Biomass assessments were conducted to determine the N uptake in leaves, stalk and whole of plant, with the difference between fertilised and unfertilised crops used to estimate fertiliser N recovery. Ten metres of crop was removed from all individual plots. Due to the trial being commercially harvested as strip trials, 5 metres of cane was removed from both the top and bottom of paddock to make up the 10 metres sample per plot. Each 5m subsample was collected 30 metres inside the paddock in the middle row of each treated plot, with the sampled areas evident in Figure 25a and b.

Figure 25. a) Sampled area at top of the paddock; b) Sampled area at bottom of the paddock.

A second biomass sampling event occurred prior to harvest (crop was burnt at time of harvest), with only 8-10 representative sticks collected during this event due to the large nature of Burdekin crop and inability to cut 5m strips. Representative sticks were weighed for fresh weight, and then processed into stalk as well as leaf and cabbage. The proportions of stalk to leaf/cabbage, the N concentrations in each component and the whole strip cane yield were then combined to estimate the crop N content at harvest, with the fraction of total N removed in cane yields also able to be estimated.

The crop component samples (leaf and stalk) from both biomass sampling events were then shredded and a subsample of material was collected, fresh weights recorded and then oven dried. Dry weights of the samples were then recorded and subsamples were sent to DSITI for N analysis. Total Carbon (TC) and Total Nitrogen (TC) analysis results were conducted by DSITI using the Dumas method. Leaf, stalk and total crop N uptake was then calculated based on these results.

Harvest

Treatments 2-5 were commercially harvested after the crop was burnt. Each plot consisted of 6 rows which were separately consigned as a rake. Mill rake data provided fresh weight cane yields (t/ha) and CCS for each plot, from which sugar yields (t/ha) were calculated. In the case of the Treatment 1 (Zero N) subplot, yield was captured in various ways depending on the availability of machinery. More detail is provided in Table 8.

Prior to the 2018 harvest, visual crop biomass differences were observed during biomass sampling between rep 3 and the other replications. It is believed this was more apparent than the previous year and aligned with differences in EC determined in the deeper soil layers from the Veris survey data (Figure 22). These zones were further investigated during harvest using a weigh trailer (Figure 26). Three 30 metre strips were taken from each plot, including top, middle (consistently one zone across the trial) and bottom of paddock. The trailer was also then used for the Zero N plot, where three 20 metre strips were mechanically harvested at the same time as the rest of the trial. This method was only used in 2018 in conjunction with the standard whole plot method used in 2017 and 2019.

Figure 26. Harvesting 30 metre plots using the weigh trailer in 2018. Plots were sampled in the top, middle and bottom thirds of each replicate strip to explore the impact of spatial variability on treatment responses.

RESULTS AND KEY FINDINGS

Biomass N uptake

Statistical analysis of biomass and N contents from the different parts of the field strips showed that while data were variable there was no significant difference between the top and bottom parts of the field in any growing season, nor any significant interactions between sample location and treatment. Therefore, dry biomass and crop N uptake measured in the 200d destructive sampling in each of the three consecutive growing seasons are presented as means for the different fertiliser N treatments in Table 8 below. Differences were typically recorded between the unfertilised (Nil N) plots and the fertilised plots in all seasons for both parameters, and in the 2017 season there were greater crop N contents in the 200N (urea) and the 150 N (EEF blend) treatments than in the other urea N treatments. Similar trends were evident in both 2018 and 2019, but increasing variability in the field plots resulted in a lack of statistical significance for these differences between N treatments.

Table 8. Average dry biomass and total N uptake for 2017 (224 after harvest), 2018 (230 days since harvest) and 2019 (253 days since harvest). Different letters denote statistically significant differences at P<0.05.

		2017		2018		2019	
N Rate (kg/ha)	N product	Dry biomass (t/ha)	Crop N uptake (kg/ha)	Dry biomass (t/ha)	Crop N uptake (kg/ha)	Dry biomass (t/ha)	Crop N uptake (kg/ha)
0#	-	21.97a	88.4a	22.98a	79.1a	16.30a	53.1a
200 (DYP 180)	Urea	29.46bc	140.9c	27.81b	120.8b	28.02b	75.9b
150 (PZYP)	Urea	25.41ab	114.5b	25.66ab	95.6ab	24.96b	63.8ab
150 (PZYP)	EEF	34.65c	140.6c	28.97b	124.8b	27.50b	72.3b
170 (DYP 150)	Urea	30.32bc	110.4b	31.32b	119.3b	26.75b	66.0ab

Means of 3 replicate samples collected from a single unreplicated plot with no applied fertiliser at the top of the field in each season

An analysis of the combined data set for the three consecutive growing seasons was conducted, as well as an assessment of the cumulative crop N accumulated over the three seasons. Sampling location again had no impact on treatment effects on biomass production or crop N accumulation, and as expected from Table 8, both the N treatment and the growing season/ratoon age had significant impacts on both parameters, but there was no statistically significant interaction between treatment and season. The results of the analysis for crop N accumulation are shown in Table 9, with the dry biomass production showing similar trends. Crop N content declined by 10% from R2 to R3, but by 45% in R4. The PZYP/EEF treatment (150N) produced identical crop N contents across the experiment as the 180t DYP rate (200N), with the PZYP/urea treatment showing 20% lower N content and the 150 t DYP rate (170N) was intermediate (12% lower).

Table 9. Effects of growing season/ratoon age and fertiliser N treatment on crop N accumulation from ratoons grown in 2016/17, 2017/18 and 2018/19.

Variable	Ratoon/season	Crop N content (kg N/ha)	Variable	Fertiliser treatment	Crop N content (kg N/ha)
Growing season (ratoon)	2016/17 (R2)	127	Fertiliser N treatment	200N (Urea)	113
	2017/18 (R3)	115		150N (Urea)	91
	2018/19 (R4)	70		150N (EEF)	113
	LSD (P<0.05)	9.2		170N (Urea)	99
				LSD (P<0.05)	15

The cumulative analysis of crop N uptake over the three crops (Figure 27), including the data from the unfertilised (Nil N) control shows similar treatment differences between fertilised treatments (although this time not quite statistically significant), but also demonstrates the net contributions of fertiliser application to crop N uptake. In effect, cumulative N applications of 600 kg (DYP 180), 510kg (DYP 150) and 450kg (PZYP) of fertiliser N across three seasons has resulted in net N accumulation in crop biomass of 117 kg (200N urea and 150N EEF), 75 kg (170N urea) and 53 kg (150N urea), respectively. These represent recovery efficiencies ranging from 12-15% in the lower urea rates to 26% with the EEF blend applied at the PZYP rate.

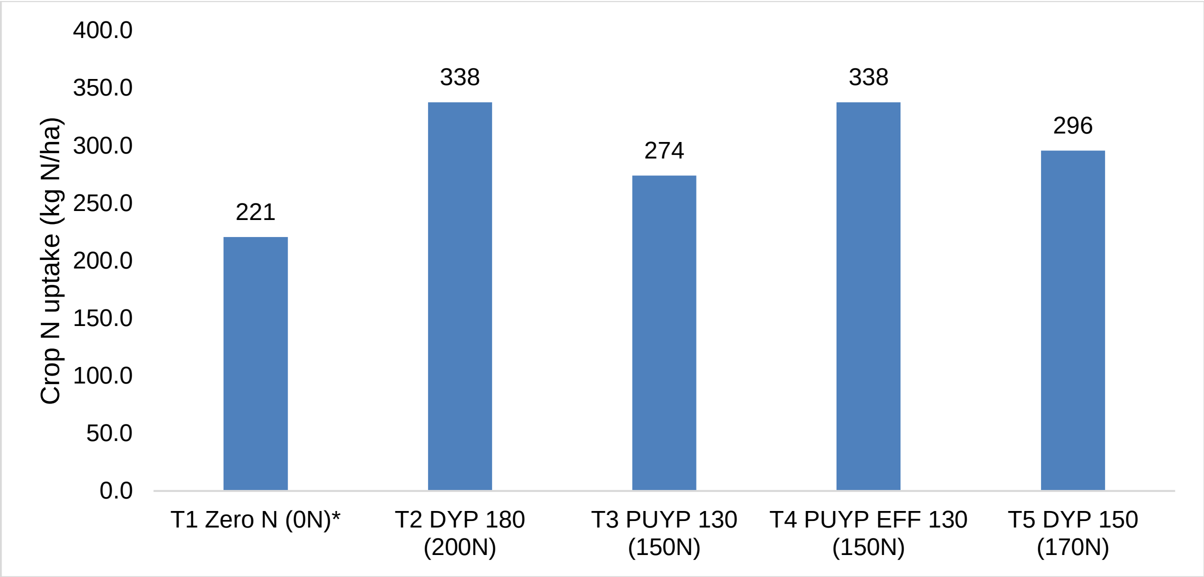


Figure 27. Cumulative N uptake (kg/ha) across treatments (2017 – 2019). The LSD ($P<0.05$) for this analysis is 45 kg N/ha.

It must be noted that there was significant variation across the paddock, especially at the bottom of the paddock, which became more noticeable as the duration of the experiment continued (i.e. 2017,2018<2019). This is evident in the satellite image taken at the time of biomass sampling in June 2019, where rep 1 and the two northern plots of rep 2 were clearly more lodged in the sampling area than in the southern side of the trial (Figure 28). This was corroborated by on-ground photos during sampling (Figure 29), and was consisted with lower biomass and crop N contents in that last ratoon.

An analysis of the variation in the biomass sampling locations from Figure 28 was undertaken using Farmacist's GSM software for yield estimation based on satellite imagery. An example of this estimated variability is shown for treatment 5 at the top of the paddock indicated in the field map in Figure 30 – biomass yield variations are shown in Table 10 with T5R3A being significantly less than replicates 1 and 2. This analysis also suggested that there was little variability in the middle part of the field – either due to treatments or site-related factors.

Figure 28. Satellite image of the bottom of the trial paddock after June 2019 biomass sampling.

Figure 29. Differences in crop lodging in plots at the bottom end of the trial. Left - upright T2R3; Right - lodged T3R1B.

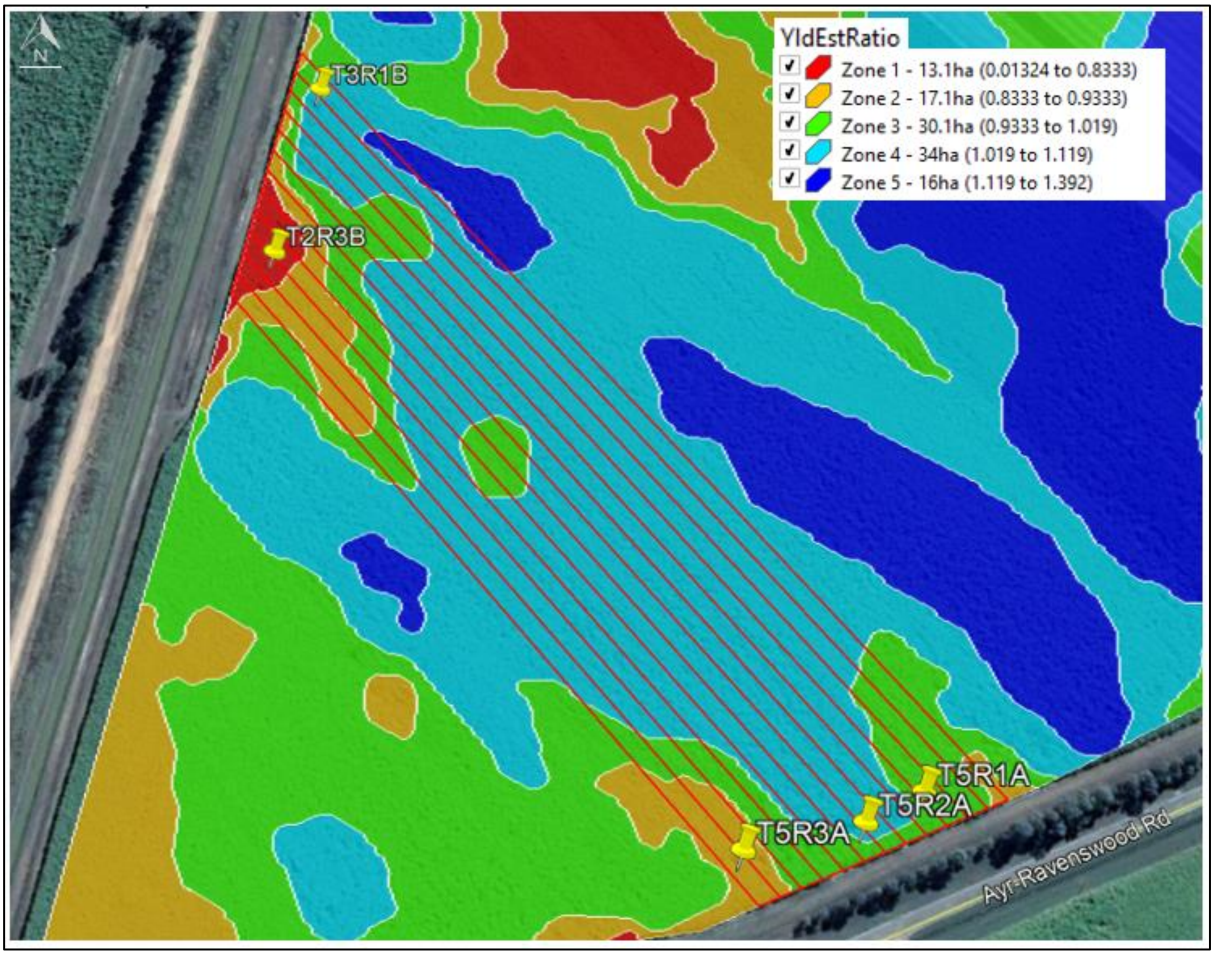


Figure 30. Yield estimation map generated by Farmacist GSM software based on satellite imagery for 2019 only.

Table 10. Biomass yield predictions from satellite imagery collected mid-season in 2019 for treatment 5 in plots at the top of the field.

Plot	Biomass Yield (t/ha)
T5 R1 A	104.24
T5 R2 A	116.36
T5 R3 A	69.70

Due to the nature of the large Burdekin crops, and weather events such as Cyclone Debbie, sampling protocols were adjusted to combat the heavily lodged crop in the pre-harvest biomass sampling event. It was impossible to collect and weigh all stalks from a 5m length of crop row at any distance from the top or the bottom of the field due to the lodged cane, so various methods were used to estimate crop N contents at the end of the season, and also the amount of N removed in harvested cane. Ultimately, determination of Biomass and N allocations in a selection of representative stalks from each plot, scaled against the cane yields harvested in each plot, were used for this purpose.

Harvest Results (By year and Cumulative)

The yield responses to fertiliser N application and rate/product assessed from mill rake data are presented for each growing season in Tables 11-13. Crops showed a declining cane yield response to applied N fertiliser with increasing age of ratoons, with the Nil N treatment yielding 52% (R2) 79% (R3) and 85% (R4) of the yields obtained in the 200N (urea) treatment, with this declining N response related to variable yields in the Nil N treatment (64-92 t/ha) combined with declining yields with fertiliser N addition.

Table 11. Harvest results for the 2R crop harvested 18th August 2017. Means followed by the same letter or symbol do not significantly differ (P=0.05).

Treatment	tCane/ha	CCS	tSugar/ha
T1 Zero N (0N)*	63.67 b		
T2 DYP 180 (200N)	121.81 a	14.97 -	18.23 a
T3 PZYP 130 (150N)	115.24 a	15.47 -	17.83 a
T4 PZYP EFF 130 (150N)	122.66 a	15.07 -	18.47 a
T5 DYP 150 (170N)	115.47 a	15.33 -	17.72 a

* T1 – Hand cut green on 27th July 2017. Therefore no CCS available.

Table 12. Harvest results for the 3R crop harvested 2nd-3rd October 2018. Means followed by the same letter or symbol do not significantly differ (P=0.05).

Treatment	tCane/ha	CCS	tSugar/ha
T1 Zero N (0N)*	91.77 b	18.62 -	17.07 -
T2 DYP 180 (200N)	115.28 a	17.20 -	19.80 a
T3 PZYP 130 (150N)	106.48 ab	16.73 -	18.68 a
T4 PZYP EFF 130 (150N)	115.56 a	16.61 -	19.09 a
T5 DYP 150 (170N)	112.80 a	17.25 -	19.43 a

* T1 – Machine harvested burnt using weigh trailer and mini mill used to determine CCS.

Table 13. Harvest results for the 4R crop harvested 24th-25th October 2019. Means followed by the same letter or symbol do not significantly differ (P=.05, LSD).

Treatment	tCane/ha	CCS	tSugar/ha
T1 Zero N (0N)*	82.14 -	18.70 a	15.38 -
T2 DYP 180 (200N)	95.70 -	16.37 b	15.66 a
T3 PZYP 130 (150N)	90.69 -	15.98 b	15.00 a
T4 PZYP EFF 130 (150N)	97.00 -	16.47 b	15.97 a
T5 DYP 150 (170N)	93.92 -	16.75 b	15.69 a

* T1 – Hand cut burnt and mini mill used to determine CCS.

Aside from differences between the Nil N control and the fertilised plots for CCS, there was no effect of N application rate or product on CCS in any year, and so sugar yields reflected differences in cane yields year to year (Tables 11-13). While these differences may have been related to N availability, it is unrealistic to compare CCS values (and hence sugar yields as well) between the Nil N control and the fertilised treatments because of the differences in methods of determining CCS (mill rake CCS v mini-mill).

An analysis of the combined data set was conducted to explore both the effects of treatment on cumulative cane and sugar production, and also the interaction between treatment and season for either yield parameter (Table 14). There was no statistically significant effects of N rate/product on cumulative cane or sugar yields, although there was a slight trend for declining urea-N rates to result in progressively lower cane and sugar yields. The use of the EEF blend completely overcame those effects, with annual applications of 150 kg N/ha as the EEF blend producing the same cane and sugar yields over the three growing seasons as annual applications of 200 kg N/ha.

The crop variability referred to in the biomass sampling was also evident in cane growth at the time of harvest (Figures 31-32), and the weigh trailer and 30m subplot harvests were used in an attempt to relate this variation to the observed differences in subsoil EC from the original Veris survey of the field taken at the time of experiment establishment (Figure 22). The 30m harvest zones were located on the field map, and the average EC reading for each harvest area was calculated. These data were used as a covariate to determine wheather the crop variability observed in the field, regardless of treatment, was related to this underlying soil condition.

Table 14. Effects of (a) fertiliser N treatment on cumulative cane and sugar production over the experimental period, and (b) the impact of growing season/ratoon on these yield parameters. Analyses were conducted from harvest data from the 2017, 2018 and 2019 seasons.

(a) Effects of N treatment	**Cane yield (t/ha)**	**Sugar yield (t/ha)**	**(b) Effects of ratoon/season**	**Cane yield (t/ha)**	**Sugar yield (t/ha)**
DYP 180 urea (200N)	333	53.7	R2 (2016/17)	119	18.1
PZYP urea (150N)	312	51.5	R3 (2017/18)	113	19.3
PZYP EFF (150N)	335	53.5	R4 (2018/19)	94	15.6
DYP 150 urea (170N)	322	52.8			
LSD (P<0.05)	ns	ns	**LSD (P<0.05**)	3.9	0.6

Figure 31. Variability becoming more evident in 3rd ratoon. Harvesting plot T5R3 (approximately 50-100 metres from the top of paddock). Variability showed down the drill.

Figure 32. Variability observed from the bottom headland before (top) and after burning (bottom). (Rep 3 on the right-hand side).

There were no significant relationships between deep soil EC and the cane yields harvested from the different paddock zones in 2018. The data did illustrate the variability in growth in different parts of the field in the different urea rates, but also encouragingly illustrated the relative stability of yields with the EEF product (Figure 33).

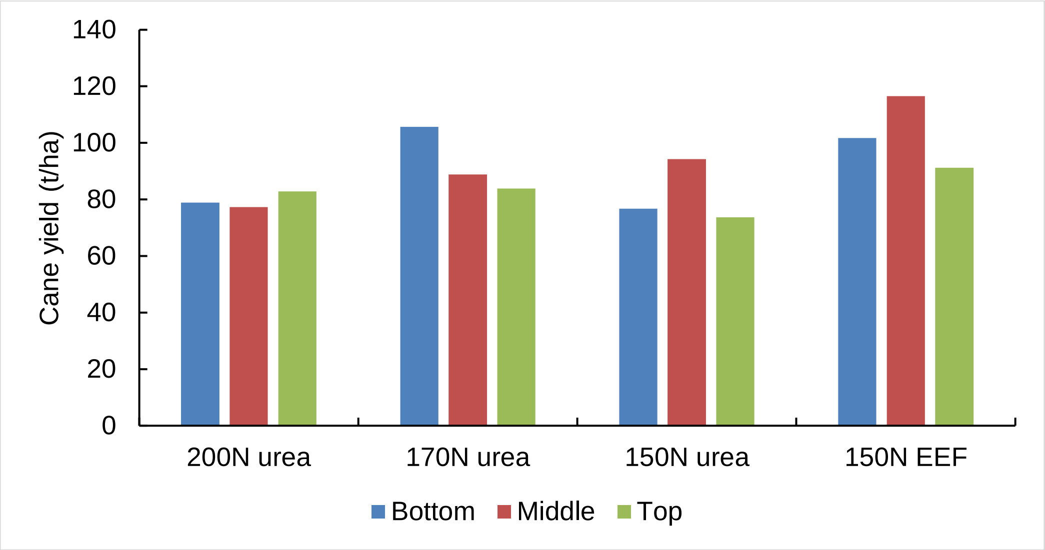


Figure 33. Cane yield variability measured for the different N rates in different parts of the field. Differences were not statistically significant, but did indicate relative yield stability with the EEF blend compared to the urea applications, regardless of rate.

Attachment A: Site characterisation soil test

Nutrient Advantage®

Nutrient Advantage Advice® Recommendation Report

Report Print Date:	16/08/2016
Agent/Dealer:	
Advisor/Contact:	Rob Milla
Phone:	
Purchase Order No:	488922

Grower Name:		**Nearest Town:**	AYR
Sample No:	020946135	**Test Code:**	A43
Block Name:	326 Block6	**Sample Type:**	Soil
Sample Name:		**Sampling Date:**	08/07/2014
Sample Depth (cm)	0 To 20		

Analyte / Assay	Unit	Value	Very Low / Marginal / Optimum / High / Excess	Optimal
Soil Colour		Grey	Information Only	
Soil Texture		Clay	Information Only	
pH (1:5 Water)		7.2	Neutral	5.5 - 8.0
pH (1:5 CaCl2)		6.6	Not Chart Referenced	
Electrical Conductivity (1:5 Water)	dS/m	0.31	Not Chart Referenced	
Electrical Conductivity (Saturated Extract)	dS/m	1.9		<1.0
Chloride	mg/kg	40		
Organic Carbon (OC)	%	1.0		
Organic Matter	%	1.7		
Nitrate Nitrogen (NO3)	mg/kg	<1		
Ammonium Nitrogen	mg/kg	2		
Phosphorus (Colwell)	mg/kg	16	Not Chart Referenced	
Phosphorus (BSES)	mg/kg	18		20 - 50
Phosphorus Buffer Index (PBI-Col)		170		140 - 280
Potassium (Nitric K)	cmol(+)/kg	2.00		>0.7
Sulphur (MCP)	mg/kg	51		>10 - >15
Cation Exchange Capacity	cmol(+)/kg	24.6		>4
Calcium (Amm-acet.)	cmol(+)/kg	14.0		>1.5
Magnesium (Amm-acet.)	cmol(+)/kg	9.1		>0.25
Sodium (Amm-acet.)	cmol(+)/kg	1.20	Not Chart Referenced	
Potassium (Amm-acet.)	cmol(+)/kg	0.32		>0.26 - >0.40
Available Potassium	mg/kg	130		
Calcium % of cations	%	57.0	Not Chart Referenced	
Magnesium % of cations	%	37.0	Not Chart Referenced	

Analyses conducted by **Nutrient Advantage Laboratory Services**

For a copy of Laboratory Methods of Analysis please go to www.nutrientadvantage.com.au

8 South Road, Werribee VIC 3030

NATA Accreditation No: 11958 Tel: 1800 803 453

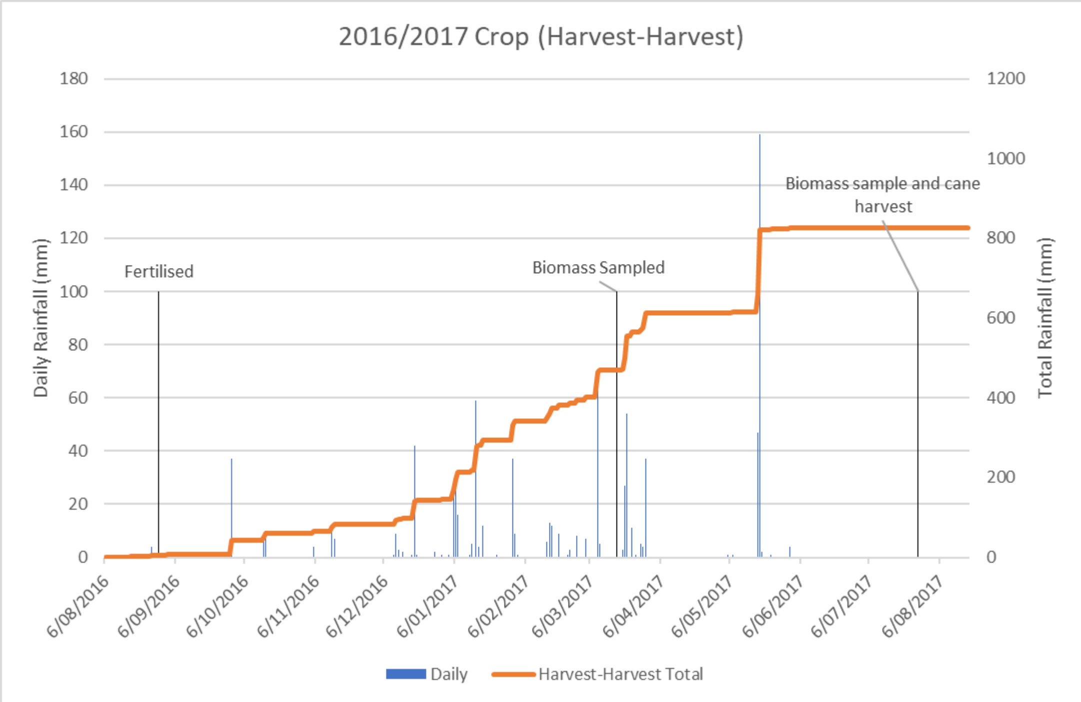
Certificate of Analysis is available upon request. Email: lab.feedback@incitecpivot.com.au

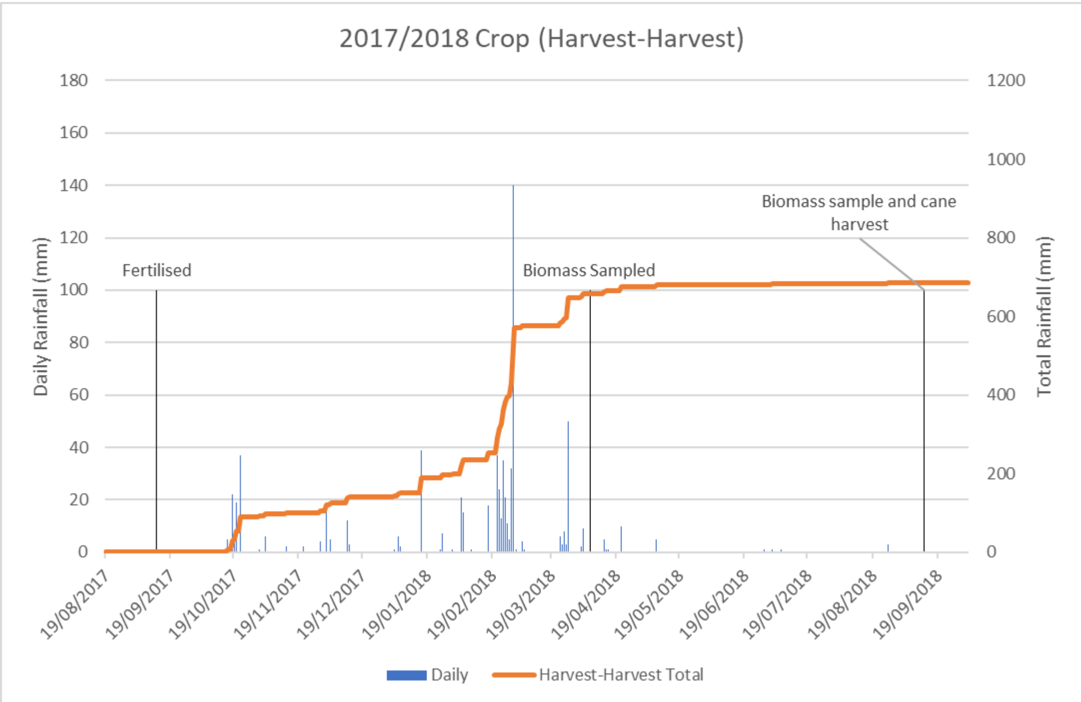
Sample No 020946135 Version: 2 Page 1 of 5

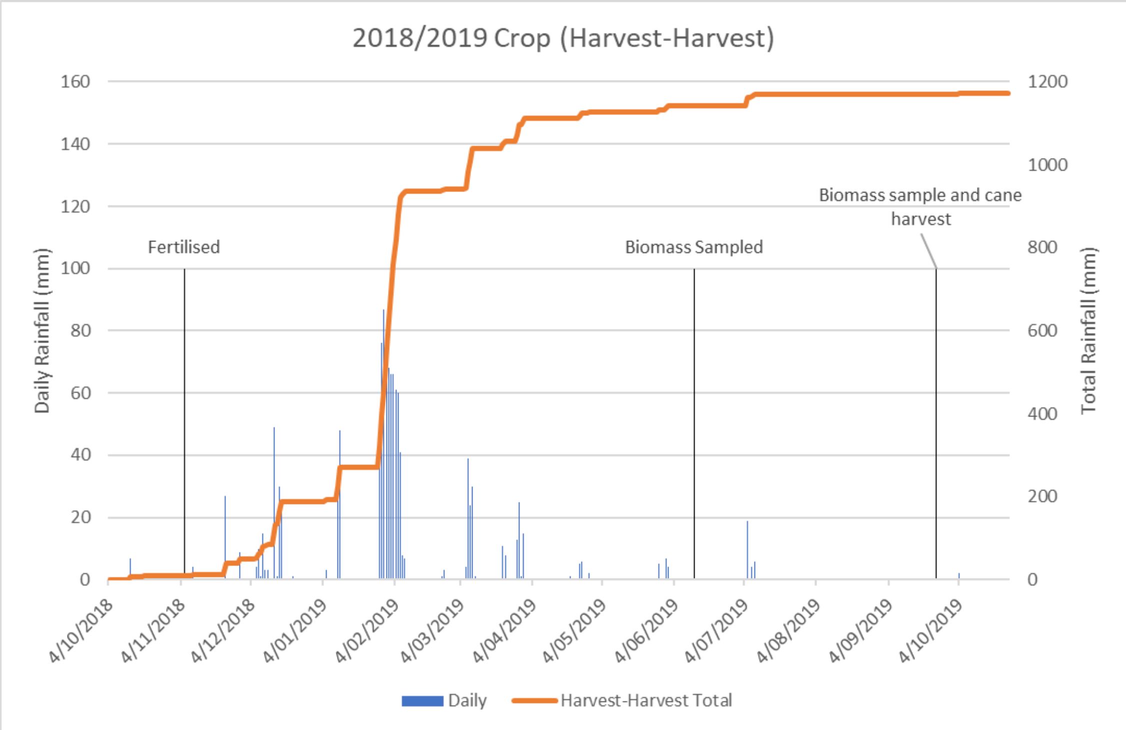
Attachment B: Characterisation of site variability in profile mineral N just before N application (16/11/2016)

Sample ID	Site	Location	Depth (cm)	2M KCl extr.	
				NH4-N	NO3-N
				mg/kg	mg/kg
1	NESP BDK	1	0-20	4	0.6
2	NESP BDK	1	20-40	2.1	1
3	NESP BDK	1	40-60	2	<0.5
4	NESP BDK	1	60-80	1.6	<0.5
5	NESP BDK	1	80-100	2.1	<0.5
6	NESP BDK	2	0-20	3.3	<0.5
7	NESP BDK	2	20-40	2.4	0.5
8	NESP BDK	2	40-60	1.9	0.7
9	NESP BDK	2	60-80	2	<0.5
10	NESP BDK	2	80-100	2.1	0.6
11	NESP BDK	3	0-20	3	1.1
12	NESP BDK	3	20-40	2.2	0.6
13	NESP BDK	3	40-60	1.6	0.6
14	NESP BDK	3	60-80	2.1	0.8
15	NESP BDK	3	80-100	2	<0.5
16	NESP BDK	4	0-20	1.7	5
17	NESP BDK	4	20-40	1.6	4.3
18	NESP BDK	4	40-60	1.8	10.2
19	NESP BDK	4	60-80	1.8	23.9
20	NESP BDK	4	80-100	1.9	58.9

Attachment C: Seasonal rainfall data






2018/2019 Crop (Harvest-Harvest)
Daily Rainfall (mm)
Total Rainfall (mm)
160
140
120
100
80
60
40
20
0
1200
1000
800
600
400
200
0
Fertilised
Biomass Sampled
Biomass sample and cane harvest
4/10/2018
4/11/2018
4/12/2018
4/01/2019
4/02/2019
4/03/2019
4/04/2019
4/05/2019
4/06/2019
4/07/2019
4/08/2019
4/09/2019
4/10/2019
Daily
Harvest-Harvest Total

Attachment D: Historical yield data at the experimental site

Date Cut	Pdk/Blk #	Variety	Class	Yield Cane	Yield Sugar
2016	6-1	Q240	PLT	196.51	26.57
2015	6-1	F	F	-	-
2014	6-4	KQ228	5R	94.01	13.72
2013	6-4	KQ228	4R	102.18	12.67
2012	6-4	KQ228	3R	91.31	12.81
2011	6-4	KQ228	2R	111.94	17.16
2010	6-4	KQ228	1R	117.20	17.71
2009	6-4	KQ228	Re-Plant	115.81	18.76

The calculated PZYP for ratoon cane grown in this block was 130 t/ha

Attachment E: Biomass sampling methodology

Pre-Sampling

Mark out all plots (5 N rates by 3 reps) by top (A) and bottom (B):

- With flagging tape mark the middle two rows of cane for each plot (eg 3-4 of a 6 row plot). This will clearly display which furrow for the cutter and carriers to walk up and down.
- Recommend placing a pink survey peg with the treatment, rep and either A/B on it to minimise confusion later on especially when weighing.
- Using a measuring tape, walk in 30m from top/bottom between the two middle rows.
- Flag tape the first cane stalk on row three. Measure 5m and flag tape the last stalk. This will be the 5m section to cut.
- Measure another 5m and flag the last stalk. Both these 5m sections make up the 10m for the stalk count.
- Recommend using a 10m piece of rope with flagging tape tied half way to speed up the process.
- Count all stalks above 1m in the 10m.

