Rural R&D for Profit Program

More Profit from Nitrogen

RRDP1718 (June 2016 – May 2020)

Smart Blending of Enhanced Efficiency Fertilisers to Maximise Sugarcane Profitability

Final Technical Report

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Table of Contents

List of tables

List of figures

Abbreviations and acronyms

6ES: Six Easy Steps, or recommended N application rate based on the Six Easy Steps guidelines

CCS: Commercial cane sugar content in cane stalks

CRF: Controlled-release fertiliser

DAF: Days after fertiliser application

DAH: Days after harvest of the previous crop

DMPP: 3,4-Dimethylpyrazole phosphate (a nitrification inhibitor)

EEF: Enhanced-efficiency fertiliser

FNR: Fertiliser nitrogen recovery (%)

N: Nitrogen

N_2O: Nitrous oxide

NH_4^+: Ammonium

NI: Nitrification inhibitor

NI+U: Nitrification inhibitor-coated urea

NO_3^-: Nitrate

NUE: Nitrogen use efficiency

PCU: Polymer-coated urea

SD: Standard deviation

Executive summary

Australian sugarcane farms receive about 60,000 tonnes of fertiliser nitrogen (N) each year. Nonetheless, only 35-70% of the applied N can be used by the crops or be retained in soil, with the remaining lost into deep ground, air and/or waterways. Nitrogenous fertiliser use on cane farms is the main source of anthropogenic dissolved inorganic N entering into the Great Barrier Reef waters, which poses a great threat to the natural balance of the reef ecosystems. Effective and efficient N management techniques are required to improve farming profitability whilst minimising the environmental impacts.

There has been increasing interest in Enhanced-Efficiency Fertilisers (EEFs) as a management strategy to improve fertiliser N use efficiency. For example, polymer-coated urea (PCU) can control N release after application into soil, thereby potentially better matching fertiliser N supply with plant N uptake. Another type of EEF is nitrification inhibitor-impregnated or -coated urea (NI+U). Nitrification inhibitors can reduce the accumulation of nitrate, which is susceptible to losses through leaching, runoff and/or denitrification. Numerous research trials have demonstrated that EEFs can improve fertiliser N use efficiency, reduce N loss and increase crop yield or maintain productivity at lower N application rates in various cropping systems worldwide including Australian sugarcane farms. However, EEFs are generally $120-600/t more expensive than normal urea and their agronomic and environmental benefits vary with soil, crop, weather and farming system management practices. The higher costs and efficacy variability are the main inhibitors to the adoption of EEFs.

Jointly funded by the Department of Agriculture, Water and the Environment, Sugar Research Australia, Queensland Government, and industry and research partners, this project aimed to: (1) characterise PCU N release dynamics in relation to crop N uptake and identify the most desirable PCU formulation for enhanced synchronisation between N supply and crop N uptake; (2) assess the potential benefits of blending PCU with conventional urea as a means to improve N use efficiency and profitability; (3) investigate if use of NI+U or PCU blend could decrease nitrate leaching; and (4) develop a decision support tool to assist with product selection and use.

Six field trials were established in major sugarcane growing regions (Bundaberg, Mackay, Ingham, Tully and Innisfail) in late 2016 and continued at the same sites for three cropping seasons until late 2019. Twelve N fertiliser management practices including different fertiliser formulations, blending ratios and application rates were included in each trial. The dynamics of N release from different PCU fertilisers and N uptake by crops were measured to help identify the most desirable PCU formulation to match N supply with crop demand. Soil mineral N dynamics and movement into deep layers were also monitored. Cane and sugar yields were measured at harvest, followed by determination of plant N uptake and economic analyses, in support of the above project objectives.

Nitrogen accumulation in sugarcane crops generally followed sigmoidal dynamics. The crop N uptake rates were low during the first 50-60 days after harvest (DAH) of the previous crop, peaked approximately from 50 to 200 DAH and declined to low levels afterwards. Therefore, it is important to ensure sufficient N supply to the crops during the high N-demanding period between approximately 50 to 200 DAH.

Nitrogen release dynamics from PCU fertilisers applied from late September to December did not vary considerably between the different sites. Thus, N release from a PCU product was controlled primarily by time and can be described accurately with a single model across the regions studied.

Among the four PCU fertilisers tested, the N release rate decreased in the order: Meister-15® (Yates) = Agromaster Standard® > 2018 Agromaster Tropical® with 44% N > 2017 Agromaster Tropical® with 41% N. A PCU product with a N release rate between the latter two products would be desirable to better synchronise fertiliser N supply with crop N uptake in these farming systems.

The EEFs appeared to offer considerable environmental benefits. The NI+U (ENTEC®) increased the proportion of soil mineral N as ammonium (a more stable form) compared to normal urea in nitrifying soils for about 1-1.5 months, which was in line with previous findings that the NI+U could significantly reduce nitrous oxide emissions from sugarcane cropping systems. Following urea or NI+U application, soil mineral N contents in the 0-20 cm depth increased immediately but declined to low levels in most circumstances within 2.5-3 months, attributable to N movement and perhaps immobilisation in soil and loss into the environment in addition to crop N uptake. PCU and urea blends consistently maintained higher mineral N contents in the 0-20 cm soil during the mid to late season compared to normal urea and NI+U. Substantial downward movement of nitrate N into deep soil occurred at most sites following high rainfall events, particularly in the urea or NI+U treatments. This indicated that PCU can effectively reduce the risk of nitrate leaching during the first 2-3 months after fertiliser application, particularly for late harvested crops in the wet tropics.

Responses of cane and sugar yield to EEFs, compared to normal urea, varied substantially at different sites and in different years, with statistically significant yield increases achieved only occasionally. Likewise, reducing urea application rate from the recommended rates (based on the Six Easy Steps guidelines) by 25% or 40% did not lead to significant yield loss, apart from in one out of the eighteen trials. Increasing urea application from the recommended rates by 25% or 40% resulted in significant yield increase only in two of the eighteen trials. The lack of yield response to changes in fertiliser formulations and application rates could be due to: (1) crop growth not being restricted by N availability in soil or following fertiliser N application at ≥ 75% of the recommended rate; (2) adverse conditions (e.g., waterlogging, drought and lodging in 8 out of the 18 field trials) limiting the crop yield responses to variation in N management practices; (3) modest N demand by crops during the middle to late season; (4) the N moved to the deep soil layers in the normal urea treatments still being accessible by the crop roots (i.e., not completely lost); and (5) high spatial variability.

The decision on fertiliser selection depends on many factors, including the choice between the environmental and economic benefits. In terms of N supply and demand, use of PCU by itself should be able to meet crop N requirements during the early part of the cropping season. Thus, the benefit of blending with urea centres on cost saving, rather than improved N supply. The optimum blending ratio of PCU to urea needs to be assessed by considering N loss risks, soil N availability, the PCU N release dynamics and cost. For paddocks with low to moderate N loss risks during the 3-4 months after fertiliser application, a low percentage of PCU can be used. If the N loss risks are considered very low, use of normal urea should be a more economical option. A decision support tree was developed to assist with selection of N fertilisers, based on the potential environmental, agronomic and economic benefits of EEFs.

We recommend a coordinated and comprehensive review, analysis and modelling of all data collected in the completed and current EEF experiments in Australian sugarcane cropping systems. This should help improve our understanding of the factors, processes and their complex interactions determining the agronomic, economic and environmental benefits of EEFs and more accurately identify where, when, what, and how EEFs should be used.

1. Introduction

The Australian sugar industry is facing increasing challenges for effective and efficient fertiliser nitrogen (N) management to protect the environment and improve farming profitability. Approximately 60,000 tonnes of fertiliser N are used on our sugarcane farms each year; but only 35-70% of the fertiliser N can be used by the crops or retained in soil, with the remaining lost into the environment (Chapman *et al.* 1994; Vallis *et al.* 1996; Prasertsak *et al.* 2002). Sugarcane farms account for about 1.4% of the Great Barrier Reef catchment area. Nonetheless, nitrogenous fertilisers applied for sugarcane crops are considered to be the largest source to the anthropogenic dissolved inorganic N (DIN) exported to reef lagoons, which poses a great threat to the natural balance of the reef ecosystems (Waterhouse *et al.* 2017).

Several factors are responsible for the low N use efficiency (NUE) on sugarcane farms. Sugarcane crops are characterised by a long growing season (> 10 months). However, fertilisers must be applied at the early stage because the crop heights later in the season can impede operation of farm machinery in the field. This results in a temporary excessive N supply relative to the demand by crops during the early growing season. The predominant nitrogenous fertiliser used on Australian cane farms is urea, due to its low cost, high N content, good compatibility with other (e.g., phosphorus, potassium and sulphur) fertilisers and abundant supply. After application, urea is usually transformed to ammonium (NH_4^+) and ammonia (NH_3) in the soil within a few days, which can be further converted to nitrate (NO_3^-) through nitrification by soil microbes. As both NO_3^- and soil particles are negatively charged, NO_3^-, unlike NH_4^+, cannot be held firmly by soil particles and thus moves freely in soil solution. In addition, NO_3^- can be easily decomposed into gases through denitrification by soil microbes under anaerobic conditions when soil is wet, especially when waterlogged. As sugarcane farms are generally located in high rainfall regions (> 1000 mm per year), the excessive NO_3^--N accumulated following fertiliser application is susceptible to losses through leaching, runoff and gaseous emissions (denitrification) following high rainfall events in wet summers.

Improved management practices, such as using the optimum amount of fertiliser N with the right placement at the best times for weather and crop needs, are important to maximise productivity and profitability whilst minimising the impact on the environment. Enhanced-Efficiency Fertilisers (EEFs) that can release N gradually or stabilise it in a form less susceptible to losses have been found to have the potential of significantly improving the efficiency of fertiliser N use by crops (Chen *et al.* 2008; Verburg *et al.* 2014). For example, controlled-release N fertilisers (CRFs) or polymer-coated urea (PCU), can extend N supply for crops by controlling N release through the coating material, thereby better matching fertiliser N supply with plant N uptake. Another major type of EEF is nitrification inhibitor-impregnated or -coated urea (NI+U). Nitrification inhibitors can suppress the microbial conversion of NH_4^+ to NO_3^- in soil, thus reducing the accumulation of NO_3^- that is susceptible to losses through leaching, runoff or denitrification. Previous studies demonstrated that EEFs can improve NUE, reduce N losses and increase crop yield or maintain productivity at lower N application rates in various cropping systems worldwide (Trenkel 2010; Li *et al.* 2018a), including Australian sugarcane farms (Di Bella *et al.* 2013; Di Bella *et al.* 2014; Verburg *et al.* 2014; Wang *et al.* 2016a). However, EEFs are generally $120-600/t more expensive than normal urea and yield response varies with soil, crop, weather and management of the farming systems. The higher costs and variable yield responses have been the major factors that sometimes compromise profitability and adoptability associated with EEF use.

The objectives of this project were to:

1) characterise PCU N release dynamics in relation to crop N uptake and, if possible, identify the most desirable PCU formulation for enhanced synchronisation between N supply and crop N uptake;
2) assess the potential benefits of NI+U and blending commercially available PCU with conventional urea as a means to increase NUE and reduce N application rate;
3) investigate if NI+U and blended use of PCU and urea could decrease NO_3^- leaching; and
4) develop a decision support tool to assist with product selection and use by growers.

The results of this project should contribute to the development of efficient and effective N fertiliser management strategies for the sugar industry. The expected outcomes were improved NUE in the sugar industry with lower fertiliser N inputs, lower N exports to waterways and enhanced farming profitability.

2. Materials and methods

2.1. Experimental sites and soil properties

Six field experiments were established in five major sugarcane cropping regions (Fig. 1) with a main focus in the wet tropics where conventional fertiliser N is more vulnerable to loss into the environment. The experimental sites were located at Bundaberg (24°50'51"S, 152°24’ 7"E), Mackay (21°24'37"S, 149°09'34"E), Lilypond near Ingham (18°35'34"S, 146°13'58"E), Lannercost near Ingham (18°36'11"S, 146°03’01"E), Tully (18°03'12"S, 145°52'40"E) and Innisfail (17°46'19"S, 146°00'48"E). The long-term mean annual rainfall is 1027 mm in the subtropical Bundaberg region, 1697 mm in the tropical Mackay region and 2100-3500 mm in the remaining moist/wet tropical regions. Green cane trash blanketing has been practised at all sites in the past two to three decades.

Soil profile samples were collected from 0-90 cm at Mackay and 0-120 cm at other sites before commencement of the field trials (see Section 8.2.4), separated into 0-20, 20-40, 40-60, 60-90 and 90-120 cm depths. The soil samples at each depth were analysed for pH, electrical conductivity (EC), effective cation exchange capacity (ECEC), and sand, silt, clay, total organic carbon (TOC), total N and mineral N (NH_4^+-N and NO_3^--N) contents. Major soil physico-chemical properties in the surface 20 cm depth at each site are summarised in Table 1.

In addition, nutrient availability indices were determined for phosphorus (P), potassium (K), sulphate (S), calcium (Ca), magnesium (Mg), copper (Cu), manganese (Mn), zinc (Zn), iron (Fe) and silicon (Si) for the 0-20 cm soil, either before cane planting or field trial establishment using standard analytical methods (Rayment and Lyons 2010). If any of the nutrients were found to be deficient in soil, fertilisers containing these nutrients were applied as base before planting (by farmers) or before N fertiliser application in the 2016-17 season at amounts determined in accordance with the Six Easy Steps (6ES) nutrient management guidelines (Schroeder *et al.* 2005).

Figure 1. Location of the field trials (indicated by red stars). The map was adapted with permission from the Queensland Cane Growers Organisation (2020).

Table 1. Initial major soil properties (mean) in the 0-20 cm and 20-40 cm depths.

Site & Depth	Sand %	Silt %	Clay %	pH[1]	TOC[2] mg/g	TN[3] mg/g	ECEC[4] cmol/kg	EC[5] µS/cm	Nmin[6] kg/ha
Bundaberg									
0-20 cm	17.3	23.1	59.6	6.7	18.6	1.9	9.9	47	2.9
20-40 cm	17.0	20.6	62.4	6.7	17.9	1.8	9.1	53	10.0
Mackay									
0-20 cm	43.7	32.5	23.8	6.5	14.0	1.3	7.6	52	18.5
20-40 cm	40.5	28.8	30.7	6.7	7.2	0.9	8.5	48	5.5
Lilypond									
0-20 cm	44.6	28.1	27.3	5.9	15.4	1.2	9.4	34	7.2
20-40 cm	40.6	30.5	28.9	6.1	10.2	0.9	9.9	24	3.7
Lannercost									
0-20 cm	37.0	34.6	28.4	4.9	11.8	1.1	4.4	36	4.8
20-40 cm	35.6	34.5	29.9	5.2	7.3	0.8	4.7	27	1.6
Tully									
0-20 cm	49.6	21.1	29.3	5.2	18.6	1.3	4.1	51	26.7
20-40 cm	45.6	23.7	30.8	5.2	12.6	0.9	3.7	34	14.2
Innisfail									
0-20 cm	52.2	17.0	30.8	5.2	28.5	1.7	4.0	44	12.1
20-40 cm	51.5	17.1	31.4	5.1	15.2	1.0	3.4	30	9.0

[1] Determined with a soil:water ratio of 1:5; [2] Total organic carbon; [3] Total nitrogen; [4] Effective cation exchange capacity; [5] Electrical conductivity; [6] Mineral N (NH_4^++NO_3^-)-N stock calculated using an average bulk density of 1.3 t/m³.

All field trials commenced from October to December 2016 on farms grown with the first or third (Mackay only) ratoon crops. The crop varieties were Q242 at Bundaberg and Q208 at the other sites. The field trials in the following two years continued at the same sites to allow assessment of multi-year cumulative effects of different fertiliser management practices. The crop harvest and fertiliser application dates in each cropping season are given in Table 2.

Table 2. Crop harvest and fertiliser application dates (dd/mm/yy) immediately prior to and during the experimentation across three crop-growing seasons from 2016 to 2019.

Site & Depth	Pre-trial Harvest	2016-17		2017-18		2018-19	
		Fertilisation	Harvest	Fertilisation	Harvest	Fertilisation	Harvest
Bundaberg	20/11/16	22/12/16	24/10/17	22/12/17	24/09/18	13/12/18	24/09/19
Mackay	10/09/16	23/10/16	21/09/17	12/12/17	28/09/18	14/11/18	14/11/19
Lilypond	22/10/16	09/12/16	15/11/17	19/12/17	18/10/18	13/12/18	24/10/19
Lannercost	29/10/16	06/12/16	04/12/17	22/12/17	18/09/18	19/10/18	22/10/19
Tully	23/09/16	28/10/16	07/09/17	06/11/17	31/08/18	31/10/18	26/09/19
Innisfail	29/09/16	09/11/16	25/09/17	28/11/17	25/09/18	16/11/18	23/10/19

2.2. Treatments and implementation

Twelve treatments were included in each field trial (Table 3), with emphasis on the effects of different blending ratios of PCU (Agromaster®, ICL Specialty Fertilisers) and urea on sugarcane yield, sugar productivity, fertiliser NUE and profitability. Treatments with a nitrification inhibitor-coated urea product (ENTEC® with DMPP, 3,4-dimethyl pyrazole phosphate, as the nitrification inhibitor; Incitec Pivot Ltd) were also included for comparison. Four fertiliser N application rates were tested in the 2016-17 and 2017-18 seasons as follows: (i) Nil fertiliser N application (0N); (ii) the recommended N application rate for all fertiliser types as estimated with the 6ES guidelines for conventional urea (6ES rate); (iii) a reduced rate for all fertiliser types (75% 6ES); and (iv) 125% 6ES for urea only. The 6ES rate was 130 kg N/ha at Bundaberg, Lilypond and Tully, 140 kg N/ha at Mackay, 145 kg N/ha at Lannercost, and 110 kg N/ha at Innisfail. The N rates were re-assessed for the 2018-19 cropping season based on the yield responses in the previous seasons. Consequently, the 75% 6ES N rate was reduced to 60% 6ES and the 125% 6ES rate increased to 140% 6ES at Bundaberg, Mackay, Tully and Innisfail in the third year, in an attempt to discern treatment effects of different N fertiliser types at lower and higher application rates (Table 3). The N application rates at Lilypond and Lannercost in the 2018-19 season remained unchanged from the previous years.

