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Impact on crop performance of application timing of nitrogen fertiliser and interaction with harvest time

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Abstract In the Wet Tropics, fertilisation of early-harvested crops is often delayed as ratoons are slower growing and growers focus on land preparation, sugarcane planting operations and early crop establishment. However, as the harvest season progresses and the risk of experiencing high rainfall increases, fertilisation often occurs immediately behind the harvester. A trial was established on a clay loam soil at Tully to explore the impact of nitrogen (N) fertiliser application timing on a range of crop traits including N uptake, yield, and nitrogen-use efficiency (NUE). Treatments included three different application times (3-, 6- and 8-weeks post-harvest) and four N application rates (0, 80, 130 and 180 kg N/ha). An additional treatment (harvest time) was established in the second-ratoon crop. This allowed the effect of fertiliser application time to be assessed for ratoon crops established at different times of the harvest season (e.g, early versus late). There were statistically significant differences in crop traits associated with N rate and the timing of fertiliser application. For the early-harvested crop, there were no adverse effects on yields or NUE from delaying N fertiliser application up to 8 weeks after harvest. There was no statistically significant difference in yield or crop N uptake for fertiliser application timing in the late-harvested crop. The outcome of this research supports existing grower practices in the Wet Tropics region whereby fertiliser application is often delayed to crops harvested early in the season but applied immediately after harvesting crops ratooned late in the season.

Key words Wet Tropics, nitrogen, application timing, response

INTRODUCTION

Nutrient-management research has mostly focussed on opportunities to sustainably improve nitrogen (N) fertiliser management by better matching N supply to crop demand (Schroeder *et al.* 2014; Thorburn et al 2018). This has included investigating N fertiliser requirements for different soil types and locations (Salter *et al.* 2008; Wood *et al.* 2008; Schroeder *et al.* 2009; Skocaj et al 2012), climatic conditions (Skocaj 2015) and new fertiliser technology (Bell *et al.* 2019; Panitz and Schroeder 2020; Connellan *et al.* 2022). However, in-field management practices, including the timing of N fertiliser application to the crop, are also important for optimising crop N uptake and reducing N losses to the environment (Calcino 2018). Applying fertiliser too early or too late can increase the risk of N losses. Where N fertiliser is applied subsurface, it is advisable to wait until the crop has emerged and is actively growing. If practical, fertilisation may be delayed for up to 6 weeks after harvest unless adverse weather conditions are expected to impact the crop, or the crop is harvested late in the season (Calcino 2018). For late-harvested crops, it is advisable to apply fertiliser straight after harvest (Calcino 2018).

Throughout the Wet Tropics region, fertilisation of early-harvested crops is often delayed as ratoons are slower growing and growers focus their efforts on land preparation, planting, and early crop establishment activities in

other blocks. However, as the harvest season progresses and the risk of experiencing high rainfall increases, fertilisation often occurs soon after harvesting, especially for late-harvested crops. Late-harvests often coincide with the onset of the wet season where high rainfall can increase soil moisture content and reduce field trafficability potentially preventing the operation of fertilisation equipment for extended periods. These conditions also increase the potential for high N losses.

A study at Mackay found no statistically significant difference between applying N fertiliser approximately 2 or 10 weeks after planting/harvest on N uptake, nitrogen-use efficiency (NUE) and crop performance (Salter and Kok 2023). However, it did not investigate the impact of harvest time on the timing of N fertiliser application. Here, we report on a concurrent field experiment conducted at Tully, investigating the impact of N fertiliser application timing on crop performance and interaction with harvest time, in a rainfed farming system.

METHODOLOGY

The trial site was located at the Sugar Research Australia (SRA) Tully Station (17° 58′ S, 145° 55′ E) on a clay loam soil of the Bulgun series (Murtha 1986). The trial was arranged as a randomised complete-block design in the first ratoon (1R) and as a split-plot design in the second ratoon (2R) with harvest time as the main plot and N application time and N rate as sub-plots. Data related to each harvest time were analysed separately to ensure meaningful interpretation. There were four replicates in the 1R and two replicates in the 2R (due to the introduction of different harvest times).

