POTENTIAL PRODUCTION AND ENVIRONMENTAL BENEFITS FROM CONTROLLED RELEASE FERTILISERS—LESSONS FROM A SIMULATION ANALYSIS

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Abstract

CONTROLLED RELEASE FERTILISERS (CRFs) are promoted as a means to reduce nitrogen (N) losses and allow lower N application rates in sugarcane systems. The idea behind controlled release fertilisers is that a slow release of N synchronised with crop N uptake will keep the levels of mobile soil nitrate low. This will reduce the risk of N loss by denitrification, runoff or leaching and therefore make more N available to the crop. Experimental trials have in some cases demonstrated the effectiveness of controlled release fertilisers, but questions remain around the magnitude and consistency of benefits. Using simulation analysis we quantify the production and environmental benefits for a case study in Tully, Queensland. There is a role for controlled release fertilisers to reduce nitrogen loss, improve nitrogen use efficiency and sometimes increase yield, but results are seasonally variable and depending on conditions as well as fertiliser release characteristics. Successful implementation will likely require decision support.

Introduction

Under pressure to reduce the amount of dissolved inorganic nitrogen (N) lost to waterways draining into the Great Barrier Reef Lagoon, the Australian sugarcane industry is showing increasing interest in the use of enhanced efficiency fertilisers (EEF) to improve N use efficiency (NUE) and reduce N loss.

Several experimental trials have been carried out (see Verburg *et al.*, 2016) or are underway (*e.g.* on-farm trials as part of Project Catalyst and GameChanger (reefcatchments.com.au/land/gamechanger-case-studies-2; Thompson *et al.*, 2016) and as part of the National Environmental Science Program Tropical water Quality Hub (http://nesptropical.edu.au/index.php/round-2-projects/project-2-1-8/) and other formal and informal trials across the industry) to evaluate yield and/or N loss benefits of both controlled release fertilisers, which release N more slowly than conventional fertilisers (*e.g.* Agrocote®[*]), and nitrification inhibitors, which temporarily stabilise the N in ammonium form (e.g. Entrench™ or Entec®[*]).

While the results from these trials have shown some positive results, it has often proven difficult to obtain statistically significant treatment effects in individual trials and results have been sensitive to climatic and soil conditions. It has been noted that trials that experienced wet conditions, particularly in the two months after fertilisation, were more likely to show benefits than those performed in years with below average rainfall (Verburg *et al.*, 2014; IPF, 2014).

[*] Please note: the mention of a commercial product does not constitute an endorsement by CSIRO.

For controlled release fertilisers the experimental trials have provided support for the principle behind their enhanced efficiency, namely that slow release keeps the concentration of dissolved N in the soil lower, which reduces the risk of N loss and makes more N available to the crop. However, to answer the question what role controlled release fertilisers can play, we need to quantify their benefits and establish what determines the magnitude of benefits, including season-to-season consistency of benefits.

In addition, we need to determine whether there is room to fine-tune the controlled release fertiliser products or their integration into the farming system. With benefits appearing to be highly dependent on soil, climatic and seasonal conditions, it is difficult to extract this information from experimental trial data alone. This paper, therefore, employs simulation analysis to explore the following set of questions:

- What are the benefits of CRFs?
- What is the expected magnitude of production and environmental benefits?
- What determines the magnitude of benefits?
- Can CRFs or their management be further improved?

The work is part of a larger analysis for SRA funded project (2014/011). Here we focus on the initial lessons from one case study: rainfed sugarcane on an alluvial clay soil experiencing the wet climate of Tully, Queensland. An economic analysis of a subset of the scenarios is presented separately (Kandulu *et al.,* 2017).

Methodology

The simulation analysis was carried out using the APSIM-Sugar model (Keating *et al*., 1999; Thorburn *et al.,* 2005; Holzworth *et al.,* 2014) using historical climate data from Tully Sugar Mill (station 032042, 1902–2015; obtained from SILO Point Patch Data; Jeffrey *et al*., 2001) and a local soil from the Tully region, which has been described as a alluvial clay soil and classified as a Brown Dermosol or Coom series (Cannon *et al*., 1992). The parameterisation of this soil has previously been used and verified by Thorburn *et al.* (2011).