The N fertilisers were applied between late September and late December in each cropping season, approximately 1-2 months after harvest of the previous crops, except at Mackay in 2017 and at Bundaberg in 2018 when the fertiliser application was delayed to about 2.5 months after the previous crop harvest due to weather conditions (see Fig. 12 in Section 8.3.4 for the fertilisation dates). The treatments were arranged in a randomised block design with four replicates and stayed in the same plots over all seasons. Each plot consisted of six rows (row spacing varied from 165 to 185 cm at different sites) with approximately 20 m in length. All N fertilisers were incorporated about 10 cm below the soil surface, with the fertiliser slits closed gravitationally or mechanically (Fig. 2).

Table 3. Treatments used in the field experiments. The N application rates in 2018-19 were adjusted at Bundaberg, Mackay, Tully and Innisfail, while unchanged at other sites.

Treatment #	Fertiliser types/ratios	N application rates	N application rates at Bundaberg, Mackay, Tully and Innisfail in the 2018-19 season
1	Control	0	0
2	U[1]	75% 6ES[4]	60% 6ES[4]
3	U	6ES	6ES
4	U	125% 6ES	140% 6ES
5	NI+U[2]	6ES	6ES
6	NI+U	75% 6ES	60% 6ES
7	25% PCU[3]	6ES	6ES
8	50% PCU	6ES	6ES
9	75% PCU	6ES	6ES
10	25% PCU	75% 6ES	60% 6ES
11	50% PCU	75% 6ES	60% 6ES
12	75% PCU	75% 6ES	60% 6ES

[1] U: urea; [2] NI+U: nitrification inhibitor-coated urea; [3] 25% PCU: 25% polymer-coated urea + 75% U; [4] 6ES: fertiliser N application rate based on the Six Easy Steps nutrient management guidelines, being 110 kg N/ha at Innisfail, 140 kg N/ha at Mackay, 145 kg N/ha at Lannercost, and 130 kg N/ha at Bundaberg, Lilypond and Tully.

Figure 2. Application of nitrogen fertilisers in the experimental plots using a variable rate fertiliser applicator at the Lilypond site.

2.3. Characterisation of N release dynamics from PCU

Field incubation studies of various PCU products were conducted over two crop growing seasons. A 2017 Agromaster Tropical product (ICL Specialty Fertilizers) was tested at all sites in the 2017-18 season. Agromaster Standard, 2017 Agromaster Tropical, 2018 Agromaster Tropical and Meister-15 (Yates), which contained 45%, 41%, 44% and 42% N respectively, were included in the 2018-19 season, with each product tested at three different sites.

A mesh bag incubation method was used to monitor N release dynamics from the PCU products. Fertiliser granules were weighed into nylon mesh bags (50 mm x 50 mm with a mesh size of 1 mm) in an amount equivalent to the 6ES rate at each site (Fig. 3). The mesh bags were buried at 10 cm in an unfertilised guard row in each block of the field trial. Soil temperature and moisture probes were installed at 7-13 cm and 10 cm depth, respectively, in the 2018-19 season to allow assessment of the relationships of the PCU N release dynamics to soil temperature and moisture. One bag was excavated from each replicate at approximately 20, 45, 70, 95, 120, 150, 180, 210, 270, and 350 (around harvest) days after fertilisation (DAF). After removal of mud and plant roots in the laboratory using a tap water jet, the mesh bags containing fertiliser granules were dried in an oven at 60 ^{o}C for about 48 h. The fertiliser N remaining in each bag was determined based on the weight loss method, which was initially tested against analysis of N in the remaining PCU capsules.

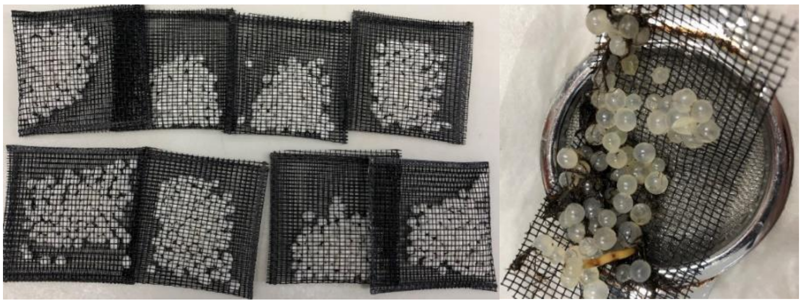

Figure 3. PCU granules contained in mesh bags (left) and recovered after incubation in the field and washing (right).

2.4. Soil sampling and analysis

Initial soil profile samples were collected 1-2 months before fertiliser application in the first year at 0-20, 20-40, 40-60, 60-90 and 90-120 cm depths, for analyses of major soil physicochemical properties as described in Section 8.2.1. The samples were taken from about 3-4 points on crop beds in each block (replicate), and bulked by depth.

Soil profile samples were also taken from all plots following the first and second major rainfall events (> 75 mm) after fertiliser application to monitor downward NO_3^- movement under different N management practices. After harvest of the crops, deep soil samples were collected again to quantify mineral N contents in the soil profile (Fig. 4). The in-season and post-harvest soil samples were taken from 3 points in the fertiliser slits of each fertilised plot (and similar positions in the Control), separated into 0-20, 20-40, 40-60, 60-90 and 90-120 cm depths and then bulked by depth.

In addition, soil samples were collected 3-4 times during the crop growing season from the fertiliser slits at the 0-20 cm depth. Together with the 0-20 cm soil samples from the deep profile sampling, these soils were used to monitor the dynamics of soil mineral N contents in different treatments during the crop growing season.

After collection, the soil samples were packed in Eskies with adequate ice blocks and sent to the laboratory. The samples were then stored at 4 ^{o}C, mixed and extracted with 2 M potassium chloride (KCl) solution within about 1 week for determination of mineral N contents using the spectrophotometry method (Rayment and Lyons 2010). Soil moisture contents were determined by drying in ovens at 105 °C for >24 h. All soil mineral N and other component contents were expressed on a dry-soil basis.

Figure 4. Deep soil sampling at Bundaberg after cane harvest.

2.5. Plant sampling and analysis

Plant samples were taken to measure crop N uptake dynamics in the presumably N-sufficient treatment (U_6ES) in all the cropping seasons. Aboveground biomass samples were taken approximately monthly in the early 4-5 months after fertilisation and then less frequently until cane harvest. A 10 m section of the central two rows in each replicate plot was designated for stalk counts at plant sampling. In the 2018-19 season, the 0N and 75% PCU_6ES treatments were also sampled for comparison with the U_6ES treatment. These measurements allowed assessment of the PCU N release patterns (Section 8.2.3) against crop N uptake dynamics.

In the first 4-5 months post fertilisation, plant samples were taken from a 1-m section in the second rows from each side of a plot, avoiding the two central rows that would be used for yield determination at harvest. The number of stalks and the total biomass in the 1-m sections were recorded either in field or in laboratory. Immediately after weighing of the total biomass, ten whole stalks were mulched and subsampled for determination of water content. The dried sub-samples were fine ground and analysed for total N contents using a dry combustion method (C/N/S Determinator, LECO Australia). Total aboveground crop N uptake was then calculated.

From 4-5 months after fertilisation onward, when the stalks were of considerable size, 20 whole canes were randomly sampled from Rows 2 and 5. Each sample was partitioned into two components: (i) stalks and (ii) leaves and cabbages (LC). To separate the LC from stalks, the canes were cut between the 5th and 6th dewlaps for non-flowered plants and between the 7th and 8th dewlap for flowered plants; all green and dead leaves, sheaths and stalk tips from the canes were combined in the LC sample. The stalk and LC samples were weighed separately. Then, 6 stalks or 0.5-1.0 kg of LC samples were mulched, subsampled and dried at 60 °C for > 48 h for determination of water content. The dried subsamples were processed for analysis of total N content as described above.

2.6. Sugarcane harvest

Sugarcane yield was measured by mechanically harvesting the entire middle two rows with a plot harvester and a truck equipped with a weighing bin, or by manually harvesting two 5-m sections in the middle two rows (Bundaberg only). If mechanically harvested, an additional 20 whole stalk samples were manually taken from the second rows from each side of a plot. At Bundaberg, 20 whole stalk samples were randomly taken from the manually harvested canes after weighing. The whole stalk samples were partitioned into millable stalk and LC components, weighed and subsampled. Water contents in the millable stalk and LC subsamples were determined. The dried subsamples were fine ground and analysed for total N content as described above. In addition, 6 millable stalks were sent to regional laboratories for juice CCS (commercial cane sugar) analysis with near infrared spectroscopy.

2.7. Data processing and statistics

All statistical analyses were performed using GenStat V.18 (VSN International Ltd, UK). Prior to analysis of variance (ANOVA), data were tested for normal distribution and box-cox or log-transformed where appropriate. Differences among treatments were assessed using the ANOVA procedure and the least significant difference (LSD) test. Treatment differences were considered statistically significant at $P \leq 0.05$ and marginally significant at $P \leq 0.10$.

NUE of fertilisers was assessed using the apparent fertiliser N recovery (FNR%) by crops as follows:

$$\mathrm{FNR\%} = \frac{\mathrm{ABN_f} - \mathrm{ABN_0}}{\mathrm{FNU_a} \times \mathrm{FN}} \times 100\% \qquad \text{Eq. 1}$$

where $\mathrm{ABN_f}$ and $\mathrm{ABN_0}$ were aboveground biomass N (kg/ha) for the fertilised and 0N treatments, respectively; $\mathrm{FNU_a}$ was the proportion of total plant N uptake allocated to the aboveground biomass, which was 0.862 on average based on previous studies with ^{15}N-labelled urea in Australian sugarcane cropping systems (Chapman *et al.* 1994; Prasertsak *et al.* 2002). Thus, FNR% represents the percentage of fertiliser N recovered in the above- and belowground biomass.

Economic analysis was conducted by calculating gross margins using the Farm Economic Analysis Tool (FEAT; https://www.daf.qld.gov.au/business-priorities/agriculture/plants/crops-pastures/sugar/farm-economic-analysis-tool). The analysis took into account sugarcane sales revenue based on sugar yield and all operational expenses but did not include fixed costs like rates, insurance, land leasing and building depreciation. This allowed comparison of profitability between fertiliser treatments. Costs associated with fertiliser application and weed control were standardised across all regions. Costs associated with irrigation were applied to the Bundaberg site only. Prices for sugar, urea, PCU and NI+U products used in the analysis were $420/t, $500/t, $1100/t and $620/t, respectively.

3. Results and discussion

3.1. Weather conditions and dynamics of N release from PCU

The rainfall amounts and patterns in the 2017-18 cropping season, when the N release dynamics from the 2017 Agromaster Tropical were measured, differed substantially at different sites, especially from the second to the fourth months after fertiliser application (Fig. 5a). In comparison, the air temperature did not vary as markedly as rainfall among the six sites. The cumulative air temperature (sum of daily mean temperatures after fertiliser application) in the first 100 DAF ranged from 2564 °C·days at Bundaberg to 2714-2767 °C·days at the other sites (Fig. 5b). That is, the average daily temperature in the first 100 DAF differed by ≤ 2.13 °C·across the six sites. Over the whole crop growing season, the cumulative air temperature remained lower at Bundaberg than at the other sites.

The dynamics of N release from the 2017 Agromaster Tropical followed a slightly sigmoidal pattern, with no significant differences between different sites (Fig. 6a). As the soils had significantly different properties (Table 1), it was evident that N release from this PCU product was not markedly affected by soil properties. The relationships between the cumulative N release from the PCU and cumulative rainfall varied substantially at different sites (Fig. 6b). For example, 80% of the PCU N was released when the cumulative rainfall reached about 600 mm and 2200 mm at Bundaberg and Tully, respectively. Thus, N release rates from the PCU were not significantly affected by variation in the rainfall amount and time at different sites. This result was in agreement with previous findings that changes in soil moisture above the crop wilting point had little influence on N release from PCU fertilisers (Christianson 1988; Golden *et al.* 2011).

The shape and goodness of fit for the cumulative N release curve against degree days were similar to those against the time only (Fig. 6a, c). Such similarity demonstrated that the differences in air temperature among the sites had little impact on N release from the PCU. Previous laboratory incubation studies demonstrated that temperature was a key factor regulating the rate of N release

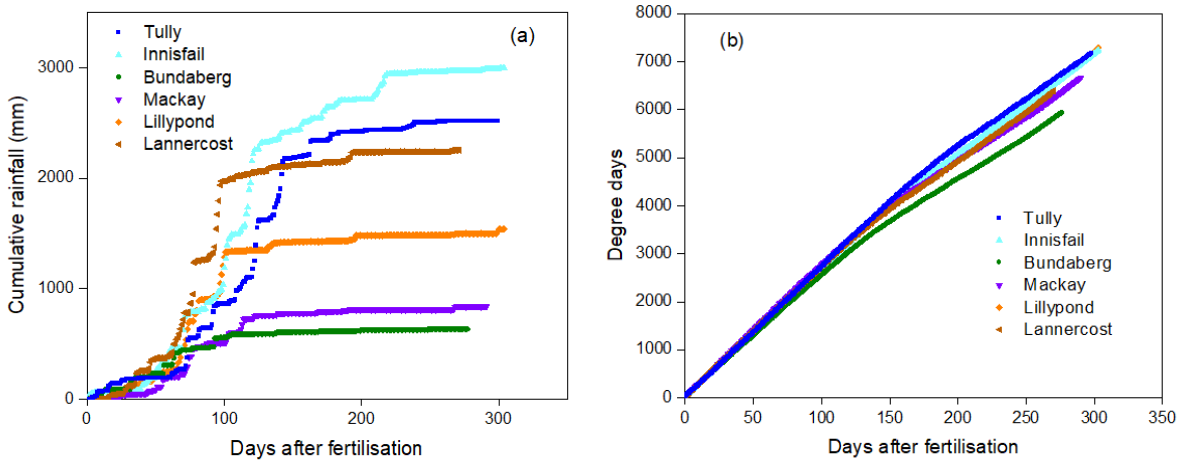

Figure 5. Cumulative rainfall (a) and cumulative air temperature (b, sum of daily mean air temperatures) at the experimental sites during the periods from fertiliser application to cane harvest in the 2017-18 cropping season.

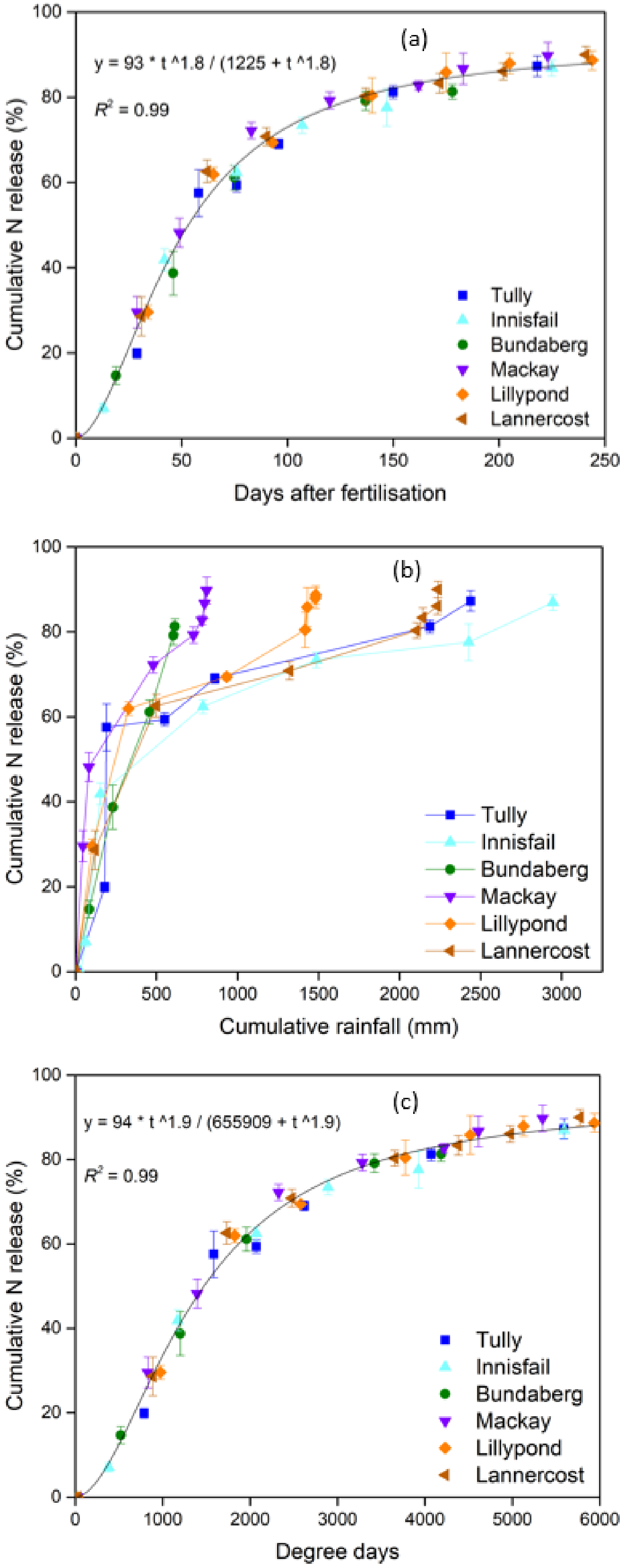

Figure 6. Nitrogen release from a PCU fertiliser (2017 Agromaster Tropical) in relation to time (a), cumulative rainfall (b) and cumulative temperature (c, sum of daily mean air temperature) at different sites in the 2017-18 cropping season. The error bars are standard deviation.

from PCU fertilisers (Verburg *et al.* 2014; Verburg *et al.* 2017; Trolove *et al.* 2019). In the laboratory studies, the temperatures tested generally differed by 5-20 °C. With fertilisers applied at all six sites between 06 November and 22 December 2017 in the 2017-18 cropping season, the mean daily air temperature in the first 100 DAF ranged from 25.6 °C at Bundaberg to 27.7 °C at Mackay. While there was a general trend that the PCU released slightly less N at Bundaberg than at Mackay (Fig. 6a), the similar N release dynamics across the six sites indicated that N release from this PCU product was not very sensitive to the relatively small differences in daily mean temperature (≤ 2.1 °C) within the sugarcane growing regions studied. Therefore, if the 2017 Agromaster Tropical PCU is applied in these regions in November and December, N supply dynamics from the fertiliser can be accurately predicted with time only using the equation in Fig. 6a. However, if the PCU is applied on a much earlier date when the mean daily temperature in the first 100 DAF is substantially lower than 25.6 °C, the model based on degree days (Fig. 6c) should provide a more accurate prediction.