Sugarcane cultivar Q240$^{\phi}$ was planted on 2 September 2018 following an almost 8.5 month sprayed-out bare fallow. The site was zonally cultivated using a wavy disc and rotary hoe immediately prior to planting. Using the soil-test organic carbon (OC %) value and the SIX EASY STEPS^{TM} N guidelines for the Wet Tropics region (Schroeder *et al.* 2007), the plant crop had a N requirement of 100 kg N/ha following a bare fallow. A total of 37 kg N/ha was applied at planting. The total amount of N fertiliser applied to the plant crop was greatly reduced to minimise the potential for residual N (from an experiment conducted in the previous crop cycle) to influence crop responsiveness in the subsequent ratoons. Crop responses to applied N were assessed in the 1R and 2R crops. The timing of sampling events and operations are provided in Table 1.

Table 1. Timing of management and sampling events at the Tully N fertiliser application timing trial site in relation to crop harvest date (DAH refers to days after harvest).

Crop class and activity	Date	DAH		
Plant crop establishment	2/09/2018	-		
Harvest (of plant crop)	27/09/2019	390		
1R crop				
Soil sampling	19/10/2019	5		
N application 1	14/10/2019	10		
N application 2	11/11/2019	38		
N application 3	4/12/2019	61		
Crop N assessment (3 month)	17/12/2019	74		
Leaf sampling	20/03/2020	168		
Crop N assessment (6 month)	24/03/2020	172		
Crop N assessment (9 month)	6/07/2020	276		
	Eary harvest treatment		Late-harvested treatment	
	Date	DAH	Date	DAH
Harvest (of 1R crop)	18/07/2020	288	16/10/2020	378
2R crop				
N application 1	11/08/2020	24	9/11/2020	24
N application 2	27/08/2020	40	27/11/2020	42
N application 3	15/09/2020	59	11/12/2020	56
Crop N assessment (3 month)	26/10/2020	100	25/01/2021	101
Leaf sampling	n/a	-	25/03/2021	160
Crop N assessment (6 month)	20/01/2021	186	29/03/2021	164
Crop N assessment (9 month)	24/05/2021	310	02/08/2021	290
Crop N assessment (12 month)	05/08/2021	383	18/10/2021	367
Harvest (of 2R crop)	15-16/11/2021			
Soil sampling	30/11/2021			

Following harvest of the plant crop on 27 September 2019, three N application times (2-3 weeks [1], 6 weeks [2] and 8 weeks [3] after harvest) and four N rate treatments (0, 80, 130 and 180 kg N/ha) were imposed in the 1R crop. These were continued into the 2R crop. Nitrogen was applied as urea subsurface beside the stool using a side-dress applicator. Nutrients other than N were applied according to the results of soil tests and using the SIX EASY STEPS nutrient management guidelines for the Wet Tropics region.

An additional treatment (harvest time) was established in the 2R crop. This allowed the effect of application time to be assessed for ratoon crops established at different times throughout the growing season (e.g, early versus late). The early-harvested treatment was imposed on 18/07/2020, whereas the late-harvested treatment was imposed on 16/10/2020.

A 200 mm mid-section from the third leaf was collected from 20 stalks in each plot around 160 days after harvest according to the industry standard leaf sampling procedure (Schroeder *et al.* 2007). Samples were oven-dried at 60°C and sent to the SRA laboratory for analysis. Third-leaf samples were not collected for the early-harvested treatment in the 2R crop due to persistent rainfall between 24 December 2020 and 28 February 2021. As there were only 14 days where no rainfall was recorded, conditions were not favorable for active crop growth and the crop suffered moisture stress due to prolonged waterlogging. Leaf analysis results are not reliable if samples are collected from plants suffering from moisture stress (Schroeder *et al.* 1999; Skocaj *et al.* 2020).

At 9 months (1R crop) and 12 months (2R crop), the total number of stalks for two 10 m lengths of row in the centre of each plot were counted to determine stalk population. Twenty stalks were randomly selected and cut off at ground level from each plot. These stalks were weighed and partitioned into two components: millable stalk; green leaf and cabbage. The individual components were then weighed to allow the percent millable stalk and percent green leaf and cabbage to be calculated. Total fresh biomass was calculated by combining stalk number, stalk weight and the percentage of each crop component. A sample from each crop component (n=6) was mulched with a garden chipper-shredder (Greenfield Peacemaker). A subsample of the mulched material was weighed, placed into an oven set at 60°C and reweighed after drying for the calculation of moisture content and dry biomass. Dried samples were ground (<2 mm) and analysed for total % N content (Dumas).