Sampling

- Cut first 5m section of each plot
- Carry to closest end of paddock. Keep stalks together in front of each plot next to pink survey peg.
- Move weigh trailer to each pile of bundles to reduce carrying. Tare and record total weight.
- Keep 10 stalk for N analysis, bundle and tag
- Discard remaining stalks

Processing

- Work from zero N upwards
- Weigh bundle of 10 stalks. (Figure 34)
- Then partition into:
    - Millable stalk (Figure 35)
    - Tops which includes cabbage and green leaves (Figure 36)
        - To determine between millable stalk and cabbage cut between the 5th and 6th dewlaps for stalks that have not flowered or the 7th and 8th dewlaps for stalks that have flowered
        - Include all green leaves, even those attached to the millable stalk into the top sample

Figure 34. Weigh bundle of 10 stalks

Figure 35. Millable stalk

Figure 36. Tops, including leaf and cabbage

- Weigh each component separately and record weights
  - Weight of 10 millable stalks
  - Weight of 10 tops
- To minimise cross-contamination, mulch stalks and tops in batches if possible rather than alternating individual stalk-top-stalk samples.

Figure 37. Shredding of material

- Discard the first mulched material to remove any carry-over from previous samples.
- Collect a subsample of the mulched material and record the fresh weight
  - Fresh weight mulched millable stalk sample
  - Fresh weight mulched top sample

Figure 38. Subsampling and weighing of fresh material

- Dry subsamples in an oven set at 60°C for 7 days and record dry weight
  - Dry weight mulched millable stalk sample
  - Dry weight mulched top sample
- Calculate moisture content
  - Moisture content % = ((net fresh weight – net dry weight) / net fresh weight) * 100
- Grind dry millable stalk and top samples (pass through <2 mm sieve) in batches if possible to minimise cross-contamination.
- Discard the first ground material to remove any carry-over from previous samples.
- Collect a 20g subsample from the ground millable stalks and tops.
- Send samples to DSITI for analysis of N concentration and $^{15}N/^{14}N$ determination.

Figure 39. Farmacist team taking a well earnt break whilst collecting biomass samples (200 DAA)

APPENDIX 3: TULLY SITES

Author: Dr Danielle Skocaj
Affiliation: Sugar Research Australia

ACKNOWLEDGEMENTS

This project is supported with funding from the Australian Government's National Environmental Science Program Tropical Water Quality Hub. The field experiments discussed in this report were managed by Sugar Research Australia. We are grateful for the opportunity to collaborate in this research project and contribute towards improving the understanding of nitrogen use efficiency in the Wet Tropics sugar industry. Ingham Farm Centre is also acknowledged for blending the enhanced efficiency fertiliser product each season. We are also grateful to the grower collaborator (L &R Collins Pty Ltd) at Tully for hosting these field experiments and cooperating with treatment applications and sampling activities and Dr Phil Moody and Angelique Woods from the Department of Environment and Science, for timely analysis and reporting of soil and plant tissue samples.

EXECUTIVE SUMMARY

Identifying opportunities within the sugarcane production system to improve nitrogen use efficiency (NUE) whilst maintaining productivity and profitability is challenging, especially in regions experiencing high rainfall and extreme interannual climate variability. Increases in NUE can result from producing higher yield with the same amount of N fertiliser, the same yield with less N fertiliser or higher yield with less N fertiliser (Wood and Kingston, 1999). One option is to substitute the yield discriminator (district yield potential) used in determining the SIX EASY STEPS^{TM} N management guidelines with an achievable yield potential (Bell and Moody, 2015; Bramley *et al.,* 2017). Using a more refined yield target may allow N rates to be adjusted in response to spatial and possibly temporal variability in cane yields. However, lower yielding crops may not always be less responsive to applied N compared to higher yielding crops. In these situations, applying less N without changing other agronomic or fertiliser N-management aspects, can reduce productivity and profitability (Schroeder *et al.,* 2018, Thorburn *et al.*, 2018).

The use of enhanced efficiency fertilisers (EEF) has also been promoted as having potential to improve NUE without compromising productivity. These products attempt to better synchronize N availability with crop-N demand by modifying the release of fertiliser-N or controlling the rate of N transformations in and around the fertiliser band. The effectiveness of EEF products to improve NUE through either higher cane yields or lower fertiliser-N rates has been highly variable (Di Bella *et al.*, 2017, Panitz *et al.,* 2019, Verburg *et al.* 2017 and 2018). In addition, the higher cost of these products/kg N applied compared to urea, also typically results in lower profitability (Panitz *et al.,* 2019). Blending EEFs with different modes of action may lower the risk of N losses and increase crop-N recovery. This may provide an opportunity to reduce fertiliser-N rates without increasing the risks of productivity loss or increasing fertiliser input costs.

A total of seven field experiments were established with funding from the Australian Government's National Environmental Science Program to further investigate these options. The results presented and discussed in this report relate to two of the small-plot field experiments conducted in the Tully mill area (referred to as NESP 1 and NESP 2) and managed by Sugar Research Australia. The main purpose of the Tully field experiments was to 1) compare the impact of applying the best available blend of EEF products against urea at fertiliser-N rates determined using the historical block level productivity potential (PZYP) and 2) compare the effect of fertiliser-N rates with and without adjustment for the soil-N mineralisation potential, on productivity, fertiliser NUE and profitability. At these sites, there was also an opportunity to assess the impact of applying the EEF blend at a lower fertiliser-N rate.

The field experiments supported the SIX EASY STEPS discount for soil N mineralisation in the N guidelines for the Wet Tropics region. Applying higher rates of N in the form of urea did not result in significantly higher biomass, yields, N uptake or NUE. Applying the EEF blend tended to result in higher nitrogen uptake efficiency (NUpE) but this wasn't always reflected in higher crop yields or improved agronomic efficiency of fertiliser N ($AgronEff_N$) relative to the same rate of urea. Applying the EEF blend reduced grower and industry partial economic returns. This is not surprising given the cost of N on a per kg basis for the EEF blend is more expensive than urea. Applying the EEF blend at a lower N rate helped minimise economic losses but was also associated with lower productivity in some seasons.

The experiments also showed crops growing on poorly drained soils can be as productive, profitable and efficient in using applied N as well-drained soils under favourable growing conditions. However, it will be extremely difficult to predict circumstances where the EEF blend is likely to deliver a productivity, profitability and NUE benefit compared to urea with sufficient certainty to influence fertiliser decisions. Soil texture, position in the landscape, climatic conditions and the timing of when environmental stresses occur, in relation to crop growth stage and proximity to fertiliser application have a major influence on crop growth, N uptake and NUE. Growers and advisors can do their best to identify and implement N management strategies that encourage crop N uptake and minimise the risk of yield loss and off-site impacts, but ultimately, factors outside of their control can have a greater influence on NUE.

METHODOLOGY

Wet Tropics field experiments NESP 1 and NESP 2

Trial sites

In the Wet Tropics, two small-plot N response experiments referred to as sites NESP 1 (Lat. 17° 59' 34.23" S, Long. 145° 59' 55.44" E) and NESP 2 (Lat. 17° 59' 27.29" S, Long. 145° 59' 23.55" E), were established in 2R sugarcane crops during 2016. The sugarcane cultivar Q208[A] was growing at both sites. The experiments were located on the following soil series:

NESP 1 – Tully series soil (Kandosol). The soil survey report describes this soil as a well-drained soil formed on alluvium (Murtha, 1986). These soils occur on stream levees, floodplains, and higher terraces along most major streams (Cannon *et al.,* 1992). Their position in the landscape, good fertility and physical properties making them highly desirable for sugarcane production (Schroeder *et al.,* 2007). It is also the major sugarcane growing soil in the Tully mill region.

NESP 2 – Timara series soil (Hydrosol). The soil survey report describes this soil as a poorly drained soil formed on alluvium (Murtha, 1986). These soils are found in minor floodplain depressions and swamps, remain wet for most of year and can have permanent water tables at a depth of around 1 m (Cannon *et al.,* 1992). Their deep dark topsoils indicate organic matter has accumulated under wet conditions (Schroeder *et al.,* 2007). The Timara series is one of the major sugarcane growing soils in the Tully mill region

Treatments, trial design and details

Each site hosted a Nil N treatment each year (fertiliser-N was withheld for that growing season), but these plots/strips were alternated with a fertilised plot annually. Having the Nil N treatment always located on a plot with a history of fertiliser-N application provided a realistic assessment of the soil N supply which the fertiliser-N application was designed to augment. The productivity unit yield potential (PZYP) was calculated as:

PZYP = *mean historical plant, 1R and 2R cane yields + (2 * standard error).*

The mean cane yield for the plant, 1R and 2R crops at sites NESP 1 and 2 were obtained from block records for the period from 2002 to 2015. Both sites have the same PZYP when all plant, 1R and 2R crops are considered. When reviewing the block data, large variations in yields were observed between La Niña (wet) and normal or El Niño (dry) seasons. Hence, a separate PZYP was calculated for wet and dry years to better reflect the impact of seasonal conditions on crop performance. Previous research identifying the importance of spring-summer rainfall on cane yields in the Tully mill area was used to qualitatively classify seasons into wet and dry years (Skocaj 2015). The PZYP is much lower in wet years, especially at the poorly drained NESP 2 site. In dry years, the PZYP of the NESP 2 site is greater than NESP 1. This is driven by differences in soil type and position in the landscape as both sites are owned and operated by the same farming enterprise. NESP 2 occupies a lower position in the landscape. This results in prolonged waterlogging in wet years but sufficient soil moisture in dry years. The PZYP values used to calculate N fertiliser rates and corresponding calculated N rates for each site are reported in Table 15. The N requirement factor and N mineralisation discounts used in the SIX EASY STEPS N guidelines were applied to the PZYP values to determine the corresponding N rates.

Table 15. Productivity Unity Yield Potential (PZYP) and corresponding calculated N rates for NESP 1 and NESP 2.

Site	PZYP (t cane/ha) Overall	PZYP N rate (kg N/ha)	PZYP (t cane/ha) Wet Years	PZYP N rate (kg N/ha) Wet Years	PZYP (t cane/ha) Dry Years	PZYP N rate (kg N/ha) Dry Years
NESP 1	132.1	150	104.4	120	131.6	150
NESP 2	132.4	120	94.3	90*	141.1	130

*the actual N rate corresponding the PZYP for wet years at the NESP 2 site was 82 kg N/ha

Based on the topsoil organic carbon (Org C) values reported in Table 18, the N mineralisation index for sites NESP 1 and NESP 2 is categorised as medium low (ML) and high (H), respectively (Schroeder *et al.,* 2005). This equates to a 20 and 50 kg N/ha discount to the SIX EASY STEPS baseline N guideline for the Wet Tropics region (of 160 kg N/ha) for NESP 1 and NESP 2, respectively (Schroeder *et al.*, 2007). Hence, the SIX EASY STEPS^{TM} N guideline for ratoon crops at NESP 1 and 2 is 140 kg N/ha and 110 kg N/ha, respectively (Schroeder *et al.*, 2007). Given the N rate derived from the PZYP values for these sites only differed by 10 kg N/ha at NESP 1 (140 vs 150 kg N/ha) and NESP 2 (110 vs 120 kg N/ha), the SIX EASY STEPS N guideline was not included as a separate treatment. The treatments imposed at the trial sites are reported in Table 16.

Previous research has shown climate forecasting indices are capable of forecasting rainfall in Australian sugarcane growing regions (Everingham, 2007, Stone and Auliciems, 1992, Everingham *et al.*, 2008). The chance of experiencing high spring-summer rainfall increases when the June-August Oceanic Niño Index (ONI) is in the La Niña phase. High spring summer-rainfall is associated with lower cane yields at Tully (Skocaj and Everingham, 2014). Hence, it was decided to link the exploratory treatment N rate (e.g. Treatment Number 5) to the June to August ONI in each year of the trial. The ONI is a principal measure for monitoring, assessing and predicting the state of the El Niño Southern Oscillation (ENSO) and is based on the three-month running-mean sea-surface temperature (SST) departures from average in the Niño 3.4 region (Smith and Reynolds, 2003). Typically, if the running average of SST anomalies for the previous three months is greater than plus 0.5ºC, then an El Niño phase month is defined (Everingham, 2007). A La Niña month exists if the running average of SST anomalies for the previous three months is less than minus 0.5ºC (Everingham, 2007). If the previous three month running average of SST anomalies is between minus 0.5ºC and plus 0.5ºC, inclusively, then neutral conditions exist (Everingham, 2007). The June to August Nino 3.4 sea surface temperature anomalies for the period 2016 to 2019 were downloaded from the Climate Prediction Center website (http://www.cpc.ncep.noaa.gov).

The June to August ONI values for 2016, 2017, 2018 and 2019 (-0.3, 0.2, 0.1 and 0.3, respectively) indicated ENSO was in the neutral phase. As the PZYP N rate for dry years was similar to the overall PZYP N rate, the PZYP N rate for wet years was used as the exploratory treatment for all crops at both sites. This also presented an opportunity to assess whether N rates could be reduced when using a blended enhanced efficiency fertiliser product.

Table 16. Treatment details for the 2R, 3R, 4R and 5R crops at NESP 1 and NESP 2.

Treatment Number	Treatment Description	NESP 1 N rate (kg N/ha)	NESP 2 N rate (kg N/ha)
1	Unfertilised control	0	0
2	PZYP using urea	150	120
3	PZYP using EEF blend	150	120
4	PZYP without soil N mineralisation discount	170	170
5	Exploratory using EEF blend	120	90

The EEF blend consisted of one-third of the urea coated with the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP, marketed commercially as Entec®) and two-thirds the polymer-coated urea with a reported 90-day release period (product of Everris Pty Ltd and marketed as Agromaster Tropical®). This blend was chosen as the best possible combination of products that would protect fertiliser-N from risk of loss – initially by retaining the N in the ammonium-N form, and subsequently by slowing the release of urea-N into the soil solution (Bell *et al.*, 2019).

The trial consisted of a randomised complete block design containing four replicates. Each plot was 6 rows (9.6 m) wide and 30 m long. Treatments 2, 3, 4 and 5 were applied to the same plot locations each year. There were two unfertilised control plots (Treatment Number 1) each year and these alternated between years (e.g. Treatment Number 2 was applied to two of the four unfertilised control plots each year).

A single row fertiliser box with a hydraulic variable rate controller was used to apply the fertiliser subsurface to the shoulder on each side of the cane row in all crops.

In the 2R crop, fertiliser was applied at sites NESP 1 on 16/11/2016 and NESP 2 on 17/11/2016. This was approximately one month after harvesting the 1R crop. Treatment 1 (unfertilised control) was located in replicates 1 and 3 as per trial protocol.

In the 3R crop, fertiliser was applied at sites NESP 1 on 2/11/2017 and NESP 2 on 1/11/2017. This was approximately two months after harvesting the 2R crop and after the large October 2017 rainfall event where 327.8mm fell over 9 days, most of which (221.0 mm) was received on 19/10/2017. Treatment 1 (unfertilised control) was located in replicates 2 and 4 as per trial protocol.

In the 4R crop, fertiliser was applied at sites NESP 1 and 2 on 9/10/2018. This was approximately two and a half months after harvesting the 3R crop. Treatment 1 (unfertilised control) was located in replicates 1 and 3 as per trial protocol.

In the 5R crop, fertiliser was applied at sites NESP 1 and 2 on 26/09/2019. This was approximately two months after harvesting the 4R crop. Treatment 1 (unfertilised control) was located in replicates 2 and as per trial protocol.

Nutrients other than N were applied at both sites according to the results of soil tests and using the SIX EASY STEPS™ nutrient management guidelines for the Wet Tropics region. This resulted in muriate of potash (100 kg K/ha) being surface banded in the centre of the sugarcane row for all plots at both sites on 18 Nov 2016 (2R), 3 Nov 2017 (3R), 10 Oct 2018 (4R) and 26 Sep 2019 (5R).

SAMPLING, DATA COLLECTION AND ANALYSES

Rainfall and temperature

Daily rainfall data for the period July 2016 to October 2020 was accessed from the Bureau of Meteorology station located at Tully Sugar Mill [Lat. 17.94ºS, Long. 145.93ºE (Station 32042)] and daily minimum and maximum temperature data for the same period was accessed from the Bureau of Meteorology station located at the South Johnstone Experimental Station [Lat. 17.61º S, Long. 146.00ºE (Station 32037)] from the Bureau of Meteorology (BOM) website (http://www.bom.gov.au/climate/data). The long-term mean monthly and annual rainfall was calculated for the period 1970 to 2020. Thermal time (°D) was calculated using the method outlined by Baskerville and Emin (1969) with a base temperature of 9°C.

Site characterisation and soil mineral nitrogen

Composite soil samples were collected from 0-20 cm and 20-40 cm soil depths for soil chemical and textural analyses. Samples were collected with a soil sampling tube using a mechanical jackhammer at the commencement of the 1R crops from the same block but from a location immediately adjacent to the NESP trial area (as part of project 2015/065 funded by Sugar Research Australia and the Department of Environment and Science, refer to Skocaj *et al.,* 2020). The soil collected for each soil depth was thoroughly mixed and air-dried at ambient temperature. A sub-sample from each soil depth was dispatched to the Incitec Pivot Nutrient Advantage Advice laboratory.

Composite soil samples were collected in 20 cm increments to a depth of 80 cm from all plots associated with Treatment 1 (unfertilised control) and Treatment 2 (PZYP N rate urea). Samples were collected with a soil sampling tube using a mechanical jackhammer immediately prior to applying N fertiliser treatments. Each soil sample was thoroughly mixed, air-dried at ambient temperature and ground to pass a 2-mm screen. Sub-samples were dispatched to the Department of Environment and Science laboratory for nitrate-N and ammonium-N analyses. Samples were collected as follows:

- NESP 1: 7 Nov 2016 (post 1R), 21 Sep 2017 (post 2R), 30 Aug 2018 (post 3R), 26 Aug 2019 (post 4R) and 22 Sep 2020 (post 5R).
- NESP 2: 4 Nov 2016 (post 1R), 25 Sept 2017 (post 2R), 31 Aug 2018 (post 3R), 27 Aug 2019 (post 4R) and 22 Sep 2020 (post 5R).

Bulk density was measured by collecting undisturbed soil cores in 5 cm increments to a depth of 100 cm from two locations within each block (as part of project 2015/065 funded by Sugar Research Australia and the Department of Environment and Science, refer to Skocaj *et al.,* 2020). Samples were collected by inserting a soil sampling tube containing 12 metal rings into the soil with a mechanical jackhammer. The rings used to collect the soil cores had an internal diameter of 9.84 cm, were 5 cm high and had a volume of 380.23 cm^3. The rings were individually exposed, the soil extracted, fresh weight recorded in the field and dry weight recorded after the samples were dried at 105°C in a fan forced drying cabinet. The mean bulk density for 0-20, 20-40, 40-60, 60-80 and 80-100 cm soil depths were then calculated from the measurements taken from the 5 cm depth intervals (e.g. for 0-20 cm the mean bulk density was calculated from the bulk density measured at 0-5, 5-10, 10-15 and 15-20 cm).

The mean bulk density values for the four different soil depths (0-20, 20-40, 40-60 and 60-80 cm) were applied to the nitrate-N and ammonium-N concentration results received from the laboratory. This allowed nitrate, ammonium and total mineral N values to be reported as kg NO_3^- N/ha, kg NH_4^+ N/ha and total kg mineral N/ha, respectively. Total mineral N was determined by summing the nitrate-N and ammonium-N values.

Biomass

The total number of stalks in the centre 10 m of rows 3 and 4 of every plot were counted. All of the stalks within 5 consecutive meters of row 3 were cut off at ground level in each plot and the total aboveground biomass weighed. A twenty-stalk subsample was randomly selected from the hand harvested material for partitioning into millable stalk (MS), green leaf and cabbage (LC) and dead leaves/trash. The fresh weight of each biomass component was recorded. This method was adapted from Hogarth and Skinner (1967). There was a slight change in determining biomass and yield in the 4R crop with 45 whole stalks hand harvested instead of 5 consecutive meters of row 3. This sampling methodology is routinely used in other small plot research trials and is unlikely to impact the results obtained for the 4R crop.

Biomass, crop N uptake and CCS were measured on the following dates:

- NESP 1: 8 Aug 2017 (2R), 30 Jul 2018 (3R), 24 Jul 2019 (4R) and 5 Aug 2020 (5R).
- NESP 2: 4 Aug 20176 (2R), 1 Aug 2018 (3R), 29 Jul 2019 (4R) and 6 Aug 2020 (5R).

Each crop was commercially harvested on the following dates:

- NESP 1: 21 Oct 2016 (1R), 11 Sep 2017 (2R), 3 Aug 2018 (3R), 5 Oct 2019 (4R) and 12 Sep 2020 (5R)
- NESP 2: 17 Oct 2016 (1R), 8 Sep 2017 (2R), 4 Aug 2018 (3R), 6 Oct 2019 (4R) and 12 Aug 2020 (5R)

Crop nitrogen uptake

At the time of biomass sampling, six-MS and six-LC samples were also randomly collected from each plot to determine moisture content and N concentration. The six-MS and six-LC samples were shredded separately using a garden mulcher. A subsample of the shredded MS and LC plant tissue was placed into a clean brown paper bag, weighed, and dried at 60^{O}C. Dry weights of the samples were determined once consistent weights were attained. Percentage DM (%DM) was calculated and recorded. The dried samples were then ground to pass a 0.5 mm screen using a FRITSCH cutting mill (Pulverisette model). Sub-samples of the ground dried plant tissue were dispatched to the Department of Environment and Science laboratory for analysis (total N% and total C% DM).

Cane yield and CCS

Cane yield was determined from the stalk population and biomass sampling results. At the time of biomass sampling, six stalks were also randomly collected from each plot to determine the CCS content using the standardised NIR methodology (Berding *et al.* 2003). Sugar yields (t sugar/ha) were calculated from the sugarcane yield and CCS values. Despite high levels of variation in treatment performance between replicates in some seasons, no plots were omitted from the statistical analysis for this report.

Nitrogen use efficiency (NUE)

The mean data from the unfertilised control plots was used to calculate the agronomic responses in cane yields and crop N uptake from the fertilised treatments for the 2R, 3R, 4R and 5R crops at sites NESP 1 and 2.

Agronomic Efficiency of fertiliser N use ($AgronEff_N$) = Fertiliser N rate/($Yield_{N1}$ – $Yield_{N0}$) = kg fertiliser N required to produce an additional tonne of cane yield. In this calculation, $Yield_{N1}$ is the cane yield at fertiliser rate N_1, while $Yield_{N0}$ is the yield with no N applied. It measures the efficiency with which fertiliser N is used to produce cane yield and separates the yield derived from the soil N pool and N supplied by fertiliser.

Nitrogen uptake efficiency (NUpE) = ($Crop_{N1}$ – $Crop_{N0}$)/Fertiliser N rate = the additional crop N uptake/kg fertiliser N applied. In this calculation, $Crop_{N1}$ is the biomass N content for N rate 1, while $Crop_{N0}$ is the biomass N content with no applied N fertiliser. It measures the efficiency with which applied N fertiliser is accumulated in crop biomass and separates the crop N derived from the soil N pool and N supplied by fertiliser.

Economic return

Grower and industry partial economic returns ($/ha) were calculated to account for the cost of N fertiliser, harvesting and levies. A standard cane price formula, using a sugar recovery rate of 0.009, sugar price of $420/t, harvesting and levies cost of $10/t cane and N cost of $1.23/kg N (for urea) and $3.31/kg (for the EEF blend) was applied to the mean cane yield, CCS and sugar yield data for each treatment. The same parameters were applied to all ratoon crops. The cost of N was calculated from 2017 fertiliser prices.

RESULTS AND DISCUSSION

Rainfall

Measured rainfall for the trial period was used to calculate the total monthly, spring-summer and annual rainfall for the 2R, 3R, 4R and 5R crops for the period July to June each year as this tended to correspond well with the growing season at sites NESP 1 and NESP 2 (

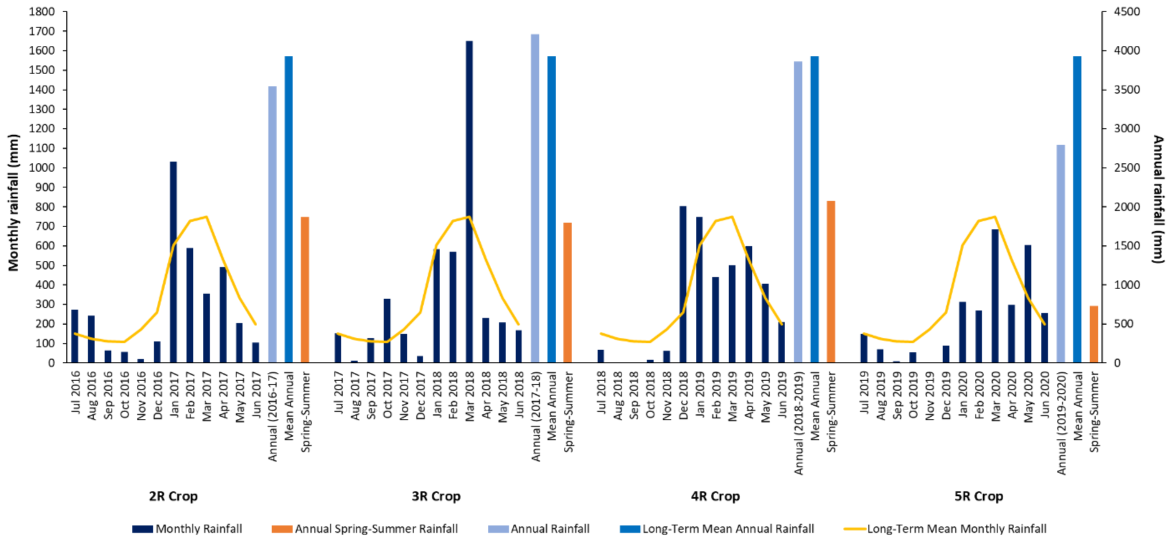


Figure 40. Figure 40). The mean long-term annual rainfall (covering the period July 1969 to June 2020) for Tully is 3924 mm. The total annual rainfall (defined as July to June) experienced during the 2R, 3R, 4R and 5R crops was 3540 mm, 4214 mm, 3863 mm 2793 mm, respectively.

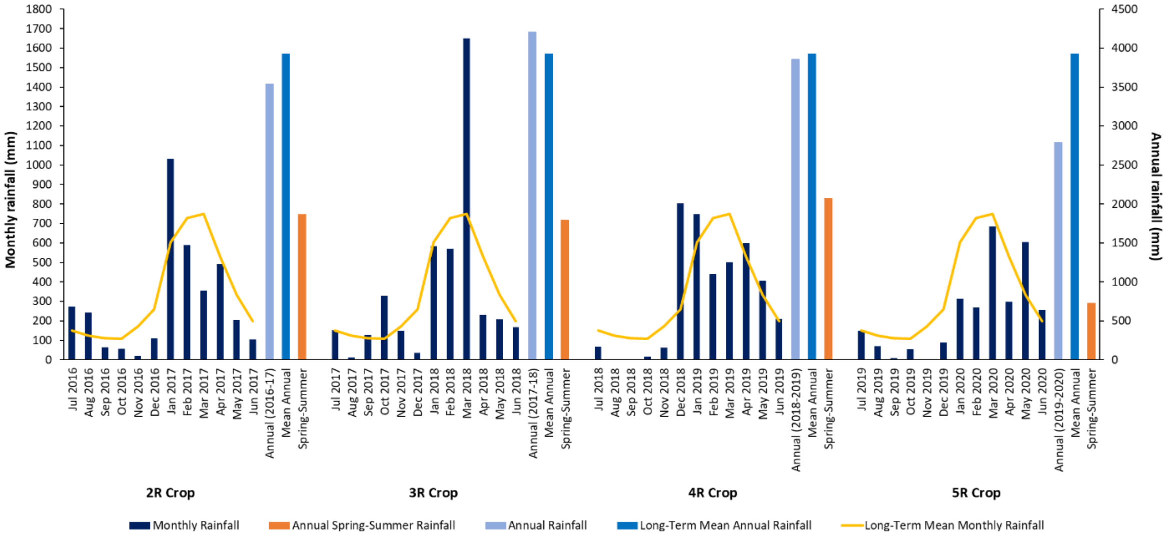


Figure 40. Monthly and annual rainfall recorded at the Tully Sugar Limited Bureau of Meteorology station (32042) pertaining to the 2R, 3R, 4R and 5R crops.