Like the observations with the 2017 Agromaster Tropical in the 2017-18 season, there were no significant differences in the N release dynamics of the same PCU product between the different sites in 2018-19 (Fig. 7). These results with four PCU products applied over a wider period (late September to December 2018; see Fig. 12) confirmed that variations in the site and weather conditions among the trials had no considerable effects on N release dynamics from the same PCU product. As discussed above, this was most likely due to the small differences in mean daily temperature between the different sites in the first 100 DAF (26.9-28.1 °C; Supp. Fig. 1b). In addition, the daily mean soil temperature at the 7-13 cm depth where the fertiliser mesh bags were placed

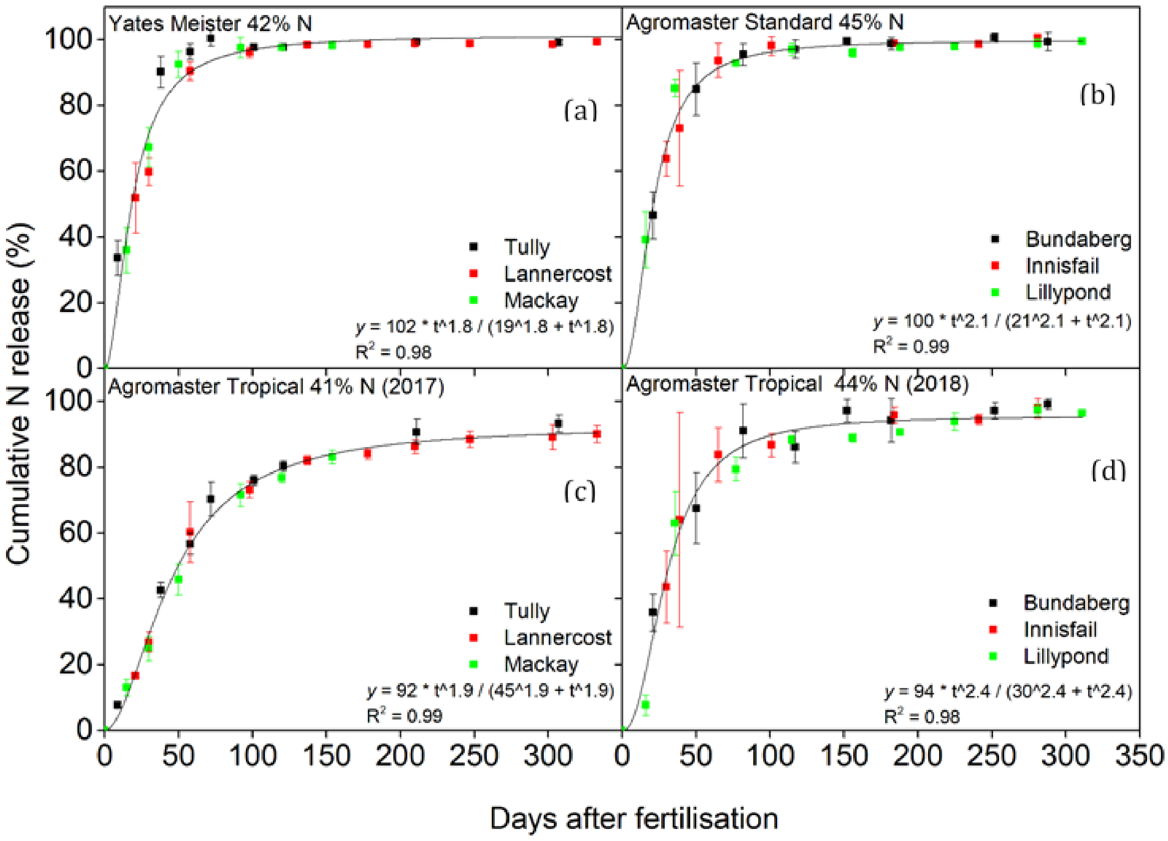

Figure 7. Dynamics of N release from four PCU products at different sites in the 2018-19 cropping season. The error bars are standard deviation.

was not consistently lower or higher than daily mean air temperature (Supp. Fig. 1a). In fact, the cumulative soil temperature varied slightly more than the cumulative air temperature between the sites (Supp. Figs. 1b,c). Thus, the similar N release dynamics of a specific PCU product in different regions were not due to smaller differences in sub-soil temperature compared to air temperature.

Each of the four PCU products displayed their own N release characteristics. In the 2018-19 cropping season, similar N release dynamics for the 2017 Agromaster Tropical (41% N) were observed as those in the previous season (Fig. 8). However, N release from the 2018 Agromaster Tropical product (44% N) was more rapid than its 2017 predecessor, perhaps due to changes in the formulation (as indicated by the different N contents) and manufacturing facilities (S. Stacey, personal communication). Surprisingly, Meister-15 and Agromaster Standard had similar N release patterns, with about 90% of the fertiliser N released within the first 2 months (Fig. 8). By the time of harvest, almost all N in Meister-15 and Agromaster Standard had been discharged. In comparison, N release from the 2017 and 2018 Agromaster Tropical products was slower and continued for longer periods, with 90% of the fertiliser N released by 335 and 110 DAF, respectively. Thereafter, N release rates from both products were very slow, and based on the models, 9.7% and 6.2% of the fertiliser N still remained in the polymer capsules by 365 DAF for the 2017 and 2018 Agromaster Tropical products, respectively. The N release characteristics of different PCU fertilisers can be used to assist in developing N management strategies (e.g., product selection and fertiliser application time) to better synchronise N supply to crop N uptake after taking into account soil N availability.

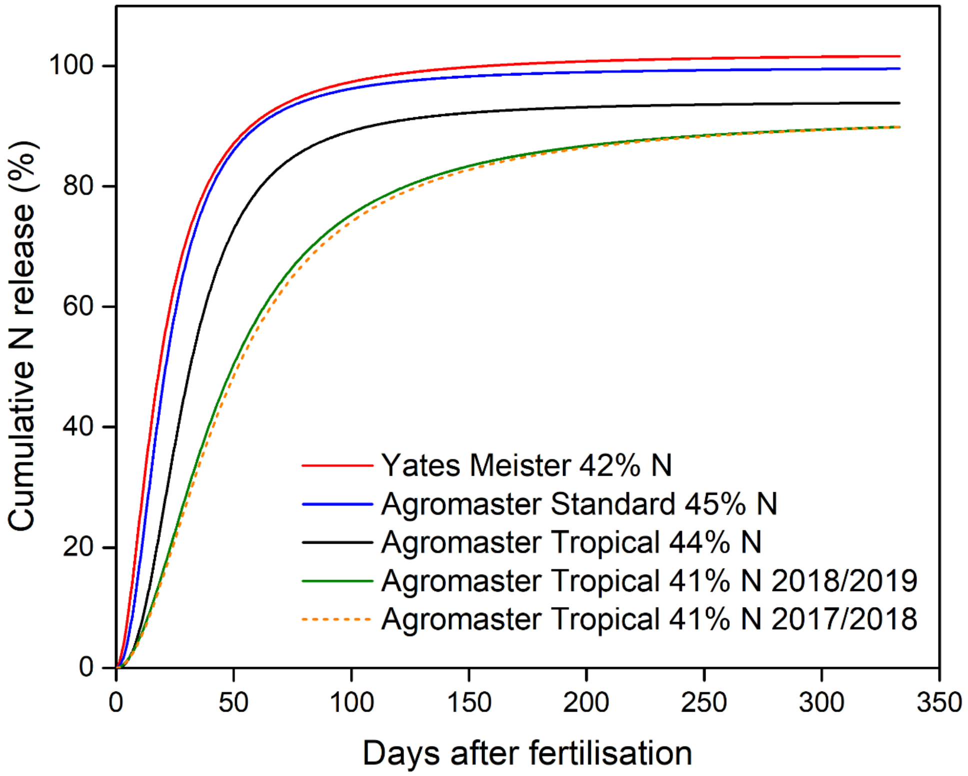

Figure 8. Fitted curves of N release dynamics from four PCU products across different sites in the 2018-19 cropping season (including one for Agromaster Tropical in the 2017-18 cropping season for comparison).

3.2. Dynamics of crop N uptake *versus* PCU N release

The N uptake for the ratoon crops also followed sigmoidal trajectories (Fig. 9). Following harvest of the previous crops, the ratoon crops started with slow N uptake for approximately 50-60 days after harvest (DAH), then grew into a rapid N uptake phase until about 200 DAH, followed by low and then little N uptake until the crop harvest.

The sigmoidal plant N uptake dynamics resulted from sigmoidal or exponential plant biomass accumulation and exponential decline in N contents in the plant tissues (Supp. Figs 2, 3). The differences in plant biomass between the fertilised and unfertilised treatments were mostly developed between 100 to 200 DAH. Higher N concentrations in plant biomass were recorded in the fertilised treatments than in the 0N treatment from about 60 to 250 DAH, depending on fertiliser application time. From 250-300 DAH onwards, the N concentrations in plant biomass became very similar between the fertilised and unfertilised treatments.

Nitrogen management strategies should aim to maintain adequate, but not excessive, N supply to the crops during the high N demand period approximately between 50 and 200 DAH. During the first 50-60 DAH, plant N accumulation ranged from 5 to 28 kg N/ha (Fig. 9). Analyses of the soil samples taken soon after harvest of the previous crop suggested that the top 0-60 cm soil (hosting most plant roots) contained 8 to 48 kg N/ha at the beginning of the 2016-17 season, and 16-39 kg N/ha in the normal U_6ES treatment at the beginning of the 2017-18 and 2018-19 seasons. In combination with the N to be mineralised from soil organic matter, it appeared that soils should have the capacity to supply sufficient N to the crops during the first 50 DAH in many circumstances. Thus, there would be little need to apply much fertiliser N until 50 DAH, as long as the ground condition and the forecast and outlook for rainfall allow fertiliser application later. After N fertiliser application around 50 DAH, it would be highly desirable to sustain fertiliser N supply for the following 150 days or so. Unless the soil has the capacity to supply adequate N or retain fertiliser N for about 150 days, PCU would provide an effective means to sustain N supply during the high N demand period.

It appeared that the 2017 Agromaster Tropical PCU fertiliser continued to supply N during the whole cropping season (Fig. 9; 2017-18), while the 2018 product released 90% of the fertiliser N by 120 DAH (Fig. 9; 2018-19). This controlled-release feature is desirable particularly in circumstances where normal urea N can be easily lost through leaching, runoff and/or denitrification in the early months after application. The N release dynamics from the 2017 Agromaster Tropical product coincided closely to the dynamics of crop N uptake until the mid-season, but 17-25% of the fertiliser N had not been released by 200 DAH. In comparison, the cumulative N release from the 2018 Agromaster Tropical substantially exceeded the cumulative crop N uptake in the first 100-150 DAH in most cases, with on average 74% of the fertiliser N released by 100 DAH (except at the Bundaberg site where fertiliser was applied at 80 DAH) and only 3-5 kg N/ha were released from 150 to 200 DAH. An ideal PCU fertiliser should provide N at such a rate that ensures adequate N availability to the crops whilst minimising surplus mineral N accumulation in soil to curtail the risk and magnitude of N losses. It appeared that a PCU product with a N release rate between those of the 2017 and 2018 versions of Agromaster Tropical should match sugarcane N uptakes more closely, if applied alone with no other N fertilisers around 50-60 DAH between October and December. As the N release dynamics of a PCU fertiliser applied during this time period did not vary substantially with soil

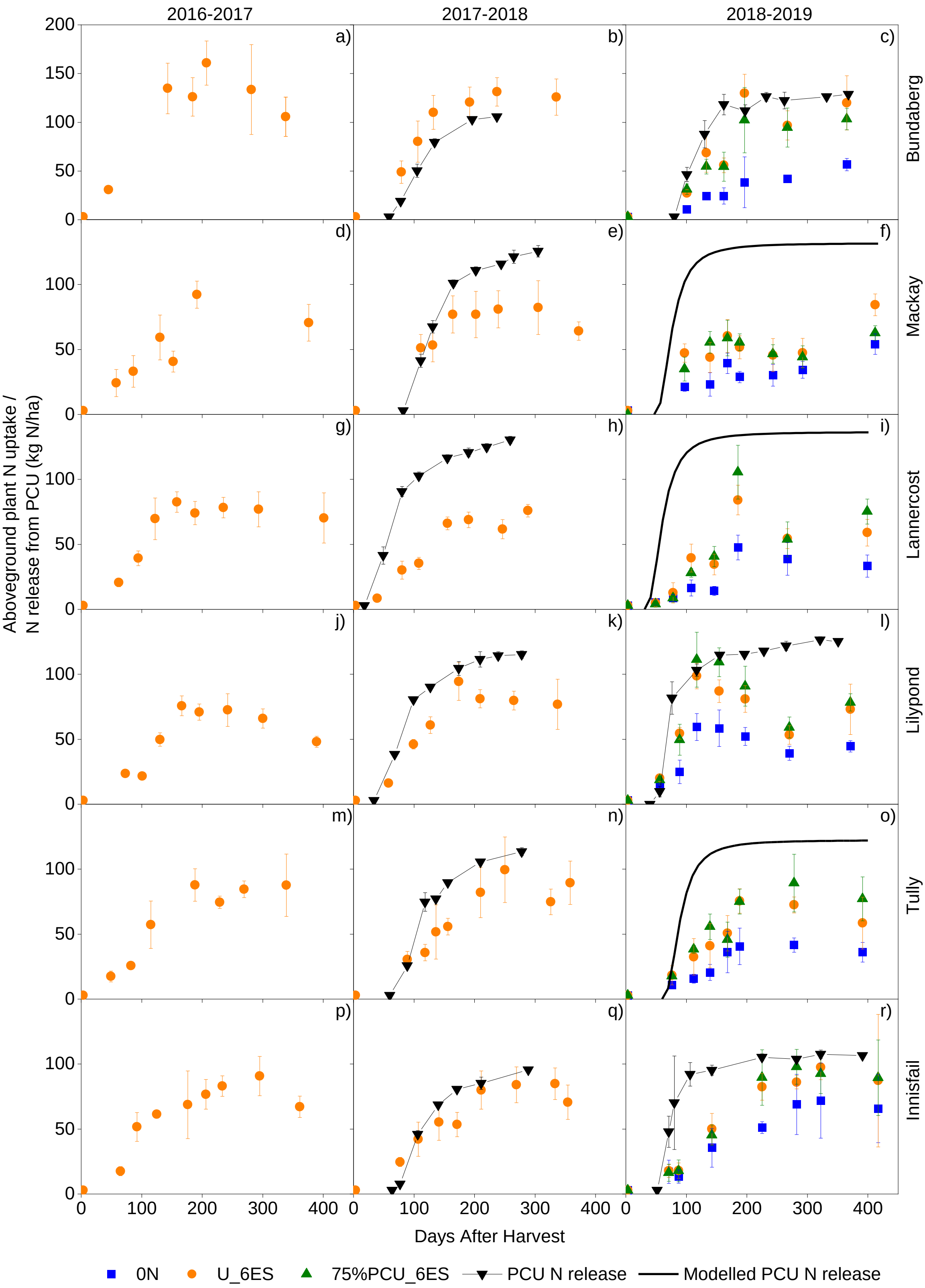

Figure 9. Dynamics of aboveground plant N uptake and N release from PCU at 6ES rates. The 2017 Agromaster Tropical was used in the 2017-18 season; the 2018 Agromaster Tropical was used in the 2018-19 season. The black curves in f, i and o were modelled N release dynamics for the 2018 Agromaster Tropical based on measurements at the other sites. See Table 3 for the 6ES rates. The error bars are standard deviation.

and weather conditions within the Queensland sugarcane growing regions (Section 8.3.1), it would be possible to manipulate the PCU formulation by choosing the right coating material and thickness to make it more suitable for Queensland sugarcane crops. Alternatively but less ideally, a PCU with slow N release can be applied earlier and *vice versa*, after considering soil N availability and fertiliser N loss risks.

Blended use of PCU and urea has been increasingly used by farmers as a means to minimise fertiliser cost because PCU products are approximately $600/t more expensive than urea. Blending with urea can significantly change the pattern of fertiliser N supply and thus the degree of synchronisation with crop N uptake. In terms of N supply and demand, PCU product alone should be able to meet crop N requirements during the early crop growing season. Thus, the potential benefits of blending PCU with urea would merely be limited to cost saving, rather than improved N supply to crops. Given that surplus fertiliser N accumulation in soil during the early stages (e.g., before 120 DAH) could be susceptible to losses after heavy rainfall, the optimum blending ratio of PCU to U needs to be assessed by taking into account N loss risks, soil N availability, the PCU N release dynamics and costs. For paddocks with low to moderate N loss risks from 50 to 200 DAH (e.g., low probability of high rainfall or soils with low leaching and denitrification potentials), a lower proportion of PCU can be used. If the N loss risks are considered very low during the 3-4 months after fertiliser application, use of normal urea will be a more economical option. This will be elaborated and discussed further in Section 8.3.8.