Six-stalk samples were randomly collected from each plot for the determination of commercial cane sugar (CCS) using near infrared spectroscopy (Berding *et al.* 2003). Sugar yields (t sugar/ha) were calculated from the cane yield and CCS values.

Two N-use efficiency (NUE) factors were calculated from data collected from crop N and biomass assessments:

- Nitrogen Loss Reduction Index (NiLRI) (Thorburn *et al.* 2022) = N application rate (kg/ha)/Cane yield (t/ha)
- Fertiliser N uptake efficiency (NUpEFert) = (Crop N (kg/ha) for fertilised N rate – Crop N (kg/ha) for nil N rate) / N fertiliser rate (kg/ha)

Rainfall figures were based on data accessed from the Bureau of Meteorology (BOM) website for Tully Sugar Mill (Station 32042).

RESULTS AND DISCUSSION

Weather

The timing and amount of rainfall following fertilisation can impact crop growth, responsiveness to applied N and potential for N loss. In the 1R crop, monthly rainfall (Figure 1) tended to be below the long-term average (except for May), especially in the months immediately following N fertiliser application (September 2019 to February 2020). Total annual rainfall was well below the long-term average for Tully and spring-summer rainfall (734 mm) was also well below the threshold used to categorise wet years (Skocaj 2015).

Rainfall increased in the 2R crop with total annual rainfall well above the long-term average for Tully (Figure 1). Total spring-summer rainfall (2846 mm) was also well above the threshold used to categorise wet years (Skocaj 2015). Higher daily rainfall totals were frequently experienced soon after applying N fertiliser to the late-harvested crop (for all application times) compared to the early-harvested crop. In the early-harvested crop, the first major rainfall event (>100 mm) was experienced 101 days after fertiliser application time 3, whereas in the late-harvested crop, the first major rainfall event was experienced 44 days after fertiliser application time 3. During the first approximately 120 days following the application of N fertiliser, the late-harvested crop experienced higher daily rainfall compared to the early-harvested crop. For application time 3, a total of 2892 mm was recorded in the first 120 days following N fertilisation of the late-harvested crop, compared to only 406 mm for the early-

harvested crop. Given the amount, timing and distribution of rainfall experienced by the 2R late-harvested crop, the likelihood of N loss was higher than the 2R early-harvested crop.