Previous research identified total spring-summer rainfall as having a strong influence on Tully cane yields (Skocaj & Everingham 2014; Skocaj 2015). Skocaj (2015), qualitatively defined dry years as receiving less than 1500 mm spring-summer rainfall and wet years as receiving more than 2200 mm of rainfall. The total spring-summer rainfall recorded at Tully sugar mill for the 2R, 3R, 4R and 5R crops was 1869.1 mm, 1793.9 mm, 2074.8 mm and 733.6 mm, respectively. Hence, the 2R, 3R, 4R and 5R can be likened to close to wet, close to wet, wet and dry years, respectively.
In the 2R crop, total monthly rainfall was below the long-term mean monthly rainfall from September 2016 until January 2017. Despite total spring and summer (Sep-Feb) rainfall during the growing season of the 2R crop being considered normal (1869.1 mm), a single large rainfall event resulted in widespread flooding of the Tully River on the 9 January 2017. This resulted in water inundation at both trial sites and prolonged waterlogging at the poorly drained NESP 2 site due to its lower position in the landscape. This event occurred less than 2 months after applying fertiliser to the 2R crops.

In the 3R crop, total spring-summer (Sep-Feb) rainfall (1793.9 mm) was similar to the 2R crop. Rainfall increased in autumn and widespread flooding of the Tully River occurred on the 7-8 March and again on the 27-28 March 2018. Both sites were inundated with floodwater but it was much slower to recede at the poorly-drained NESP 2. Approximately 1.5 m of floodwater inundated the trial area at this site with cane trash deposited in the lower green leaves. The 3R flood event occurred two months later than the 2R flood event (approximately 4 months after applying fertiliser to the 3R crops).

In the 4R crop, total spring-summer (Sep-Feb) rainfall (2074.8 mm) was higher than previous years with approximately 75% of the total occurring in December 2018 and January 2019. Total monthly rainfall remained above the long-term mean through to April. This resulted in a higher number of wet days and potentially higher waterlogging potential than previous seasons. There were no major flood events.

In the 5R crop, total spring-summer (Sep-Feb) rainfall (733.6 mm) was the lowest experienced during the trial period. There were no flooding events and total monthly rainfall was below the long-term mean monthly average except for January and March 2020. Only 55.9 mm of rainfall was recorded at Tully Sugar Limited (approximately 10 km in a direct line from the experimental sites) in the immediate two months following fertiliser application.

Timing of sampling activities

Crop age (months after harvest and fertilising) and accumulated degree days for key sampling events pertaining to the 2R, 3R, 4R and 5R crops at sites NESP 1 and NESP 2 are reported in Table 17. There was little difference in crop age and ^{o}D between sites for the key sampling events.

Biomass and crop N uptake was measured around 9 to 10 months after applying the N treatments (ranged from 8.6 to 10.4 months) or between 3,000 and 3,900 ^{o}D after harvest.

Soil sampling was completed as soon as possible after harvest (normally within one month) and always prior to applying N treatments. The N treatments were typically applied between one and two months after harvest.

Table 17. Crop age after harvest and fertilising for key experimental activities in the 2R, 3R, 4R and 5R crops.

Activity	Crop age (months after harvest)		Crop age (months after fertilising)		Accumulated degree days (since harvest)	
	NESP 1	NESP 2	NESP 1	NESP 2	NESP 1	NESP 2
Harvest 1R						
Soil 1R	0.6	0.5			182.4	189.9
Fertilise 2R	0.9	0.9			297.4	351.1
Biomass 2R	9.6	9.4	8.7	8.5	2784.0	2803.9
Harvest 2R	10.7	10.6	9.8	9.7	3143.5	3163.8
Soil 2R	0.3	0.5			94.6	169.1
Fertilise 3R	1.7	1.7			522.7	544.3
Biomass 3R	10.6	10.7	8.9	9.0	3056.0	3107.9
Harvest 3R	10.7	10.8	9.0	9.1	3093.5	3134.5
Soil 3R	1.0	1.0			272.4	275.2
Fertilise 4R	2.3	2.2			652.2	630.2
Biomass 4R	12.7	12.8	9.6	9.8	3423.8	3448.3
Harvest 4R	13.1	13.1	10.0	10.1	3493.9	3489.2
Soil 4R	0.8	0.8			174.0	179.6
Fertilise 5R	1.9	1.8			510.8	506.2
Biomass 5R	13.1	13.1	10.3	10.4	3574.8	3420.8
Harvest 5R	14.4	13.3	11.6	10.6	3896.3	3475.5
Soil 5R	0.4	1.5			74.8	402.1

Site characterisation

The impact of these soils different positions in the landscape on soil chemical and physical properties are evident in the site characterisation results for the topsoil (0-20 cm soil depth) and subsoil (40-60 cm soil depth) reported in Table 18 (Skocaj *et al.,* 2020). There are no soil chemical constraints impacting crop growth at any of these sites.

The poorly drained NESP 2 site has a much higher Org C, PBI and clay content, and lower percentage of fine sand compared to the well-drained NESP 1 site in both the topsoil and subsoil.

Table 18. Mean topsoil (0-20cm) and subsoil (40-60 cm) soil chemical and textural properties for NESP 1 and 2 (taken from Skocaj *et al.*, 2020).

Experimental site		**NESP 1**	**NESP 2**	**NESP 1**	**NESP 2**
Soil depth		**0-20cm**	**0-20cm**	**40-60cm**	**40-60cm**
Soil series		Tully	Timara	Tully	Timara
pH (1:5 water)		5.15	5.00	5.15	5.00
Electrical Conductivity	dS/m	0.05	0.05	0.03	0.03
Organic Carbon	%	1.00	2.30	0.37	2.15
Phosphorus (BSES)	mg/kg	100	135	14	92
Phosphorus Buffer Index		200	330	290	515
Potassium (Amm-acet.)	meq/100g	0.18	0.20	0.05	0.07
Potassium (Nitric K)	meq/100g	3.55	2.35	3.65	2.10
Sulphate Sulphur (MCP)	mg/kg	20	17	61	23
Calcium (Amm-acet.)	meq/100g	2.40	3.80	1.20	1.30
Magnesium (Amm-acet.)	meq/100g	0.57	0.78	0.21	0.34
Sodium (Amm-acet.)	meq/100g	0.05	0.08	0.06	0.11
Copper (DTPA)	mg/kg	0.48	0.87	0.18	0.52
Zinc (HCl)	mg/kg	1.10	1.10	0.80	1.10
Silicon (BSES)	mg/kg	180	295	215	320
Silicon (CaCl2)	mg/kg	28	41	35	48
Cation Exchange Capacity	meq/100g	5.09	7.15	3.92	6.96
Calcium/Magnesium Ratio		4.20	4.85	5.95	3.85
Sodium % of cations	%	0.95	1.10	1.55	1.50
Aluminium Saturation	%	38	32	61	74
Sand (fine)	%	32.5	19.5	37.0	19.5
Sand (coarse)	%	1.0	4.0	0.5	2.0
Silt	%	35.0	34.0	33.5	34.5
Clay	%	31.5	42.5	29.0	44.0

Soil bulk density and mineral N

The mean soil bulk density for the different sampling depths at sites NESP 1 and NESP 2 is reported in table 19 (Skocaj *et al.*, 2020). The well-drained NESP 1 site had higher bulk densities for all soil depths sampled. The variation in bulk density between sampling depths was very small at both sites.

Table 19. Mean soil bulk density for the different soil sampling depths at NESP 1 and 2 (taken from Skocaj *et al.*, 2020).

Soil depth (cm)	Mean bulk density (g/cm^3)	
	NESP 1	NESP 2
0-20	1.36	1.15
20-40	1.36	1.16
40-60	1.34	1.15
60-80	1.31	1.12

The results of soil samples collected immediately prior to establishing the trial and after harvesting the 2R, 3R and 4R crops for ammonium N is shown in Figure 41, nitrate N is shown in Figure 42 and total mineral N (ammonium and nitrate) is shown in Figure 43 for Treatment 1 (0N) and Treatment 2 (150N at NESP 1 and 120N at NESP 2) at the well-drained NESP 1 and poorly drained NESP 2 sites.

At the well-drained NESP 1 site, mean soil ammonium N (Figure 41) almost doubled after the first year of the experiment and then remained stable between the 2R and 3R crops before decreasing slightly after harvesting the 4R crop. The opposite was observed for mean soil nitrate N (Figure 42), with levels reducing after the first year of the experiment and then remaining relatively stable between the 2R and 3R crops before increasing slightly after harvesting the 4R crop.

At the poorly drained NESP 2 site, mean soil ammonium N has increased overtime (between the initial and post 3R harvest sampling events), for all sampling depths (0-20, 20-40, 40-60 and 60-80 cm) except for the 4R crop where there was a dramatic decrease. Interestingly, mean soil nitrate N (Figure 42) decreased overtime (between the initial and post 3R harvest sampling events), for all sampling depths except for the 4R crop where there was a dramatic increase.

The reduction in mean soil ammonium N and increases in mean soil nitrate N levels in the 4R sampling event, compared to previous sampling events, were consistent at both sites.

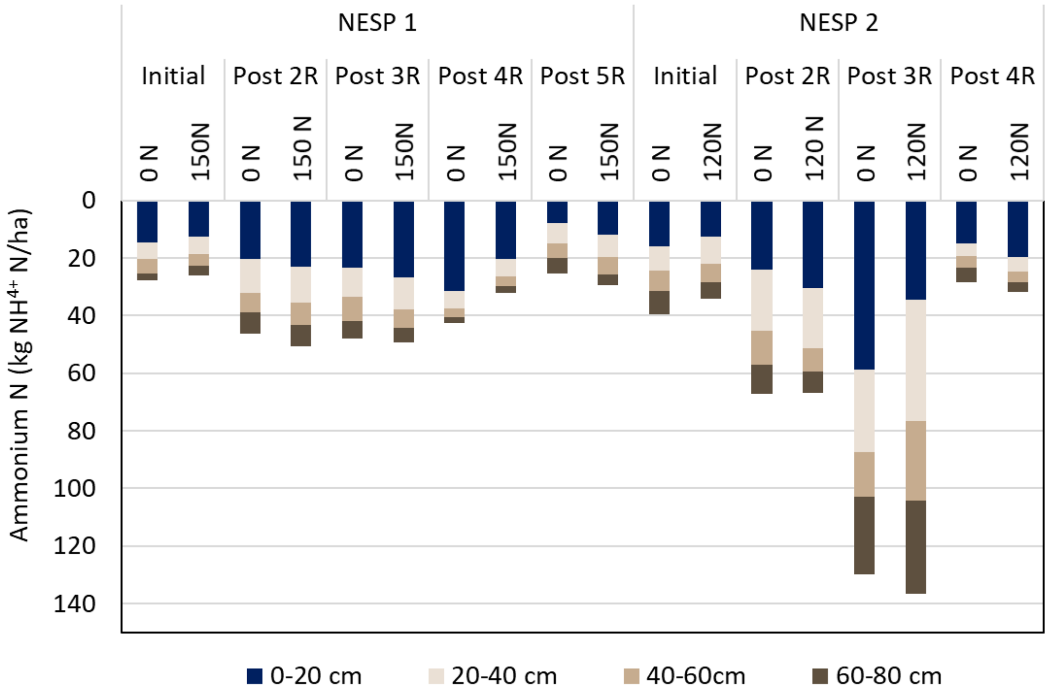


Figure 41. Mean soil ammonium N (kg NH_4^+ N/ha) levels for each soil depth sampled after harvesting the 1R (initial), 2R, 3R and 4R crops at sites NESP 1 and NESP 2 for Treatment 1 (unfertilised control) and 2 (PZYP urea).

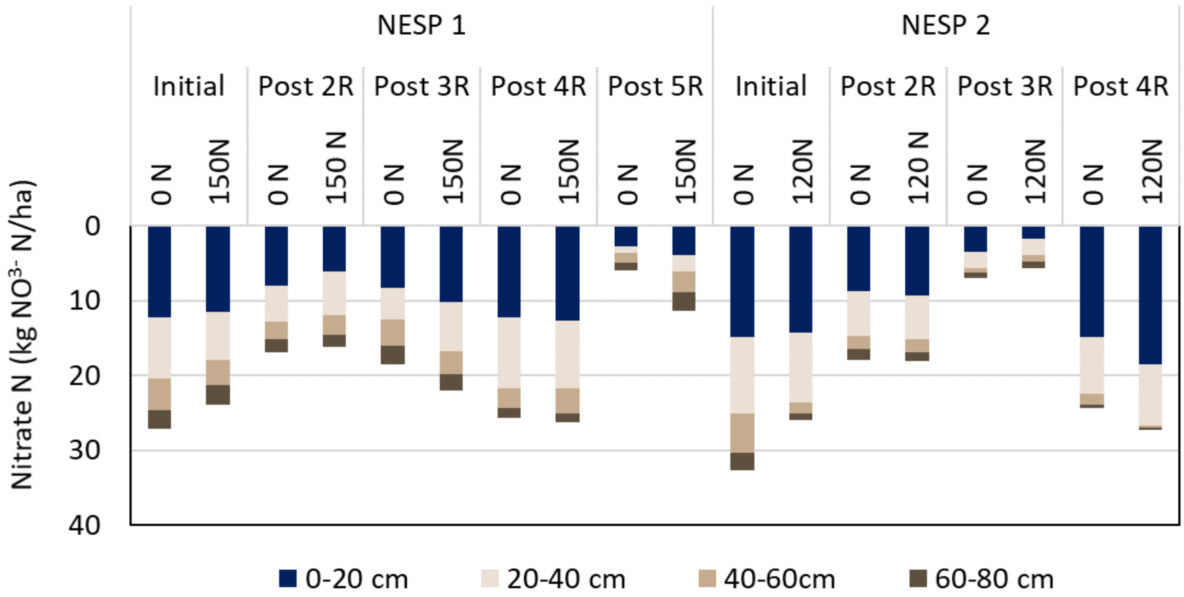


Figure 42. Mean soil nitrate N (kg NO_3^- N/ha) levels for each soil depth sampled after harvesting the 1R initial), 2R, 3R and 4R crops at sites NESP 1 and NESP 2 for Treatment 1 (unfertilised control) and 2 (PZYP urea).

As shown in Figure 43, total soil mineral N was higher at the poorly drained NESP 2 site during the first three years of the project. The greatest difference in total soil mineral N levels between the well-drained and poorly drained sites occurred after sampling the 3R crop in 2018 for all sampling depths. For the first time, total soil mineral N levels at the poorly drained NESP 2 site were lower than the well-drained NESP 1 site for both N treatments after sampling the 4R crop. This is due to the dramatic reduction in ammonium N at the poorly drained NESP 2 site as nitrate N levels were similar between sites. At the well-drained NESP 1 site, total soil mineral N has remained relatively stable and most changes have occurred in the surface 0-20cm between sampling events. The majority of total soil mineral N reported for the different sampling events and soil depths was present as ammonium.

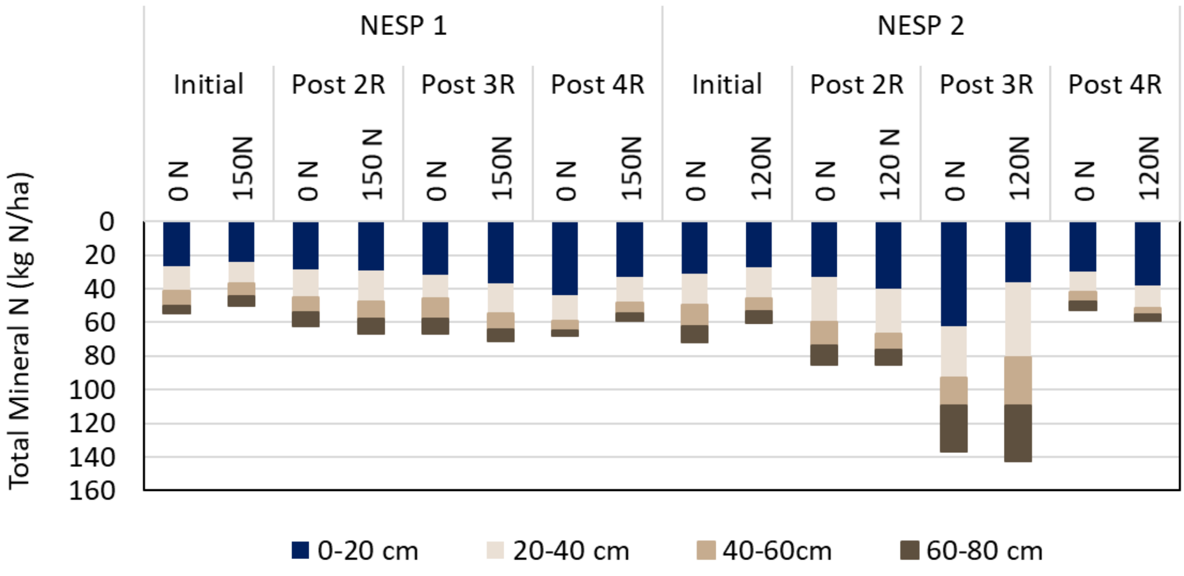


Figure 43. Mean total soil mineral N (kg N/ha) levels for each soil depth sampled after harvesting the 1R initial), 2R, 3R and 4R crops at sites NESP 1 and NESP 2 for Treatment 1 (unfertilised control) and 2 (PZYP urea).

There were significant differences in ammonium, nitrate and total mineral N levels between soil sampling depths, but these differences varied between treatments and sites for each sampling event. At both sites, and for all sampling events, the results also indicated ammonium or nitrate is not accumulating at greater soil depths (highest levels in the 0-20 and 20-40 cm soil depths, especially for nitrate). More detailed information is provided in Attachment A.

There are not enough degrees of freedom to perform a valid statistical analysis to compare differences in ammonium, nitrate and total mineral N levels between N treatments for each soil depth sampled. After sampling the 2R and 3R crops there was no trend for ammonium, nitrate or total mineral N to differ between Treatments 1 and 2 in any of the soil depths sampled at both sites NESP 1 and 2. However, after sampling the 4R crop, at the well-drained NESP 1 site, there was a trend for ammonium and total mineral N to differ between Treatments 1 and 2 in the surface 0-20cm soil depth and Treatment 1 also tended to have higher total mineral N than Treatment 2. At the poorly drained NESP 2 site, there was a trend for nitrate and total mineral N to differ between Treatment 1 and 2 in the surface 0-20cm soil depth and Treatment 2 tended to have higher nitrate and total mineral N than Treatment 1, after sampling the 4R crop.

Crop Biomass

Stalk population, total fresh and total dry biomass produced for the different fertiliser treatments at the NESP 1 and NESP 2 sites for the 2R, 3R, 4R and 5R crops is reported in Table 20.

At both sites, biomass production varied between seasons and tended to be higher in the 2R and 4R crops and lowest in the 3R and 5R crop. However, these seasonal variations in biomass production were less evident in some treatments. For example, at the poorly drained NESP 2 site, biomass production was similar in the 2R, 4R and 5R crops for Treatment 3 (PZYP using EEF blend).

Biomass production at the poorly drained site was similar to the well-drained site in the 3R, 4R and 5R crops, when comparing results for the same N treatment (Treatment 4). This highlights the potential for poorly drained soils to perform well under favourable climatic conditions. Interestingly, the total amount of fresh and dry biomass measured in the 3R crop at the poorly drained site was similar to the well-drained site despite lower N application rates for Treatments 2, 3 and 5. In the 3R crop, spring and summer rainfall was better distributed (and remained below the long-term average after applying N fertiliser) and high rainfall leading to waterlogging and flooding occurred much later in the growing season compared to other seasons. This would have reduced the impact and severity of soil constraints such as waterlogging on early crop growth, N uptake and potential for N losses.

There was no statistically significant difference between treatments for the total amount of fresh or dry biomass produced in the 2R, 3R, 4R and 5R crops (e.g. neither the N fertiliser source, higher rates of N in the form of urea or lower rates of N in the form of the EEF blend had a significant effect) at both the NESP 1 or NESP 2 sites.

There was a trend towards higher total fresh biomass production in the EEF treatment where the same N rate (150 kg N/ha) was applied in 2R and 3R crops at the well-drained NESP 1 site. At the poorly drained NESP 2 site, there was a trend towards higher total fresh biomass production in the EEF treatment where the same N rate (120 kg N/ha) was applied in the 3R and 5R crops. However, in some seasons, there was a marked reduction in biomass production for the EEF treatment compared to urea applied at the same N rate (e.g., 4R crop at NESP 1, and 1R and 4R crops at NESP 2).

In most seasons, the lower EEF N rate (Treatment 5) performed similar to, or better than the higher EEF N rate (Treatment 3) in terms of the total fresh and dry biomass (e.g., 4R and 5R crops at NESP 1, and 2R and 4R crops at NESP 2).

There was a significant difference in stalk population for the 2R crop at the poorly drained NESP 2 site, with the stalk population for Treatment 5 significantly lower than Treatments 2 and 4. Stalk population did not decrease with increasing ratoon age but appears to have been affected by seasonal climatic conditions (highest in the 2R crop at NESP 1 and 3R crop at NESP 2).

Although not significant, at both sites, for the urea treatments, the higher N rate tended to produce higher total biomass in the 2R, 3R and 5R crops but not the 4R crop.

Table 20. Effect of fertiliser rate and product on stalk population (stalks/m^2), total fresh biomass (t/ha) and total dry biomass (t/ha) for the 2017 (2R), 2018 (3R), 2019 (4R) and 2020 (5R) crop harvests. Statistical testing for treatment effects found no statistically significant differences (ns) for any parameter other than stalk population in the 2R crop at the poorly drained NESP 2 site.

LOCATION	SEASON	Stalk	Fresh Biomass	Dry Biomass	Stalk	Fresh Biomass	Dry Biomass	Stalk	Fresh Biomass	Dry Biomass	Stalk	Fresh Biomass	Dry Biomass	Stalk	Fresh Biomass	Dry Biomass
		Treatment 2 150N, urea			Treatment 3 150 N, EEF			Treatment 4 170N, urea			Treatment 5 120N, EEF			Sig		
WELL DRAINED NESP 1	2R (2017)	12.3	149.2	36.5	13.2	157.4	35.0	12.9	150.2	36.8	12.4	148.8	34.7	ns	ns	ns
	3R (2018)	11.6	113.9	30.2	11.8	115.0	30.5	12.4	122.4	33.9	11.7	119.7	32.6	ns	ns	ns
	4R (2019)	11.2	132.6	38.3	11.0	119.6	33.0	10.8	127.4	33.7	10.6	124.3	36.5	ns	ns	ns
	5R (2020)	11.6	114.7	31.8	11.1	114.4	31.8	11.6	122.5	34.4	11.2	127.5	35.9	ns	ns	ns
		Treatment 2 120N, urea			Treatment 3 120N, EEF			Treatment 4 170N, urea			Treatment 5 90N, EEF			Sig		
POORLY DRAINED NESP 2	2R (2017)	11.0^{A}	128.4	29.7	10.6^{AB}	114.2	29.7	11.2^{A}	129.0	34.6	10.2^{B}	128.3	34.8	0.29	ns	ns
	3R (2018)	12.2	114.3	33.1	11.7	122.4	34.4	12.0	127.8	36.2	10.8	111.7	32.6	ns	ns	ns
	4R (2019)	10.1	124.2	35.5	9.7	113.2	32.3	10.0	121.7	33.3	9.6	117.6	33.1	ns	ns	ns
	5R (2020)	11.2	104.1	28.7	11.5	115.2	31.5	11.2	119.4	33.0	11.2	114.7	31.7	ns	ns	ns

Means followed by the same letter $^{(A,B)}$ in the same row, are not significantly different (P=0.05)

Cane yield, CCS and sugar yield

Cane yield (t cane/ha), CCS and sugar yield (t sugar/ha) for the different fertiliser treatments at the NESP 1 and NESP 2 sites for the 2R, 3R, 4R and 5R crops is reported in Table 21.

The impact of seasonal climatic conditions is evident in the measured cane yields. A linear mixed model using restricted maximum likelihood was used to analyse the effect of treatment, crop class and interaction between treatment and crop class on cane and sugar yields. At both sites, there was no significant treatment effect or interaction between treatment and crop class. Crop class had a significant effect on both cane and sugar yields. At the well-drained NESP 1 site, cane yield was significantly ($p<0.01$) higher in the 2R and 4R crops compared to the 3R and sugar yield was significantly ($p<0.01$) higher the 2R and 5R crops compared to the 3R crop. At the poorly drained NESP 2 site, cane yield was significantly ($p<0.05$) higher in the 3R and 4R crops compared to the 2R and sugar yield was significantly ($p<0.01$) higher in the 3R and 5R crops compared to the 2R crop.

Seasonal variations in cane yield were less evident for some treatments. For example, cane yield remained similar for the 3R, 4R and 5R crops for Treatment 3 (PZYP using EEF blend) at both trial sites.

Cane yield at the poorly drained NESP 2 was similar to the well-drained site in the 4R and 5R crops, but higher in the 3R crop, where comparing results for the same N treatment (Treatment 4). This highlights there is potential for poorly drained soils to perform well under favourable climatic conditions. For the well-drained NESP 1 site, it also appears to indicate the potential impact of lodging on reducing biomass accumulation (and yield) when N is overapplied.

There was no statistically significant difference between treatments for cane yield, CCS or sugar yield in the 2R, 3R, 4R and 5R crops (e.g. neither the N fertiliser source, higher rates of N in the form of urea or lower rates of N in the form of the EEF blend had a significant effect) at both the NESP 1 and NESP 2 sites.

The highest N rate in the form of urea (Treatment 4) produced only marginally higher cane yields compared to the lower rate of urea (Treatment 2), indicating N rates above the SIX EASY STEPS guidelines do not produce significantly higher cane yields.

Interestingly, the EEF applied at the lower N rate (Treatment 5) produced similar and at times slightly higher cane yields compared to the EEF applied at the higher N rate (Treatment 3) and demonstrates the potential for higher NUE. The exception being the 3R crop at the poorly drained NESP 2. In the 3R at the NESP 2 site, the higher urea (Treatment 4) and EEF (Treatment 3) N rates produced higher cane yields (111.1 and 105.3 t cane/ ha, respectively) than the lower urea (Treatment 2) and EEF (Treatment 5) N rates (99.3 and 96.6 t cane/ha, respectively). The same effect was evident for total fresh biomass. This is most likely a result of the climatic conditions experienced. In the 3R, early crop growth and N uptake may have been reduced as a result of the exceptionally dry spring following low winter rainfall and N losses increased following high December and January rainfall (as Treatments 3 and 4 also had higher total crop N uptake). In a year such as this, despite the results not being statistically significant, it may not be possible to reduce N rates below the SIX EASY STEPS N guideline even if applying an EEF blended product to these wetter soils occurring lower in the landscape.

In the 4R crop at both NESP 1 and NESP 2, the EEF treatments did not produce higher yields than the urea treatments. Although this difference was not statistically significant, it suggests in years not conducive to experiencing N losses, there is unlikely to be a yield benefit from using this EEF product (when applied at the same N rate, yields were 13.3 and 10.1 t cane/ha lower in the EEF treatment at sites NESP 1 and 2, respectively). In the 4R crop, prolonged rainfall later in the growing season doesn't appear to have constrained crop growth compared to previous seasons (e.g. 4R yields higher than 3R at NESP 1 and higher than both 2R and 3R at NESP 2) and the extremely dry spring/early summer wasn't conducive to N losses.

In most seasons, for the same N rate, the EEF product (Treatment 3) did not result in higher cane yields compared to urea (Treatment 2) at the well-drained NESP 1 site. However, at the poorly drained NESP 2 site, the EEF product (Treatment 3) produced higher cane yield than urea (Treatment 2) when applied at the same N rate in the 3R and 5R crops. Cane yield was maintained or slightly higher when the EEF was applied at a lower rate (Treatment 5), in comparison to Treatments 2 and 3, except for the 2R crop at both sites and the 3R crop at NESP 2. This tends to indicate differences in crop lodging (both timing and severity) between treatments may be influencing cane yields in some seasons.

The cumulative data (which represents the combined results of the four ratoon crops for each treatment) indicates applying the EEF blend at a lower N rate (Treatment 5) maintained cane and sugar yields when compared to urea at the PZYP N rate (Treatment 2) at NESP 1. At NESP 2, the EEF blend produced similar cumulative cane and sugar yields to urea at the PZYP N rate (Treatment 2) irrespective of N rate. At both sites, cumulative cane and sugar yields were highest for Treatment 4 (PZYP without N mineralisation discount applied as urea).

Seasonal climatic conditions also influenced the CCS results. CCS tended to be lowest in the 4R crop and highest in the 5R crop at both trial sites. CCS was determined from sound, clean, whole stalk samples. These values tend to be higher than CCS measured at the mill and may not represent the true effect of the different N fertiliser treatments as differences in crop condition (e.g. suckering, rat damage) and presentation (e.g. lodged, sprawled) at harvest are known to influence CCS.

Table 21. Effect of fertiliser rate and product on cane yield (t cane/ha), CCS and sugar yield (t sugar/ha) for the 2017 (2R), 2018 (3R), 2019 (4R) and 2020 (5R) crop harvests. Statistical testing for treatment effects found no statistically significant differences (ns) for any parameter in any crop season at all sites.

LOCATION	SEASON	Cane Yield	CCS	Sugar Yield	Cane Yield	CCS	Sugar Yield	Cane Yield	CCS	Sugar Yield	Cane Yield	CCS	Sugar Yield	Cane Yield	CCS	Sugar Yield
		Treatment 2 150N, urea			Treatment 3 150 N, EEF			Treatment 4 170N, urea			Treatment 5 120N, EEF			Sig		
WELL DRAINED NESP 1	**2R (2017)**	122.4	14.5	17.8	118.1	14.7	17.3	120.5	14.9	17.9	112.1	14.7	16.5	ns	ns	ns
	3R (2018)	98.6	14.7	14.5	98.6	14.2	14.1	106.6	15.1	16.1	104.8	14.8	15.5	ns	ns	ns
	4R (2019)	119.3	14.0	16.7	106.0	14.1	14.9	115.3	13.8	15.8	110.7	14.4	15.9	ns	ns	ns
	5R (2020)	101.9	15.8	16.1	101.8	15.9	16.1	108.4	15.7	17.0	114.4	15.5	17.7	ns	ns	ns
Cumulative yield		444.2	-	65.1	425.3	-	62.5	450.9	-	66.8	442.0	-	65.6			
		Treatment 2 120N, urea			Treatment 3 120N, EEF			Treatment 4 170N, urea			Treatment 5 90N, EEF			Sig		
POORLY DRAINED NESP 2	**2R (2017)**	98.3	14.5	14.3	90.2	14.1	12.7	100.9	14.6	14.7	91.9	14.7	13.5	ns	ns	ns
	3R (2018)	99.3	14.8	14.7	105.3	15.3	16.1	111.1	14.7	16.3	96.6	14.7	14.2	ns	ns	ns
	4R (2019)	111.5	13.3	14.8	101.4	13.9	14.1	109.7	13.9	15.2	105.6	13.7	14.4	ns	ns	ns
	5R (2020)	91.9	15.7	14.4	101.7	15.8	15.9	105.9	15.7	16.5	101.5	15.5	15.6	ns	ns	ns
Cumulative yield		401.0	-	58.2	398.6	-	58.8	427.6	-	62.8	395.6	-	57.7			

Crop N uptake

Crop N uptake (MS, LC and total) for the different fertiliser treatments at the NESP 1 and NESP 2 sites for the 2R, 3R, 4R and 5R crops is reported in Table 22. These results do not discriminate N uptake between soil and fertiliser N contributions. At the well-drained NESP 1 site, for the fertilised treatments, the only statistically significant difference in MS N uptake occurred in the 2R crop. The lower EEF N rate (Treatment 5) resulted in significantly lower MS N uptake compared to all other treatments. Despite there being no statistically significant difference in MS N uptake for the 4R crop, there was a statistically significant ($p<0.05$) difference in the MS N concentration. The stalk N concentration for the high urea N rate (Treatment 4) was significantly higher than the lower urea (Treatment 2) and EEF (Treatment 5) N rates but not the high EEF (Treatment 3) N rate.