3.3. Soil mineral N dynamics and nitrate leaching after fertilisation

Mineral N contents in the 0-20 cm depth varied significantly with fertiliser forms, blending ratios of PCU to urea and time (Fig. 10). As expected, the fertilised treatments had substantially higher soil mineral N than the 0N treatment during the first 2-3 months after fertiliser application. Among the fertilised treatments, normal urea and NI+U application generally resulted in higher mineral N contents in the first 2 weeks compared to the blended PCU treatments. However, soil mineral N declined to low levels (< 10-20 mg N/kg) in the urea and NI+U treatments approximately 2-3 months after fertiliser application, following large rainfall events. Thereafter, there were no significant differences in soil mineral N contents between the 0N, urea and NI+U treatments in most circumstances. In contrast, the PCU treatments tended to have lower soil mineral N contents shortly after fertiliser application, but relatively higher mineral N contents (> 10-20 mg N/kg) during the mid- to late crop growing seasons. There was also a general trend that 75% PCU in the blended fertilisers resulted in the highest mineral N content in the 0-20 cm soil during the mid- to late cropping season. Thus, use of PCU maintained the fertiliser N availability throughout the whole season.

A number of processes could have influenced mineral N dynamics in the 0-20 cm soil after fertiliser application, including fertiliser N inputs/release, mineral N immobilisation, soil organic N mineralisation, crop N uptake and losses through ammonia volatilisation and NO_3^- leaching, runoff and denitrification. Ammonia volatilisation should be minor in these cropping systems as the fertilisers were buried approximately 10 cm below the soil surface (Prasertsak *et al.* 2002; Macdonald *et al.* 2009). Assuming that soil net N mineralisation was not affected substantially by the treatments and that the crop N uptakes were similar between the fertilised treatments at a specific time (Fig. 9, 2018-19), the rapid mineral N decreases in the 0-20 cm soil in the U and NI+U treatments during the 2-3 months after fertiliser application could be attributed largely to N leaching beyond the main root

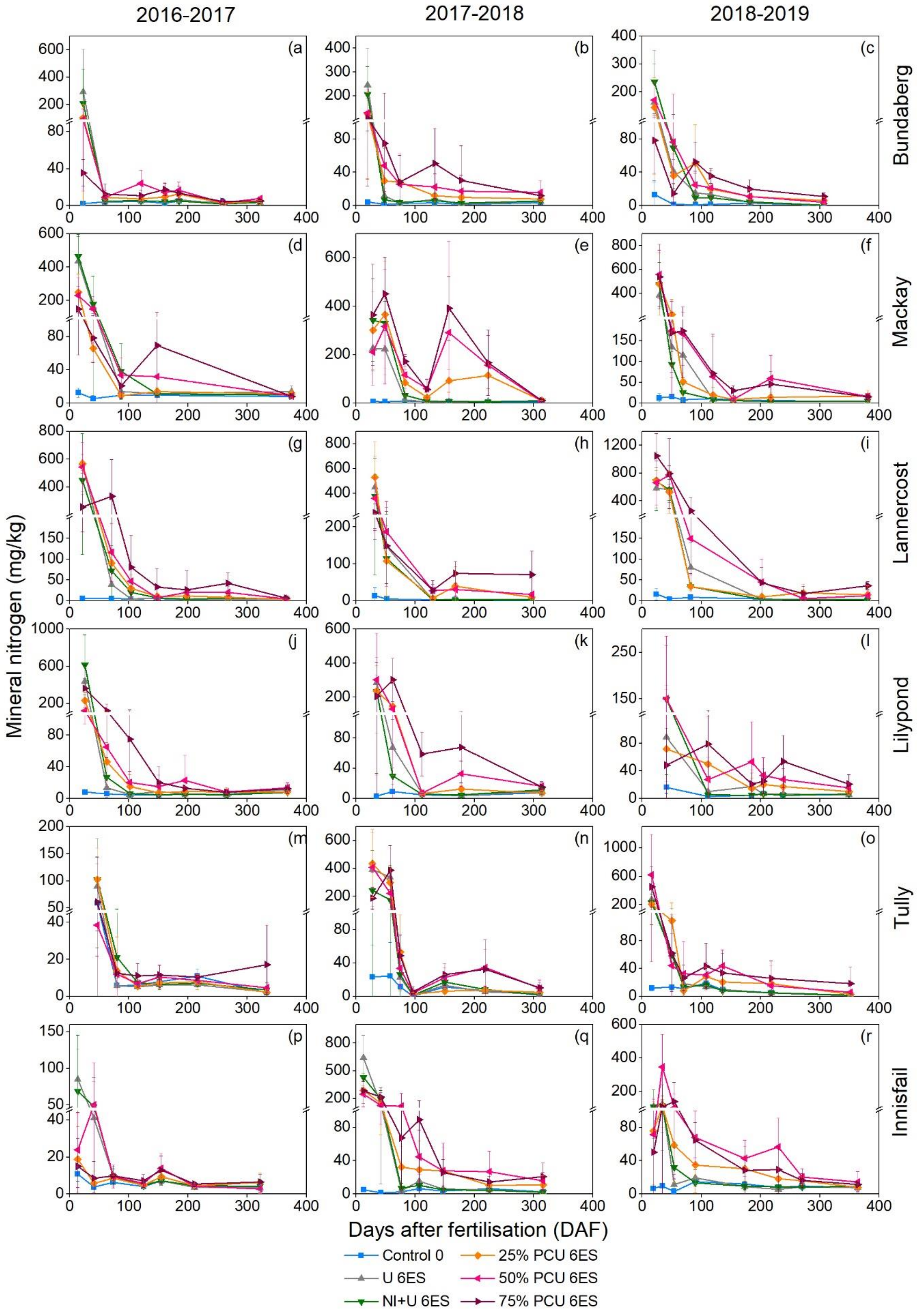

Figure 10. Dynamics of mineral N contents in the 0-20 cm soil after application of different forms of fertiliser at the recommended 6ES rate. The error bars are standard deviation.

zone or losses into the environment. Therefore, use of PCU appeared to offer the benefit of substantially reducing fertiliser N movement or loss from the root zone.

The efficacy of PCU for reducing NO_3^- leaching in well drained soils was evident, compared to urea alone or NI+U (Fig. 11). Greater mineral N contents in the deeper parts of soil profiles (> 60 cm) were observed in the fertilised treatments compared to the 0N treatment at most sites apart from Lilypond and Innisfail. These observations demonstrated the risk of fertiliser N loss from the main root zone into deep soil through leaching. Among the fertilised treatments, use of urea or NI+U resulted in the highest N leaching (Fig. 11; Bundaberg a,c,d,f; Lannercost c,d; Tully c,f). Thus, PCU could significantly reduce the risk of fertiliser N leaching during the high rainfall season, particularly for the well-drained Ferrosol at Bundaberg and the Hydrosol in the high rainfall Tully region.

Significant downward movement of NO_3^--N was not recorded at Lilypond and Innisfail in spite of high rainfall in these regions. This was most likely due to poor drainage at these sites as depletion of NO_3^--N through denitrification was less likely in deep soil. However, the deep soil sampling method used could occasionally fail to detect NO_3^--N movement in soil profiles because a severe leaching event might have washed most NO_3^- out of the 0-120 cm depth at the time of sampling, although the soil sampling was conducted shortly after the first and second major rainfall events (> 60 mm), where possible, to maximise the chance of capturing NO_3^--N movement. Lysimeters can provide a more reliable technique for quantifying N leaching (Abdulkareem *et al.* 2015), but the associated setup costs can be inhibitive. Regardless, PCU would not offer the benefit of N leaching mitigation at sites with poor drainage or low rainfall.

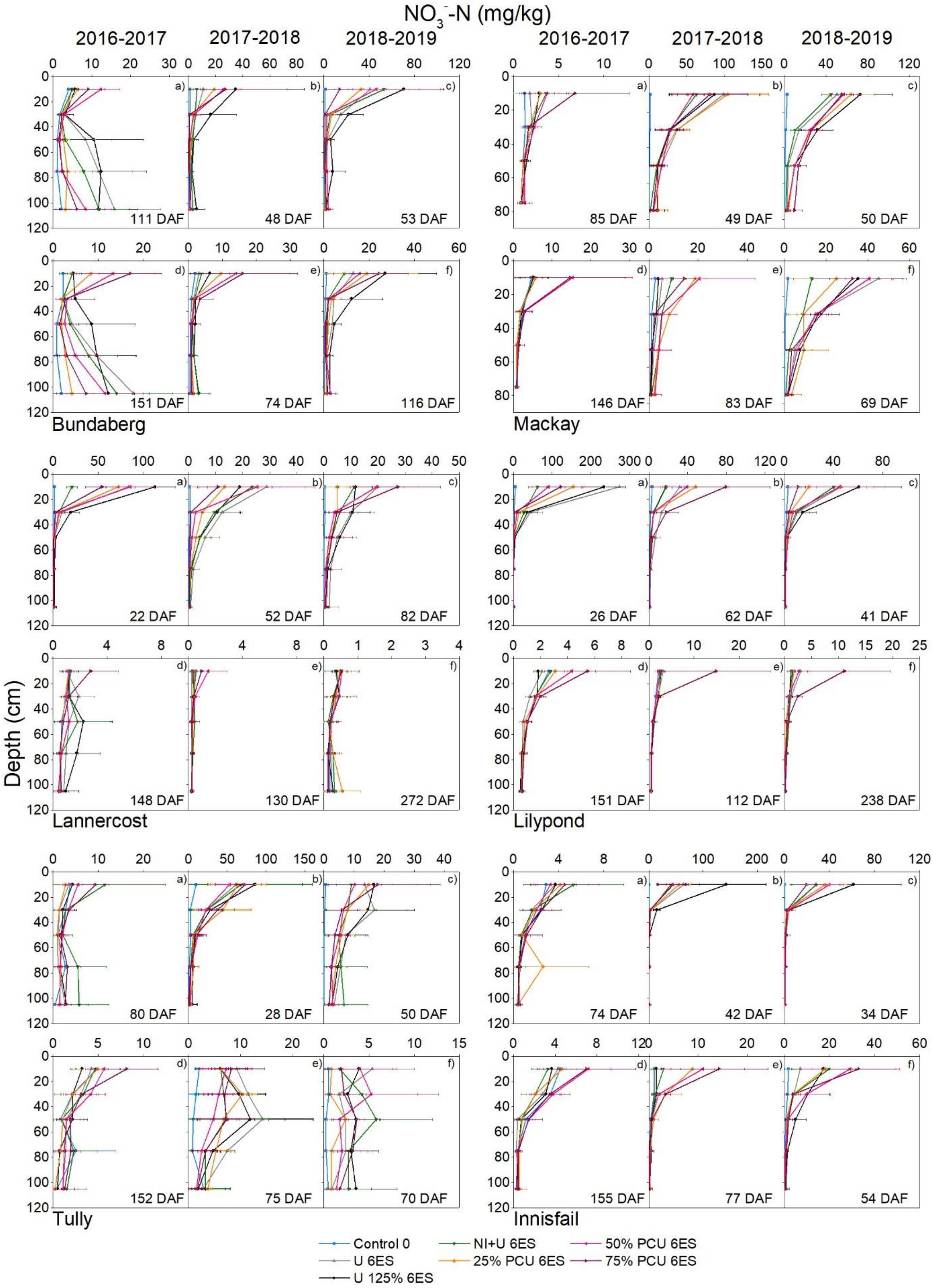

Figure 11. Nitrate (NO_3^-) contents in soil profiles in the early to middle cropping season under different fertiliser N treatments. The error bars are standard deviation.

3.4. Effectiveness of the nitrification inhibitor (DMPP)

The effectiveness of DMPP was assessed by comparing the proportion of soil mineral N as NH_4^+ in the U_6ES and NI+U_6ES treatments, assuming that NH_4^+ or NO_3^- transformation processes other than nitrification were not different between these two treatments in the first few months after fertiliser application. The percentage of soil mineral N as NH_4^+-N differed significantly between different sites (Fig. 12). Soil mineral N was generally dominated by NO_3^- at the Bundaberg site, demonstrating strong nitrification activities in the soil. In contrast, most mineral N existed as NH_4^+ in the Lannercost soil, indicating a weak nitrification capacity. The soil pH was close to neutral at Bundaberg (6.73) and very low (4.94) at Lannercost (Table 1), which could be responsible for the differences in soil nitrification capacity (Meier *et al.* 2006; Sahrawat 2008). Across all sites and years, the soil mineral N pools during the first 1-1.5 months after fertiliser application generally had higher proportions as NH_4^+ in the NI+U than in the urea treatments (Fig. 12). This was particularly evident in the strongly nitrifying Bundaberg soil, but non-significant in the Lannercost soil with low nitrification capacity. These results suggested that DMPP remained effective in these soils for about 1-1.5 months, and that use of NI+U was more beneficial on farms with strongly nitrifying soils than those with weakly nitrifying soils.

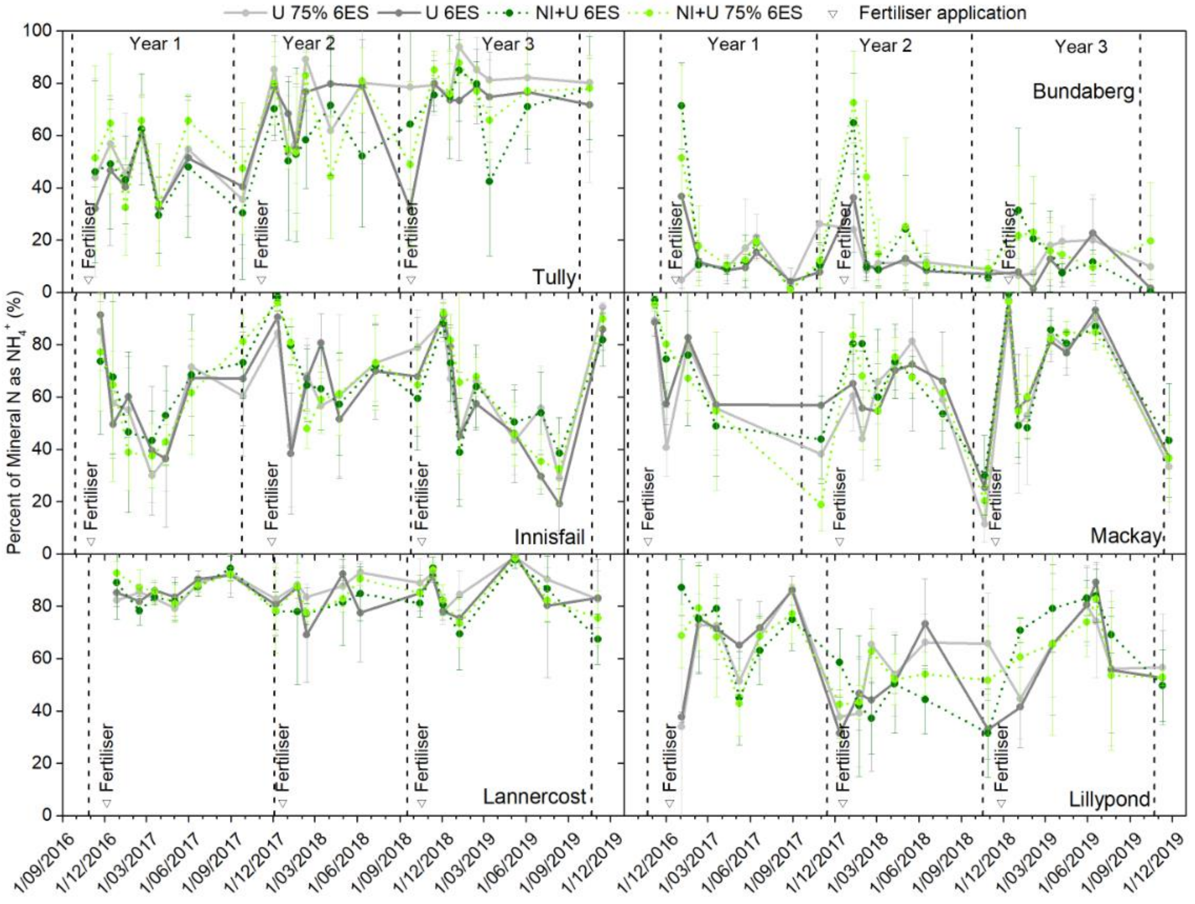

Figure 12. Percentage of soil mineral N as NH_4^+-N (an indicator of soil nitrification capacity) at 0-20 cm soils depth in the urea (U) and nitrification inhibitor-coated urea (NI+U) treatments. The dotted lines were cane harvest dates. The error bars are standard deviation.

The reduction in soil nitrification rates in the NI+U treatments was consistent with our findings in previous studies that use of DMPP-coated urea significantly decreased nitrous oxide (N_2O, a potent greenhouse gas) emissions from Australian sugarcane cropping soils (Wang *et al.* 2016a; Wang *et al.* 2016c). Combined with the results in section 3.3, these observations suggest that different types of EEFs (e.g., NI+U *vs*. PCU) can potentially improve fertiliser N use efficiency through different mechanisms and have different environmental benefits.

3.5. Cane and sugar yields

The effects of treatments on cane and sugar yields varied substantially between sites and between years at the same site (Figs. 13). The treatments did not result in significant variation in CCS%, except between a few treatments at Tully in 2016-7 and at Lilypond in 2018-19 (Spp. Fig. 4).

At Bundaberg, no significant differences in cane and sugar yields were recorded between the treatments in the 2016-17 season. The cane and sugar yields in 2017-18 were much lower than those in the previous season (Figs. 13a, 14a), most likely due to the drought experienced from March to September 2018. Significantly higher yields were obtained in the fertilised treatments than in the 0N treatment in both 2017-18 and 2018-19 seasons ($P < 0.05$). However, the cane and sugar yields were not significantly different between different fertiliser formulations at the same application rate and between different N fertiliser application rates of the same fertiliser in the last two cropping seasons.