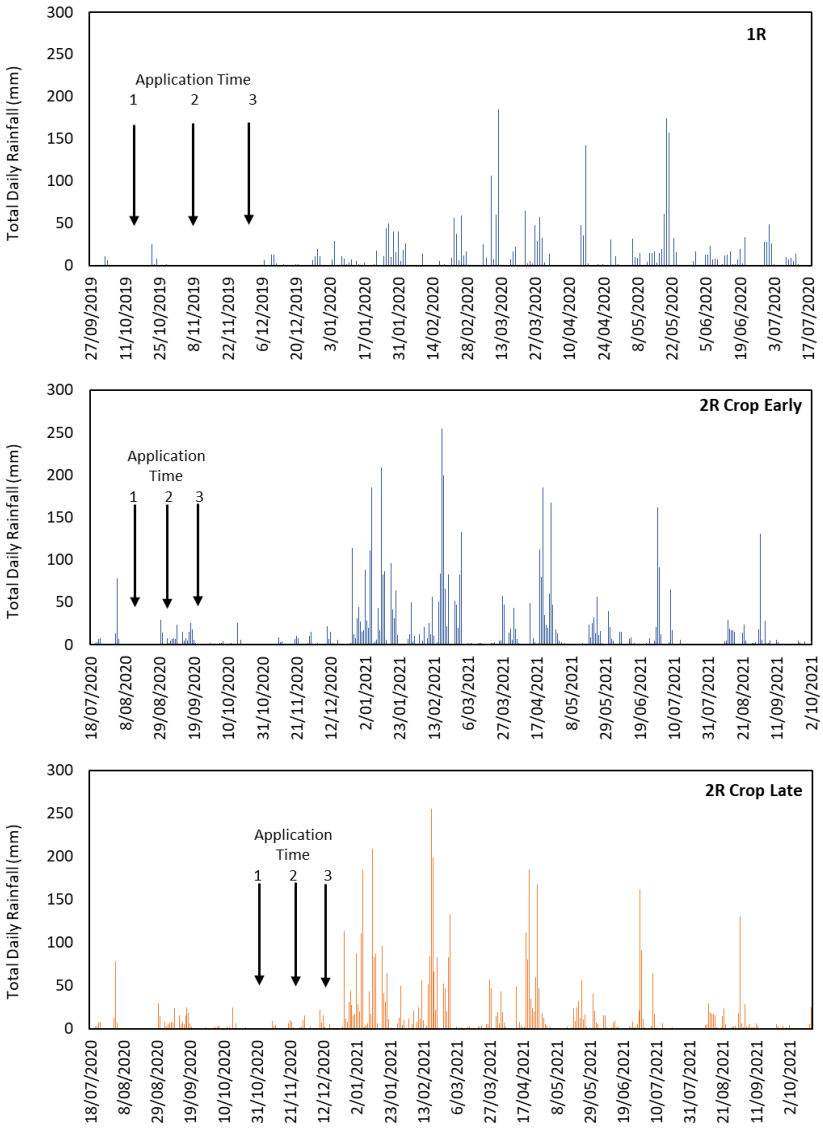

Figure 1. Total daily rainfall for the first ratoon (2019-20), second ratoon early-harvested (2020-21) and second ratoon late-harvested (2020-21) ratoon crops at the Tully N fertiliser application timing trial site. Data obtained from the Bureau of Meteorology Tully rainfall station (No. 32042), approximately 1.1 km from the site.

Crop N uptake

Leaf N concentrations in the 1R crop were above the third-leaf critical value (1.70% as the crop was sampled on 20 March 2020) for all application time and N rate treatments except for the nil N treatment (Table 2). A possible N deficiency was indicated by the mean third-leaf N concentration being significantly lower ($p<0.001$) than where N fertiliser was applied.

In the late-harvested 2R crop, leaf N concentrations for all N rate treatments were below the critical value (1.7 % as the crop was sampled on 25 March 2021) for application time 1. For application times 2 and 3, leaf N concentrations were either close to or above the critical value at the higher N rates (130 and 180 kg N/ha) only. These results indicate N supply was insufficient at the lower N rates (0 and 80 kg N/ha).

Table 2. Leaf N% for 1R and 2R late-harvest sugarcane crops grown at four N rates (0, 80, 130 and 180 kg N/ha) applied at three different application times. Values in bold are above the critical value of 1.70%.

Crop class	Application time	N rate (kg/ha)				Application time mean
		0	80	130	180	
1R	1	1.49	**1.73**	**1.76**	**1.74**	1.68
	2	1.47	**1.75**	**1.74**	**1.74**	1.67
	3	1.60	**1.73**	1.66	**1.78**	1.69
	Overall Mean	1.52^{B}	**1.74^{A}**	**1.72^{A}**	**1.76^{A}**	
	LSD(0.05)	Application time: ns, N rate: 0.08 (p<0.001); Application Time*N rate: ns				
2R Late	1	1.54	1.64	1.66	1.65	1.63
	2	1.62	1.56	**1.75**	**1.75**	1.67
	3	1.60	1.60	1.68	1.67	1.60
	Overall Mean	1.59^{B}	1.60^{B}	**1.70^{A}**	1.69^{A}	
	LSD(0.05)	Application time: ns, N rate: 0.09 (p<0.01); Application Time*N rate: ns				

ns – not statistically significant.

Results from the 9-month sampling event in the 1R crop show N rate had a statistically significant effect (p<0.001) on crop N content up to 180 kg N/ha but there was no significant difference between application times nor significant interaction between N rate and application time (Table 3). There was a trend towards higher crop N content for application time 3 (late).

In the 2R crop, there was no statistically significant interaction between N rate and application time in either the early- or late-harvested treatments. N rate had a statistically significant effect on crop N content up to 80 kg N/ha in the early harvested treatment (p<0.001) and up to 130 kg N/ha in the late-harvested treatment (p<0.001). There was also a statistically significant difference in crop N content between application times for the early-harvested treatment. Crop N content was significantly higher (p<0.05) for application time 3 (mean value of 69.3 kg N/ha) compared to application times 1 (mean value of 58.8 kg N/ha) and 2 (mean value of 59.3 kg N/ha).