At the poorly drained NESP 2 site, the only statistically significant difference in MS N uptake occurred in the 3R crop. The lower urea (Treatment 2) and EEF (Treatment 5) resulted in significantly ($p<0.05$) lower MS N uptake than the high urea rate (Treatment 4) in the 3R crop. These results align with the significant ($p<0.001$) differences in MS N concentrations observed in the 3R crop (e.g., MS N concentration for Treatments 2 and 5 were significantly lower than Treatment 4) as there was no significant difference in dry MS biomass.

There was no significant difference in LC N uptake or N concentration in any crop at both sites. There was also no consistent trend for LC N uptake to be higher in the EEF treatments or high urea N rate (Treatment 4). The only noticeable difference was in the 2R crop at the well-drained NESP 1 site, were LC N uptake was extremely low. There was no significant difference in LC biomass, N uptake or N concentration between fertiliser treatments. However, dry LC biomass was lower compared to the following seasons, due to higher moisture content. The 2R crop severely lodged and by the time of sampling the crop had already recommenced growing.

A linear mixed model using restricted maximum likelihood was used to analyse the effect of treatment, crop class and interaction between treatment and crop class on crop N uptake. There was no significant treatment effect or interaction between treatment and crop class. However, crop class had a significant effect on crop N uptake at both sites. At NESP 1, crop N uptake was significantly ($p<0.001$) higher in the 5R crop compared to all other crops and the 4R crop was significantly higher than the 2R and 3R crops. At NESP 2, cane yield was significantly ($p<0.001$) higher in the 5R crop compared to all other crops and the 3R crop was significantly lower than the 2R crop.

There was a trend for the EEF blend to result in higher N uptake than urea when applied at the same N rate (e.g. Treatment 3 vs 2). The exception was in the 4R crop at NESP 2. In this situation, total N uptake for the EEF blend (Treatment 3) was lower than urea (Treatment 2) applied at the same rate. In the 4R crop at NESP 2, the EEF product recorded lower crop N uptake compared to the urea treatments, irrespective of N rate.

The results from four consecutive ratoon crops also indicate applying more N in the urea form (Treatment 4) does not result in significantly higher N uptake. However, the higher N rate applied as urea (Treatment 4) tended to result in higher crop N uptake in the 4R and 5R crops at NESP 1 and 2R and 5R crops at NESP 2 compared to all other treatments.

The cumulative data (which represents the combined results of the four ratoon crops for each treatment) indicates applying the EEF blend resulted in higher N uptake, especially at NESP 2, compared to urea at the PZYP N rate (Treatment 2). At NESP 1, N uptake was lowest for the EEF blend applied at the lower rate (Treatment 5). At both sites, cumulative total N uptake was highest for Treatment 4 (PZYP without N mineralisation discount applied as urea).

Table 22. Effect of fertiliser rate and product on stalk, top and total N uptake (kg N/ha) for the 2017 (2R), 2018 (3R), 2019 (4R) and 2020 (5R) crop harvests. Statistical testing for treatment effects found no statistically significant differences (ns) for most parameters.

LOCATION	SEASON	Stalk N	Top N	Total N	Stalk N	Top N	Total N	Stalk N	Top N	Total N	Stalk N	Top N	Total N	Stalk N	Top N	Total N
		Treatment 2 150N, urea			Treatment 3 150 N, EEF			Treatment 4 170N, urea			Treatment 5 120N, EEF			Sig		
WELL DRAINED NESP 1	**2R (2017)**	71.1^{A}	15.7	86.8	71.6^{A}	18.6	90.2	65.7^{A}	17.1	82.8	54.2^{B}	19.8	74.0	2.82	ns	ns
	3R (2018)	46.8	40.3	87.2	48.0	40.9	88.9	49.1	38.1	87.2	49.8	39.6	89.4	ns	ns	ns
	4R (2019)	61.3	37.4	98.7	59.7	42.2	101.9	67.6	38.2	105.9	53.7	37.9	91.6	ns	ns	ns
	5R (2020)	64.6	46.8	111.4	73.2	43.5	116.7	74.2	54.5	128.7	64.7	45.4	110.1	ns	ns	ns
Cumulative N uptake		243.8	140.3	384.1	246.5	146.6	393.1	256.6	148.0	404.6	222.4	142.7	365.1			
		Treatment 2 120N, urea			Treatment 3 120N, EEF			Treatment 4 170N, urea			Treatment 5 90N, EEF			Sig		
POORLY DRAINED NESP 2	**2R (2017)**	42.8	29.2	72.0	50.7	44.5	95.2	54.4	38.4	92.7	57.2	37.6	94.8	ns	ns	ns
	3R (2018)	36.0^{B}	36.7	72.7	46.1^{AB}	35.9	82.0	52.7^{A}	34.8	87.5	36.2^{B}	31.2	67.3	4.97	ns	ns
	4R (2019)	54.0	39.3	93.3	43.2	35.2	78.4	48.8	44.6	93.5	44.0	35.2	79.3	ns	ns	ns
	5R (2020)	52.2	43.8	96.0	59.6	50.5	110.1	61.0	43.4	104.4	58.0	46.0	104.0	ns	ns	ns
Cumulative N uptake		185.0	149.0	333.9	199.6	166.1	365.7	216.9	161.2	378.0	195.4	150.0	345.3			

Means followed by the same letter (A,B) in the same row, are not significantly different (P=0.05)

Nitrogen use efficiency

The impact of the different fertiliser treatments on NUE parameters at the NESP 1 and NESP 2 sites for the 2R, 3R, 4R and 5R crops is reported in Table 23.

The most efficient agronomic response to fertiliser N tended to occur in the 2R crop while the least efficient occurred in the 5R crop, for both sites. In the 2R crop, the agronomic response to fertiliser N ranged from 3.0 to 3.6 and 2.3 to 3.5 kg N/t additional cane yield at the well-drained NESP 1 and poorly drained NESP 2 sites, respectively.

In the 2R crop, at the poorly drained NESP 2 site, when the same rate of N was applied, the EEF blend (Treatment 3) had higher NUpE compared to urea (Treatment 2) but this only resulted in slightly higher agronomic efficiency. However, in the 3R and 5R crops the higher NUpE for Treatment 3 also resulted in higher agronomic efficiency (e.g., the amount of N required to produce an additional tone of cane yield was lower than the urea treatments).

Agronomic efficiency will not necessarily improve with higher NUpE if environmental conditions (e.g. high rainfall, low solar radiation, severe waterlogging, increased lodging) reduce the ability of the crop to use the additional N captured for biomass production. Similarly, if environmental conditions are not conducive to N losses, EEF treatments may not result in increased NUpE or agronomic efficiency. The timing of when the environmental stress occurs, especially in relation to the timing of fertiliser application, is also likely to have a major influence. For example, the 2R crop experienced severe moisture stress much earlier in the growing season compared to the 3R crop.

At the poorly drained NESP 2 site, the agronomic response to fertiliser N in the 3R crop was similar to the 2R crop but better than the 3R crop at the well-drained NESP 1 site. This effect was largely due to improved crop growth. However, it clearly demonstrates the impact of climatic conditions on NUE.

In the 5R crop, the agronomic response to fertiliser N dramatically reduced. The agronomic response to fertiliser N was poorest for the lower urea N rate (Treatment 2), at 8.5 kg and 10.4 kg N/t additional cane yield at the well-drained NESP 1 and poorly drained NESP 2 sites, respectively. At the well-drained site, applying the EEF product at the same N rate (Treatment 3) as urea did not improve the agronomic response to fertiliser N. However, at the poorly drained NESP 2 site, applying the EEF product at the same N rate as urea (Treatment 3) greatly improved the agronomic response to fertiliser N.

Nitrogen uptake efficiency (NUpE) was calculated using the mean cane yield and crop N uptake data. At both sites, NUpE tended to be higher in the 2R and 3R crops and lowest in the 5R crop. At the well-drained NESP 1 site, when the same rate of N was applied, NUpE tended to be higher for the EEF (Treatment 3) compared to urea (Treatment 2) in all seasons. Applying more N in the form of urea (Treatment 4) did not improve NUpE. Treatment 4 had the lowest NUpE in the 2R and 3R crops compared to all other treatments, equalled the EEF at the higher N rate (Treatment 3) in the 4R crop but was the highest in the 5R crop. The NUpE of the EEF at the lower rate (Treatment 2) was similar to (or slightly higher) than the EEF at the higher rate (Treatment 3) and urea at the lower N rate (Treatment 2).

In most seasons, NUpE for the two EEF treatments tended to be higher at the poorly drained site compared to the well-drained NESP 1 site. At the poorly drained NESP 2 site, NUpE was higher for the EEF treatments in the 2R, 3R and 5R crops. When the same rate of N was applied, the EEF blend (Treatment 3) resulted in higher NUpE compared to urea (Treatment 2) in the 2R, 3R and 5R crops. The higher N rate applied as urea (Treatment 4) had higher NUpE in the 2R, 3R and 5R crops when compared to urea at the lower N rate (Treatment 2) but not the EEF blend (Treatments 3 and 5).

The NESP 2 site is likely to be more susceptible to N losses due to its position in the landscape. The data tends to indicate the EEF blend may allow the crop to recover more fertiliser N in situations likely to be associated with high risk of N losses such as the 2R crop but is unlikely to deliver a benefit in situations not conducive to N losses such as the 4R crop. In the 4R crop unseasonably low spring rainfall following a dry winter and delayed onset of the wet season was experienced post fertilisation. Despite prolonged rainfall being experienced from late summer through to winter, there were no major flooding or extreme rainfall events. Hence the potential for early waterlogging was greatly reduced compared to previous seasons and potentially resulted in lower N losses during early ratooning (the first four months after harvest). In situations similar to this, there appears to be no benefit from applying the EEF blend (as NUpE and agronomic response to fertiliser N was lower than urea applied at the same N rate).

The cumulative data (which represents the combined results of the four ratoon crops for each treatment) indicates applying the EEF blend resulted in higher N uptake, especially at the poorly drained NESP 2 site, compared to urea at the PZYP N rate (Treatment 2). At NESP 1, N uptake was lowest for the EEF blend applied at the lower rate (Treatment 5). At both sites, cumulative total N uptake was highest for Treatment 4 (PZYP without N mineralisation discount applied as urea).

Table 23. Agronomic responses in cane yields and crop N uptake from the fertilised treatments at each site. Data are used to derive indices of AgronEff$_N$ and NUpE for the different fertiliser N treatments.

LOCATION	SEASON	AGRONOMIC RESPONSE TO FERTILISER N T CANE/HA (KG N APPLIED/T EXTRA CANE YIELD)				APPARENT FERTILISER N UPTAKE KG FERTILISER N/HA (% APPLIED N)			
		Treatment 2 150N, urea	Treatment 3 150N, EEF	Treatment 4 170N, urea	Treatment 5 120N, EEF	Treatment 2 150N, urea	Treatment 3 150N, EEF	Treatment 4 170N, urea	Treatment 5 120N, EEF
WELL DRAINED NESP 1	**2R (2017)**	49.3 (3.0)	45.0 (3.3)	47.4 (3.6)	39.0 (3.1)	45.6 (30%)	49.0 (33%)	41.6 (24%)	32.8 (27%)
	3R (2018)	31.1 (4.8)	31.1 (4.8)	39.1 (4.4)	37.3 (3.2)	33.5 (22%)	35.2 (23%)	33.5 (20%)	35.7 (30%)
	4R (2019)	45.2 (3.3)	31.9 (4.7)	41.3 (4.1)	36.6 (3.3)	25.8 (17%)	29.0 (19%)	33.0 (19%)	18.8 (16%)
	5R (2020)	17.7 (8.5)	17.6 (8.5)	24.2 (7.0)	30.2 (4.0)	15.8 (11%)	21.1 (14%)	33.1 (19%)	14.5 (12%)
Cumulative NUE*		144.9 (4.1)	127.9 (4.7)	153.6 (4.4)	144.6 (3.3)	124.8 (20.8%)	133.9 (22.3%)	145.4 (21.4%)	105.9 (22.1%)
		Treatment 2 120N, urea	Treatment 3 120N, EEF	Treatment 4 170N, urea	Treatment 5 90N, EEF	Treatment 2 120N, urea	Treatment 3 120N, EEF	Treatment 4 170N, urea	Treatment 5 90N, EEF
POORLY DRAINED NESP 2	**2R (2017)**	45.7 (2.6)	37.6 (3.2)	48.3 (3.5)	39.3 (2.3)	14.8 (12%)	38.0 (32%)	35.5 (21%)	37.6 (42%)
	3R (2018)	35.6 (3.4)	41.6 (2.9)	47.4 (3.6)	32.9 (2.7)	30.6 (26%)	39.9 (33%)	45.4 (27%)	25.2 (28%)
	4R (2019)	33.4 (3.6)	23.2 (5.2)	31.6 (5.4)	27.5 (3.3)	38.8 (32%)	23.9 (20%)	39.0 (23%)	24.8 (28%)
	5R (2020)	11.5 (10.4)	21.3 (5.6)	25.5 (6.7)	21.1 (4.3)	12.3 (10%)	26.4 (22%)	20.7 (12%)	20.3 (23%)
Cumulative NUE*		123.8 (3.9)	121.5 (4.0)	150.5 (4.5)	118.5 (3.0)	92.8 (19.3%)	124.5 (25.9%)	136.9 (20.1%)	104.2 (28.9%)

*These values were calculated using the cumulative cane yield reported in Table 21. and cumulative total N reported Table 22. .

Economics

The mean grower partial and industry economic net returns for the different treatments at the NESP 1 and NESP 2 sites for the 2R, 3R, 4R and 5R crops are reported in Table 24. In most seasons, economic returns tended to be highest at the well-drained NESP 1 site because of the higher yields produced. However, in the 3R crop, the grower and industry economic returns at the poorly drained NESP 2 site were similar to the well-drained NESP 1 site. This demonstrates the potential for poorly drained soils to be productive and profitable, in seasons favouring good crop growth.

At both sites, grower partial economic returns for most treatments tended to be highest in the 5R crop. At the well-drained NESP 1, industry economic returns for most treatments tended to be highest in the 2R crop. At the poorly drained NESP 2, industry economic returns for each treatment peaked in different seasons (e.g. Treatments 2 and 3 where highest in the 3R crop whereas Treatments 4 and 5 were highest in the 5R crop).

Treatment 4 (urea at the higher N rate with no discount for N mineralisation) produced the highest grower partial economic returns in all seasons at both trial sites. Treatment 4 also produced the highest industry economic returns except for the 5R crop at well-drained NESP 1 site.

Applying the EEF blend (Treatment 3) at the same N rate as urea (Treatment 2) resulted in lower grower and industry partial economic returns at both sites for most seasons. This is not surprising given the cost of N on a per kg basis for the EEF blend ($3.31/kg N) is around 2.5 times more expensive than urea ($1.23/kg N). Applying the EEF blend at a lower N rate (Treatment 4) improved grower and industry partial economic returns compared to the EEF blend at the PZYP N rate (Treatment 3). In the 5R crop, applying the EEF blend at a lower N rate (Treatment 4) resulted in higher economic returns than urea at the PZYP (Treatment 2).

Applying urea at the PZYP N rate (Treatment 2) produced higher cumulative economic returns compared to the EEF blend at the same (Treatment 3) and lower (Treatment 5) N rate. These results are being influenced by the higher cost of the EEF blend compared to urea ($3.31/kg N for the EEF blend vs $1.23/kg N for urea). To deliver an economic benefit (in addition to maintaining productivity and improving NUE), the cost of this EEF blend needs to be lower.

Table 24. Grower and Industry partial net returns ($/ha) for the fertilised treatments at each site. The mean cane yield, CCS and sugar yield data were used to derive net returns.

LOCATION	SEASON	GROWER PARTIAL NET RETURN ($/HA)				INDUSTRY NET RETURN ($/HA)			
		Treatment 2 150N, urea	Treatment 3 150N, EEF	Treatment 4 170N, urea	Treatment 5 120N, EEF	Treatment 2 150N, urea	Treatment 3 150N, EEF	Treatment 4 170N, urea	Treatment 5 120N, EEF
WELL DRAINED NESP 1	2R (2017)	3450	3099	3551	3058	6068	5589	6104	5412
	3R (2018)	2817	2679	2319	2833	4920	4929	4440	5065
	4R (2019)	3132	2490	2909	2848	5637	4702	5274	5174
	5R (2020)	3342	3065	3501	3432	5559	5248	5847	5893
Cumulative Net Return*		12741	11333	12280	12171	22184	20468	21665	21544
		Treatment 2 120N, urea	Treatment 3 120N, EEF	Treatment 4 170N, urea	Treatment 5 90N, EEF	Treatment 2 120N, urea	Treatment 3 120N, EEF	Treatment 4 170N, urea	Treatment 5 90N, EEF
POORLY DRAINED NESP 2	2R (2017)	2771	2144	2825	2500	4875	4035	4956	4453
	3R (2018)	2913	3048	3173	2643	5033	5312	5526	4700
	4R (2019)	2657	2383	2799	2518	4953	4511	5078	4694
	5R (2020)	2998	3122	3415	3099	4981	5264	5662	5239
Cumulative Net Return*		11339	10697	12212	10760	19842	19122	21222	19086

CONCLUSIONS

The results from the well-drained NESP 1 and poorly drained NESP 2 research experiments indicate:

- Crops growing on poorly drained soils can be as productive, profitability and efficient in using applied N as well-drained soils under favourable growing conditions.
- Applying a higher rate of N in the form of urea did not result in statistically significant higher biomass, yields, N uptake or NUE. These results support the SIX EASY STEPS discount for soil N mineralisation in the N guidelines for the Wet Tropics region.
- Applying the EEF blend at the same rate as urea did not result in significantly higher biomass, yields, N uptake or NUE.
- There was no statistically significant difference in biomass, yield or N uptake between fertiliser products (e.g EEF blend vs urea applied at the same rate) or when the same fertiliser product was applied at different rates.
- There was no significant treatment effect or interaction between treatment and crop class. However, crop class had a significant effect on cane yield, sugar yield and total crop N uptake.
- Applying the EEF blend at the same rate as urea tended to result in higher NUpE in most seasons. However, improved NUpE wasn't always reflected in higher crop yields or improved agronomic efficiency of fertiliser N relative to the same rate of urea.
    - Agronomic efficiency is unlikely to improve with higher NUpE if environmental conditions (e.g. high rainfall, low solar radiation, severe waterlogging, increased lodging) reduce the ability of the crop to utilise the additional N captured for biomass production.
    - Similarly, if environmental conditions are not conducive to N losses, EEF products may not result in increased NUpE or agronomic efficiency compared to using urea at the same N rate.
    - Soil texture, position in the landscape, environmental conditions and the timing of when environmental stresses occur, in relation to crop growth stage and timing of fertiliser application are likely to have a major influence on whether higher NUpE is associated with greater agronomic efficiency. For example, in the 2R crop where severe moisture stress was experienced much earlier in the growing season compared to the 3R crop, appears to have restricted the crop's ability to produce biomass.
- Applying the EEF blend at the same N rate as urea resulted in lower grower and industry partial economic returns at both sites for most seasons. This is not surprising given the cost of N on a per kg basis for the EEF blend is more expensive than urea. Applying the EEF blend at a lower N rate helped minimise economic losses in some seasons.
- In some seasons, cane yield was maintained or slightly increased when applying the EEF blend at lower application rates (e.g., comparing Treatment 3 and 5). However, it may not be possible to consistently reduce N rates in all seasons and for all soil types, below the PZYP (and SIX EASY STEPS N guidelines) even if applying the EEF blend. For example:
    - In the 3R crop, where crop responsiveness to applied N was increased, especially at the poorly drained NESP 2 site due to favourable growing conditions.

  - In the 4R crop where environmental conditions were not conducive to N losses, applying the EEF at a lower rate tended to improve NUE but restricted biomass and yield at both the well- and poorly drained sites. A similar effect may have been produced from applying urea at a lower rate. However, this is not able to be determined from these experiments.
- The EEF blend resulted in cumulative cane and sugar yields being maintained, even when applied at a lower N rate (e.g. NESP 1) and improved NUE, especially at poorer drained NESP 2 site. However, the higher cost of the EEF blend resulted in lower profitability compared to using urea, even at a lower N rate. The cumulative data suggests reducing the cost of the EEF blend may allow productivity and profitability to be maintained whilst improving NUE.
- It is difficult to predict circumstances where the EEF blend is likely to deliver a productivity, profitability and NUE benefit compared to urea with sufficient certainty to influence fertiliser decisions.
  - These experiments were the precursor to the more extensive field assessment of combinations of reduced N rates and EEF products in the Reef Trust 4 EEF60 program. It will be interesting to see if these trials identify situations where EEF products are more certain to deliver productivity, profitability and NUE benefits.
- These experiments also highlighted the impact of climatic conditions on NUE, crop performance and N uptake. Growers and advisors can do their best to identify and implement N management strategies that encourage crop N uptake and minimise the risk of yield loss and off-site impacts, but ultimately, factors outside of their control can have a greater influence on NUE.

ATTACHMENT A: RESULTS OF SOIL MINERAL N ANALYSIS

After harvesting the 2R crop, at NESP 1 there was a statistically significant (*$p<0.001$*) difference in ammonium, nitrate and total mineral N levels between soil depths for both Treatments 1 and 2 (refer to Table 25). The surface 0-20 cm soil depth contained significantly higher total mineral N than all other sampling depths. The 20-40 cm soil depth contained significantly higher total mineral N than the 40-60 and 60-80 cm soil depths but there was no statistically significant difference in total mineral N between the 40-60 and 60-80 cm soil depths at either site. At NESP 2, there was a statistically significant (*$p<0.001$*) difference in soil nitrate levels for Treatment 1 and soil ammonium, nitrate and total mineral N levels for Treatment 2.

Table 25. Mean ammonium, nitrate, and total mineral N values for Treatment 1 and 2 at the well-drained NESP 1 and poorly drained NESP 2 sites after harvesting the 2R crop in 2017.

NESP 1						
	Ammonium ($NH4^{+}$ kg/ha)		Nitrate ($NO3^{-}$ kg/ha)		Total mineral N (kg/ha)	
Soil depth	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)
0-20 cm	20.3^{A}	23.2^{A}	8.0^{A}	6.2^{A}	28.3^{A}	29.3^{A}
20-40 cm	11.8^{B}	12.2^{B}	4.8^{B}	5.9^{A}	16.6^{B}	19.1^{B}
40-60 cm	7.0^{C}	7.9^{B}	2.3^{C}	2.6^{B}	9.3^{C}	10.5^{C}
60-80 cm	7.2^{C}	7.3^{B}	1.8^{C}	1.7^{B}	9.0^{C}	9.0^{C}
Lsd $_{(0.05)}$	2.9	5.6	2.3	2.2	1.9	5.7
$^{A\text{-}C}$ Means with the same letter in the same column are not significantly different (P=0.05)						
NESP 2						
	Ammonium ($NH4^{+}$ kg/ha)		Nitrate ($NO3^{-}$ kg/ha)		Total mineral N (kg/ha)	
Soil depth	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)
0-20 cm	24.3	30.3^{A}	8.8^{A}	9.3^{A}	33.1	39.6^{A}
20-40 cm	21.0	21.2^{B}	5.9^{B}	5.9^{B}	26.9	27.1^{B}
40-60 cm	12.0	7.8^{C}	1.8^{C}	1.6^{C}	13.8	9.4^{C}
60-80 cm	10.2	7.6^{C}	1.5^{C}	1.1^{C}	11.7	8.7^{C}
Lsd $_{(0.05)}$	ns	7.4	2.1	1.8	ns	8.7
$^{A\text{-}C}$ Means with the same letter in the same column are not significantly different (P=0.05)						

After harvesting the 3R crop, there were significant ($p<0.001$) differences in soil ammonium, nitrate and total mineral N levels between soil depths for Treatment 2 at NESP 1 (refer to Table 26). The surface 0-20 cm soil depth contained significantly higher ammonium, nitrate and total mineral N than all other sampling depths. The 20-40 cm soil depth contained significantly higher ammonium, nitrate and total mineral N than the 40-60 and 60-80 cm soil depths but there was no statistically significant difference between the 40-60 and 60-80 cm soil depths. For Treatment 1, soil ammonium and total mineral N levels were significantly (*$p<0.01$*) higher in the surface 0-20 cm soil depth compared to all other sampling depths, but nitrate did not significantly differ between soil sampling depths. At NESP 2, there was no significant difference in ammonium, nitrate or total mineral N between soil sampling depths for both treatments.

Table 26. Mean ammonium, nitrate, and total mineral N values for Treatment 1 and 2 at the well-drained NESP 1 and poorly drained NESP 2 sites after harvesting the 3R crop in 2018.

NESP 1						
	Ammonium ($NH4^+$ kg/ha)		Nitrate ($NO3^-$ kg/ha)		Total mineral N (kg/ha)	
Soil depth	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)
0-20 cm	23.4^A	26.9^A	8.3	10.2^A	31.7^A	37.1^A
20-40 cm	10.1^B	11.0^B	4.2	6.5^B	14.3^B	17.5^B
40-60 cm	8.4^B	6.3^C	3.5	3.2^C	11.9^B	9.4^C
60-80 cm	6.2^B	5.0^C	2.5	2.2^C	8.6^B	7.3^C
Lsd $_{(0.05)}$	5.2	4.4	ns	1.6	6.5	4.5
$^{A-C}$ Means with the same letter in the same column are not significantly different (P=0.05)						
NESP 2						
	Ammonium ($NH4^+$ kg/ha)		Nitrate ($NO3^-$ kg/ha)		Total mineral N (kg/ha)	
Soil depth	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)
0-20 cm	58.8	34.6	3.5	1.7	62.2	36.2
20-40 cm	28.7	42.1	2.2	2.3	30.9	44.4
40-60 cm	15.6	27.7	0.6	0.8	16.2	28.5
60-80 cm	26.7	32.3	0.8	0.9	27.4	33.2
Lsd $_{(0.05)}$	ns	Ns	ns	ns	ns	ns
$^{A-C}$ Means with the same letter in the same column are not significantly different (P=0.05)						

After harvesting the 4R crop at NESP 1, there was a significant (*p<0.01*) difference in ammonium, nitrate and total mineral N levels between soil depths for both treatments sampled (refer to Table 27). The surface 0-20 cm contained significantly more ammonium N compared to all other sampling depths for the treatments sampled. For Treatment 1 (0 kg N/ha), total soil mineral N was significantly higher in the surface 0-20 cm and there was no significant difference between all other sampling depths, whereas for Treatment 2 (150 kg N/ha), there were significant differences in total soil mineral N between the 0-20 cm and 20-40 cm soil depths and the 20-40 cm soil depth also contained significantly more total mineral N than the 40-60cm and 60-80 cm soil depths.

For Treatment 1 (0 kg N/ha) there was no significant difference in nitrate N levels between the 0-20 cm and 20-40 cm depths but these soil depths contained significantly more nitrate N than the remaining soil depths (e.g. 40-60 cm and 60-80 cm). For Treatment 2 (150 kg N/ha), nitrate levels decreased significantly between 0-20 cm and 20-40 cm and between 20-40 cm and the remaining soil depths.

At NESP 2, there was a significant (*p<0.01*) difference in the amount of nitrate and total mineral N for Treatment 1 (0 kg N/ha) between soil depths and the amount of ammonium, nitrate and total mineral N for Treatment 2 (120 kg N/ha) between soil depths.

Despite the surface 0-20 cm of Treatment 1 (0 kg N/ha) containing a higher amount of ammonium N (15.1 kg $NH4^+$/ha) compared to the other soil depths (less than 5.0 kg $NH4^+$/ha), there was no statistically significant difference between soil depths. For the Treatment 2 (120 kg N/ha), the surface 0-20 cm contained significantly more ammonium compared to all other soil sampling depths.

There were significant differences in nitrate between the 0-20 cm and 20-40 cm soil depths and the 20-40 cm soil depth also contained significantly more nitrate N than the 40-60cm and 60-80 cm soil depths for both Treatment 1 (0 kg N/ha) and Treatment 2 (120 kg N/ha).

Total soil mineral N in Treatment 1 (0 kg N/ha) was significantly higher in the surface 0-20 cm but there was no significant difference between all other sampling depths. For Treatment 2 (120 kg N/ha), there were significant differences in total soil mineral N between the 0-20 cm and 20-40 cm soil depths and the 20-40 cm soil depth also contained significantly more total mineral N than the 40-60cm and 60-80 cm soil depths.

Table 27. Mean ammonium, nitrate, and total mineral N values for Treatment 1 and 2 at the well-drained NESP 1 and poorly drained NESP 2 sites after harvesting the 4R crop in 2019.

NESP 1

	Ammonium ($NH4^{+}$ kg/ha)		Nitrate ($NO3^{-}$ kg/ha)		Total mineral N (kg/ha)	
Soil depth	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (150 kg N/ha)
0-20 cm	31.5^{A}	20.4^{A}	12.2^{A}	12.7^{A}	43.7^{A}	33.2^{A}
20-40 cm	5.9^{B}	6.0^{B}	9.6^{A}	9.0^{B}	15.5^{B}	15.0^{B}
40-60 cm	3.1^{B}	3.2^{B}	2.6^{B}	3.3^{C}	5.7^{B}	6.6^{C}
60-80 cm	2.0^{B}	2.5^{B}	1.2^{B}	1.8^{C}	3.2^{B}	4.2^{C}
Lsd $_{(0.05)}$	10.9	4.4	4.4	2.3	12.9	5.2

$^{A-C}$ Means with the same letter in the same column are not significantly different (P=0.05)

NESP 2

	Ammonium ($NH4^{+}$ kg/ha)		Nitrate ($NO3^{-}$ kg/ha)		Total mineral N (kg/ha)	
Soil depth	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)	Treatment 1 (0 kg N/ha)	Treatment 2 (120 kg N/ha)
0-20 cm	15.1	19.7^{A}	14.9^{A}	18.5^{A}	30.0^{A}	38.2^{A}
20-40 cm	4.1	5.1^{B}	7.6^{B}	8.2^{B}	11.7^{B}	13.3^{B}
40-60 cm	4.1	3.7^{B}	1.5^{C}	0.2^{C}	5.7^{B}	4.0^{C}
60-80 cm	5.0	3.2^{B}	0.4^{C}	0.3^{C}	5.4^{B}	3.5^{C}
Lsd $_{(0.05)}$	ns	2.5	2.5	1.3	9.2	3.3

$^{A-C}$ Means with the same letter in the same column are not significantly different (P=0.05)

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APPENDIX 4: MACKAY SITES

Author: Mr Nick Hill, Mr John Turner and Mr John Markley
Affiliation: Farmacist Mackay

OVERVIEW

The Mackay component of the NESP project established two experiments on different locations, both of which explored the possibility of targeting fertiliser N management to productivity zones identified at the sub-block scale. The initial site was located at North Eton with trial activities spanning the 2015/16 (preliminary study), 2016/17 and 2017/18 growing seasons. This site had to be terminated after the 2018 harvest due to a change in the crop rotation of the cooperating grower. A second site was established in Homebush, with the experiment run over the 2018/2019 and 2019/20 growing seasons.