At the Mackay site, the EEFs did not show superiority compared to urea. In the 2016-17 and 2017-18 seasons, the cane and sugar yields were significantly higher for the fertilised treatments than the 0N treatment but were not significantly different between different N application rates for the same fertiliser type. There were also no significant differences in the cane and sugar yields between different fertiliser types or PCU percentages in the blends at the same N application rate. In the 2018-19 season, only the U_6ES, U_140% 6ES and 50% PCU_6ES treatments significantly increased yields compared to the 0N treatment ($P < 0.05$). These three treatments also had significantly higher yields than some other fertilised treatments. Reducing fertiliser application from the 6ES rate to 60% of the 6ES rate in the last year did not significantly decrease cane or sugar yields except for the 50% PCU treatment.

For the Lannercost trials, N fertiliser application generally increased cane and sugar yields compared to the 0N treatment, but the yield increases were not statistically significant ($P = 0.15$) in the 2016-17 season (Figs. 13c, 14c). Among the fertilised treatments in 2017-18, urea application at 125% 6ES rate and 50% PCU at the 6ES rate produced similar sugar yields, with 1.9 to 3.9 t sugar/ha higher than the other fertilised treatments (Fig. 14c). However, these two treatments did not show yield advantage compared to other fertilised treatments in 2018-19. At the same N application rates, fertiliser forms and blending ratios had no significant effects on cane and sugar yields in the last year. However, reducing N application from the 6ES rate to 75% 6ES consistently resulted in lower yield regardless of fertiliser forms in both 2017-18 and 2018-19 seasons although the yield reductions were minor and statistically non-significant in most cases.

The treatment effects varied irregularly at Lilypond among the different seasons (Figs. 13d, 14d). Use of EEFs generally resulted in higher yield than the 0N and urea treatments in the 2016-17 season, but only the 50% and 75% PCU_6ES treatments increased yield significantly. All fertilised treatments increased cane and sugar yields in the last two cropping seasons, but no fertiliser formulation or application rate consistently performed better than others. The field trial at Lilypond was inundated for a few weeks following a flood in March 2018, which affected crop growth (as shown by lower yields than the other years) and perhaps responses to the different fertiliser management practices in the 2017-18 season. The experimental site was also wet and often inundated from December 2018 to February 2019. Increasing urea application from the 6ES rate to 125% 6ES and substituting EEF for urea at the 6ES rate did not increase productivity. Nonetheless, cane and sugar yields in the 2018-19 season decreased significantly when the N application rate decreased by 25% from the 6ES rate with urea, but not with EEFs.

At Tully, the yield measurements varied erratically and appeared erroneous for the 2016-17 season. The crops were impacted by serious lodging in 2017-18 and 2018-19 and did not recover until harvesting. The lodging must have affected crop growth as demonstrated by the lower yields in the last two cropping seasons than in the 2016-17 season (Figs., 13e, 14e). The lodging could also have undermined possible treatment effects due to compromised N demand or uptake by the crops and considerable errors in the yield measurements of the lodged crops. Consequently, no significant differences in the cane and sugar yields were observed between the 0N treatment and the fertilised treatments or between fertiliser forms at the same N application rate over the three years, except that the U_125% 6ES treatment resulted in higher yield than most other treatments in 2017-18.

At Innisfail, main effects of fertiliser forms, N application rates and their interactions on cane and sugar yield were recorded in the 2017-18 season (Figs. 13f, 14f). Application of N fertilisers generally increased cane and sugar yields compared to the 0N treatment. Among the treatments receiving EEFs, the 100% 6ES rate resulted in higher, but non-significant in some cases, cane and sugar yields than the 75% 6ES rate. The cane and sugar yields did not differ significantly between urea, NI+U and PCU+U blends at the 75% 6ES rate. However, at the 100% 6ES rate, NI+U and 25% and 50% PCU+U blends significantly increased cane yield compared to the conventional urea treatment. In the 2018-19 season, serious crop lodging occurred at Innisfail. As a result, crop harvesting from the plots was difficult, and the results could carry large errors.

Overall, the efficacy of EEFs varied considerably at different sites in the same year and at the same site in different years (Supp. Fig. 5). Significant yield response to urea application at the 6ES rate was not recorded in 8 of the 18 trials. Furthermore, reducing urea application from the 6ES rate by 25% or 40% did not result in significant yield loss, apart from one trial at Lilypond in 2018-19. Similarly, increasing urea application rate from the 6 ES rate by 25% or 40% significantly increased yield only in 2 out of the 18 trials. Significant cane yield increases from use of EEFs, compared to urea at the same N rate, were recorded only at Lilypond in 2016-17 and at Innisfail in 2017-18 (Fig. 13 d,f). It appeared that the sustained N availability and reduced N leaching under the PCU treatments (Figs. 10, 11) and reduced nitrification in the NI+U treatments (Fig. 12) did not translate into yield benefits in most cases. Lack of yield response to N application or EEF is not uncommon in Australian sugarcane cropping systems (Verburg *et al.* 2014; Thorburn *et al.* 2017; DAF 2020). Possible causes of such results could include: (1) crop growth not being restricted by N availability either in the unfertilised soil or after fertiliser application at ≥ 75% 6ES rate; (2) adverse crop growing conditions (e.g., waterlogging at Lilypond in 2017-18 and 2018-19; drought at Mackay and Bundaberg in 2017-18; lodging at Mackay in 2016-17, at Tully in 2017-18 and 2018-19 and at Innisfail in 2018-19) limiting the yield potential of EEFs; (3) modest crop N demand during the middle to late season; (4) substantial amounts of the fertiliser N moved to deep soil still accessible by the crop roots (i.e., not completely lost); and (5) spatial variability or operational errors (e.g., harvesting of lodged plots). If any of the first four circumstances is expected to occur, use of EEFs would not be recommended.

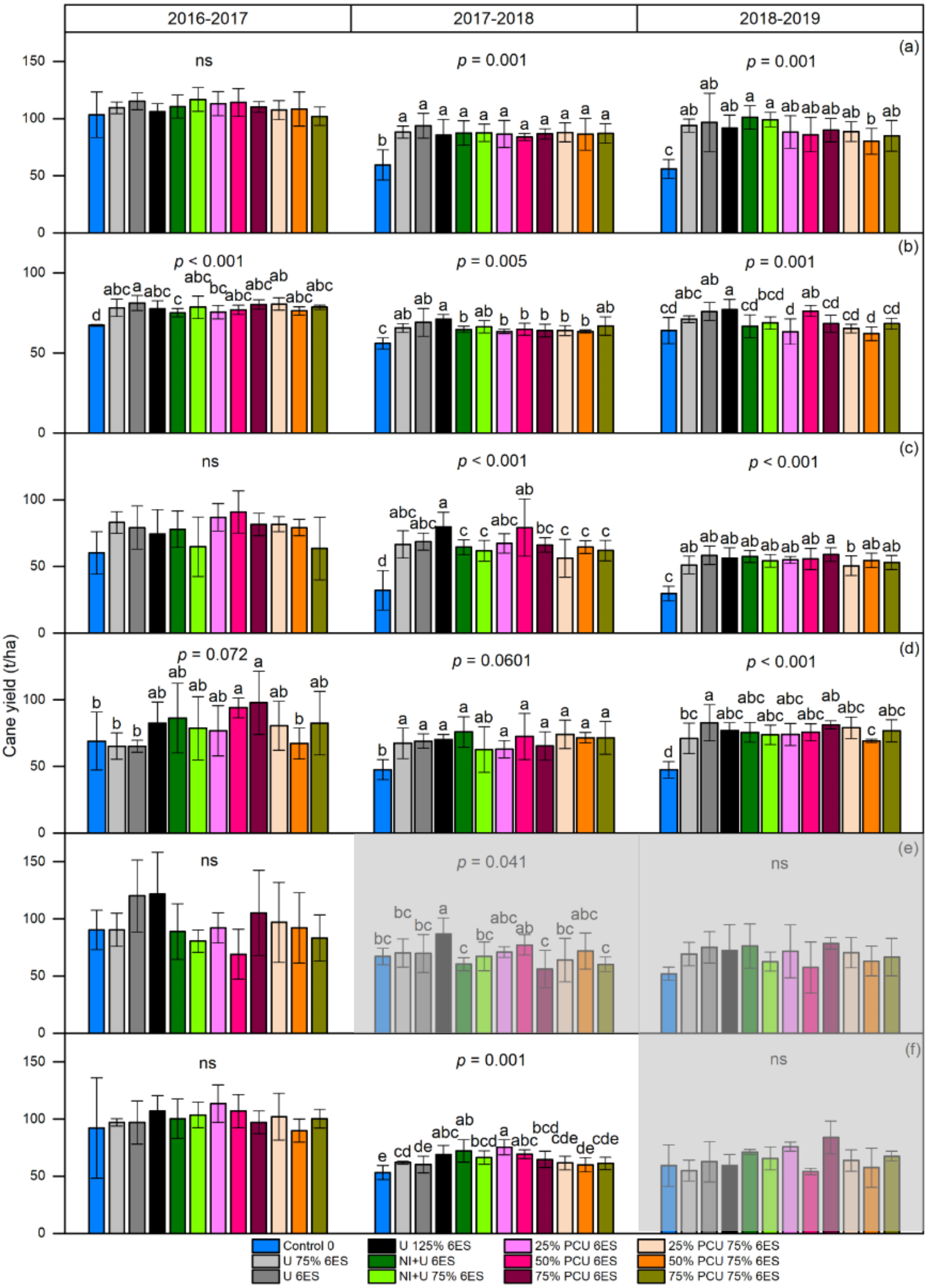

Figure 13. Cane yields under different N application rate, fertiliser forms and percentages of PCU in PCU+U blends across three growing seasons. The shaded graphs show results of the field trials that were severely impacted by crop lodging at Tully and Innisfail. The 75% and 125% 6ES rates were adjusted to 60% and 140% 6ES rates, respectively, at Bundaberg, Mackay, Tully and Innisfail in 2018-19. See Table 3 for the 6ES rate at each site. The error bars are standard deviation.

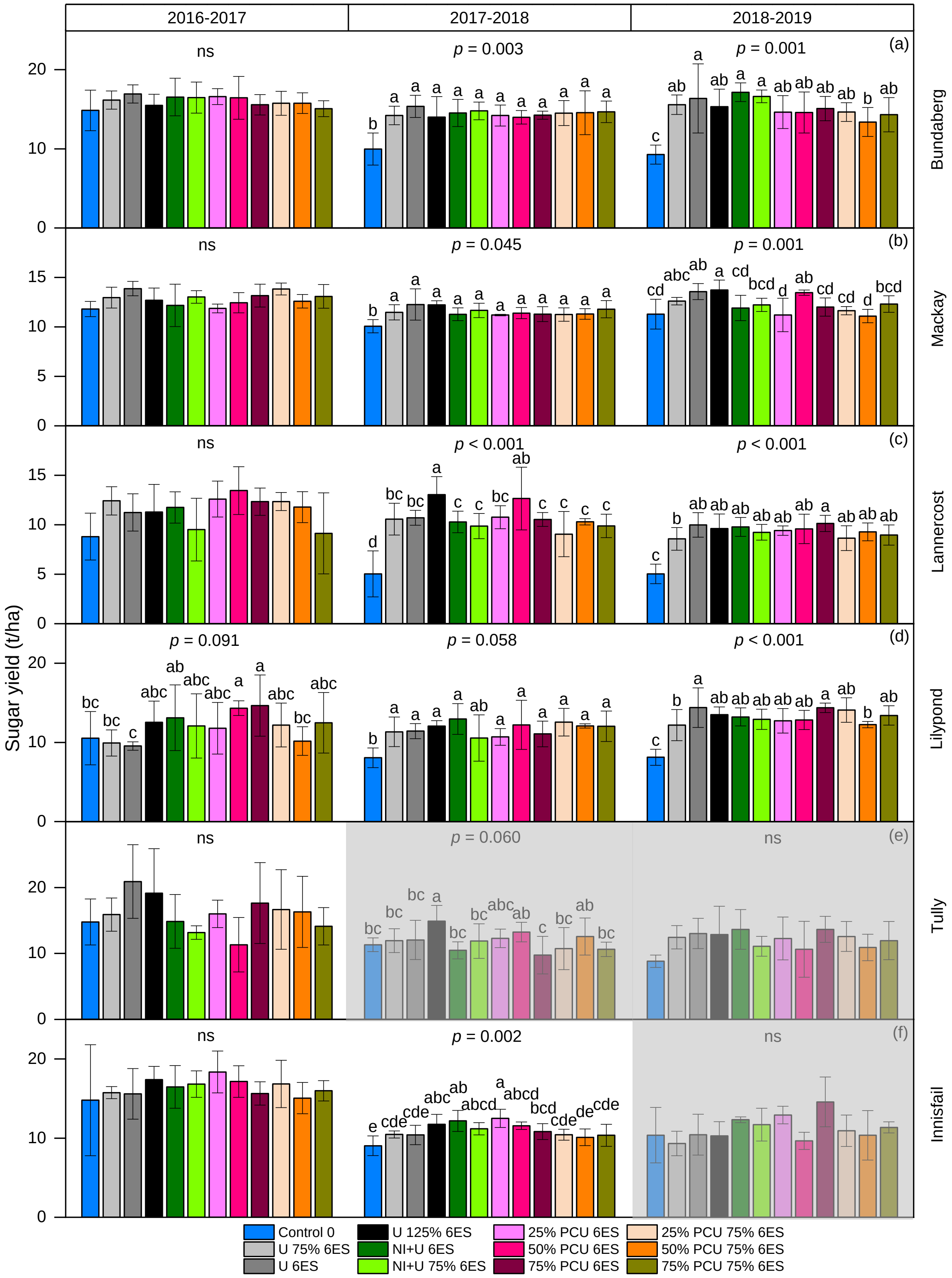

Figure 14. Sugar yields under different N application rate, fertiliser forms and percentages of PCU in PCU+U blends across three growing seasons. The shaded graphs show results of the field trials that were severely impacted by crop lodging at Tully and Innisfail. The 75% and 125% 6ES rates were adjusted to 60% and 140% 6ES rates, respectively, at Bundaberg, Mackay, Tully and Innisfail in 2018-19. See Table 3 for the 6ES rate at each site. The error bars are standard deviation.

3.6. Crop N uptake and fertiliser N use efficiency

Like the crop yields, the aboveground crop N uptakes responded variably to the various N fertiliser formulations and application rates between different sites and at the same site in different years (Fig. 15). The aboveground biomass N in the 0N treatment at each site was generally higher in the 2016-17 season than the following years. These results support the above supposition that the lack of yield responses to different N fertiliser treatments in the first year was at least in part attributable to less- or non-limiting soil N supply. The irrigated crops at Bundaberg on a Ferrosol always had higher aboveground N uptake than the rainfed crops at other sites, which is consistent with the observations of crop yields (Figs. 13 and 14).

At the Bundaberg site, lower aboveground crop N uptake was recorded in the 0N treatment than the fertilised treatments particularly in the last two cropping seasons ($P < 0.05$). The total aboveground biomass N was not significantly different among the fertilised treatments in the first two cropping seasons. In 2018-19, use of urea at 140% 6ES rate or NI+U at 6ES rate resulted in the highest crop N uptake, although such effects were not observed on cane yield (Fig. 13a). There were no significant differences in crop N uptake among the other fertilised treatments, and compared to normal urea, PCU application did not improve crop N use at this site.

At Mackay, all fertilised treatments had higher crop N uptakes than the 0N treatment in the 2017-18 season, but this was not always the case in the other cropping seasons (Fig. 15b). Among the fertilised treatments, different N application rates for the same fertiliser, or different fertiliser forms at the same N rate, did not result in significantly different biomass N at harvest in the first two years. In the 2018-19 season, the highest biomass N was observed for the U_6ES (140 kg fertiliser N/ha) treatment at 84.5 kg N/ha, followed by the 50% PCU_6ES treatment at 74.5 kg N/ha. These two treatments generally had higher crop N uptake than other EEFs applied at the 6ES rate. Applying urea at 140% 6ES did not increase the crop N uptake compared to the 6ES rate. In addition, the crop biomass N did not differ significantly among the different N fertiliser forms (except between 50% PCU and 75% PCU) at the 60% 6ES rate, nor between these treatments and the 0N treatment.

At the Lannercost site, the treatment effects on crop N uptakes also varied considerably, with those for the fertilised treatments significantly higher than the 0N treatment in the 2017-18 and 2018-19 cropping seasons (Fig. 15c; $P < 0.001$). There were no significant differences in the crop N uptake between different N application rates for the same fertiliser, or between different fertiliser forms at the same N application rate in the 2016-17 cropping season. In the 2017-18 cropping season, there was a general trend that N application at the 6ES rate (125 kg N/ha) resulted in higher crop N uptakes than at 75% 6ES regardless of fertiliser types, although the differences were often non-significant. Among the treatments receiving N at the 6ES rate, the 50% PCU had the highest biomass N in the second season. In the 2018-19 cropping seasons, use of 75% PCU at the 6ES rate led to the highest amount of crop N uptake among all the fertilised treatments ($P < 0.05$). When applied at the 75% 6ES rate, different fertiliser forms or blending ratios did not significantly affect the crop N uptakes at Lannercost in all three years.

At Lilypond, no consistent treatment effects on crop N uptake were observed either. All the fertilised treatments had significantly higher biomass N than the 0N treatment in the last two cropping seasons. EEFs generally resulted in higher crop N uptakes compared to urea when applied at 6ES (130 kg N/ha) in the 2016-17 season, although the differences were not always significant at *P*

< 0.05 (Fig. 15d). However, such results were not observed in the following two seasons, with no significant differences in the N uptake between any fertilised treatments in 2017-18. In 2018-19, reducing urea application rate from 6ES to 75% 6ES significantly decreased crop N uptake, but the 125% 6ES rate for urea did not significantly increase crop N uptake compared the 75% and 100% 6ES rates. Like at Lannercost in the 2018-19 season, the crop N uptake increased with increasing percentages of PCU in the PCU+U blends when applied at the 6ES rate, although the PCU blending ratio did not significantly affect the yields at either site in this cropping season. No significant treatment effects were observed among the 75% 6ES treatments, similar to the 2016-17 results.