Table 3. Crop N (kg N/ha) at 9 months for 1R and 2R sugarcane crops grown at four N rates (0, 80, 130 and 180 kg N/ha) applied at three different application times.

Crop class	Application time	N rate (kg/ha)				Application time mean
		0	80	130	180	
1R	1	74.44	90.03	86.53	102.44	88.36
	2	70.32	95.36	101.22	117.84	96.19
	3	75.17	101.55	102.98	115.81	98.88
	Overall Mean	73.31^{C}	95.65^{B}	96.91^{B}	112.03^{A}	
	LSD(0.05)	Application time: ns, N rate: 11.41 (p<0.001); Application Time*N rate: ns				
2R Early	1	40.14	59.16	62.72	73.31	58.83B
	2	40.49	71.58	67.59	57.70	59.34B
	3	47.04	67.66	75.66	86.70	69.27A
	Overall Mean	42.56^{B}	66.13^{A}	68.65^{A}	72.57^{A}	
	LSD(0.05)	Application time: 9.65 (p<0.05), N rate: 11.14 (p<0.001); Application Time*N rate: ns				
2R Late	1	46.85	60.39	63.94	64.93	59.03
	2	37.23	57.32	72.28	79.50	61.58
	3	39.39	68.58	57.68	73.62	59.82
	Overall Mean	41.16^{C}	62.10^{B}	64.63^{AB}	72.68^{A}	
	LSD(0.05)	Application time: ns, N rate: 10.14 (p<0.001); Application Time*N rate: ns				

ns – not statistically significant.

Yield response

It is important to note that cane yield for the 1R crop was determined based on the 9-month sampling event and should not be compared directly to the cane yield obtained in the 2R crop. There were no statistically significant interactions between N rate and application time on cane yields in the 1R or 2R crops (Table 4). Nitrogen rate

had a statistically significant effect on cane yield in the 1R ($p<0.001$), 2R early-harvested ($p<0.001$) and 2R late-harvested ($p<0.001$) crops.

In the 2R crop, sugarcane yields tended to be higher in the late-harvested treatment compared to the early-harvested treatment. For the early-harvested treatment, there was a significant ($p<0.001$) increase in cane yield up to 130 kg N/ha. However, there was no significant difference between 80 and 130 kg N/ha or benefit in applying 180 kg N/ha which is above the SIX EASY STEPS guideline for this site. There was also a statistically significant difference in cane yield between application times ($p=0.05$). Cane yields were significantly lower for application time 1 compared to application time 3.

For the late-harvested treatment, there was no significant difference in cane yield at N rates above 80 kg N/ha. There was also no statistically significant difference in cane yield between fertiliser application times.

Table 4. Sugarcane yield (t cane/ha) for 1R and 2R sugarcane crops grown at four nitrogen rates (0, 80, 130 and 180 kg N/ha) applied at three different application times. Note, yields pertaining to the 1R crop relate to the 9-month sampling event.

Crop class	Application time	N rate (kg/ha)				Application time mean
		0	80	130	180	
1R	1	61.1	70.1	68.2	75.5	68.7
	2	53.4	74.9	72.3	83.4	71.0
	3	58.7	80.4	74.6	81.9	73.9
	Overall Mean	57.8^{C}	75.2^{AB}	71.7^{B}	80.3^{A}	
	LSD(0.05)	Application time: ns, N rate: 8.01 ($p<0.001$); Application Time*N rate: ns				
2R Early	1	43.9	63.3	68.1	63.7	59.8B
	2	43.8	73.0	78.9	60.2	64.0AB
	3	45.3	74.8	76.0	72.4	67.1A
	Overall Mean	44.4^{C}	70.4^{AB}	74.3^{A}	$65.^{5B}$	
	LSD(0.05)	Application time: 6.56 ($p=0.05$), N rate: 7.57 ($p<0.001$); Application Time*N rate: ns				
2R Late	1	47.4	77.6	70.2	78.0	68.3
	2	45.7	70.3	84.3	86.8	71.8
	3	45.1	70.9	77.4	80.8	68.6
	Overall Mean	40.1^{B}	72.9^{A}	77.3^{A}	81.9^{A}	
	LSD(0.05)	Application time: ns, N rate: 10.16 ($p<0.001$); Application Time*N rate: ns				

ns – not statistically significant.