Trial site selection was based upon clearly delineated high and low yielding zones within the same block, determined using historical satellite imagery, to create a maximum yield potential map (e.g. Figure 1 for the North Eton site). Imagery was normalised to account for the impact of different seasonal growing conditions and to address data concerns for cane > 2nd ratoon, to reduce the influence of harvester damage and pest and disease upon yield potential. Statistical analysis of the data was used to convert the results of the satellite analysis into maximum yield potential using the formula:

Maximum yield potential = Mean yield data calculated over multiple growing seasons + 2 Std error of the mean*

Nitrogen (N) Treatments were applied soon after harvest using a commercial stool splitter as per standard grower practice. N rates for the individual treatments were applied based upon either the district yield potential of 130tc/ha or the calculated zonal yield potential, with subsequent rate calculations based on the Six Easy Steps (6ES) method including the discount for N mineralisation derived from site organic carbon % (Walkley Black). Pre-trial soils analysis was used to identify the requirement for other major and minor nutrients which were applied prior to N treatments.

Treatment effects were monitored via biomass sampling to determine crop N uptake and N removal in harvested cane, mechanical cane harvest to determine cane yield, CCS and sugar yield and also post-harvest soil sampling to determine differences in soil mineral N (ammonium-N and nitrate-N). A full description of sampling methodologies for each component being monitored is listed in Attachment A. Following the finalisation of data, all information was provided to the NESP team for further in-depth analysis.

Harvest and biomass data from each experiment (seasonal and cumulative) were analysed using R Studio regression analysis. As required for individual models, outliers were removed and /or transformation was applied to the raw data. Analysis of variance and Tukey's HSD post-hoc analysis was applied to the resulting model(s) to determine significance of outcomes at $P<0.05$.

Mackay NESP 2015-2018: Nth Eton: MKY-3082A, 15-1.

Mackay NESP trial activities commenced in 2015 in first ratoon block of Q208 in the Mackay Mill district of North Eton on Farm no: MKY-3082A Block 15-1 (Figure 44) and concluded post-harvest 2018. The trial site was located on a Sodosol (Pindi soil classification) classified as an acid, bleached, mottled, yellow duplex soil with abundant iron-stained gravel and developed on sedimentary rocks of the Carmila Beds and Lizzie Creek Volcanics.

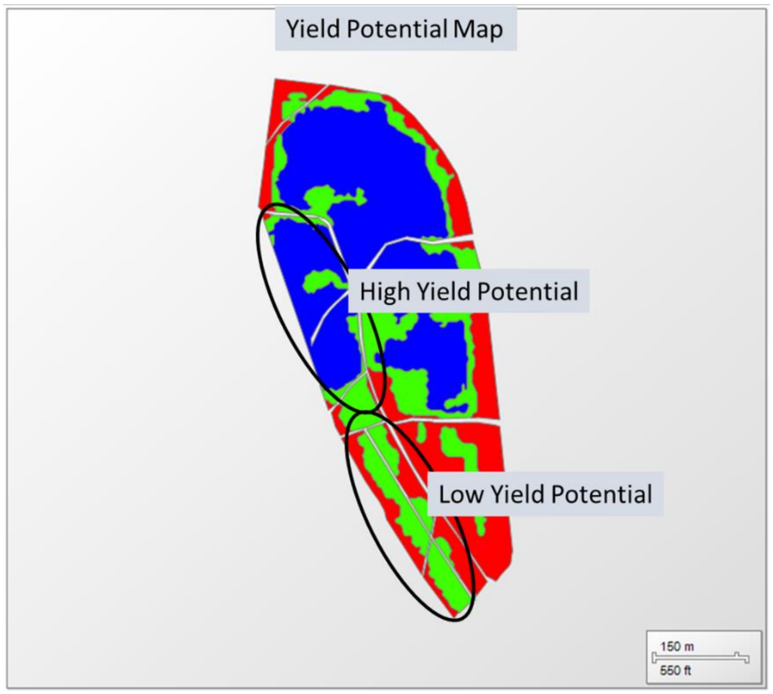

Figure 44. Zonal yield potential for the 2015-2018 NESP trial block at Nth Eton MKY-3082A.

The productivity zone yield potential (PZYP) of the high yielding zone (HYZ) (Figure 44) was identified as 120 t/ha, and as 90 t/ha for the low yielding zone (LYZ). A composite soil sample collected from the block provided data to derive fertiliser requirements to meet phosphorus, potassium and sulphur requirements using 6ES guidelines, while the soil organic carbon (1.0 %) was used to calculate the N mineralisation discount to yield-based N rates. Using the Mackay district yield potential of 130 t/ha and 1% organic carbon, the site was identified as requiring 150 kg N/ha in the standard/benchmark management system.

In an exploratory season in 2015-2016, fertiliser treatments were only based on comparisons of urea and Entec® (urea treated with the nitrification inhibitor DMPP). To provide a comparison with standard district practice, both zones included a urea treatment based upon the 6ES DYP with the soil mineralisation discount, and also a 170 kg N/ha urea rate was also included to determine the impact of increased rates of N upon trial outcomes. Prior to application of individual N treatments, a basal application of liquid fertiliser was applied to achieve required rates of phosphorus, potassium, and sulphur. The rate of N applied via basal application was factored into the total amount of Treatment N applied. Treatments were randomised across the different sections of the individual yield zone(s) and replicated as identified in Table 1. Treatments were 3 rows wide and applied across the length of individual zones (Figures 44 and 45).

At the request of the advisory panel, in 2016-2017 Entec treatments were replaced with a blend of Entec and Polymer coated urea, and the 170kg N/ha urea treatment was replaced with Entec/Polymer blend at 30% less than the 6ES rate. A complete listing of annual N treatments and rates is listed in Table 28.

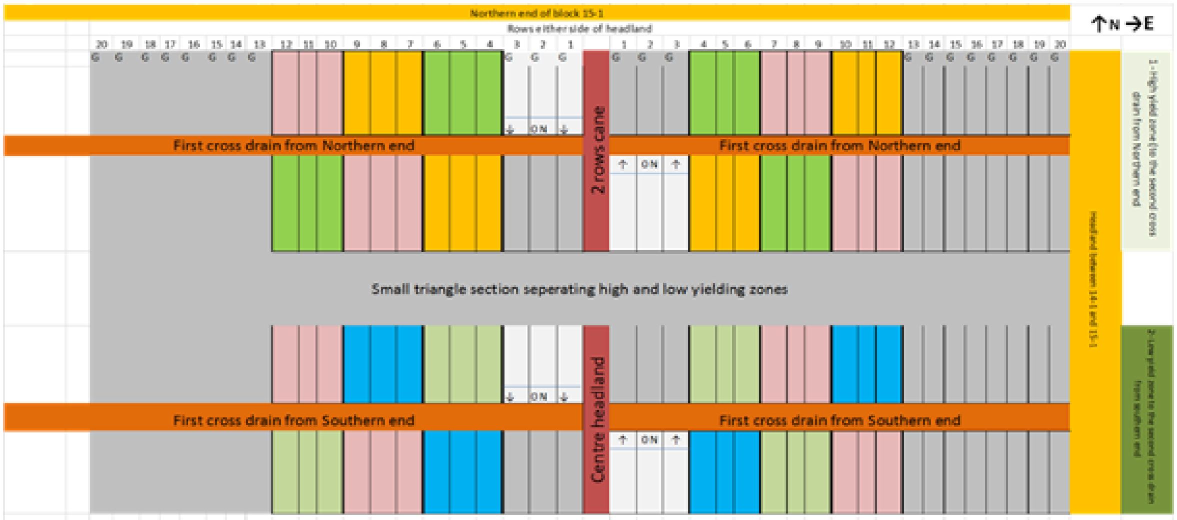

Figure 45. Trial plan for the 2015-2018 experiments at Nth Eton.

2015_2018 rainfall (source: Qld government - SILO Long Paddock)

Total annual rainfall over the duration of the Nth Eton trial fluctuated substantially when compared to the Mackay annual average rainfall of 1585mm (BOM). In 2015, annual rainfall was well below the Mackay average with 868mm recorded. Rainfall distribution declined from February to August, with a minimal increase observed up until December.

Table 28. Treatment, product and nitrogen rate from 2015-2018 for the NESP experiment at Nth Eton MKY-3082A, 15-1.

Year	Zone	N rate	N product	Rep	Year	Zone	N rate	N product	Rep	Year	Zone	N rate	N product	Rep
2015/16	High yield	0	-	2	2016/17	High yield	0	-	2	2017/18	High yield	0	-	2
		155	Urea	4			155	Urea	4			155	Urea	4
		136	Entec	4			136	Entec/ PCU blend	4			136	Entec/ PCU blend	4
		155	Urea	4			155	Urea	4			155	Urea	4
		170	Urea	4			110	Entec/ PCU blend	4			110	Entec/ PCU blend	4
	Low yield	0	-	2		Low yield	0	-	2		Low yield	0	-	2
		155	Urea	4			155	Urea	4			155	Urea	4
		155	Urea	4			155	Urea	4			155	Urea	4
		130	Urea	4			130	Urea	4			130	Urea	4
		104	Entec	4			104	Entec/ PCU blend	4			104	Entec/ PCU blend	4

The 2016 rainfall was consistent with the regional average, with 1526mm recorded. Rainfall increased from January to March, and then declined for the following months with the exception of spikes in June, July, and December.

Rainfall in 2017 was above district average due to the impact of Cyclone Debbie, which contributed almost half of the annual total of 1871mm recorded. Peak rainfall occurred at the start of the year, and Cyclone Debbie caused 831mm of rainfall in March. After that, minimal rainfall was received from June through to September, before rainfall again increased from October through to December.

The 2018 rainfall was again below the district average with a total of 875mm recorded. January through to April received consistent rain which then declined for the following months, with June, August, and December recording no rainfall at all.

The patterns of rainfall as they related to growing seasons and application of N fertiliser are shown in Figure 46.

2016_2017 NESP Trial activities

N Treatments were applied on the 30th of December 2016. Liquid “Soy Starter” @ 3.7m3 was applied as the basal application. In March 2017 Cyclone Debbie impacted upon the trial site which resulted in lodging and reduced site access. Biomass sampling occurred on the 31/10/2017 with samples analysed for TN, TC and CCS. Harvest and post-harvest soil sampling were conducted on the 24/11/2017. It was noted that prior to the harvest >100mm of rainfall was received and concerns were raised regarding the impact of harvester compaction upon future trial outcomes.

2017_2018 trial activities

Trial site fertilisation was conducted on the 21/11/2017. Basal application of liquid “Low P Planter” was applied at 4.0 m3/ha. At the time of fertilising plots 11, 13 and 29 received a double fertiliser application and have been deleted from subsequent analyses. Biomass and CCS sampling occurred on the 16/10/2018 and harvest 26/10/2018. Post-harvest soil sampling was conducted on the 7/11/2018. The trial site crop was observed to be impacted upon by water stress and rat damage. Due to a change in the grower cropping rotation the trial site was not re-established.

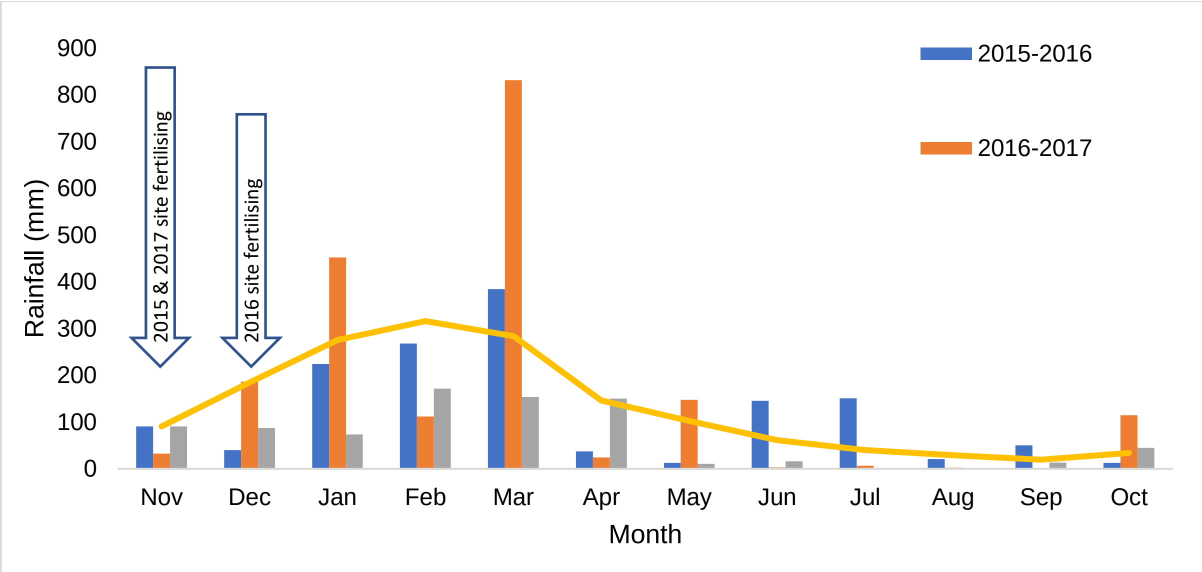

Figure 46*. 2015-2018 Nth Eton MKY-3082A, 15-1. Monthly rainfall totals vs long term monthly average*. Source: Monthly: Qld Gov Silo Long paddock; Long term average: Bureau of Meteorology Mackay Airport, site number: 033119 (1959-2020).

Figure 47. Biomass samples collected at harvest in the Nth Eton NESP experiment. These were used to assess crop N balance (N removed and N returned in residues).

RESULTS: MACKAY NESP 2015-2018: NTH ETON

Biomass

For the 2015-2016 and 2016-2017 trial years no significant treatment effect was measured, either within or between individual yield zones for the biomass NUE factors (Table 29). In 2017-2018 the HYZ recorded significantly higher proportion of N uptake from applied fertiliser than the LYZ and significant treatment effects were observed within both the HYZ and LYZ. The HYZ GS (Urea @ 155kgN/ha) achieved significantly more crop N uptake than T4 (Urea @ 130kgN/ha) and the 0N control but was not significantly different to the remaining treatments which were not significantly different to T4. In the LYZ, GS (Urea @ 155kgN/ha) recorded significantly more crop N uptake than T4 (Urea @ 130kgN/ha) and the 0N control, and significantly a greater uptake of applied fertiliser N than T3 (Urea @ 155kgN/ha) and T4 (Urea @130kgN/ha). In this zone, T1 (Entec/Polymer @ 104kgN/ha was not significantly different from any of the N treatments.

The cumulative analysis over the 2016-2018 seasons (Table 30) indicated that the LYZ had a significantly lower proportion of N taken up from the applied fertiliser than the HYZ. Within the LYZ, only the treatment GS (Urea @ 155kgN/ha) accumulated significantly more crop N than the 0N control.

Figure 48. Nth Eton NESP trial site harvest.

Table 29. Mackay NESP 2015-2018: Nth Eton: MKY-3082A, 15-1. Within zone / trial year: biomass average Nitrogen use efficiency analysis.

Year	Zone	N rate and product	Biomass N (kg/ha)	Fertiliser recovery (%)	Year	Zone	N rate and product	Biomass N (kg/ha)	Fertiliser recovery (%)	Year	Zone	N rate and product	Biomass N kg/ha)	Fertiliser recovery (%)
2015/16	High yield	0	26.9	NA	2016/17	High yield	0	41.8	NA	2017/18	High yield *a*	0	32.6 c	NA
		155 urea	33.0	3.9			155 urea	55.2	9			155 urea	78.5 a	30
		136 Entec	50.9	17.6			136 EEF blend	54.4	9			136 EEF blend	71.6 ab	29
		155 urea	55.7	18.5			155 Urea	51.1	6			155 Urea	73 ab	26
		170 urea	62.3	20.8			110 EEF blend	53.4	11			110 EEF blend	64.4 ab	29
	Low yield	0	21.1	NA		Low yield	0	54.1	NA		Low yield *b*	0	48.3 b	NA
		155 urea	63.4	27.2			155 urea	63.3	6			155 urea	90.8 a	27
		104 Entec	47.0	24.9			155 urea	59.5	3			155 urea	63.7 ab	10
		155 urea	26.3	4.0			130 urea	59.1	4			130 urea	60 ab	9
		130 urea	51.7	23.5			104 EEF blend	58.8	5			104 EEF blend	62.9 ab	14

Table 30. Cumulative analysis of crop N uptake and fertiliser N recovery from common treatments applied in the 2016/17 and 2017/18 growing seasons at Nth Eton

Trial year(s)	Zone	Product	N Rate (kg/ha)	Crop N (kg/ha)	Proportion of applied N fertiliser uptake (%)
2016-2018	HYZ NUptEfert : a	Urea	310	138.4	21
		Entec/Poly	272	123.6	18
		Urea	310	121.0	15
		Urea	260	103.4	17
		Entec/Poly	220	116.2	19
		Control	0	77.4	NA
	LYZ NUptEfert : b	Urea	310	154.1 a	17
		Entec/Poly	208	121.6 ab	9
		Urea	310	123.2 ab	7
		Urea	260	119.0 ab	6
		Control	0	104.3 b	NA

Analysis within trial years and individual zones (Table 4) shows no significant treatment effects on cane yield, CCS or sugar yield for the 2015-2016 and 2016-2017 seasons. Interestingly, the productivity in the low and high yielding zones was actually reversed in 2015/16, with yields at least as high (if not higher) in the supposedly low yielding zone. The 2016/17 crop was seriously damaged by cyclone Debbie, so whilst there appeared to be a similar reversal of high and low yielding in this season, it was impossible to ascribe treatment effects with any confidence. In 2017-2018 significant treatment effects were seen for both cane and sugar yields only within the low yielding zone, but the variability for the 155 kg N/ha urea rates (95 and 76 t/ha) cast some doubt on these findings.

Agronomic Efficiency (the kg N applied to produce an additional t of cane yield) was generally very poor and extremely variable across the seasons and yield zones, with the exception of the high yielding zone in 2017/18 (4-6 kg N/t).

Table 31. Cane yields, CCS, sugar yields and agronomic efficiency of fertiliser N use at Nth Eton 2015-2018:

Trial Year	Zone	N rate/ product	Cane yield	CCS	Sugar yield	AE (kg N/t extra cane	Trial Year	Yield zone	N rate/ product	Cane yield (t/ha)	CCS	Sugar yield	AE (kg N/t extra cane	Trial Year	Yield zone	N rate/ product	Cane yield (t/ha)	CCS	Sugar yield	AE (kg N/t extra cane
2015-2016	High	0	84.7	14.9	12.6		2016-2017	High	0	47.8	18.7	7.6		2017-2018	High	0	56.8	18.7	10.6	
		155 urea	88.2	17.1	15.1	45.3			155 urea	57.9	18.8	10.5	15.3			155 urea	88.0	18.1	15.9	5.0
		136 Entec	83.4	15.7	13.3	NA			136 EEF blend	60.9	18.5	11.8	10.3			136 EEF blend	89.0	18.3	16.1	4.2
		155 urea	91.3	14.7	13.5	23.6			155 Urea	59.0	18.6	10.1	13.8			155 Urea	83.0	18.0	14.7	5.9
		170 urea	71.5	15.1	10.7	NA			110 EEF blend	58.4	18.3	10.2	10.4			110 EEF blend	83.9	18.3	15.3	4.1
	Low	0	100.8	16.8	16.8			Low	0	63.6	18.2	11.6			Low	0	68.4 b	18.8	12.8 ab	
		155 urea	91.2	17.8	16.2	NA			155 urea	69.9	17.8	12.4	24.5			155 urea	95.4 a	18.6	17.9 a	5.7
		104 Entec	86.1	17.0	14.6	NA			155 urea	63.0	18.2	11.5	NA			155 urea	76.5 ab	18.8	14.4 ab	19.1
		155 urea	79.7	15.8	12.9	NA			130 urea	64.9	17.9	11.6	98.5			130 urea	69.7 b	18.2	12.7 b	100.0
		130 urea	89.6	16.4	14.7	NA			104 EEF blend	64.0	18.2	11.6	260.0			104 EEF blend	83.2 ab	18.7	15.6 ab	7.0

The analysis of cumulative cane and sugar production across the 2016-2018 seasons (Table 32) reflects the points observed in the individual seasons, with the supposedly high yielding zone producing no more cane or sugar over the two year crop cycle. It was interesting to note what appeared to be higher yields without any applied N in the low yielding zone, perhaps reflecting carryover N from previous poor crops.

Table 32. Cumulative cane and sugar production from common treatments in the 2016-2018 seasons at North Eton. The Agronomic Efficiency of applied N is shown for each zone.

Trial year(s)	Zone	Product	N Rate (kg/ha)	TCH	TSH	Agron Eff (kg N/t extra cane))
2016-2018	HYZ	Control	0	104.6	18.2	
		Urea	155	145.9	26.4	7.5
		Entec/Poly	136	149.9	28.0	6.0
		Urea	155	142.0	24.8	8.3
		Entec/Poly	110	142.2	25.5	5.8
	LYZ	Control	0	132.0	24.4	
		Urea	155	165.3	30.3	9.3
		Urea	155	139.5	25.9	40.9
		Urea	130	134.6	24.3	99.2
		Entec/Poly	104	147.2	27.2	13.7

Post-harvest soil sampling

There appeared to be a gradual build-up of residual mineral N in all fertilised treatments across the monitoring period (Figures 49-51) in both yield zones. After harvest of the 2015/16 crop, there was very little, if any, detectable NO_3-N found in the soil in any treatment (Figure 49), with the residual mineral N almost exclusively present as NH4-N. While the treatments sampled did not allow a direct comparison across the high and low yielding zones, there were suggestions of higher NH4-N concentrations in the high yielding zone, particularly in the top 40cm of the soil profile, but no apparent effect of N rate or product.

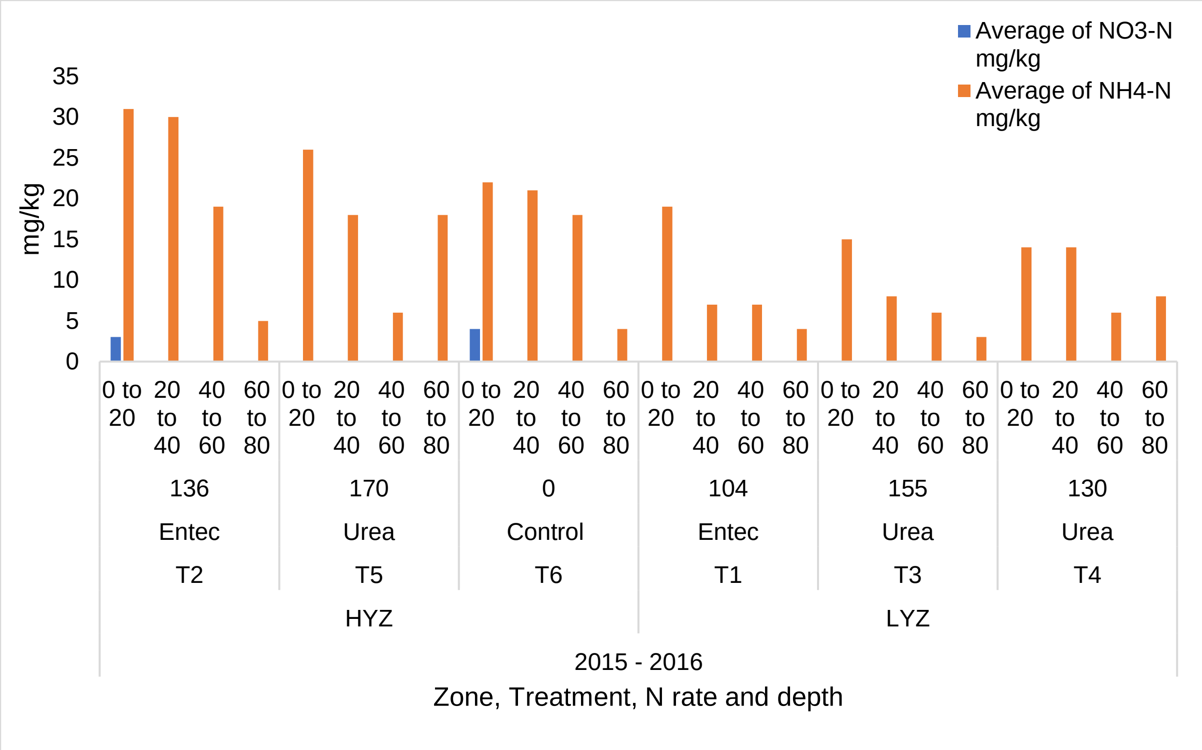

Figure 49. Concentrations of NH_4-N and NO_3-N (mg N/kg) found at different profile depths in selected fertiliser treatments from the high and low yielding zones after the harvest of the 2015/16 crop at North Eton.

After the 2016-2017 harvest there was detectable NO_3-N in profiles of all treatments tested, often at comparable concentrations to NH_4-N, but there were no consistent differences between yield zones (Figure 50) or in response to the non-application of fertiliser N. While NO_3-N concentrations were noticeably higher, there appeared to be lower NH_4-N concentrations than after 2015/16 harvest (i.e. 4-10 mg N/kg compared to 10-30mg N/kg in the top 20-40cm), but the total mineral N concentration was similar.

In 2017-2018 (Figure 51) there was again detectable NH_4-N and NO_3-N, but also what appeared to be the beginnings of detectable differences in mineral N concentrations between the unfertilised control plots and those that had received fertiliser over the preceding three crop seasons in both low and high yielding zones. The highest concentrations were again observed in the top 20-40cm of the soil profile, and in the fertilised treatments, these now exceeded the mineral N concentrations found after the 2015/16 and 2016/17 harvests – especially in the low yielding zone.

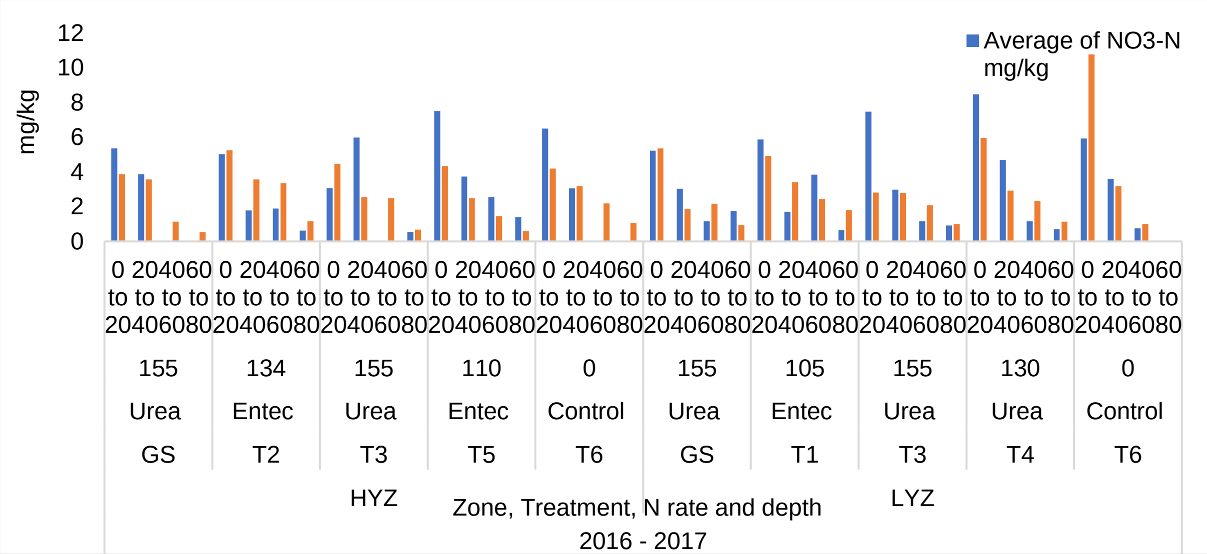

Figure 50. Concentrations of NH_4-N and NO_3-N (mg N/kg) found at different profile depths after the harvest of the 2016/17 crop in response to fertiliser treatments applied in the high and low yielding zones at North Eton.

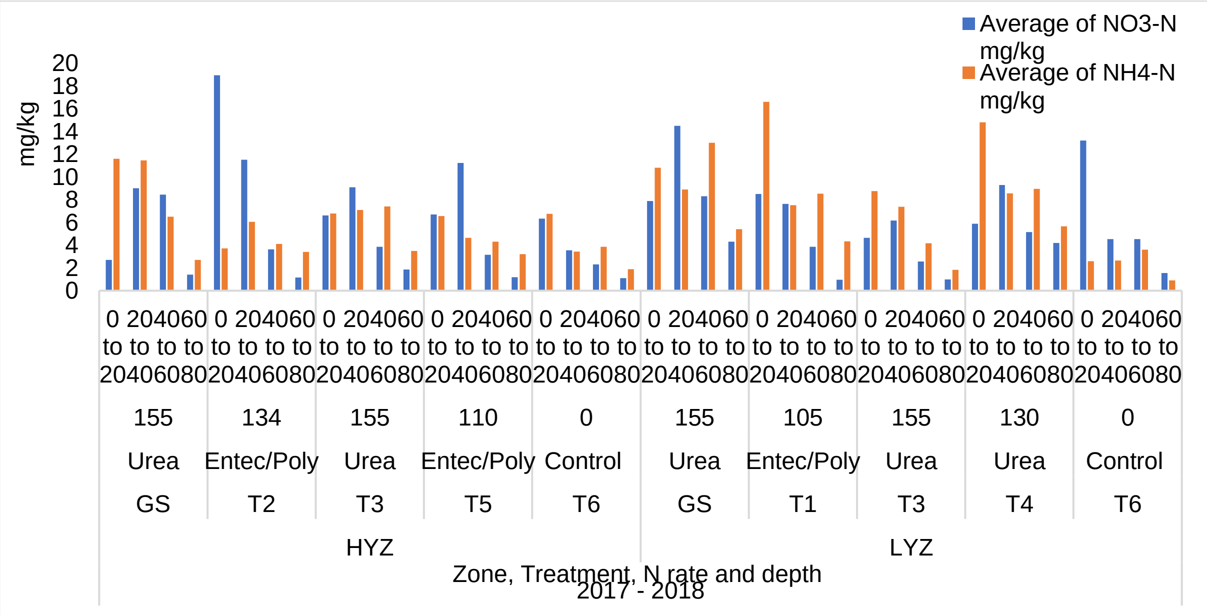

Figure 51. Concentrations of NH_4-N and NO_3-N (mg N/kg) found at different profile depths after the harvest of the 2017/18 crop in response to fertiliser treatments applied in the high and low yielding zones at North Eton.

Key Findings: 2015-2018 Nth Eton: Mky-3082a, 15-1.

2015-2016. The first trial year saw few significant impacts of fertiliser N treatments on cane or sugar yields in either yield zone – an observation not uncommon in the first year of many N fertiliser trials. However, there were two observations from that season that were unexpected – the relatively strong performance of the crop in what was historically designated as a low yielding part of the paddock (Table 31), and the apparently very low crop N contents at the time of biomass sampling (Table 29). The latter effect may be a result of the biomass sampling being undertaken close to final harvest in this season, with canopy senescence and release of above ground N back to the soil a possible explanation. A particular concern was the variability in apparent N uptake by crops receiving ostensively identical N rates as urea in both paddock zones, with differences of 25-30 kg N/ha crop uptake representing a doubling of crop N uptake between the high and low yielding examples of the same N treatments. It is not possible to identify if this was due to sampling error or crop variability in the field, but the former is suspected given the relative stability of cane yields for the same comparison (Table 4) – especially in the high yielding zone. Apparent fertiliser N recoveries were typically <25%, and as low as 15% in the DYP treatments (155 kg N/ha).

The lack of significant N responses in either cane or sugar yields in response to N treatment, or indeed to the absence of any fertiliser N application at all, make it very difficult to make any comment about the N responsiveness of the efficiency of different fertiliser products. Needless to say, measures of agronomic efficiency of fertiliser N use (kg fertiliser N/t extra cane yield) were meaningless in this season, given there were no yield increases.