The crop N uptake measurements at Tully appeared erroneous in all years and were lower than those at other sites in the 2017-18 and 2018-19 cropping seasons (Fig. 15e). There were no consistent treatment effects across the three seasons. Serious crop lodging in the last two years must have adversely affected crop growth and made the crop yield and N uptake measurements more susceptible to operational errors.

At Innisfail, significant differences in the aboveground biomass N between the treatments were observed only in the 2017-18 season. The crop N uptakes were generally higher at the 6ES N application rate than the 75% 6ES rate, except the NI+U treatments that had similar crop N uptakes at the different N application rates. There were no significant differences in the biomass N between different fertiliser formulations or blending ratios at the same N application rate in any season.

The apparent fertiliser N recovery (FNR) by the crops (percentage of fertiliser N recovered in above- and belowground plant biomass; Eq. 1) varied between sites and years. As the fertilised treatments resulted in only moderately higher, and even occasionally lower, crop N uptakes compared to the 0N treatment in the 2016-17 season (Fig. 15), the FNR values for this year appeared erroneous and were sometimes negative. The FNR results for Tully in the last two years and at Innisfail in 2018-19 also had large error bars due to the crop lodging. Consequently, only the FNR results for the remaining trials were examined here (Fig. 16).

Averaged across the treatments over the last two years, the highest FNRs were recorded at Bundaberg (56±20%), followed by Lannercost (29±11%), Lilypond (23±12%) and Mackay (13±8%). These differences between the sites were consistent with the different cane yield responses to N fertiliser application (Fig. 13). The low fertiliser N recoveries, especially at Mackay in the 2018-19 season (9±10%) and Innisfail in the 2017-18 season (15±17%), highlight that large proportions of the fertiliser N were unaccounted for in the aboveground and belowground biomass. Previous studies in Australian sugarcane cropping systems using ^{15}N-tracing techniques found that 17-39% of the fertiliser N was taken up by plants, 13-44% was retained in soil while 28-66% was unrecovered (Chapman *et al.* 1994; Vallis *et al.* 1996; Prasertsak *et al.* 2002).

In addition to the lodged crops at Tully and Innisfail, no significant treatment effects on FNR were recorded in five out the remaining nine trials in the last cropping seasons (Fig. 16). There was a clear trend at Bundaberg in the last two years that FNR was higher at the lower N application rate. At Mackay in 2018-19, the error bars were large compared to the FNR means largely due to the relatively high N uptake for the 0N treatment. At Lannercost in 2018-19, the EEFs tended to result in higher FNRs than the conventional U_6ES treatments, but the increases were generally non-significant apart from that for the 75% PCU at 6ES. Overall, no single EEF treatment consistently outperformed better than others in terms of FNR.

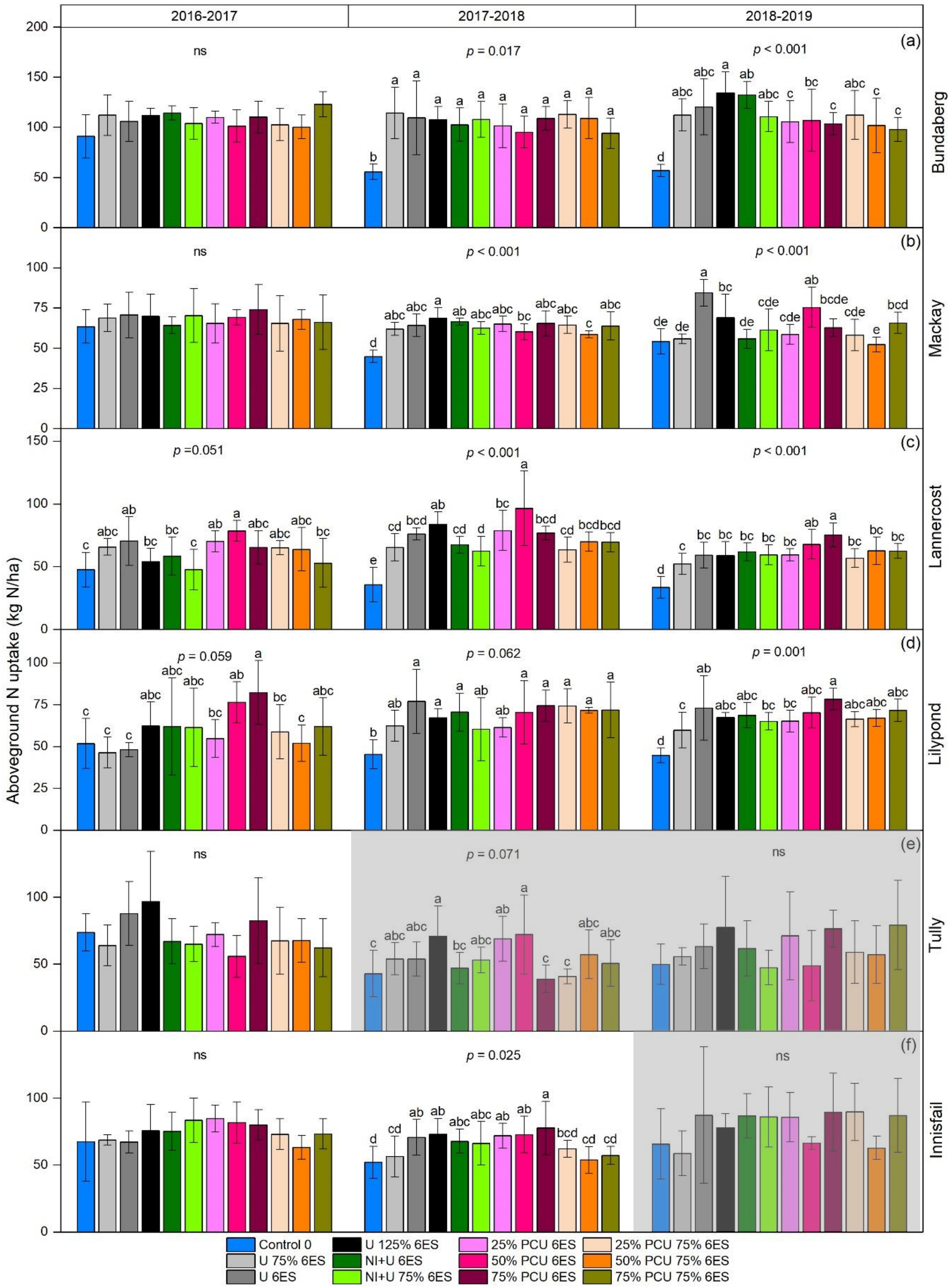

Figure 15. Total aboveground crop N uptake under different N fertiliser management practices. The shaded graphs represent results of the field trials that were severely impacted by crop lodging at Tully and Innisfail. The 75% and 125% 6ES rates were adjusted to 60% and 140% 6ES rates, respectively, at Bundaberg, Mackay, Tully and Innisfail in 2018-19. See Table 3 for the 6ES rate at each site. The error bars are standard deviation.

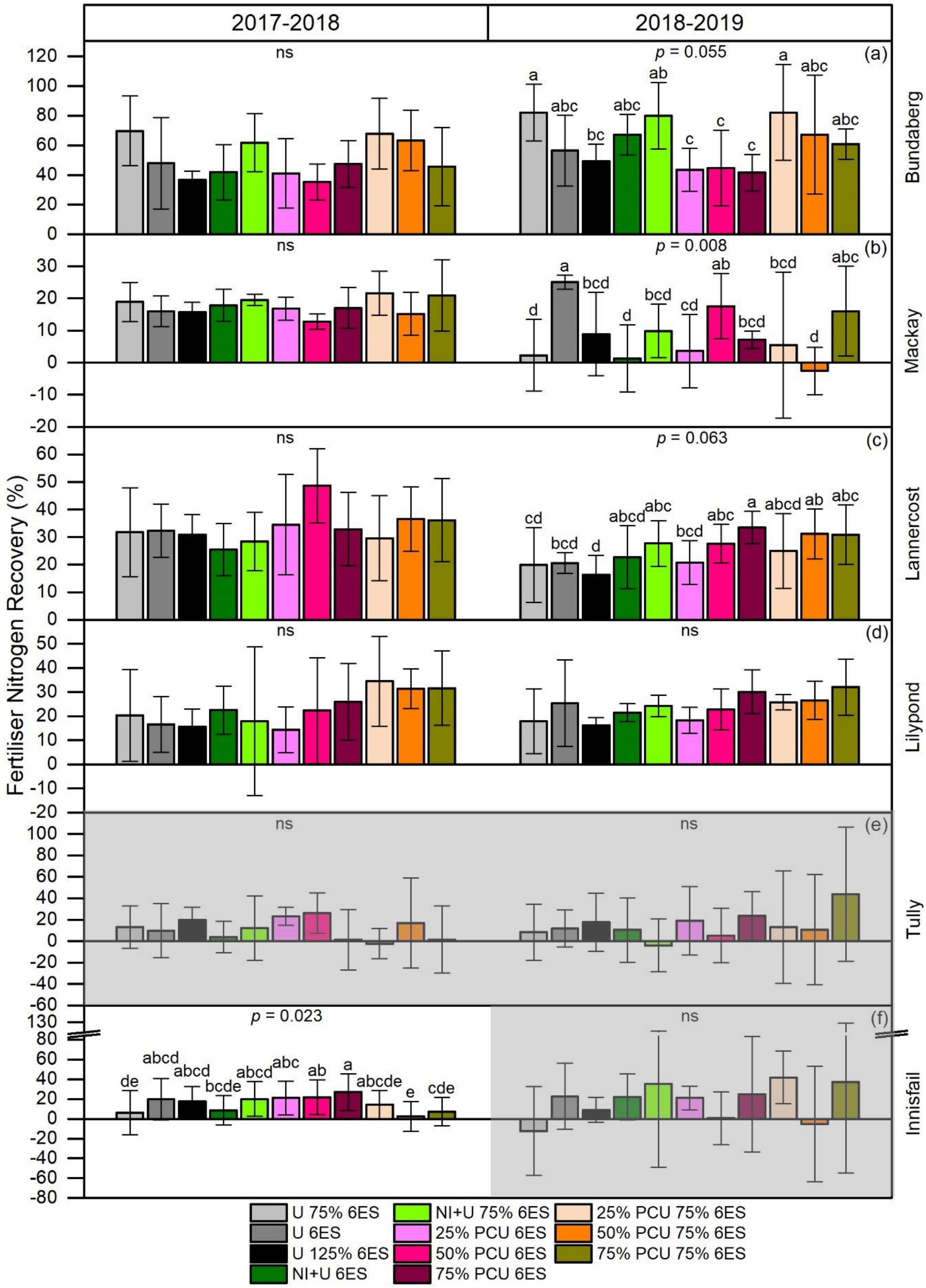

Figure 16. Apparent fertiliser N recovery in plant biomass (including roots) under different N fertiliser management practices. The shaded graphs represent results of the field trials severely impacted by crop lodging at Tully and Innisfail. The 75% and 125% 6ES rates were adjusted to 60 and 140% 6ES rates, respectively, at Bundaberg, Mackay, Tully and Innisfail in 2018-19. See Table 3 for the 6ES rate at each site. The error bars are standard deviation.

3.7. Economic benefits

On average, across all sites and years, urea applied at the recommended 6ES rate costed \$142/ha (product only). Only the urea (\$102/ha), NI+U (\$127/ha) and 25% PCU blend (\$137/ha) applied at the 75% 6ES rates costed less compared to urea at the 6ES rate. The 75% PCU blend applied at the 6ES rate was the most expensive scenario at \$287/ha.

Averaged across all treatments, the highest gross margins were recorded in Tully and Innisfail in the 2016-17 season. However, in the subsequent seasons, gross margins at these two sites declined by up to \$4000/ha, due to poor yield results caused by lodging. Overall, there was no significant ($P < 0.1$) effect of treatments on gross margins at any site in the 2016-17 season (Fig. 17).

At Bundaberg, application of N fertiliser significantly increased gross margins compared to the 0N treatment in the 2017-18 and 2018-19 seasons. However, there was no significant difference between fertilised treatments in 2017-18. In the 2018-2019 season, the PCU treatments tended to have lower gross margins compared to the urea and NI+U treatments. However, only the gross margin for the 50% PCU blend at the 60% 6ES rate was significantly lower than that for the conventional practice of urea at the 6ES rate. NI+U treatments, at 100% and 60% of the 6ES rate, had higher gross margins of +\$249/ha and +\$120/ha, respectively, than the conventional urea at the 6ES rate, although the differences were not statistically significant. There were no significant differences in the gross margin between rates of any fertiliser forms.

At the Mackay site, EEFs tended to have lower gross margins in every year, compared to urea at the 6ES rate. Only the 2018-19 season had significant differences between treatments, with four of the blended PCU treatments and the NI+U_6ES treatment having significantly lower profits than the conventional urea treatment at the 6ES rate. Applying additional conventional urea at 140% of the 6ES rate did not increase the gross margin compared to the 6ES rate. Interestingly, after three years of nil fertiliser application, the gross margin of the 0N treatment is comparable to some of the fertilised treatments.

At the Lannercost site, application of N fertilisers significantly increased gross margins compared to the 0N treatment in 2017-18 and 2018-19. All fertilised treatments had similar gross margins in 2018-19, and gross margins for the NI+U treatments and PCU blends were not significantly different from the U_6ES treatment in 2017-18. The 50% PCU_6ES treatment had a significantly higher gross margin than most other EEFs and, although not statistically significant, also higher than urea at the 6ES rate (+\$621/ha). Increased urea application in the U_125% 6ES treatment, significantly increased the gross margin by \$843/ha, compared to the U_6ES treatment.

At the Lilypond site, fertilised treatments had higher gross margins than the 0N treatment in 2017-18 and 2018-19 but the difference was only statistically significant in the 2018-19 season. Gross margins of all EEF treatments, except 50% PCU_75% 6ES, were not significantly different to urea at the 6ES rate. Decreasing the conventional urea rate from 100% to 75% of the 6ES rate significantly decreased the gross margin by \$788/ha. However, significantly different gross margins were not seen with EEFs at different rates.

At the Tully site, the lodging which likely affected cane yield in the final two seasons also likely obscured treatment effects on gross margins. Fertilised treatments were not significantly

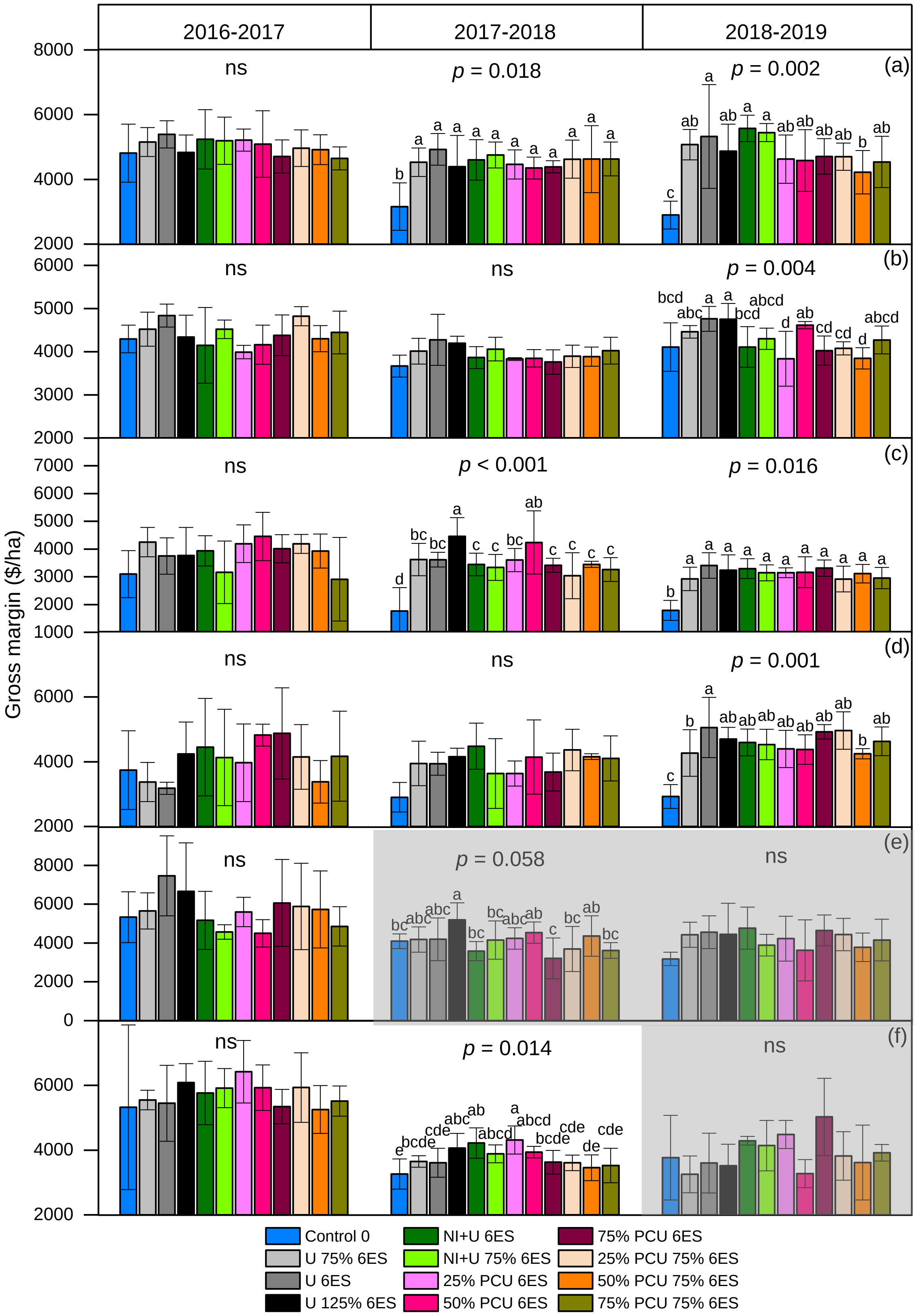

Figure 17. Gross margin in relation to different N fertiliser management practices. The shaded graphs represent results of the field trials severely impacted by crop lodging at Tully and Innisfail. The 75% and 125% 6ES rates were adjusted to 60% and 140% 6ES rates, respectively, at Bundaberg, Mackay, Tully and Innisfail in 2018-19. See Table 3 for the 6ES rate at each site. The error bars are standard deviation.

different to the 0N treatment in any years, except for a significantly higher gross margin associated with the U_125% 6ES treatment in the 2017-18 season.