Results for sugar yields were similar to those reported for cane yield (data not shown). There was no statistically significant interaction between N rate and application time on sugar yields in the 1R or 2R crops. N rate had a statistically significant effect on sugar yield in the 1R ($p<0.001$), 2R early-harvested ($p<0.001$) and 2R late-harvested ($p<0.001$) crops. In the 2R crop, delaying fertiliser application by 8 weeks resulted in significantly ($p<0.01$) higher sugar yields compared to fertilizing almost immediately after harvest for the early-harvested treatment only.

The optimum N rate (Opt N) defined as the N rate corresponding to 95 % of the maximum yield, was calculated for the 2R early and late-harvested treatments by fitting a quadratic function to the final mean cane yields. Cane yield responses for the different application times and harvest treatments are given in Figure 2.

Opt N values for application time 1, 2 and 3 in the early-harvested crop were 80, 140 and 80 kg N/ha, respectively. Opt N values for application time 1, 2 and 3 in the crop were 90, 140 and 120 kg N/ha, respectively. For both harvest treatments, Opt N values were highest for application time 2. The Opt N value for application time 2 was the same for both the early and late-harvested treatments and above the Step 4 SIX EASY STEPS N guideline rate (120 kg N/ha) for ratoon crops at this site. The Opt N value for application time 3 in the late-harvested treatment equalled the SIX EASY STEPS N guideline rate.

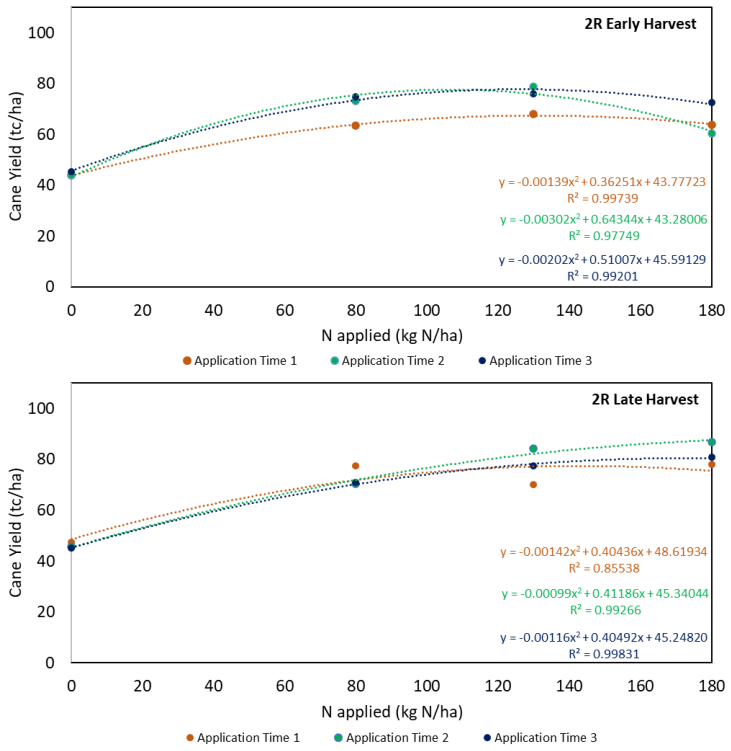

Figure 2. Cane yield (t cane/ha) response to applied N (kg N/ha) applied at three different application times for the 2R early and late-harvested crops.

Nitrogen-use efficiency

NiLRI represents the "N requirement" term used in equations calculating N fertiliser application rates (Thorburn *et al.* 2011; Schroeder *et al.* 2014) and is simply the inverse of the commonly used NUE factor (t cane (kg N)$^{-1}$). For ratoon crops, Thorburn *et al,* 2022, proposed crop growth and/or N uptake is limited when values exceed 1.7 kg N (t cane)$^{-1}$. The higher the value, the greater the crop growth and/or N uptake limitations. These limitations may be due to sub-optimal management practices, soil constraints, unfavourable environmental conditions for crop N uptake or high N losses to the environment. In these situations, higher N rates are possibly needed to maximise yields (Thorburn *et al.* 2022). NiLRI values for the 80 and 130 kg N/ha N treatments typically indicated no limitations to crop growth and/or N uptake irrespective of harvest time or fertiliser application time. The NiLRI and NUpEFert values indicate very poor NUE and N fertiliser recovery at 180 kg N/ha. This is supported by the productivity data and Opt N investigation.