2016-2017. The results for the 2016/17 growing season were no doubt impacted by cyclone Debbie, with the crop a twisted mess after the cyclone passed at the end of March. While it may have been that the crops growing better at the time of impact were worst affected by the event, no prior observations or measurements had been made. Crop N contents were more consistent than in 2015/16, but total crop N contents were still low (42-55 kg N/ha in the unfertilised treatments and 50-65 kg N/ha in the fertilised treatments) and there were still no significant response to N fertiliser application (Table 2). Apparent fertiliser recoveries were almost universally <10%.

Cane and sugar yields were reduced by 30% and 23%, respectively, compared to the previous harvest averaged across the whole trial (Table 4). There were once again very few suggestions of any N response at the site at all, with the possible exception of the Nil N treatment in the high yield zone.

2017-2018. The 2017/18 crop was the first in which there were significant responses to fertiliser N applications in terms of crop N uptake (both yield zones – Table 2) and cane and sugar yields (Table 4). Crop N contents effectively doubled in the high yielding zone, although there were no differences between rates and products, and by at least 40% in the poor yielding zone. Interestingly, while there was again little difference in crop N contents between zones for the fertilised or unfertilised treatments, there were suggestions of more efficient fertiliser N recovery by crops in the high yielding zone (26-30% of applied N) than the low yielding zone (9-27%), although no consistent differences between rates or products.

Cane and sugar yields also responded significantly to fertiliser N application in the low yielding zone, and there was a trend (although not statistically significant) in the high yielding zone as well (Table 4). There were suggestions that the EEF blend was able to maintain crop performance at N rates *ca.* 60% of those derived from the DYP calculation, but field variability (especially in treatments receiving the DYP rate) have limited the ability to draw any firm conclusions. Agronomic responses to fertiliser application were most consistent in the high yielding zone, and ranged from 4-5 kg N applied/t cane yield increase.

The combination of the lack of N responses until the 3rd crop season, and the impact of Cyclone Debbie on the 2016/17 crop, make it impossible to draw any definitive conclusions from this trial – even when considering the cumulative cane production. What was more concerning was the apparent inconsistency of high and low yielding zones identified from historical satellite records. The low yielding zone was thought to be due to extreme sodicity in subsoil layers, which might be expected to have the greatest impact in wetter than average seasons. With the exception of Cyclone Debbie, seasonal rainfall was generally below average (especially in the responsive 2017/18 season) during the years this experiment was conducted, and this may have limited the negative impacts of sodicity on crop performance. When it was wet in 2017/18, the crop had been badly wind-damaged and so differences in zonal yield potential were not able to be expressed.

Site 2 NESP 2018-2020: Homebush MKY-04202A, 10-1.

The 2018-2020 Mackay NESP trial site was established in Homebush in November 2018 on farm no MKY-04202A, Block 10-1, in fourth ratoon variety Q138. Soils of the site are classified as Chromosols/ Kurosols; Sandiford. The texture is sand or loam over friable or earthy clay - an acid to neutral, bleached, mottled, yellow duplex soil overlying sandy D horizons and developed in Quaternary alluvium. As per the Nth Eton trial, this site was selected due to having clearly defined zones of minimum and maximum yield potential within the one block (Figure 52).

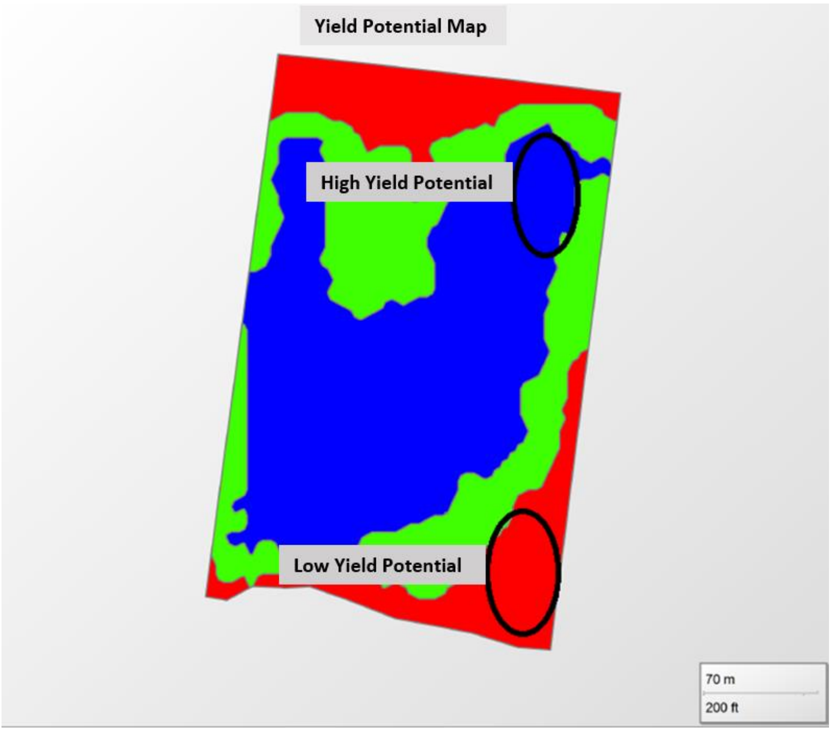

Figure 52. Zone yield potential in trial site 2 (2018_2020) at Homebush MKY-04202A, 10-1.

A maximum yield potential of 90t/ha was identified for the HYZ. Historic block soil analyses were used to identify phosphorus, potassium, and sulphur requirements which were provided via a top dressing of granular fertiliser prior to N Treatment application. Fertiliser N inputs provided via the basal application formed a component of total N applied in each treatment. Trial design was a replicated small-plot trial consisting of 30mtr long plots 3 rows wide (Figure 53). The district yield potential for this site was 130 t/ha, with an N rate of 150 kg N/ha, with applications approximating this rate (146 kg N/ha) included as a Treatment in both LYZ and HYZ. Treatments specific to the LYZ were applied at approx. 20% (urea) and 40% (EEF) less than the 146 kg N/ha, while in the HYZ the EEF blend was applied at approx. 20% and 40% less than the 146 kg N/ha. Over the duration of the trial the EEF blend remained 1/3 Entec and 2/3 Polymer coated urea. The N treatments and associated rates are listed in Table 33.

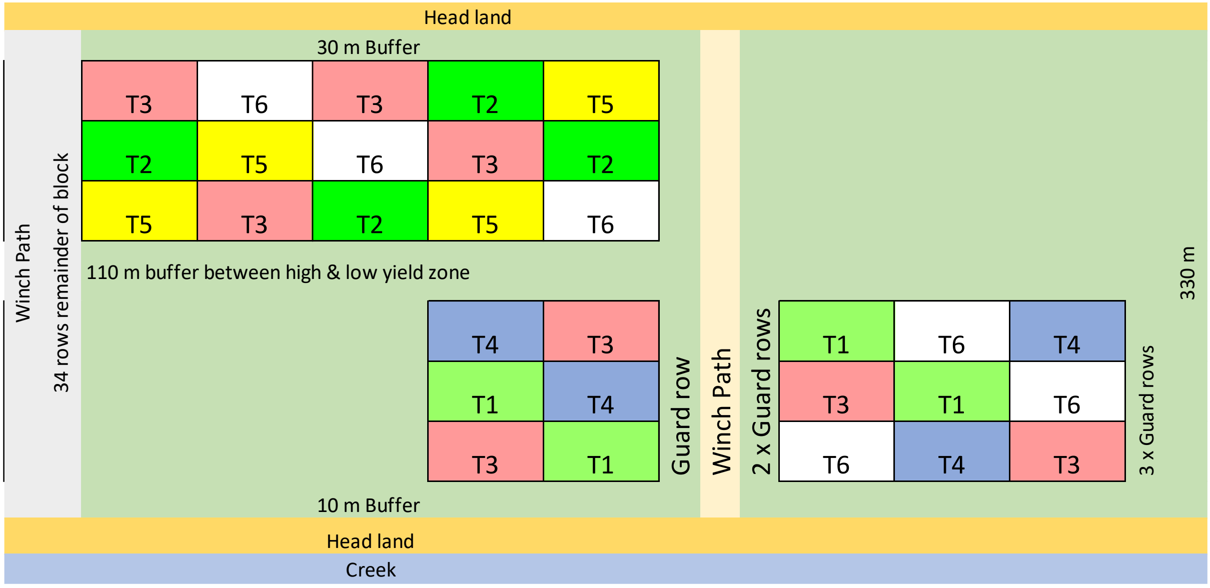

Figure 53. Trial plan for the experiment run at the Homebush site from 2018-2020.

Table 33. Nitrogen rates and treatments applied in the high (HYZ) and low (LYZ) treatments from 2018-2020 at the Homebush site.

Year	Zone	N rate	N product	Rep
2018/19 and 2019/20	High yield	0	-	3
		146	Urea	4
		117	Entec/PCU blend	4
		91	Entec/PCU blend	4
	Low yield	0	-	3
		146	Urea	4
		112	Urea	4
		83	Entec/PCU blend	4

2018_2020 rainfall (source: Qld government - SILO Long Paddock).

Over 2018-2020 trial years, annual rainfall totals for the Homebush trial site (Figure 54) were approx. 30% less than the Mackay region annual average rainfall (1585mm). Rainfall distribution typically followed the pattern of wet and dry seasons, with rainfall increasing from December through to March/April and declining from May/June through to November. Rainfall received during May to November can be observed to fluctuate between years.

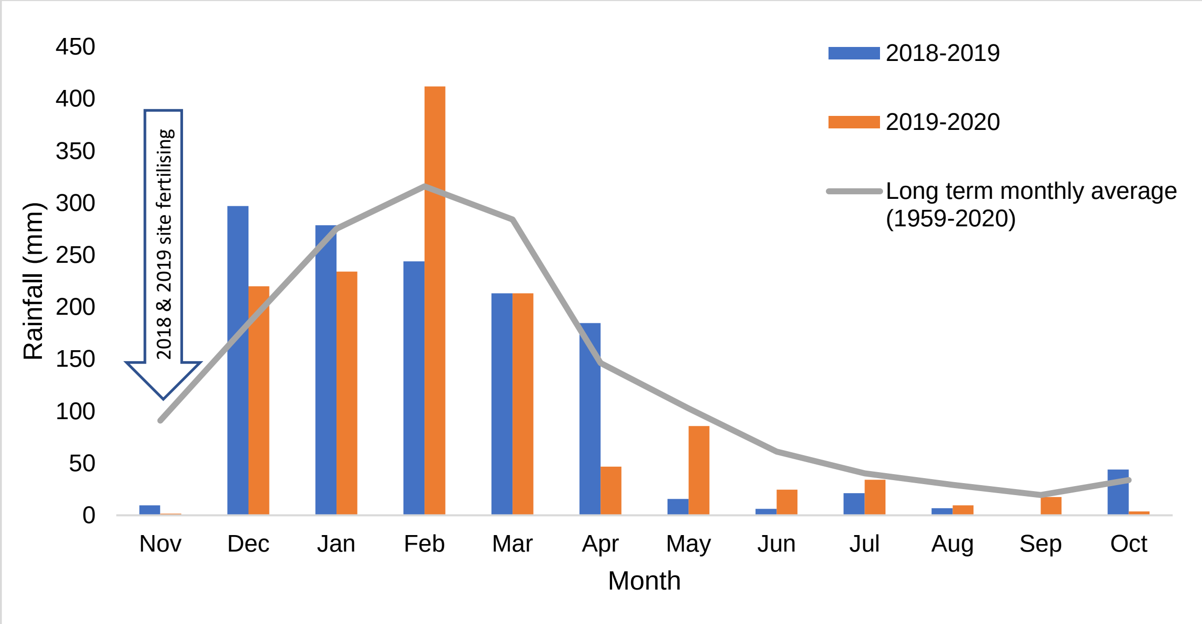

Figure 54. Monthly rainfall totals vs long term monthly average at Homebush. Source: Monthly Qld Gov Silo Long paddock; Long term average: Bureau of Meteorology Mackay Airport, site number: 033119 (1959-2020).

2018-2019 trial activities.

In 2018, basal treatments were top dressed on 9/11/2018 using a blend of di-ammonium phosphate and muriate of potash, and the experimental N Treatments were applied on 16/11/2018. During the season, the trial site was irrigated on 3 occasions receiving an approx. total of 210mm. Biomass and CCS samples were taken at the time of final harvest on 19/11/2019, approx. one year after treatment application. Soil samples were taken immediately after harvest on the 21/11/2019.

2019-2020 trial activities.

The N treatments were applied on 20/11/2019 using similar methodologies as the previous year. Biomass samples were taken at 9 months after fertilising on 4/08/2020. Whole sticks were sampled to determine CCS 3 days prior to harvest, which occurred on the 23/10/2020.

Table 34. Analysis of accumulation of N in crop biomass and the apparent recovery efficiency of fertiliser N at the Homebush site in 2018-2020. Note: Numbers followed by letters are significantly different, P<0.05. Treatment effects were analysed within zones

Year	Zone	N rate and product	Biomass N (kg/ha)	Fertiliser recovery (%)	Year	Zone	N rate and product	Biomass N (kg/ha)	Fertiliser recovery (%)
2018/19	High yield	0	31.24 b	NA	2019/20	High yield	0	49.12	NA
		117 EEF blend	37.65 ab	5			117 EEF blend	56.35	8
		146 Urea	52.28 a	14			146 Urea	57.12	7
		91 EEF blend	35.34 b	5			91 EEF blend	68.89	24
	Low yield	0	10.73	NA		Low yield	0	17.46	NA
		83 EEF blend	21.74	13			83 EEF blend	23.63	7
		146 Urea	20.32	7			146 Urea	21.96	3
		112 urea	14.76	4			112 urea	22.77	4

RESULTS MACKAY NESP 2018-2020: HOMEBUSH.

Biomass

Analysis of individual trial years (Table 34) showed a significant treatment response in 2018-2019 for the HYZ, where the DYP urea rate (146kg N/ha) accumulated significantly more N in the crop biomass than the unfertilised Control and the low rate of the EEF blend. However, there were no treatment differences in the low yielding zone which accumulated less than half the biomass N as in the high yield zone. In this season, apparent fertiliser recovery efficiencies were particularly low, with a maximum of 14% in the high yield zone and 13% in the low yield zone. Interestingly, the DYP urea treatment gave the highest apparent recovery in the high yield zone (i.e. despite the high application rate), while the EEF blend at a rate of 60% of DYP gave the highest apparent recovery in the low yielding zone.

Data collected in the 2019/20 season showed much higher crop N in the unfertilised Control and the EEF treatments in the high yield zone compared to the previous season, but no change in biomass N for the DYP urea treatment, with the result that no effects of N treatment were significant. The low yield zone again showed extremely low crop N contents and no significant response to fertiliser rates or application. In this season, the low rate EEF blend achieved the highest apparent fertiliser recovery in each yield zone (24% and 7% in the high and low yield zones, respectively) with effects due to the low application rate rather than an increase in crop N uptake by the crops. Fertiliser recovery for the DYP urea rate was extremely low at 7% and 3% in the high and low yield zones, respectively.

Cumulative analysis (Table 35) identifies no significant treatment effect upon N use efficiency for the combined trial years.

Table 35. Cumulative analysis of crop N uptake and fertiliser N recovery from common treatments applied in the 2018/19 and 2019/20 growing seasons at Homebush

Trial year(s)	Zone	Product	N Rate (kg/ha)	Crop N (kg/ha)	Proportion of applied N fertiliser uptake (%)
2018-20	HYZ a	Control	0	80.4	NA
		Entec/Poly	117	94.0	7
		Urea	146	109.4	11
		Entec/Poly	91	104.2	14
	LYZ b	Control	0	28.2	NA
		Entec/Poly	83	45.4	10
		Urea	146	42.3	5
		Urea	112	67.6	4

Note: Yield zone, biomass factor, or numbers followed by letters are significantly different, P<0.05.

Figure 55. Final harvest of the crop at the Homebush site in 2020.

Table 36. Cane yields, CCS, sugar yields and agronomic efficiency of fertiliser N use at Homebush 2018-2020.

Trial Year	Yield zone	N rate/ product	Cane yield (t/ha)	CCS	Sugar yield	AE (kg N/t extra cane)	Trial Year	Yield zone	N rate/ product	Cane yield (t/ha)	CCS	Sugar yield	AE (kg N/t extra cane)
2018-2019	High	0	80.75	16.95	13.72	NA	2019-2020	High	0	71.60	17.10	12.26	NA
		117 EEF blend	88.34	17.36	15.36	15.4			117 EEF blend	81.48	17.47	14.22	11.8
		146 Urea	97.45	17.12	16.67	8.7			146 Urea	81.94	17.07	13.94	14.1
		91 EEF blend	90.16	17.22	15.53	9.7			91 EEF blend	81.02	17.18	13.92	9.7
	Low	0	30.97	16.93	5.24	NA		Low	0	22.84	17.72	4.02	NA
		83 EEF blend	53.73	17.06	9.16	3.6			83 EEF blend	37.04	17.64	6.54	5.8
		146 urea	51.46	16.82	8.66	7.1			146 urea	27.78	17.84	5.00	29.6
		112 urea	41.89	16.54	6.94	10.3			112 urea	29.63	17.28	5.14	16.5

Note: Numbers followed by different letters are significantly different, P<0.05.

Harvest

There were no significant differences between treatments within zones in either season for cane yield, CCS or sugar yields (Table 36), and despite trends for lower yields in the unfertilised control treatment, the response to applied N in any form was never statistically significant. There were substantial yield, and in some cases CCS, differences between yield zones in each season, with the high yielding zone producing approximately twice the cane and sugar yields as the low yielding zone – although in 2019/20 season the differences in sugar yields were moderated slightly by a higher CCS in the low yielding zone.

The small and non-significant yield responses to applied N fertiliser resulted in Agronomic Efficiencies of N use that were determined primarily by the rate of applied N rather than the size of the yield response. Efficiencies tended to be lower (fewer kg of N/t cane yield increase) in the 2018/19 season than the 2019/20 season – primarily due to the lower maximum yields encountered in this older ratoon crop.

Table 37. Cumulative cane and sugar production from the Homebush site in response to differing rates and forms of N fertiliser from 2018-2020.

Zone	Treatment	Product	TCH	TSH	Agron Eff (kg N/t extra cane)
HYZ	0	Control	152.3	27.4	NA
	117 EEF blend	Entec/Polymer	169.8	30.8	13.4
	146 Urea	Urea	179.4	33.4	10.8
	91 EEF blend	Entec/Polymer	171.2	31.1	9.6
LYZ	0	Control	53.8a	10.5a	NA
	83 EEF blend	Entec/Polymer	90.8b	18.3b	4.5a
	146 urea	Urea	79.2ab	17.3b	11.5b
	112 urea	Urea	71.6ab	13.9ab	12.6b

Cumulative productivity over the two growing seasons (Table 37) showed that the HYZ produced three times the cane yield without fertiliser and roughly twice the cane with fertiliser than the LYZ. Similar responses were recorded for sugar yield. However, unlike the individual years, there were significant responses to fertiliser N in cane and sugar yield in the LYZ, with the EEF blend at only 60% of the DYP N rate producing the same or higher yields as the DYP urea treatment. These differences were reflected in Agron Eff values, with the combination of low N rates and high yields of the low rate EEF treatment resulting in the amount of N required to grow an additional t of cane more than halving, compared to the DYP urea rate in the LYZ. Otherwise, Agron Eff were similarly poor (10-13 kg N/t additional cane yield) for all other treatments in both HYZ and LYZ (Table 37).

Post-harvest soil sampling

Post-harvest soil sampling data are only presented for the 2018-2019 season as 2019-2020 soils analysis results are not available at the time of this report. Results from 2018/19 showed that the dominant mineral N species after harvest was clearly NH_4-N rather than NO_3-N in both zones (Figure 11), with that dominance especially evident in the top 40cm of the soil profile in the LYZ. Interestingly, mineral N concentrations declined much more strongly in the LYZ than the HYZ as sampling depth increased.

Despite these interesting observations, there were no effects of fertiliser N application on residual mineral N in either zone, much less any differences between fertiliser rate and product choice (i.e. urea v EEF blend). Results from the 2nd crop season will hopefully provide some confirmation of these differences (or lack of them), but given the poor apparent fertiliser N recovery at this site (Tables 7 and 8) the fate of the vast majority of applied fertiliser in both zones and from both fertiliser products requires further investigation.

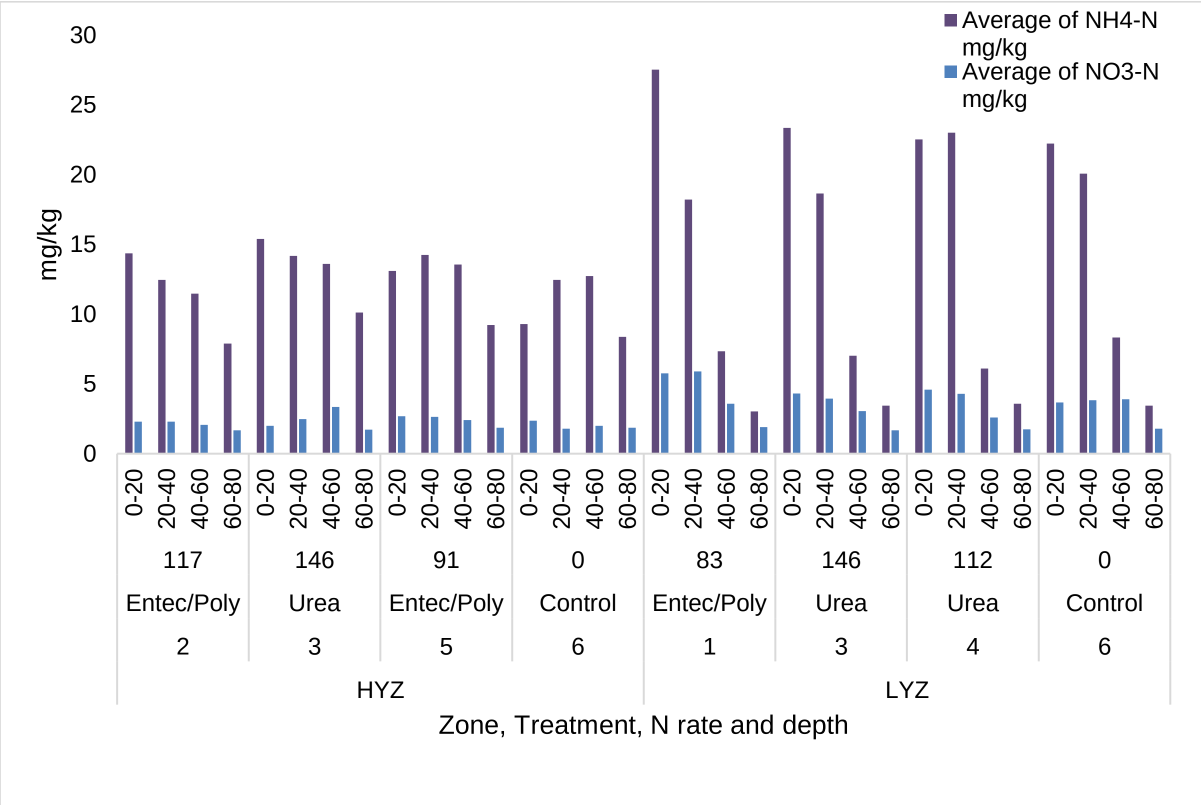

Figure 56. Concentrations of NH_4-N and NO_3-N found in the soil profile to 80cm depth at Homebush after harvest of the 2018/19 ratoon crop.

Key findings: 2018-2019 NESP 2018-2020: Homebush MKY-04202A, 10-1.

Cumulative biomass assessment over the 2018-2020 trial years (Table 35) have shown that across the different yield zones the EEF treatments at the reduced N rates maintained comparable or improved crop N uptake and proportional recovery of fertiliser N relative to urea applied at the DYP rate. This outcome was more evident in the cumulative cane and sugar yields, with no statistically significant difference in TCH, CCS or TSH between individual treatments over the monitoring period (Table 37). Within individual seasons (Table 36) similar outcomes were observed, with the performance of the 60% DYP N rate as the EEF blend of particular note in the LYZ. This treatment produced more cane at similar CCS and so higher sugar yield than the DYP urea rate in each growing season, and so was much more agronomically efficient than the DYP urea standard. However, this trend for higher productivity and agronomic efficiency with the EEF blend was not evident in the HYZ, where the response to fertiliser N application with any rate or product were much smaller.

These outcomes demonstrate the site specificity of the EEF responses, but are encouraging in that they do show that EEF products can allow N rates to be reduced without a significant impact upon either biomass or harvest yields whilst maintaining or improving NUE. The reason for the more significant responses to the EEF blend at this site, especially in the LYZ, may have been related to the timing of rainfall events following fertiliser application. In both 2018 and 2019, treatments were applied in November and were soon followed by the onset of the wet season and extended periods of rain (Figure 54). The Entec/Polymer EEFs would have slowed the production of NO_3-N, which is most vulnerable to a variety of loss pathways under these conditions (denitrification, runoff and leaching in particular). In very sandy soils, leaching losses are likely to dominate, and so slowing the formation of NO_3-N may have kept fertiliser N in the root zone for longer, allowing more efficient crop uptake. This was particularly evident in the LYZ, where background soil fertility seemed to be lower in deeper profile layers and the yield loss from withholding fertiliser N was relatively much greater. By comparison, the straight urea treatments would have been subjected to greater proportional losses and would have needed the higher N application rates to maintain crop N supply.

Figure 57. The very last bin of cane from the NESP trial site at Homebush in the 2020 harvest.

ATTACHMENT A: MACKAY NESP TRIAL SITE FIELD SAMPLING METHODOLOGY

NESP Field sampling methodology project 2015/065 – Improving NUE for crops with constrained yield potential

Biomass: approx. 8-9 months post treatment application.

- Measure all plots (5 N rates and 4 replicates) – sample all replicates individually
- Count the number of stalks in a 10 m section of row 2
- Collect 20 consecutive stalks and record total weight.
- Partition 20 stalks into:
    - Millable stalk
    - Tops which includes cabbage and green leaves
- To determine between millable stalk and cabbage cut between the 5th and 6th dewlaps for stalks that have not flowered or the 7th and 8th dewlaps for stalks that have flowered
- Include all green leaves, even those attached to the millable stalk into the top sample
- Weigh each component separately and record weights
- Weight of 20 millable stalks
- Weight of 20 tops

Crop N uptake
At time of biomass sampling:

- Randomly select 5 millable stalks and 5 tops from the partitioned material collected at biomass sampling.
- Mulch millable stalk and top samples separately
- Collect a subsample of the mulched material and record:
    - Fresh weight mulched millable stalk sample
    - Fresh weight mulched top sample
- Dry subsamples in an oven set at 60oC, record:
    - Dry weight mulched milable stalk sample
    - Dry weight mulched top sample
- Calculate moisture content (Moisture content % = ((net fresh weight – net dry weight) / net fresh weight) * 100)
- Grind dry millable stalk and top samples (particle size <2 mm)
- Collect a subsample from the ground millable stalks and tops
- Send samples to DSITI for analysis of N concentration

Harvest
Nth Eton MKY-3082A, 15-1

- Measure 20mtr section from each treatment within each yield zone and replicate.

Homebush MKY-04202A, 10-1.

- Harvest each 30mtr plot from each treatment, yield zone and replicate.

Each trial site location.

- From row 2 for each individual treatment collect commercial harvester yield via weigh truck and record weight.

- Collect 12 sticks from each individual treatment.
    - 6 sticks: remove tops / trash. Send for CCS analysis via SRA juice lab.
    - 6 sticks: partition into millable stalk and tops process/dispatch for N uptake as per biomass methodology.

Post-harvest Soil mineral N

- Sample all Treatments/replicates individually.
- Sample off the “shoulder” of the row.
- From each Treatment collect 4 randomly selected soil cores to 80cm in depth.
- Partition cores into 0-20, 20-40, 40-60, 60-80 cm sections.
- Bulk individual sections together, place in plastic bag and store in a cool esky.
- Dry soil samples in a cabinet circulating ambient air temperature or in a room with a fan / air conditioning.
- Grind dry soil samples (<2 mm particle size).
- Collect a 250grm subsample.
- Send samples to DSITI for analysis of mineral N (ammonium and nitrate).

APPENDIX 5: FRESHWATER SITE

Author: Dr Tony Webster
Affiliation: CSIRO Agriculture and Food, Cairns

SITE DESCRIPTION

Location

The field site is located at 16°52’43”S 145°41’49”S on the Barron Delta in the Mulgrave sugar region, near Cairns (Figure 58).

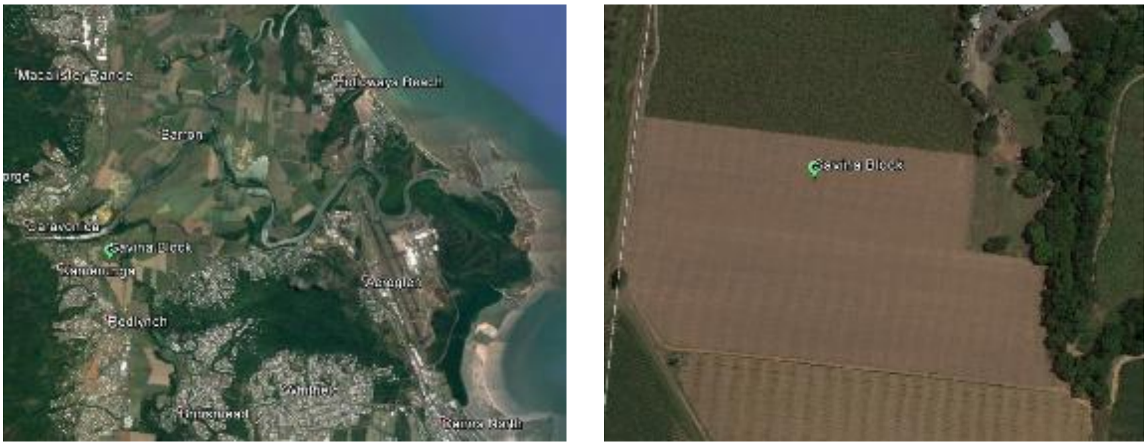

Figure 58. Location of field site

Soil

The soil is a well drained clay soil formed on alluvium, locally referred to as ‘Innisfail series’. Soil samples were taken from the site on 17th November 2016 for soil mineral nitrogen to a depth of 1.8 metres. During sampling roots were observed at 1.7 m. Soil tests from the site show a pH of 5.0, organic carbon of 0.8% with no salinity or sodicity issues (surface testing only).

Block history

The block has good block data available from 1998 (Table 38). This data was used to calculate a paddock unit yield potential of 97 t/ha. The district yield potential is 120 t/ha. From discussions with the farmer he thought the block yield potential would be lower than 97 t/ha given the late ratoon age and the late cutting time, and was happy with an 80 t/ha yield target.

Table 38. History of field trial block. R = ratoon number, RP = Replant, PL = Plant, No data = quality of block records insufficient to be able to assign block yield.

Year	Variety	Class	Harvest	C.C.S	Yield (t/ha)
2000	Q120	2R	June 2000	11.5	71
2001	Q120	3R	July 2001	13.0	68
2002	Q167	RP	Sept 2002	15.1	93
2003	Q167	1R	October 2003	11.5	100
2004	Fallow				
2005	Q200	PL	August 2005	13.7	101
2006	No data				
2007	Q200	2R	August 2007	13.9	115
2008	Q200	3R	Sept 2008	16.0	67
2009	Q200	4R	Sept 2009	15.1	97
2010	Q200	5R	Sept 2010	12.9	90
2011	No data				
2012	No data				
2013	Q208	1R	July 2013	11.1	92
2014	Q208	2R	July 2014	12.5	84
2015	Q208	3R	October 2015	13.5	84
2016	Q208	4R	Nov 2016	13.8	92

EXPERIMENTAL DESIGN 2016/17 TO 2018/19

The site was divided into two separate, but adjacent, experiments. Site one was a yield response experiment and site two was a nitrogen runoff trial.