At the Innisfail site in 2017-18, the NI+U and 25% PCU blend at the 6ES rate significantly increased the gross margin by $608/ha and $702/ha, respectively, compared to urea at the 6ES rate. All other EEF treatments were not significantly different to the U_6ES treatment. The 100% 6ES rate of the 25% blended PCU significantly increased the gross margin compared to the same blend at the lower 75% 6ES rate by $704/ha.

Overall, no individual EEF treatment consistently produced significantly higher or lower gross margins compared to conventional urea at the 6ES rate.

4. Conclusions

Nitrogen accumulation in sugarcane crops generally followed sigmoidal dynamics. The plant N uptake rates for the ratoon crops were low during the first 50-60 DAH, peaked between approximately 90 to 150 DAH and then declined to low levels after about 200 DAH. Therefore, it is important to ensure sufficient N supply to the crops during the high N-demand period between approximately 50 to 200 DAH.

Nitrogen release dynamics from four PCU products applied from late September to December did not differ considerably between different sites. Nitrogen supply from the PCU fertilisers was primarily a function of time and did not vary substantially with the soil and weather conditions within the studied regions and time periods, and thus can be accurately predicted. Therefore, it is possible to manipulate PCU product formulations to better synchronise fertiliser N supply with crop N uptake. Among the four PCU fertilisers tested, the N release rate decreased in the order: Meister-15 = Agromaster Standard > Agromaster Tropical 2018 with 44% N > Agromaster 2017 with 41% N. It appeared that a PCU product with the N release rate between those of the latter two products would match the plant N uptake dynamics more closely for crops harvested in August or latter.

EEFs offer various environmental benefits. The nitrification inhibitor DMPP-coated urea increased the proportion of soil mineral N as NH_4^+ compared to normal urea in nitrifying soils for about 1-1.5 months, which was in line with our previous findings that DMPP-coated urea can significantly reduce nitrous oxide emissions from sugarcane cropping systems. Following application of urea or DMPP-coated urea, soil mineral N contents in the 0-20 cm depth increased immediately but declined to low levels in most circumstances within 2.5-3 months following high rainfall, probably due to N loss in addition to crop uptake, immobilisation and movement in soil. PCU and urea blends consistently maintained higher mineral N contents in the surface 20 cm of soil during the mid to late season compared to normal urea and DMPP-coated urea. Substantial downward movement of NO_3^--N into deep soil occurred at most sites following high rainfall events, particularly in the urea or DMPP-coated urea treatments. Use of PCU can significantly reduce the risk of NO_3^- leaching during the first 2-3 months after fertiliser application.

Use of EEFs resulted in significant increases in cane or sugar yield only occasionally, and no single EEF treatment consistently outperformed conventional urea. Likewise, reducing urea application rate from the 6ES rates by 25% or 40% did not lead to significant yield loss, apart from in one out of the eighteen trials. Increasing fertiliser N application from the 6ES rates by 25% or 40% rarely resulted in significant yield increase too. The lack of yield response to changes in fertiliser formulations and application rates in many circumstances could be due to: (1) crop growth not being restricted by N availability in the soil or following urea application at ≥ 75% of the 6ES rate; (2) adverse crop growing conditions (e.g., waterlogging, drought and lodging in 8 out of the 18 field trials) limiting the yield response to variation in N management practices; (3) modest N demand by crops during the mid- to late season conceding the potential agronomic benefits of sustained N supply from PCU fertilisers; (4) the fertiliser N moved to deep soil still accessible by the crop roots (i.e., not completely lost); and (5) spatial variability or operational errors in sugarcane cropping systems requiring large yield differences for statistical significance.

The decision on the use of EEFs and the PCU to urea blending ratio depends on many factors. Sometimes a choice between the environmental and economic benefits has to be made as it may be difficult to achieve both simultaneously. In terms of fertiliser N supply and plant N demand, use of PCU by itself should be able to meet crop N requirements during the early cropping season. Thus, the benefit of blending PCU with urea is limited to cost saving rather than improved N supply. The optimum blending ratio of PCU to urea needs to be assessed by taking into account N loss risks, soil N availability, the PCU N release dynamics and costs. For paddocks with low to moderate N loss risks during the 3-4 months after fertiliser application, a low percentage of PCU can be used. If the N loss risks are considered very low, use of normal urea will be a more economical option. A decision support tree was developed to assist with selection of N fertilisers, based on the potential environmental, agronomic and economic benefits of EEFs.

Field trials on EEFs in Australian sugarcane cropping systems (including this project) have mainly focused their effects on productivity and profitability, and further studies are required to understand the processes and factors that drive the variability in the efficacy of EEFs. We did not measure N losses through NH_3 volatilisation, denitrification and runoff from different types of fertilisers in this project. Such information would be useful for improved understanding of the variability of yield responses to different treatments and for a comprehensive assessment of the environmental implications of different management practices. We suggest that coordinated and comprehensive review, analysis and modelling of all data collected in the completed and current EEF experiments in Australian sugarcane cropping systems should be undertaken. This will help improve the decision tree or develop a more robust and user-friendly decision support tool through better understanding of the complex factors, processes and their interactions affecting performance of EEFs under different land and weather conditions and management practices.

5. Decision tree for choosing EEFs

A decision tree has been developed to assist growers and advisors with EEF selection (Fig. 18) This was built on the previous work of L. Di Bella (personal communication; 2016) and Verburg *et al.* (2019) for the Herbert region and R. Dwyer (personal communication; 2018) for ENTEC use (DMPP-coated urea), findings from the field trials in this project, as well as our best understanding of N cycling and regulating factors in agricultural ecosystems. As more results from EEF studies in Australian sugarcane cropping systems become available, this decision tree may need to be refined and expanded based on new scientific evidence and wider consultation.

Apart from the potential yield benefits of EEFs, their environmental benefits such as the lower leaching risks with PCU and the lower nitrous oxide emissions (thus possibly lower denitrification risks) with nitrification inhibitors were also considered. Recently, concerns have been raised over the potential environmental impacts of non-biodegradable plastic polymer coatings used in many PCU products (including those tested in this project). This issue is beyond the scope of this study and is not considered in the recommendations of the decision tree. However, users are encouraged to make their own decisions in this regard.

The decision tree consists of a series of questions and decisions. The rationale for each decision in response to a question is explained below. Given the higher prices of EEF products (NI+U and PCU products are approximately $120 and $600 per tonne more expensive than urea, respectively), EEFs are not recommended in circumstances where the likelihood to generate better agronomic and/or environmental outcomes is considered low.

Q1: Do you have to apply N fertiliser on the surface?

Surface application of urea can result in substantial N loss through ammonia (NH_3) volatilisation (Freney *et al.* 1994; Prasertsak *et al.* 2002) because urea hydrolysis can elevate soil pH near the fertiliser granules to > 9. If possible, urea should be incorporated into soil (about 7-10 cm deep) and the fertiliser slit should be surface-sealed with a press wheel to minimise NH_3 volatilisation. In circumstances where N fertiliser has to be placed on the ground surface (e.g., stony or hard ground), ammonium (NH_4^+)-based fertilisers such as ammonium sulphate can be used on acidic to neutral soils to avoid NH_3 volatilisation as these fertilisers do not increase soil alkalinity, but rather increase acidity through nitrification. NO_3^--based fertiliser such as liquid calcium nitrate can also be considered, so long as high rainfall is not expected, which otherwise may cause NO_3^--N loss through leaching/runoff/denitrification. A blend of ammonium- and nitrate-based fertilisers, particularly those in liquid, also offers a low-risk option for surface application. If none of the above products is available, urea can be applied shortly before a moderate irrigation. The irrigation water can dissolve and wash the surface-applied urea into soil. However, caution should be exercised not to irrigate excessively to avoid urea loss through leaching as soil particles cannot hold urea molecules firmly. Applying urea before a moderate rainfall event (~ 15-50 mm) can be considered, but this practice may carry a degree of risk associated with weather forecast as low rainfall would not be adequate to bring the urea into soil while high rainfall could lead to urea leaching and/or runoff. Alternatively, urea impregnated or coated with a urease inhibitor can reduce NH_3 volatilisation by 25-40% compared to normal urea when applied over the cane trash layer (Cantarella *et al.* 2008; Mira *et al.* 2017). It should be noted that urease inhibitor-treated urea is much less effective in mitigating NH_3 volatilisation compared to ammonium- and nitrate-based fertilisers (Cantarella *et al.* 2008), particularly when applied over the cane trash where urease activity is usually greater than in soil. PCU is not recommended for surface application as the fertiliser granules are not soluble in water and can be easily washed away. Nitrification inhibitor-coated urea should not be surface-applied either because nitrification inhibitors may increase NH_3 volatilisation from surface-applied urea due to increases in both NH_4^+ concentration and soil pH around the urea granules.

Q2: Will you split N applications?

Split N fertiliser applications can minimise excessive accumulation of fertiliser N in soil during the early cropping season. When feasible to implement (such as for plant cane), this technique can significantly reduce the risk of fertiliser N loss, compared to a single application. Consequently, the potential benefits of using EEFs may be relatively low under normal farming conditions. If high rainfall is expected after one of the fertiliser applications, for instance with late planted crops, EEFs can be considered depending on the site and weather conditions as described below.

Q3: Will high rainfall (> 60 mm/d) or excessive irrigation be expected within 2-3 months after fertilising?

If no high rainfall or excessive irrigation is expected in the first 2-3 months after fertiliser application, the risk of substantial N loss is considered low. In such cases, use of EEFs can have limited benefits. The rainfall threshold of > 60 mm/d is indicative only, assuming the soil is sandy loam with a water content prior to rainfall at approximately half of the field capacity. This threshold should be adjusted by taking into account soil water content, soil texture, water-holding capacity and rainfall intensity. The volumetric soil moisture content at field capacity is approximately 1.5 to 2.5 mm/cm for sandy soils, 3.5 to 4.5 mm/cm for loam soils, and 4.5 to 5.5 mm/cm for clay soils (https://nrcca.cals.cornell.edu/soil/CA2/CA0212.1-3.php). Assuming the soil water content before rainfall is about half of the field capacity (drained upper limit), the amount of rainfall that can be held in the 0-40 cm depth would be approximately 30-50 mm, 70-90 mm and 90-110 mm for sandy, loamy and clayey soils, respectively. As soil profiles usually contain various amounts of water immediately before a rainfall event, the actual amount of rainfall that can be held in the 0-40 cm soil without causing significant N leaching through deep drainage would need to be adjusted accordingly.

Q4: Is the soil light textured (sandy) and therefore subject to nitrate leaching?

Based on observations in this project (Section 8.3.3), both normal urea and nitrification inhibitor-coated urea can be readily leached out of the main crop root zone in well-drained soils when high rainfall happens in the first 2-3 months after fertiliser application. PCU can effectively reduce the risk of N loss from leaching or runoff at least in early stages of the wet season (Li *et al.* 2018a; Verburg *et al.* 2019; Fig. 11) and probably be most beneficial in such situations. Blended use of PCU and urea can be considered as a cost-saving measure, but the urea-N may be susceptible to leaching and runoff losses. Thus, the higher the probability of high rainfall following fertiliser application, the lower the proportion of normal urea that should be used in the blend.

Q5: Is the soil heavy textured (clayey) or duplex and subject to water logging for more than a few days?

If the soil is moderately well drained and not subject to significant leaching or waterlogging, the risk of substantial N loss through leaching is relatively low but moderate to high denitrification may occur. In such cases, NI+U or PCU+U blend can be used at the recommended rate as a more economical option compared to use of PCU alone.

Q6: Is the soil very acidic (pH < 5.0) with low nitrification?

Many studies found that nitrification was relatively slow in acidic arable soils with pH < 5.0, and the bacterial ammonia oxidizers isolated from soils could not grow in standard laboratory medium with a pH < 5.5 (De Boer and Kowalchuk 2001; Sahrawat 2008). Anecdotal observations also showed low nitrification rates in Australian sugarcane cropping soils with pH < 5.0 (Section 8.3.4; Wang *et al.* 2016b). The weak nitrification capacity in acidic arable soils could be due to the limited availability of the substrate ammonia (NH_3) for the ammonia monoxygenase enzyme of nitrifying microbes or due to aluminium toxicity. However, some studies have detected considerable nitrification in acidic forest or tea fields with pH < 5.0 (Li *et al.* 2018b). Further investigation is required to verify the critical pH threshold for nitrification in Australian sugarcane cropping soils.

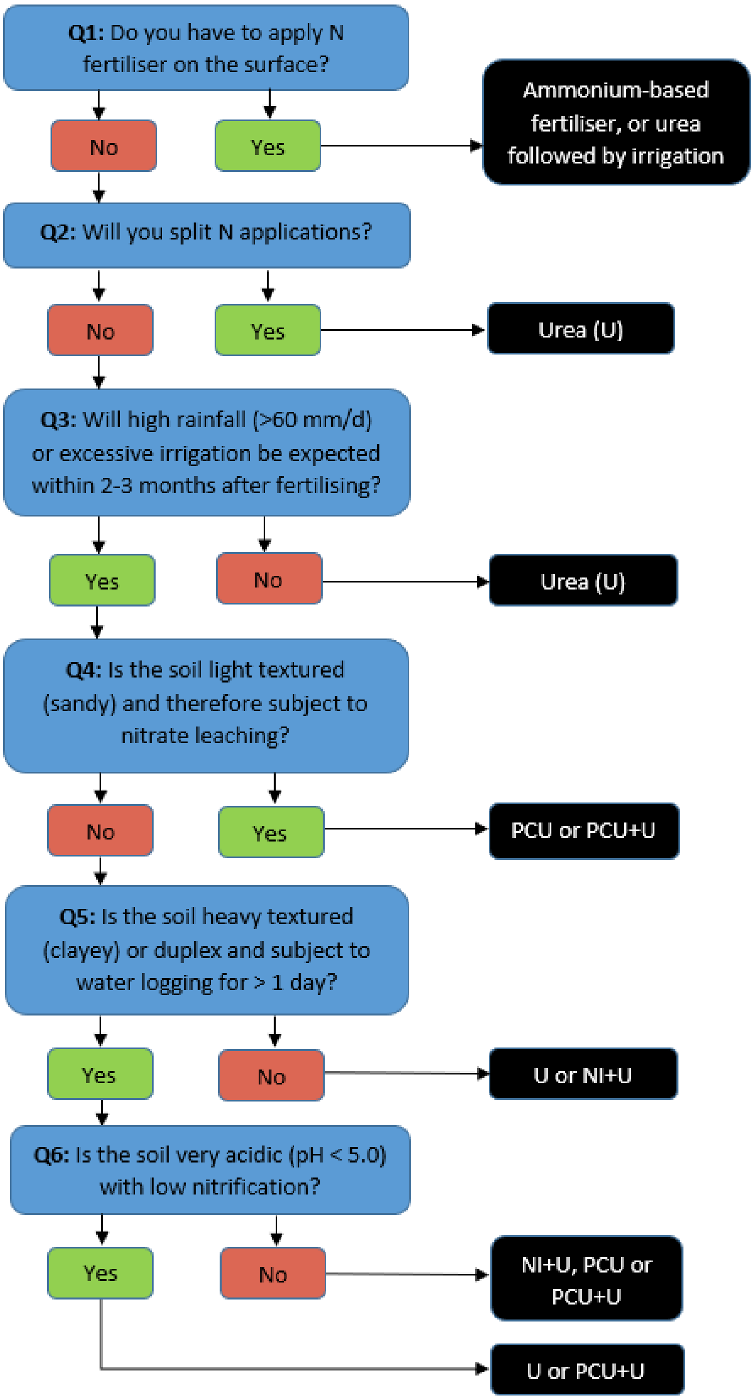

Figure 18. A simplified decision tree for selection of nitrogen fertilisers based on possible agronomic and environmental benefits and costs. Users should refer to the detailed instruction to each question in the text. U: urea; PCU: polymer-coated urea; PCU+U: blended PCU and urea; NI+U: urea with a nitrification inhibitor.