Table 5. Nitrogen-use efficiency factors for sugarcane grown at four N rates applied at three different application times in the 2R crop.

	Crop class	Application time	N rate (kg/ha)		
			80	130	180
NiLRI (kg N (t cane)$^{-1}$)	2R Early	1	1.26	1.91	2.83
		2	1.10	1.65	2.99
		3	1.07	1.71	2.49
	2R Late	1	1.03	1.85	2.31
		2	1.14	1.54	2.07
		3	1.13	1.68	2.23
NUptEFert (%)	2R Early	1	23.80	17.40	18.40
		2	38.90	20.80	9.60
		3	25.80	22.00	22.00
	2R Late	1	16.90	13.10	10.00
		2	25.10	27.00	23.50
		3	36.50	14.10	19.00

NUptEFert was calculated to assess the amount (%) of fertiliser N accumulated in the aboveground crop biomass. At 6-months (data not shown) and 9-months crop age, fertiliser N uptake efficiency tended to be highest in the 2R crop for the early-harvested treatment. However, there was a large reduction in NUptEFert values between the 6- and 9-month sampling events. For example, fertiliser N uptake efficiency for the early-harvested treatment in the 2R crop at 6 months ranged from 32.2 to 90.3% whereas at 9 months it ranged from 9.6 to 38.9%. There was also no consistent trend in NUptEFert between application times for the 2R crop. NUptEFert tended to be higher in application time 3 for the early-harvested treatment whereas application time 2 was highest for late-harvested crop.

Maximum NUptEFert at 9-months was 38.9 and 36.5% for the early and late-harvested crops, respectively. These values resulted from the 80 kg N/ha treatment for application time 2 and 3 in the early and late-harvested crops, respectively. Maximum fertiliser N recovery reduced to 22.0% and 27.0% for the 130 kg N/ha treatment in the early and late-harvested crops, respectively.

CONCLUSIONS

We applied N 2-3 weeks (1), 6 weeks (2) and 8 weeks (3) after harvest. There were statistically significant differences in crop traits associated with N rate and the timing of fertiliser application but no significant interaction with harvest time. For the early-harvested crop, there were no adverse effects on yields or NUE from delaying the timing of fertiliser application by up to 8 weeks. However, there was no statistically significant difference in fertiliser application timing for the late-harvested crop. This outcome supports existing grower practices in the Wet Tropics region whereby fertiliser application is often delayed to crops harvested early in the season but applied immediately after harvesting crops ratooned late in the season.

Differences in the optimum amount of N fertiliser required highlights the variability in crop responsiveness to applied N and difficulties associated with making N guidelines more prescriptive in the absence of accurate climate forecasting (Skocaj 2015). The optimum N rate varied with the timing of fertiliser application. However, for both time of harvest treatments, the optimum N rate was lower for application time one (2-3 weeks post-harvest) and highest for application time two (6 weeks post-harvest). The optimum N rate for application time two was slightly higher than the SIX EASY STEPS N guideline for the site, interpreted from soil test results.

It is uncertain how different seasonal climatic conditions may change these outcomes as the effect of application timing for early and late-harvested crops was only assessed for one growing season (2020/21). However, the rainfall timing, amount and distribution experienced in that season (for the 2R crop) are common for the Wet Tropics region. There were differences in the amount, timing and distribution of rainfall experienced by the early and late-harvested crops. The early-harvested crop possibly suffered from moisture stress whereas the late-harvested crop experienced high rainfall and prolonged waterlogging. This highlights the impact of climatic conditions on fertiliser N recovery.

This experiment was important for evaluating industry guidance and grower practices in the Wet Tropics region. The outcomes from the Tully experiment complement the fertiliser application timing researched conducted in Mackay (Salter and Kok 2023). Current industry advice regarding fertiliser application timing (Calcino 2018) remains appropriate, and growers should have confidence in continuing their current fertiliser application timing practices.