Yield response experiment

This experiment consisted of 21 small plots each 40 metres long by 4 rows wide (Figure 59). The small plots consist of a 0 N treatment, and 10 rates each of urea and an EEF blend in approximately 20 kg N/ha increments up to 200 kg N/ha (Table 39). The use of multiple rates of fertiliser allows crop response curves to the fertiliser to be made at harvest. Crop response curves allow the optimum rate of fertiliser to be determined after harvest, as opposed to trying to identify the optimum rate prior to fertilising by using either district or block yield potential.

Table 39. Nitrogen rates used in yield response experiment.

2016/17		2017/18		2018/19	
Urea N rate (kg N/ha)	EEF N rate (kg N/ha)	Urea N rate (kg N/ha)	EEF N rate (kg N/ha)	Urea N rate (kg N/ha)	EEF N rate (kg N/ha)
0	0	0	0	0	0
20	20	20	20	20	20
54	51	53	51	51	45
68	65	72	69	63	61
80	76	78	81	82	82
99	94	98	93	111	103
119	113	119	110	125	121
142	135	143	136	160	144
160	152	161	155	183	164
173	164	172	181	208	184
200	190	201	209	183	210

Nitrogen runoff trial

Five ‘strips’ each 6 rows wide and approximately 300 metres long (entire length of the block) were treated with 0 Nitrogen, and two rates of EEF and two rates of urea (Figure 59). The two fertiliser rates were determined by either using the current industry recommended rate (six easy steps) based on a district yield potential (150 kg N/ha recommended) or a modified rate based on a paddock unit yield potential (80 t/ha yield = 115 kg N/ha) (Table 40).

Table 40. Nitrogen rates used in nitrogen runoff trial. DYP = rate determined from district yield potential, PZYP = rate determined from paddock unit yield potential

	Fertiliser	2016/17	2017/18	2018/19
Zero	**-**	0	0	0
DYP	**Urea**	153	150	153
DYP	**EEF**	145	143	149
PZYP	**Urea**	114	115	119
PZYP	**EEF**	109	107	112

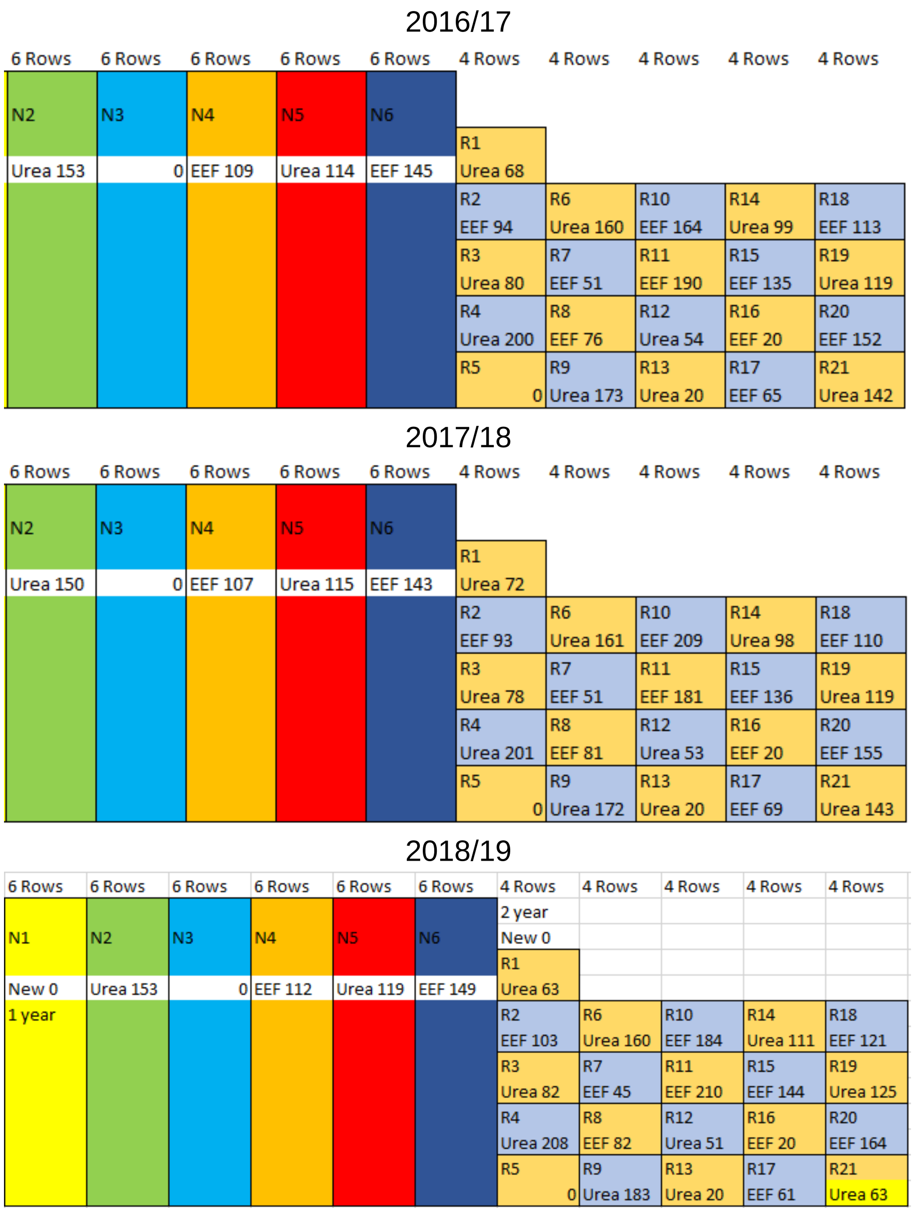

Figure 59: Layout of yield response experiment (R plots) and nitrogen runoff trial (N plots) over each year

SITE IMPLEMENTATION

All treatments were implemented as shown in Figure 2. The 2016 harvest was on 18/11/2016 and fertilizing on 15/12/2016. The 2017 machine harvest was on 16/11/2017 and fertilizing was on 8/12/2017. The 2018 machine harvest was on 16/11/2018 and fertilised on 3/12/2018. The final harvest was on 15/11/2019. In 2016/17 all treatments received 50 kg K/ha as Potash, in 2017/18 and 2018/19 all treatments received 95 kg K/ha as Potash.

Biomass

Prior to machine harvest on 14/11/2017, 14/11/2018 and 10/11/2018 for the 2017, 2018 and 2019 harvests respectively hand cut samples were taken. From the middle two rows of the small plots two 4 metre sections of sugarcane were cut at the soil surface and total biomass from those sections weighed. From each sample between 6 and 10 representative stalks were subsampled and partitioned into stem, green leaf and dead leaf. Green leaf is greater than 50% green and dead leaf greater than 50% necrotic. Each partitioned component was weighed and put through a mulcher. A mulched subsample of each component was taken and weighed, dried at 60ºC, weighed for dry matter calculation and sent to CSBP laboratory for total nitrogen analysis.

From these measurements component dry matter percent was calculated, total dry matter and fresh weight production (kg/ha) and nitrogen uptake (kg/ha).

Yield response

In the small plots crop yield was calculated as the fresh weight of stem per hectare. Yield for both urea and EEF was plotted against nitrogen rate and a mitscherlich function fitted to the data using equation 1:

$$Y = a(1 - e^{(-b(x+c))}) \qquad \text{Equation 1}$$

Where Y = yield, x = nitrogen rate and a, b and c are variables to be fitted by *minimising* the ordinary least squares (sum of square error where the error is the difference between Y estimate and Y observed).

From the fitted yield response curve the optimum nitrogen rate was determined from the rate at which 95% of the maximum yield was estimated.

Nitrogen use efficiency

Nitrogen use efficiency can be determined in a number of ways. A common way the sugarcane industry determined nitrogen use efficiency is to calculate the yield achieved per unit of fertiliser nitrogen (t/kg). Other measures of nitrogen use efficiency can be more meaningful, such as uptake efficiency or apparent nitrogen recovery, which is how much of the applied nitrogen is taken up by the crop. The agronomic efficiency of the crop is calculated from the yield increment attributed to the additional fertiliser applied. Table 41 outlines calculations for nitrogen use efficiency metrics used.

Table 41. Nitrogen use efficiency metric calculations

Metric	Name	Formula	Definitions	Comments
1	Nitrogen Use Efficiency	$NUE = DWb \div Ns$	*DWb* = Dry Weight sugarcane biomass *Nt* = plant total Nitrogen uptake	Indicates how plant turns accumulated N into plant biomass
2	Apparent Nitrogen Use Efficiency	$NUEa = FW \div Ns$	*FW* = Fresh Weight sugarcane yield *Ns* = Nitrogen supply	Indicates increase in yield per unit of applied N
3	Uptake Efficiency	$UpE = Nt \div Ns$	*Nt* = plant total Nitrogen uptake *Ns* = Nitrogen supply	Indicates efficiency of uptake of N into the plant

4	Utilisation Efficiency	$UtE = FW \div Nt$	*FW* = Fresh Weight sugarcane yield *Nt* = plant total Nitrogen uptake	Indicates the fraction of N converted into yield
5	Agronomic Efficiency	$AE = (FWf - FWc) \div Ns$	*FWf* = Fresh Weight sugarcane yield of fertilised treatment *FWc* = Fresh Weight sugarcane yield of unfertilised control *Ns* = Nitrogen supply	Indicates efficiency of converting applied N into yield
6	Apparent Nitrogen Recovery	$AR = (Ntf - Ntc) \div Ns \times 100$	*Ntf* = plant total Nitrogen uptake of fertilised treatment *Ntc* = plant total Nitrogen uptake of unfertilised control *Ns* = Nitrogen supply	Indicates efficiency of capture of N from the soil
7	Nitrogen Surplus	$Nsurp = Nex - Ns$	*Nex* = Nitrogen exported in harvested sugarcane crop *Ns* = Nitrogen supply	Indicates the gap between applied N and N 'used' by the crop

EXPERIMENTAL DESIGN 2019/20

The site that hosted the experiment described above was terminated after the 2019 harvest. The adjacent paddock was used for an experimental program commencing in 2019. The adjacent paddock has the same soil type.

The trial block was divided into thirds and harvested three separate times in 2019 (mid September, October and November harvests). Each harvested area was fertilised one month after harvest with plots of both urea and EEF at recommended and reduced rates (Figure 3). This experiment includes time of harvest (and fertilising) as an independent variable in addition to fertiliser type and rate of the previous experiment. The time of fertilising variable will deliver knowledge of the within season temporal extent of the nitrogen loss reductions benefit EEFs could deliver.

The site was divided into large (150 metre by 3 row) plots where runoff could be measured using instrumentation described below and smaller (1 meter by 6 row) plots for biomass sampling (Figure 60). The site was also instrumented with a weather station and telemetry.

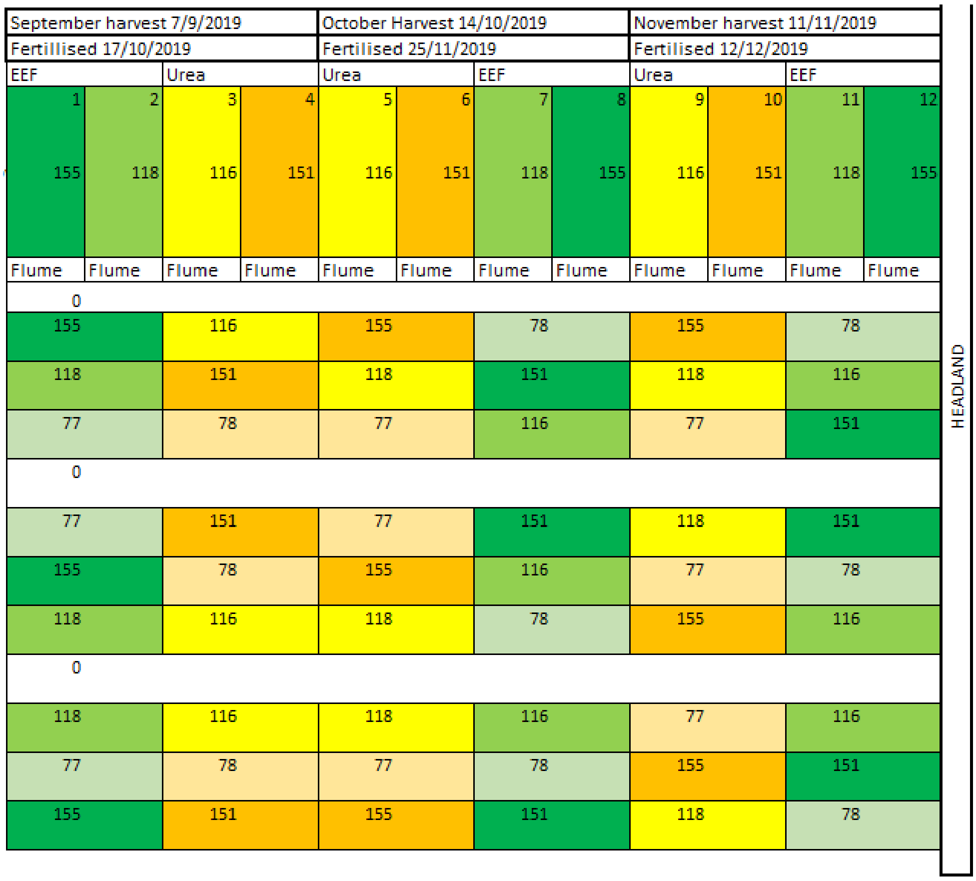

Figure 60. Trial design to determine the in-season temporal extent of the benefit from using EEFs

The experiment was hand harvested the same way as described above on 21/9/2020, 26/10/2020 and 25/11/2020 and nitrogen use efficiency metrics calculated as per Table 41.

Measuring nitrogen losses

Each strip in the nitrogen loss trial were fitted with equipment to measure runoff water volume and take discrete water samples during runoff events. These samples are analysed for nitrogen and losses (load) calculated.

Measuring runoff volume

In the middle of each strip on the downhill side of the block a san dumas flume was installed and bunding installed to direct runoff water from three interrows (or two in 2019/20) through the flume (Figure 61). In the flume water height was measured with an Odyssey water depth pressure sensor on a 10 minute continuous recording interval. Water discharge is calculated from water height using equation 2.

$$Q = 6.35\, W_T^{1.04}\, H_T^{1.5-n} \qquad \text{Equation 2}$$

Water discharge (Q) in cubic feet per second, W_T is flume width in feet, H_T is measured water height in feet, $n = 0.179\, W_T^{0.32}$. Water discharge is converted to litres per second, and then discharge (litres) per 10 minutes. Over the course of a runoff event cumulative discharge is calculated by summing the 10 minute discharges and converted to loss in mm (to compare to rainfall) by dividing by the area that discharges through each flume (in ha) and dividing by 10,000. Percentage runoff is calculated as mm runoff / mm rainfall for each event.

Figure 61. San dumas flume. Rubber bunding is used to direct flow into the flume from between the row mounds. Earth / concrete bunding used to direct water discharge from each adjacent interrow into the interrow with the flume installed approximately 3 metres uphill of the flume. The row profile is approximately 0.2 metres higher than the interrow.

Measuring nitrogen in runoff water

Each flume has a float valve which triggers an auto sampler. ICSO 24 bottle auto samplers are located in trailers near the flumes (Figure 62). When water is in the flume the float valve triggers the auto sampler to sample. Runoff water is sampled from directly down hill from the flume, and a 1.5 litre bottle filled. Discrete water samples are taken on time intervals through the runoff event until all 24 bottles are filled. The time interval is controlled depending on the duration of the anticipated rainfall event to allow sample collection during the rising, peak and falling periods of the runoff event. After each runoff event a sample from each filled bottle is collected for analysis.

Samples of water are frozen until analysis when they are thawed to room temperature, filtered through a 0.45µm filter and analysed for total nitrogen using a persulphate reduction method.

Figure 62. 24 bottle ISCO auto water sampler

Calculating runoff load

The event mean concentration for each runoff event is calculated using equation 3:

$$EMC = \frac{\sum_{i=1}^{n} V_i \ C_i}{\sum_{i=1}^{n} V_i} \qquad \text{Equation 3}$$

Where EMC = Event Mean Concentration, V_i = discharge amount corresponding to sample *i*, C_i = total nitrogen concentration in sample *i*, *i* = sample number, *n* = total number of samples. The EMC is multiplied by the total runoff event discharge volume to give a load in kg N/ha.

RESULTS AND DISCUSSION

Yield response

Fitted yield response curves for fresh weight stem yield of the small plots for each of urea and EEF in the 2016/17, 2017/18 and 2018/19 harvests are presented in Figure 63.

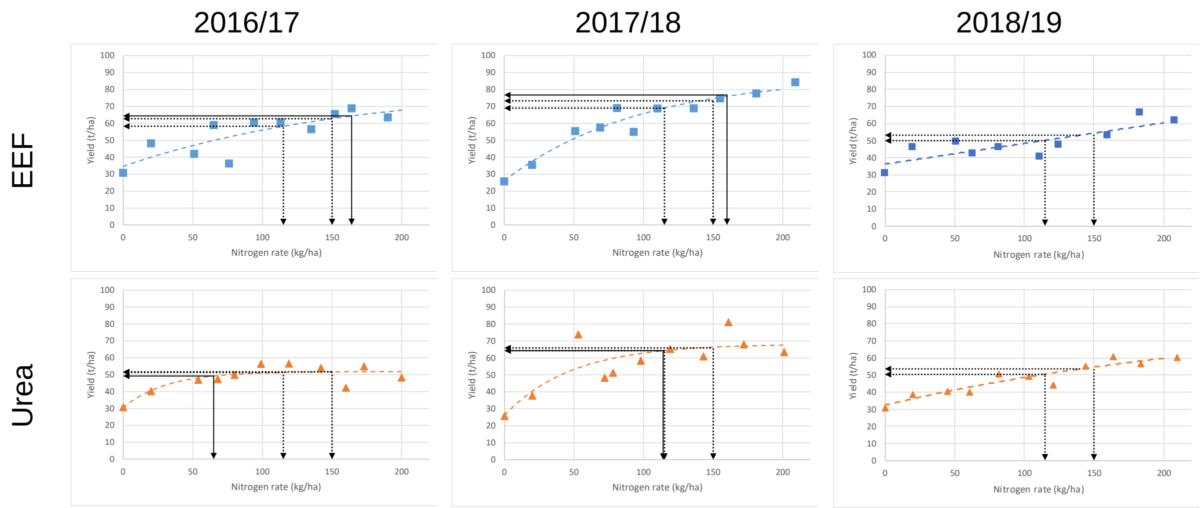

Figure 63. Mitscherlich fitted response curves to fresh weight stem yield (r^2 values are: 2016/17 urea 0.71, 2016/17 EEF 0.66, 2017/18 urea 0.67, 2017/18 EEF 0.93, 2018/19 urea 0.68, 2018/19 EEF 0.88). Solid lines indicate optimum nitrogen rate. Dotted lines indicate recommended nitrogen rates based on district yield potential and paddock unit yield potential

In the first two years the yield response showed a higher yield from using EEF than urea, the final year shows no yield difference between urea and EEF. The urea yield response plateaued much more noticeably than EEF in both years. This resulted in optimum nitrogen rates being higher for EEF than urea in each of the first two years. This result goes against the ‘theory’ of using EEFs which is that response curves have the same maximum, but the optimum nitrogen rate is realised at a lower rate with EEFs.

Figure 6 shows that in two out of three years when EEFs are used at the same rate as urea (at rates greater than about 50 kg N/ha in 2016/17 and greater than 75 kg N/ha in 2017/18), then the yield from using EEFs is greater.

Yield in the 2019/20 year is presented in Figure 64. In the September and November harvests there is an increase in yield from EEF at the lowest (77/78) nitrogen application rate, and no yield difference between EEF or urea at the higher application rates.

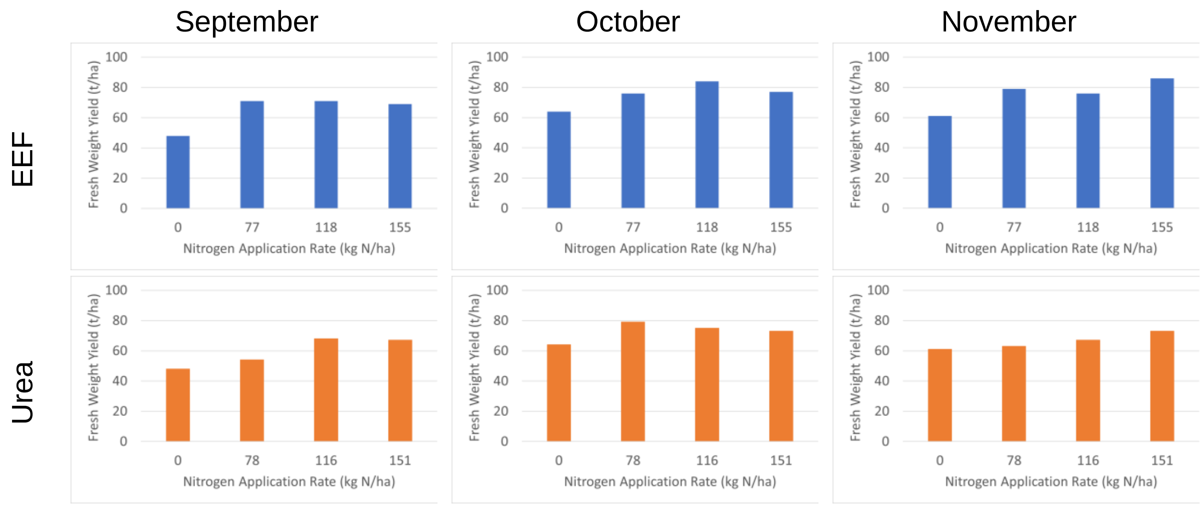

Figure 64. Yield in 2019/20

Nitrogen use efficiency

Nitrogen use efficiency metrics (Table 41) for the 2016/17, 2017/18 and 2018/19 harvests are presented in Figures 7 to 10. The nitrogen use efficiency metrics for the first two harvests (September and October) of the 2019/20 harvest are presented in Figures 11 to 13. At the time of writing (December 2020) the laboratory analysis for the November harvest samples had not been completed.

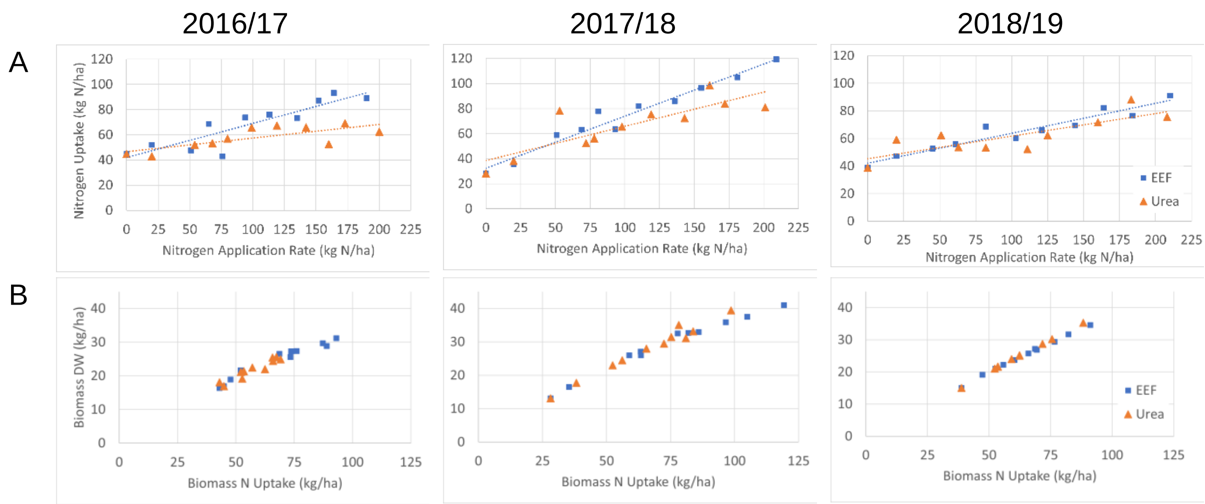

Figure 65. A: Nitrogen uptake; B: Nitrogen Use Efficiency (NUE, metric 1) for 2016/17, 2017/18 and 2018/19 harvest at Freshwater for all rates in small plot experiment for urea and EEF treatments

In all three years nitrogen uptake responded in a positive linear way for all application rates up between 0 and approximately 200 kg N/ha for both urea and EEF. In the first two harvests there was more nitrogen uptake in the EEF crops, and the rate of uptake (slope of the curve) was greater. The amount of nitrogen taken up was similar for both urea and EEF in the final year. Figure 65A also shows that nitrogen uptake in the zero treatments was between 20 and 40 kg N/ha, with this nitrogen derived from soil mineralisation. The basic nitrogen use efficiency metric of dry weight accumulation over total biomass nitrogen uptake shows an increase in biomass as nitrogen uptake increases, and no difference between urea and EEF treatments.

Essentially Figure 65B is showing that once nitrogen is taken up by the crop, it will produce the same amount of biomass whether than nitrogen was derived from urea or EEF. This metric then points to the desire to get nitrogen into the crop, as increased biomass accumulation should follow.

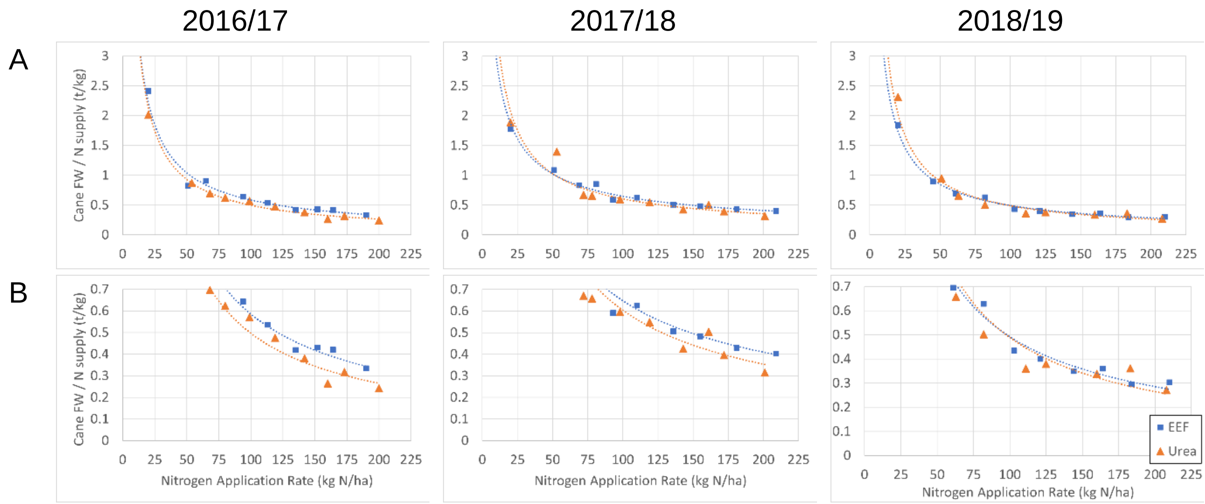

Figure 66. A: Apparent Nitrogen Use Efficiency (NUEa, metric 2) for 2016/17, 2017/18 and 2018/19 harvest at Freshwater for all rates in small plot experiment for urea and EEF treatments; B is a zoom view of A to show NUEa values below 0.7

It is quickly apparent that if optimizing nitrogen use efficiency (using a metric such as NUEa) is the only goal, then *minimising* nitrogen inputs will achieve this goal. It can be misleading to compare different nitrogen application rates using NUEa. To better interpret NUEa it is better to compare values at the same nitrogen application rate for each product. Figure 66 shows that the apparent nitrogen use efficiency when interpreted like this is higher in the first two years using EEF at all nitrogen rates greater than about 75 kg N/ha. In the final year there was no difference between urea and EEF for NUEa.

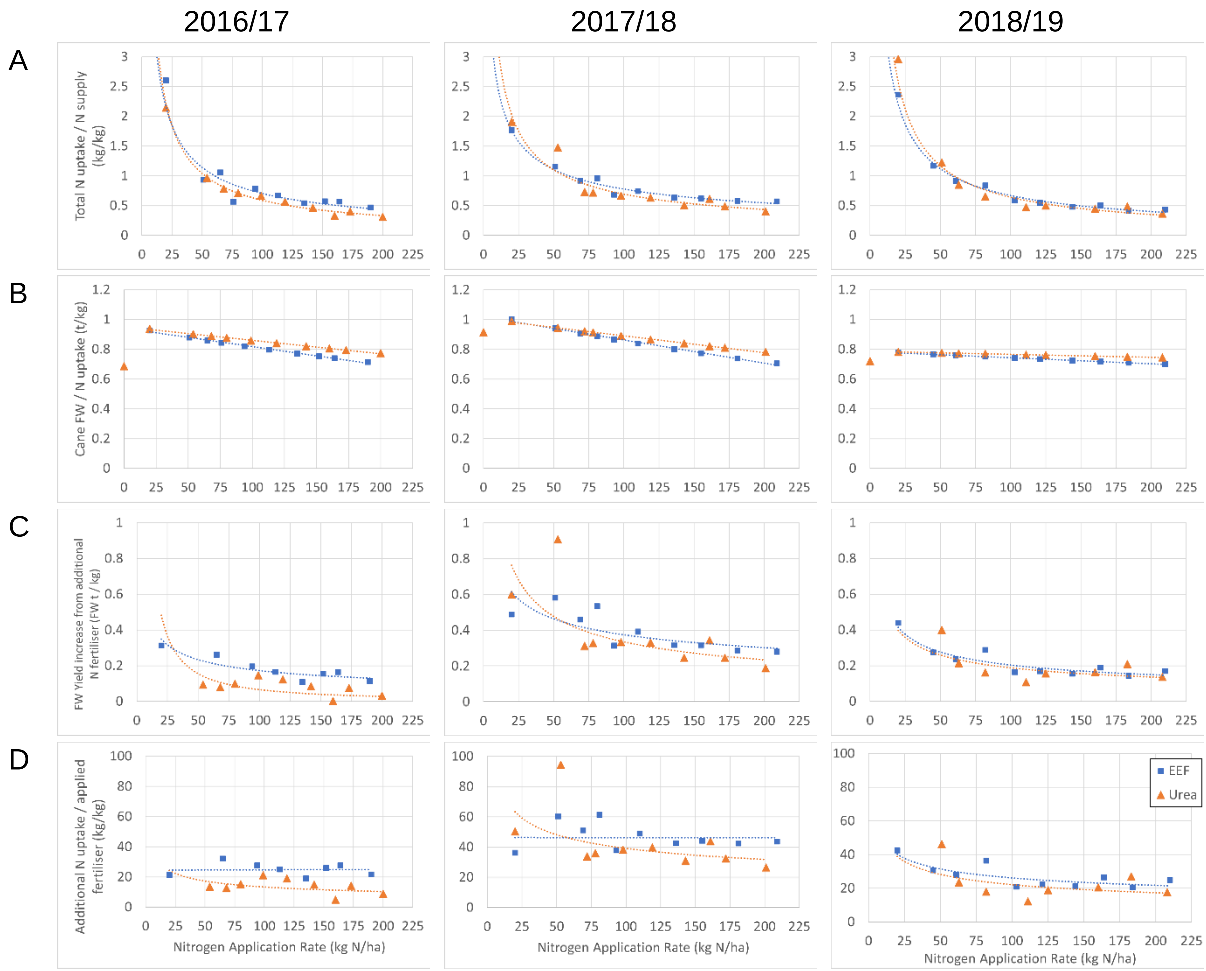

Figure 67. A: Uptake efficiency (UpE, metric 3), B: Utilisation efficiency (UtE, metric 4), C: Agronomic efficiency (AE, metric 5), D: Apparent N recovery (AR, metric 6) for 2016/17, 2017/18 and 2018/19 harvest at Freshwater for all rates in small plot experiment for urea and EEF treatments

The nitrogen uptake efficiency (Figure 67A) is a measure of how much nitrogen is taken up compared with the applied fertiliser. In all three years the UpE is approximately 1 at around a nitrogen application rate of 50 kg N/ha for urea and EEF, which is saying that at the 50 kg N/ha application rate, the crop has taken up about 50 kg N/ha. However, we know from Figure 67A that the crop is able to take up nitrogen at the zero application rate, so not all of the crops nitrogen uptake can be attributed to fertiliser nitrogen. To better represent the nitrogen uptake attributable to fertiliser, the apparent nitrogen recovery (Figure 67D) is used. This is a measure of the percent of nitrogen applied that is getting into the crop. As can be seen these values are low, generally less than 50%. Noticeable, in the first two years the percent of applied EEF that was getting into the crop was higher than urea. We also know from Figure 67A that once nitrogen gets into a crop, it has the same effect on producing biomass, so this explains the higher yields observed in the first two years.