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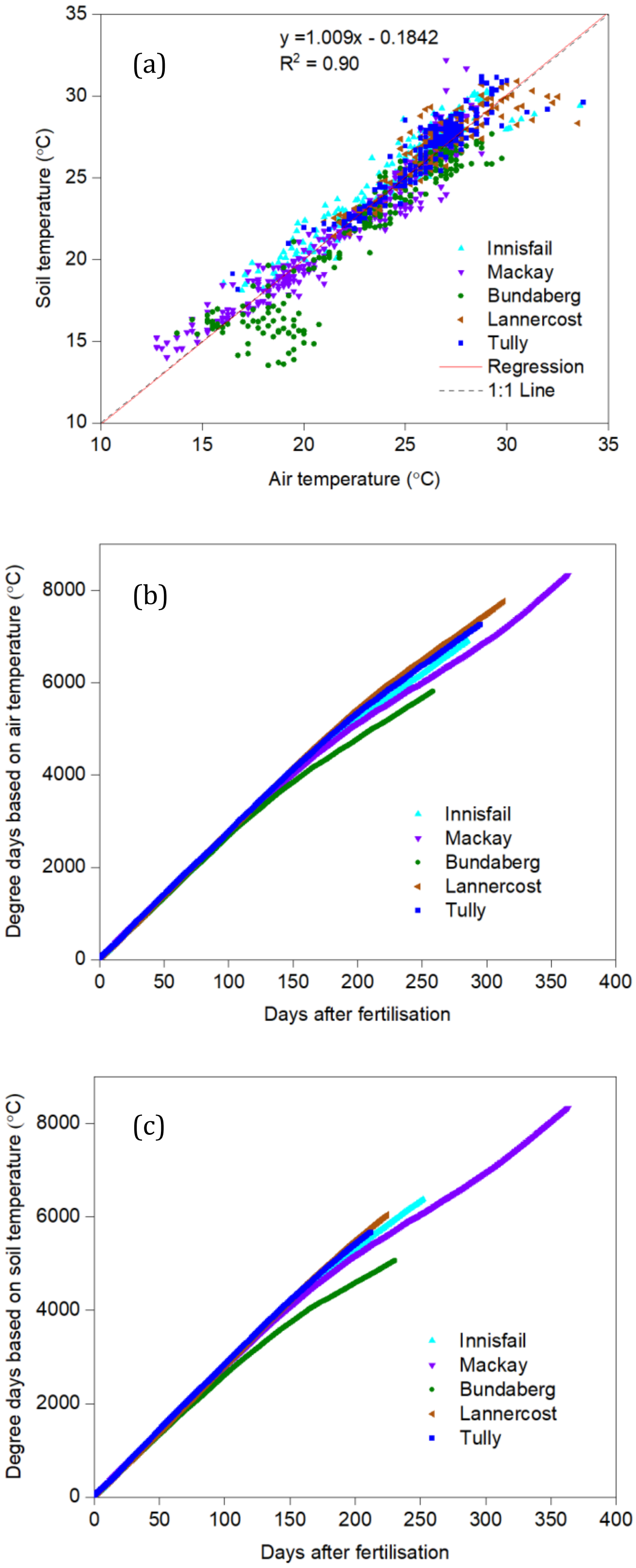
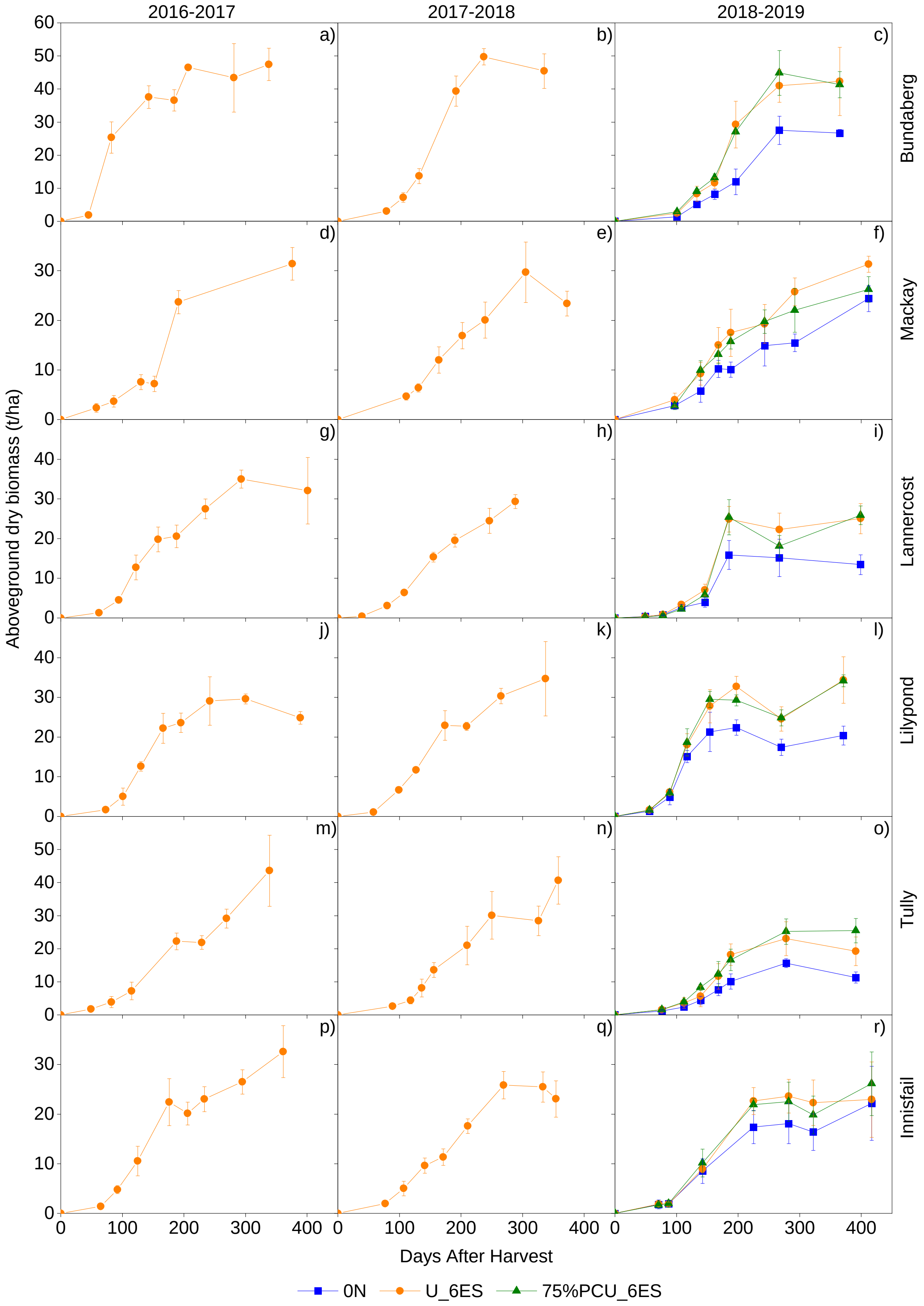
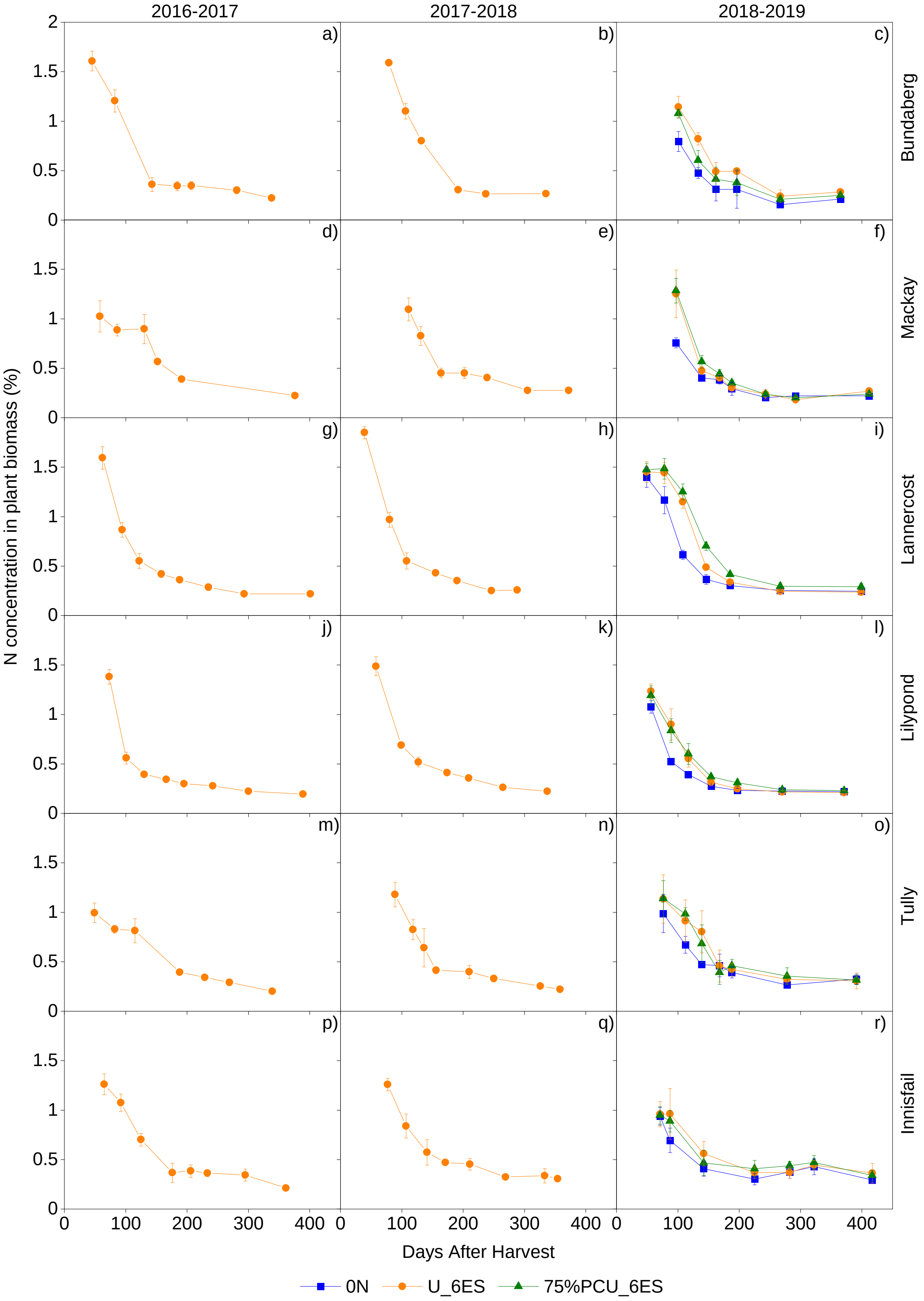
7. Supplementary figures



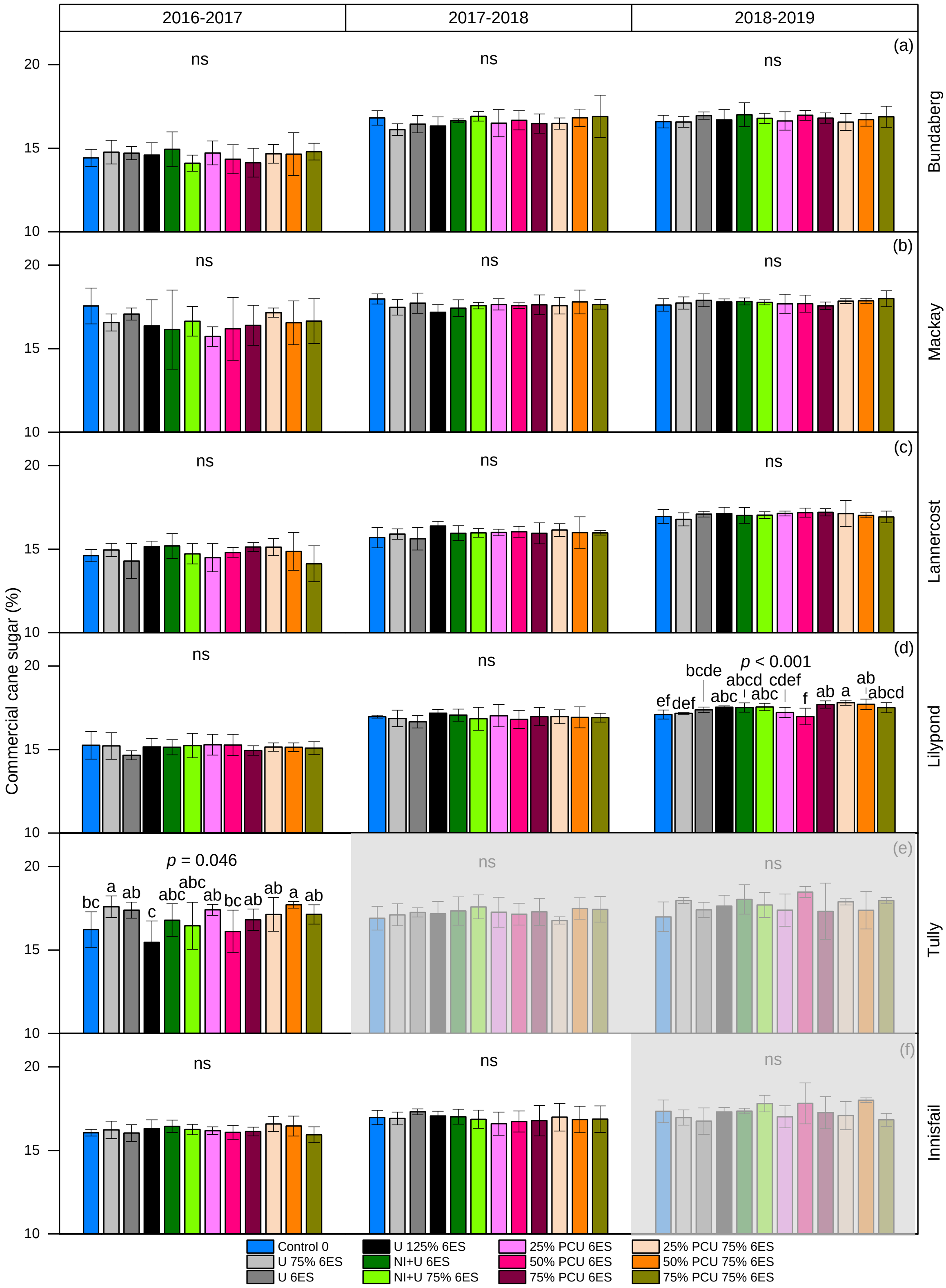
Suppl. Figure 1. Similarity between daily soil temperature at a depth of 10 cm and air temperature and between degree days calculated with air and soil temperature in the 2018-19 season.



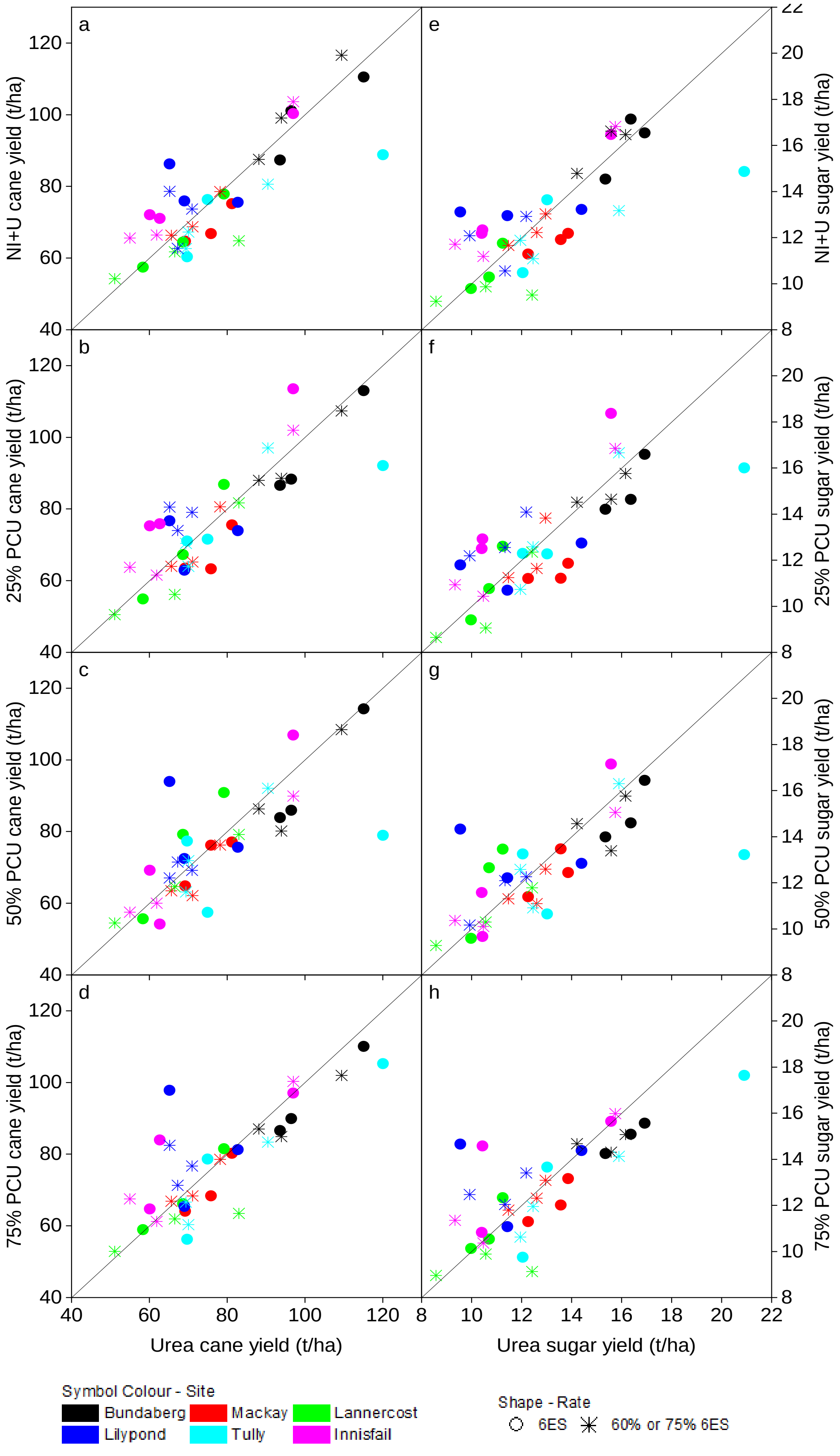
Suppl. Figure 2. Dynamics of aboveground plant biomass in selected treatments. See Table 3 for the 6ES rates at each site. The error bars are standard deviation.



Suppl. Figure 3. Dynamics of N concentration in the aboveground plant biomass in selected treatments. See Table 3 for the 6ES rates at each site. The error bars are standard deviation.



Suppl. Figure 4. Commercial cane sugar (CCS%) content under different N fertiliser management practices. The shaded graphs represent results of the field trials severely impacted by crop lodging at Tully and Innisfail. The 75% and 125% 6ES rates were adjusted to 60% and 140% 6ES rates, respectively, at Bundaberg, Mackay, Tully and Innisfail in 2018-19. See Table 3 for the 6ES rate at each site. The error bars are standard deviation.



Suppl. Figure 5. Comparison of cane (a-d) and sugar (e-h) yield responses to EEFs vs. standard urea at the same N application rate. See Table 3 for the 6ES rate at each site.