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REFERENCES

Bell MJ, Moody PW, Skocaj DM, *et al.* (2019) Can new fertiliser technology facilitate a reduction in fertiliser-N rates and improved water quality without comprising sugar production? *Proceedings of the Australian Society of Sugar Cane Technologists* 41: 185-193.

Berding N, Marston D, McClure WF, van Eerten M, Prescott B (2023) FT-NIR spectrometry and automated presentation for high speed, at line analysis of disintegrated sugarcane. In: near Infrared Spectroscopy: Proceedings of the 11th International Conference (Eds AMC Davies, A Garrido-Varo). Pp. 81-87. NIR publications: UK.

Calcino D, Schroeder B, Panitz J, *et al.* (2022) *Australian sugarcane nutrition manual*. Sugar Research Australia: Brisbane.

Connellan J, Thompson M, Salter B, Olayemi M. (2022). Evaluation of enhanced-efficiency fertilisers in Queensland sugarcane. *Proceedings of the Australian Society of Sugar Cane Technologists* 43: 20-36.

Murtha GG (1986) *Soils of the Tully-Innisfail Area, North Queensland.* CSIRO Division of Soils, Divisional Report No. 82.

Panitz JH, Schroeder BL (2020) Effect of temporal nitrogen-management strategies on sugarcane production in sub-tropical Queensland – a complete crop cycle. *Proceedings of the Australian Society of Sugar Cane Technologists* 42: 260-267.

Salter B, Kok E (2023) Effect of application timing of nitrogen fertiliser on sugarcane crop performance and NUE. *Proceedings of the Australian Society of Sugar Cane Technologists* 44: 431-439.

Salter B, Schroeder BL, Wood AW, Panitz JH, Park G (2008) Use of replicated strip-trials for demonstrating the effectiveness of different nutrient management strategies for sugarcane. *Proceedings of the Australian Society of Sugar Cane Technologists* 30: 361.

Schroeder BL, Salter B, Moody PW, Skocaj DM, Thorburn PJ (2014) Evolving nature of nitrogen management in the Australian sugar industry. In *A review of nitogen-use efficiency in sugarcane* (Ed. MJ Bell), pp. 15–87. Sugar Research Australia, Indooroopilly.

Schroeder BL, Wood AW, Moody PM, *et al.* (2007) *Soil-Specific Nutrient Management Guidelines for Sugarcane Production in the Johnstone Catchment*. Technical Publication TE07001, BSES Limited, Indooroopilly

Schroeder BL, Wood AW, Park G, Panitz JH, Stewart RL (2009) Validating the 'SIX EASY STEPS' nutrient management guidelines in the Johnstone catchment. *Proceedings of the Australian Society of Sugar Cane Technologists* 31: 177-185.

Skocaj D (2015) *Improving sugarcane nitrogen management in the wet tropics using seasonal climate forecasting*. PhD thesis, James Cook University: Townsville.

Skocaj DM, Hurney AP, Schroeder BL (2012) Validating the 'SIX EASY STEPS' nitrogen guidelines in the Wet Tropics. *Proceedings of the Australian Society of Sugar Cane Technologists* 34: 10 pp.

Skocaj DM, Schroeder BL, Wood AW (2020) Are responses to nitrogen fertiliser predictable under similar conditions? *Proceedings of the Australian Society of Sugar Cane Technologists* 42: 161-168.

Thorburn PJ, Biggs JS, McCosker K, Northey A (2022) Assessing water quality for cropping management practices: A new approach for dissolved inorganic nitrogen discharged to the Great Barrier Reef. *Journal of Environmental Management* 321: 11 pp.

Thorburn PJ, Biggs JS, Skocaj D, *et al.* (2018) Crop size and sugarcane nitrogen fertilizer requirements: Is there a link? *Proceedings of the Australian Society of Sugar Cane Technologists* 40: 210–218.

Thorburn PJ, Biggs JS, Webster AJ, Biggs IM (2011) An improved way to determine nitrogen fertiliser requirements of sugarcane crops to meet global environmental challenges. *Plant and Soil* 339: 51–67.

Wood AW, Schroeder BL, Moody PW (2008) Development of soil-specific guidelines for nutrient management in the Australian sugar industry. Soils 2008 Conference, Massey University, Palmerston North, New Zealand, 2 pp.