The utilisation efficiency (Figure 67B) and agronomic efficiency (Figure 67C) are measures of how nitrogen that is taken up from fertiliser is converted into cane yield. AE decreases at higher application rates, and again shows that at the same nitrogen rate the EEF fertiliser is more efficiently converted into sugarcane yield than urea.

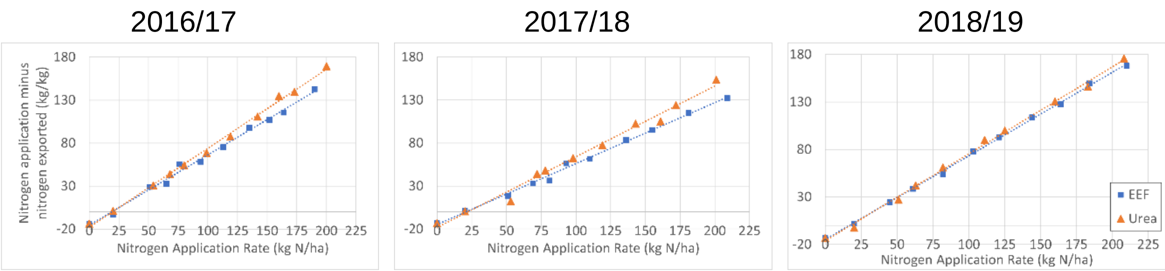

Figure 68. Nitrogen surplus (Nsurp, metric 7) for 2016/17, 2017/18 and 2018/19 harvest at Freshwater for all rates in small plot experiment for urea and EEF treatments

Nitrogen surplus (Figure 68) is the difference between the amount of nitrogen applied, and the amount of nitrogen that leaves the farm in harvested product. At zero and low application rates the nitrogen surplus is negative, indicating the crop is 'mining' nitrogen from the soil. As nitrogen application increases, the Nsurp increases linearly in all 3 years. The Nsurp is higher for urea than EEF, indicating at equal nitrogen application rates the amount of nitrogen getting into the harvested product is greater.

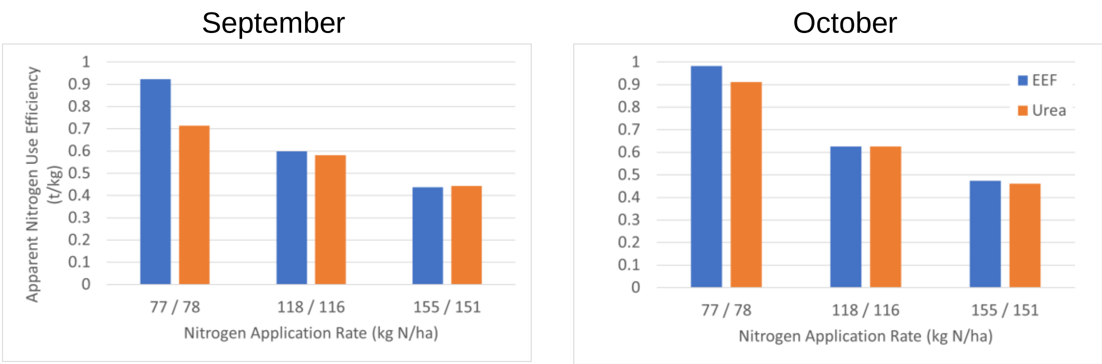

Figure 69. Apparent Nitrogen Use Efficiency (NUEa , metric 2) for harvest in 2019/20 at Freshwater site

As described above with Figure 69 it is only useful to compare NUEa values at the same rate of nitrogen application. The NUEa will decrease with higher application rates. In 2019/20 the NUEa values were very similar between urea and EEF, with higher values for the lowest application rate (77 / 78 kg N/ha).

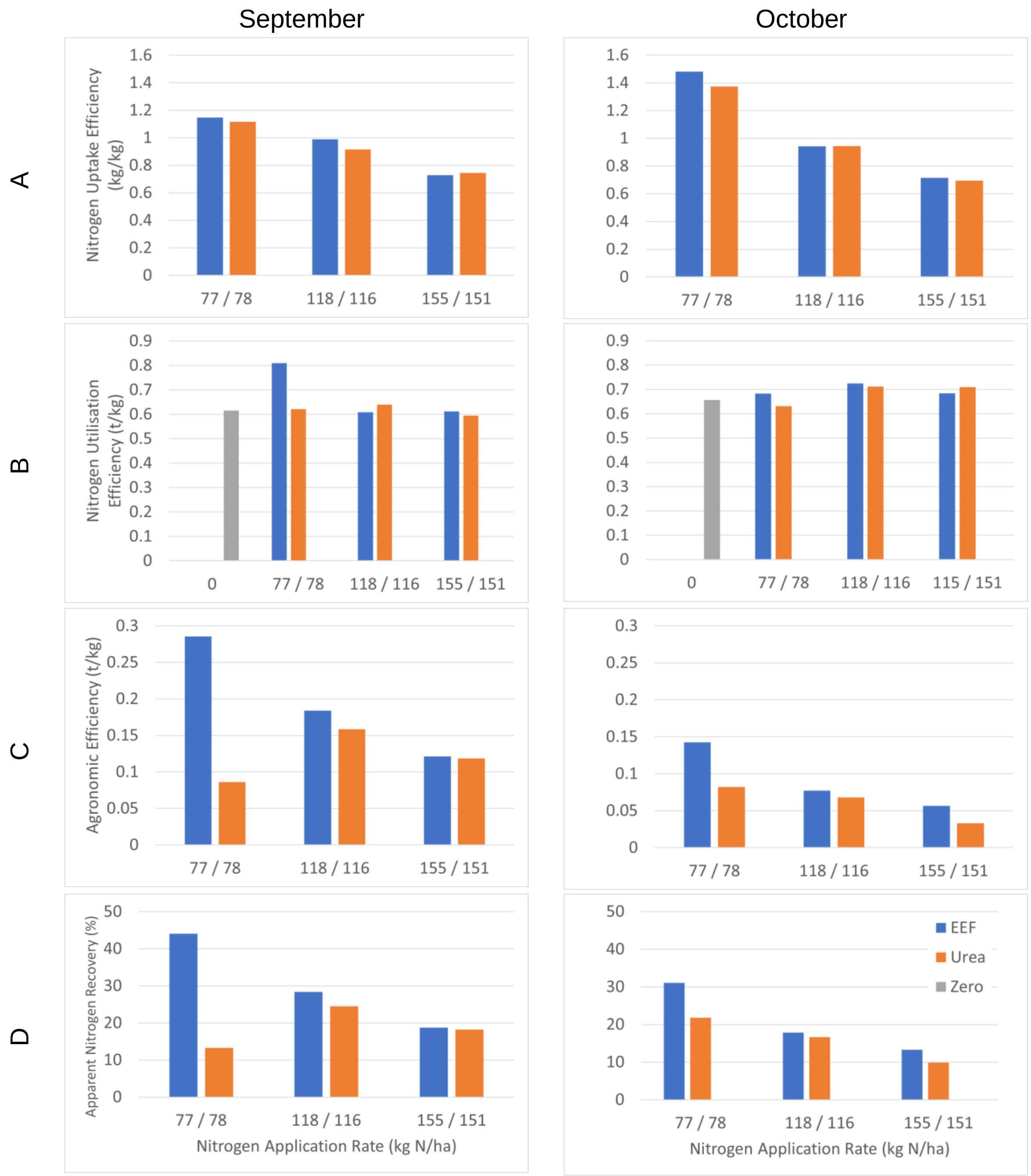

Figure 70. A: Uptake efficiency (UpE, metric 3); B: Utilisation efficiency (UtE, metric 4); C: Agronomic efficiency (AE, metric 5); D: Apparent N recovery (AR, metric 6) for harvest in 2019/20 at Freshwater site

Nitrogen uptake efficiency values (Figure 70A) decrease with increasing application rate, and these values need to be considering in concert with apparent nitrogen recovery (Figure 70D). The AR values in Figure 70D show that as the nitrogen application rate increases, the percent of that applied nitrogen is decreasing, and that is true for both October and November application dates. There is a suggestion that a higher percent of nitrogen is able to be taken up by the crop when EEF is used compared to urea. The agronomic efficiency (Figure 70C) is a measure of the tonnes of yield that is produced from additional nitrogen application. There is also a suggestion EEF is better able to produce yield compared to urea, albeit the values show the low efficiency both forms of fertiliser have in converting nitrogen application to yield.

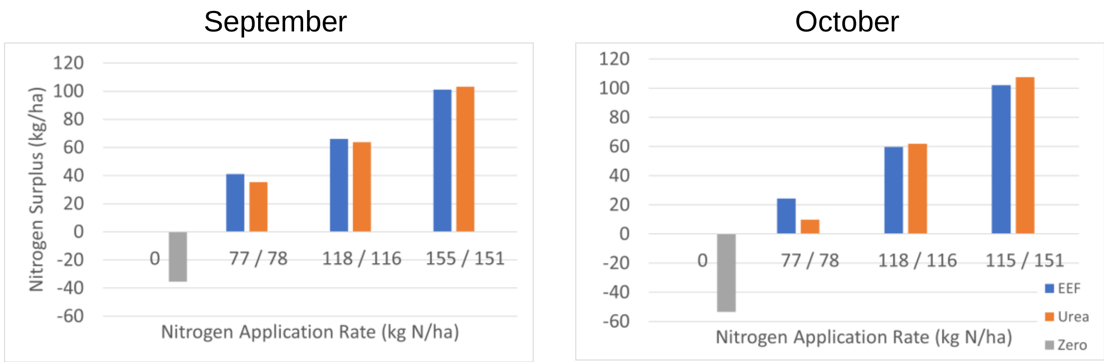

Figure 71. Nitrogen Surplus (Nsurp, metric 7) for harvest in 2019/20 at Freshwater site

Nitrogen surplus values are similar between urea and EEF fertiliser in both the September and October harvest dates (October and November fertilising respectively). As expected these values increase with application rate.

Nitrogen losses

Total recorded nitrogen losses are presented in Table 42.

Table 42: Total nitrogen losses (kg N/ha) from no fertiliser, EEF and urea

2016/17		2017/18		2018/19	
Zero	7.5	Zero	6.0	Zero	7.2
EEF 109 kg N/ha	9.2	EEF 107 kg N/ha	9.0	EEF 112 kg N/ha	9.9
EEF 145 kg N/ha	9.9	EEF 143 kg N/ha	10.6	EEF 149 kg N/ha	13.0
Urea 114 kg N/ha	12.4	Urea 115 kg N/ha	6.0	Urea 119 kg N/ha	12.5
Urea 153 kg N/ha	13.3	Urea 150 kg N/ha	13.4	Urea 153 kg N/ha	15.2

The values presented in Table 42 are not total losses experienced over the entire year, as sampling was impossible in some events due to runoff water ‘backing up’ so the flumes did not work completely. In 2018 this backing up occurred on two occasions. On the first occasion the first half of the event was sampled, and at the time backing up started, nitrogen concentrations were very low, so nitrogen losses would be expected to be very low (and similar between treatments). The second event occurred when heavy rain in the catchment flooded the area, after a number of event runoffs were captured. Again the losses would expected to be low and not different between treatments.

The data in Table 42 shows a consistent trend that when EEF is used in place of urea at both application rates, there is a reduction in nitrogen losses in surface water. The lower application rate in 2017/18 is the only set that does not show this trend. The data also shows nitrogen losses are higher with higher application rates for both urea and EEF.

Table 43. Total Nitrogen losses (kg N/ha) in 2019/20

Fertiliser	Nitrogen Application Rate (kg N/ha)	September Harvest	October Harvest	November Harvest
EEF	118	2.4	1.4	2.0
	155	2.9	3.2	
Urea	116	2.4		2.0
	151	2.8	4.2	3.4

The 2019/20 ‘wet season’ was a particularly ‘dry’ season, with only 8 runoff events recorded at the site. Four of these events occurred over the final week of January, and 3 in the final week of February. Generally, when multiple events occur in quick succession after a period (3 to 4 weeks) with no runoff, the first event shows little nitrogen runoff, the second event has higher runoff, and subsequent events have little nitrogen runoff. There were only 3 runoff events during 2019/20 where any nitrogen runoff of note was recorded, and totals over the whole year were much lower than previous years (Table 43). The November harvest values represent a repeat of the 2016/17 to 2018/19 experiment, where the crop was harvested in November and fertilised in December where there was a clear observation that EEF reduced nitrogen losses in surface water compared to urea (Table 43). The 2019/20 experiment was designed to test whether earlier harvest / fertilizing times showed similar trend. This information will be valuable to understand the temporal extent where EEF can provide a nitrogen loss reduction compared to urea.

The data from 2019/20 shows low nitrogen losses compared to the previous three seasons. Missing data is from equipment failures or lack of samples in at least one of the key three runoff events, meaning the data would be unevenly skewed. The September harvest data appears to show no difference in nitrogen losses between urea and EEF, and possibly only a slight reduction from reduced application rates. The October and November harvests show small or no reductions in nitrogen losses between comparable rates of urea and EEF. Due to the nature of the season, this nitrogen runoff data is inconclusive.

APPENDIX 6: SUMMARY – IMPACT OF APPLYING ENHANCED EFFICIENCY FERTILISERS IN CONCENTRATED BANDS

PHD PROGRAM - Banding studies
Candidate - Chelsea Janke. Degree conferred in April 2020

INTRODUCTION

The efficient use of fertiliser-nitrogen (N) is a major global challenge for intensive agricultural systems. A suite of enhanced efficiency fertilisers (EEFs) have been developed in response to poor N use efficiency (NUE) in agriculture, but mechanistic understanding to support their effective utilization is not well developed. The vast majority of research to date has focused on spread/broadcast applications with or without incorporation, rather than the banded applications typically used in the Australian sugar industry. Banding N-fertiliser creates a vastly different biochemical environment to that in which these products have been designed and tested. Differences in soil-fertiliser reactions due to application method (i.e., banding vs broadcast / incorporated) will potentially influence the efficacy of EEFs that will have consequences for (i) delivery of effective agronomic advice and (ii) mitigation of off-farm N loss. Furthermore, the influence of tropical and subtropical conditions on EEF efficacy is not well characterized. Thus, application of EEFs in cropping systems utilizing banded application and / or in (sub) tropical environments is occurring under conditions for which there is little guidance on effective use strategies.

This objective of this PhD program was to develop a mechanistic understanding of soil-fertiliser reactions arising from banded EEFs that will underpin agronomic advice supporting effective utilization in the sugarcane industry. Effective utilization of EEFs in agriculture will address the competing demands of (i) improving NUE to boost agricultural production and (ii) reducing the impact of off-site loss of N to natural environments.

MATERIALS AND METHODS

1. Fertosphere chemistry – sealed containers

The objective of this study was to determine the effectiveness of EEF technologies within the fertosphere (soil within 2.5 cm of the fertiliser band) in a range of soils with a history of sugarcane production. Urea and EEF granules were applied to achieve fertosphere conditions that were consistent with an in-band concentration (g N m^{-1} of fertiliser band) equivalent to that experienced when 150 kg N ha^{-1} is applied in the field in bands 1.8 m apart. This is typical of application practices in the Queensland sugar industry.

Measurements consisted of: (i) establishing the key chemical effects and N-transformation activity within a urea-band, and (ii) contrasting these findings with nitrification inhibitor (NI) coated urea and a controlled release polymer coated urea (PCU). The incubations were conducted under static conditions over a 112- day incubation period, to cover the reported release period of the PCU product. Containers were sealed, so there was no interaction between the fertosphere soil and unfertilised soil outside the fertosphere, as would occur in a field situation.

2. Diffusion of N species and inhibitors outwards from the fertosphere

The aim of these studies was to (i) determine the transformation and distribution of N from EEF-fertiliser bands; and (ii) identify the underlying soil biochemistry that drives these changes and therefore the impact of soil type on banded EEF efficacy. The incubation was conducted in round incubation pots (225 mm diameter PVC end-caps), using sugarcane soils with contrasting physical and chemical properties (a sandy Dermosol and a heavy clay Vertosol). Fertiliser N treatments were applied into the centre of the pot in a vertical band/column at a rate equivalent to the in-band concentration of fertiliser N applied at 150 kg N ha^{-1} in bands spaced 1.8 m apart. Cotton wicks were inserted vertically in the fertosphere, and in an offset pattern outwards from the fertiliser band to the extremities of the pots at regularly spaced intervals. Soils were kept moist at field capacity over incubation periods that ranged from 16 days (urea, and urea-based EEF's with urease of nitrification inhibitors) to 35 days (urea and PCUs), with unfertilised soils included in each assay. Destructive sampling of replicated pots of each treatment was conducted at regular intervals during the incubations. Soil in each pot was collected from a 2 cm diameter central core (designated the '0 cm' position), and then in increments moving outwards from that central core designated as the 2 cm, 4 cm, 6 cm, 8 cm and 10 cm samples. Soils were used to determine mineral N using standard methods.

Wicks were used to recover representative soil solution at different distances for the fertiliser bands, and were analysed for urea-N and also for the presence of the urease or nitrification inhibitors used in each product.

3. Three dimensional movement of N species in the field

The field study extended the findings of the two-dimensional diffusion study by investigating banded EEF dynamics in three-dimensions (i.e., vertical and horizontal distribution of N) and with the influence of water movement through fertiliser bands. The field experiment was conducted on a Vertosol soil at University of Queensland, Gatton Campus, over the 2017/18 summer season. Fertiliser treatments were applied in bands at 12.5cm depth, with each treatment replicated four times. In-band concentrations were chosen to be representative of fertiliser N rates in use in the sugarcane, grains and irrigated cotton industries.

Treatments included an unfertilised treatment, and application rates of 50, 100 and 150 kg N ha^{-1} applied as urea, or urea with the NI DMPP (ENTEC®). In addition, other EEF products tested included urea with a blend of DMPP and succinic acid (DMPSA, Eurochem Pty. Ltd), urea with the urease inhibitor NBPT (Green Urea NV®) and the PCU, Agromaster Tropical®. After fertiliser application, the distribution of urea-N and mineral N were monitored over a 71 day period, with samplings based on likely duration of EEF efficacy and in response to significant rainfall or irrigation events. Plots were maintained free of plants during this period.
At sampling events, soil monoliths were collected at right angles to the fertiliser band and dissected into zones that allowed quantitation of vertical (both above and below the fertiliser band) and lateral movement of N out of the fertiliser band, in response to both diffusion and mass flow. Samples were collected over a 30 cm vertical distance (12.5 cm above and below a fertosphere), and out to a distance of 12.5 cm horizontally. At all sampling times, chemical conditions in and around the fertiliser band were monitored, along with urea-N and mineral N species.

4. Fate of nitrification inhibitors in soil

The aim of this study was to determine the (i) soil type effects on DMPP sorption; (ii) sorption kinetics over time; (iii) reasons for inhibitor loss from soil solution (sorption or microbial degradation); (iv) the influence of urea on DMPP sorption and persistence; and (v) the diffusive mobility of DMPP by comparison of distribution coefficients (Ks) in soils of differing pH and clay mineralogy.

Three soils of varying physicochemical properties were tested in this experiment (Vertosol, Dermosol, and Ferrosol) with two of the soils (Vertosol and Dermosol) used in earlier diffusion studies. One set of the three soils was γ-irradiated to eliminate microbial activity. A range of inhibitor concentrations based on distance from fertosphere were applied in each soil type, and in each case with or without application of urea. The experimental containers were incubated under conditions similar to those of the diffusion studies (25°C, with the soil moisture at field capacity). The experiment was replicated on a smaller scale (i.e., smaller amounts of soil and inhibitor, but applied at the same concentrations) for measurement of pH and EC.

Individual, duplicate reps of containers were destructively sampled at 1 and 7 days after incubation. Analysis of CO_2 evolution to check microbial activity was conducted by sealing containers and connecting to a respirometer. Once completed, two sub-samples were taken from each incubation pot. For the first sub-sample, ultra-pure DI water was used to extract DMPP in soil solution from a soil saturation paste (1:1), with samples analysed using high performance liquid chromatography (HPLC). The second sub-sample was extracted (1:5) with 2M KCl and analysed for mineral N. Measurements of pH and EC were taken in the smaller containers, using a 1:5 soil:water ratio.

5. Diffusion study of EEF blends in fertiliser bands

This study was conducted to explore the underlying mechanisms that determine behaviour of blended fertiliser reactions in soils, to provide a mechanistic understanding that would help explain the responses to blended fertiliser treatments in the larger field program in NESP 2.1.8 and 5.1.1. An additional treatment, consisting of a commercially available biodegradable controlled-release fertiliser (CRF), was included as a preliminary test of newer fertiliser technology emerging due to concerns about persistence of polymers in the environment.

The incubation was conducted in round incubation pots (225 mm diameter PVC end-caps), using sugarcane soils with contrasting physical and chemical properties (a sandy Dermosol and a heavy clay Vertosol). Fertiliser N treatments were applied into the centre of the pot in a vertical band/column at a rate equivalent to the in-band concentration of fertiliser N applied at 150 kg N ha^{-1} in bands spaced 1.8 m apart. Soils were kept moist at field capacity over an incubation period of 60 days with treatments including, (i) urea; (ii) DMPP-coated urea (ENTEC®); (iii) 90-day release PCU (Agromaster Tropical®); (iv) 80-day biodegradable CRF (Kingenta Plant Oil Coated Urea [POCU]); (v) 1:2 fertiliser blend of DMPP-urea and PCU (1:2 DMPP-PCU); and (vi) 2:1 fertiliser blend of DMPP-urea and PCU (2:1 DMPP-PCU).

Destructive sampling of replicated pots of each treatment was conducted at regular intervals (10, 35, 60 days) during the incubation. Intact granules in the CRF treatments (i.e., PCU, POCU, PCU blends) were collected and analysed for total N to determine urea-N retention over time. Soil in each pot was collected from a 2 cm diameter central core (designated the ‘0 cm’ position), and then in increments moving outwards from that central core designated as the 2 cm, 4 cm, 6 cm, 8 cm and 10 cm samples. Soils were used to determine mineral N using standard methods.

SYNOPSIS OF RESULTS AND KEY FINDINGS

The key findings from the laboratory studies are presented as a series of extracts from the abstracts of technical manuscripts either already published (Appendix B) or currently in review. We have not presented any data in tables or figures, but readers are referred to the full manuscripts which will be uploaded into e-Atlas as they are published.

1. Initial fertosphere studies in sealed systems

A 112-day incubation experiment was conducted with the EEFs band-applied in three contrasting soils with a history of sugarcane production. In standard urea and NI-urea treated soils, the pH within the fertosphere significantly increased to a maximum of ~pH 9.2–9.3. Alkaline conditions and high ammonium concentrations promoted elevated aqueous ammonia concentrations, resulting in complete nitrification inhibition. The PCU granules released ~40% of total urea-N content within 14 days, followed by significantly slower release rates for the remainder. The initial rapid urea-N release was attributed to damaged polymer coats, while the close proximity of neighbouring granules within the band may have contributed to the slow subsequent release phase through reduced concentration gradients that restricted diffusion from granules. Variation between soils suggests that soil properties such as clay content and pH buffer capacity may influence urea hydrolysis, but not nitrification. These results suggest that both NI and controlled-release technology may not have the expected impacts on N transformations and availability when applied in a concentrated band.

2. Diffusion of N species and inhibitors outwards from the fertosphere

Inhibitors

In a 16-day laboratory incubation, the efficacy of the nitrification inhibitor (NI), 3,4-dimethylpyrazole phosphate (DMPP) and the urease inhibitor (UI), N-(n-butyl) thiophosphoric triamide (NBPT) were investigated by incubating two commercially available urea-based products containing these additives in bands at concentrations equivalent to 150 kg N ha^{-1} (row spacing 1.8 m) in contrasting soil types. Products were assessed relative to a band of granular urea applied at the same rate.

The urea band produced substantial increases in soil pH, EC, and aqueous NH_3 concentration which influenced ureolytic activity and nitrification within the fertosphere and surrounding soil for both soil types. However, key soil physicochemical factors including cation exchange capacity (CEC), impedance (to diffusion) and pH buffering capacity (pHBC) influenced the size and persistence of the impacted zone and resulted in substantial soil-type variation.

The inclusion of DMPP in the urea band did not provide any inhibitory benefits beyond those observed from urea alone, except when the inhibitor was able to diffuse beyond the zone affected by urea-N hydrolysis, because severe inhibition of nitrification was already occurring. The benefit of the NI was observed in the soil with higher clay, organic matter and pHBC, which restricted the size of the zone in which ureolytic-induced chemical changes and resulting nitrification inhibition occurred. In contrast, the urease inhibitor NBPT provided temporary benefits by slowing the rapid rise in pH, EC and aqueous NH_3 observed in standard urea bands, but effects were short-lived (*ca*. 9 days) in both soils. The benefits of NI and UI technology are likely to vary considerably between soils and application methods when compared to a standard urea band, and these studies are providing a physicochemical approach to determining where and when the benefit of 'stabilising' EEF technology may be realised.

Polymer-coated urea
Two additional experiments over 35 and 91-day incubation periods compared the N dynamics of a urea band against a band of PCU granules, with the focus on N release from the band and its subsequent diffusion. The same contrasting soil types were used as in the inhibitor studies. In the shorter duration study, PCU granules provided a sustained release of urea-N to the soil solution compared to standard urea, with the lower urea-N concentrations limiting the development of the toxic conditions associated with rapid urea hydrolysis. Differences were observed between soil types, but these were relatively small. The relatively mild fertosphere conditions for the PCU (compared to standard urea) resulted in relatively greater proportions of PCU-derived mineral N being oxidised to nitrate, potentially increasing N-loss risk.

In the 91-day incubation, the close proximity of PCU granules to each other in a band restricted the diffusion-driven release of urea-N from the granules relative to that when granules were mixed through a Dermosol. This supports earlier hypotheses of fertiliser banding impacting N release dynamics, slowing N release from PCU and impacting the availability of N for crop uptake. Soil moisture content and mass flow are therefore likely to be strong drivers of N release from bands of PCU which rely on formation of strong concentration gradients for effective release.

3. Three dimensional movement of N species in the field
This study took a mechanistic approached to investigating the potential of banded nitrification inhibitors (NIs), a urease inhibitor (UI) and a controlled release polymer-coated urea (PCU) for improving NUE under field conditions. A 71-day field trial was conducted at Gatton, Australia, with fertiliser treatments banded at rates of 50, 100, 150 kg N ha^{-1} at a band spacing of 1.8 m. Excavation of soil profile cross sections allowed quantification of urea- and mineral N species in the fertosphere and surrounding soil at set sampling intervals.

The addition of NIs extended the inhibition observed in a standard urea band for up to 50 days longer than banded urea, although the duration of NI-conferred inhibition was dependant on the rate of NI-urea application. The UI preserved urea-N at a concentration which was 16-fold higher *cf*. standard urea over 7 days, but no urea-N was detected after 21 days. This suggests that the NUE benefits of UIs are transient when applied in sub-surface bands. Slow release of urea-N from banded PCU resulted in lower concentrations of N in the soil solution. This reduced N dispersal by *ca*. 50 mm *cf*. urea, resulting in a N-enriched zone which was considerably smaller. Relatively benign chemical conditions around PCU bands enabled rates of nitrification (NH_4–N:NO_3–N ratio of 46%) which were similar to urea. Collectively, these results demonstrate the relative efficacy and risks of the different EEF technologies, when applied in fertiliser bands. This knowledge supports the effective utilization of band-applied EEFs for improved NUE in agricultural systems.

4. Fate of nitrification inhibitors in soil
A 7-day incubation of the NI DMPP applied at a range of concentrations was conducted in three soils of varying physicochemical properties. A separate set of soils was sterilized by

gamma radiation in order to determine the contribution of microbial digestion to inhibitor loss. The impact of urea on the fate of DMPP in soil was also investigated by either including or excluding granular urea in incubations.

Soil characteristics had a significant effect on the fate of DMPP in solution. A high cation exchange capacity (CEC) resulted in rapid sorption of DMPP to soil matrix with little desorption over 7 days after application. Soil with a variable charge demonstrated increased sorption of DMPP to the soil matrix when urea was applied as a result to the increased alkalinity in response to the ureolytic process. Soils with little matrix-DMPP interaction (i.e., low clay content, low CEC, not variable charge) and low microbial activity may allow DMPP to persist in soil solution at higher concentrations for longer periods.

Collectively, these findings suggest efficacy of DMPP will vary considerably with soils and co-application of other constituents (i.e., urea) needs to be considered with respect to soil characteristics.

5. Diffusion study of EEF blends in fertiliser bands

In a 60-day laboratory incubation, the efficacy of blended DMPP-urea and PCU at varying ratios (1:2, 2:1) and a commercially available biodegradable CRF (POCU) were investigated by incubating in two soils of differing physicochemical characteristics (a Vertosol and a Dermosol). These products were assessed relative to bands of pure granular urea, DMPP-urea, and PCU, with all N-fertilisers applied at in bands at concentrations equivalent to 150 kg N ha^{-1} (row spacing 1.8 m).

Banded blends of DMPP-urea and PCU typically resulted in N concentrations and distribution that were intermediate to that of pure DMPP-urea and pure PCU, within each soil. However, the coarse texture and poor chemical buffering (i.e., low CEC and pHBC) of the Dermosol meant there was minimal differences in NO_3-N formation between treatments in that soil. This suggests there is little benefit to the use of EEFs in either blends or as pure applications for regulation of NO_3-N loss pathways in soils of high permeability. In contrast, the high clay content and CEC of the Vertosol reduced the impedance of solutes in solution and contributed to a significant inhibitory effect of DMPP on nitrification. This reduced overall NO_3-N production in both pure and blended DMPP-urea treatments *cf*. to standard urea, with efficacy of fertiliser treatments in the order of: DMPP-urea-PCU blends (higher ratio of PCU may offer small but insignificant benefit) > DMPP-urea = PCU > urea.

When compared to PCU, POCU may initially release more N as a result of a higher prevalence of ‘burst’ granules. However, the overall dynamics and proportions of N in soil solution were similar to that of PCU, suggesting this technology may be a suitable option for managing the competing requirements of (i) a predictable N supply and (ii) mitigating polymer persistence in the environment.

The results provide a mechanistic understanding of fertiliser-blend dynamics which may be used to predict and / or assist in interpretations of EEF-blend efficacy in the field. Further, preliminary evidence has been provided for the suitability of biodegradable CRFs to replace existing PCU CRFs in order to address concerns of polymer persistence in the environment.

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