The simulated scenarios represented a rainfed cropping system with a fixed, six year cycle that consisted of a 15 month plant crop, three 12 month ratoon crops, a 13.5 month fourth ratoon and a 7.5 month bare fallow.

In reality the length of ratoon seasons will vary within a cycle and the fallow is probably a little shorter, but this design allowed for consistent comparison of different ratoons as well as early and late scenarios. These were achieved by planting either on 1 May (early plant) or 1 August (late plant) and harvesting on 1 August (early ratoon) or 1 November (late ratoon) respectively.

The model captures soil water and N dynamics, residue decomposition, crop growth and N uptake, including responses to environmental conditions (solar radiation, temperature, water and N stress), and management actions such as planting, ratooning, irrigation and N fertilisation.

In the case of water logging, the proportion of the root system exposed to soil water conditions at saturation or near saturation was calculated and used to calculate a water logging stress factor, based on work by Biggs *et al.* (2013).

This factor reduced photosynthetic activity via a temporary effect on radiation use efficiency. Lodging, induced by large rainfall events in combination with wet soil and dependent on crop size, was simulated through a permanent reduction in radiation use efficiency after lodging. Both these effects were used to ensure simulation of district level yields and may compensate for other not-modelled effects, such as pest and disease or harvest losses.

APSIM uses critical target N concentrations, which vary over time, for different crop components to calculate N stress (Keating *et al*., 1999). At ratooning, 17% of the roots are assumed to die (Ball-Coelho *et al*., 1992). The remainder of the roots are available to the next ratoon crop. Very little is known about root growth and root N demand immediately following ratooning. The current simulations assume there is no root N demand prior to emergence.

Full N response curves were simulated by 'applying' between 30 and 330 kg N/ha fertiliser in 10 kg N/ha increments to 60 kg N/ha and above that in 30 kg N/ha increments. For plant crops, 30 kg N/ha was assumed to have been applied with planting mix, with the remainder applied as urea or CRF one month later. Ratoon crops received urea or CRF one month after ratooning. The single urea application was compared with application of linear release and sigmoidal release CRF products as well as a 50% blend of urea and the linear release product.

The linear release product was parameterised based on literature data for the 'Meister10'* product (Trenkel, 2010) and had a release period similar to some of the products used in the experimental trials. The sigmoidal product was a hypothetical product 'tuned' to have a release pattern that closely synchronised with simulated crop N uptake in the 330 kg N/ha urea scenarios.

For both controlled release products the release was parameterised to respond to temperature with a Q_{10} = 2.5 for the linear release product and Q_{10} = 1.5 for the sigmoidal release product (rate increase of 2.5 or 1.5 times for a 10 °C increase in temperature). It was assumed soil moisture did not affect the release rate, which is a common assumption, but one that is being tested within the wider project.

Soil water and mineral nitrogen levels were re-set at every harvest to ensure that the effectiveness of different fertiliser products could be evaluated in individual years without being confounded by carry-over effects. For each scenario six parallel runs were started in 1902 through to 1907 to ensure each phase of the cropping cycle was represented in each year. Data from 1914–2015 were used in the analyses (102 plant crop seasons, 408 ratoon crop seasons).

Simulated yield N response data were fitted using Excel Solver with the Weibull model:

$$Yield = Asym - Drop \times e^{-e^{lrc} \times Nrate^{pwr}}$$

where *Nrate* is the rate of fertiliser N applied and *Asym*, *Drop*, *lrc* and *pwr* are fitted parameters. Due to the close spacing of N rates near the inflection point, the Weibull model provided good fits of the data and was found to be one of the better models, in particular in the region of the inflection point.

The fitted functions were then used to calculate an agronomic 'optimum' fertiliser N rate, Nopt, for each response curve. It was defined as 95% of the maximum yield. As the Weibull function is an asymptotic model, Nopt could not be defined as the N rate at which the slope of the response curve becomes zero. For practical purposes 95% of maximum yield is often chosen as Nopt (*e.g.* Schroeder *et al.*, 2014), although often in conjunction with other fitting functions.

Results

Climate

Based on the historical climate data from Tully Sugar Mill, the simulated crops experienced a climate characterised by high temperatures and a high and highly variable annual average rainfall (1914–2015 average 3 966 mm, range 1 818–7 898 mm, coefficient of variation = 26%) that is summer dominant with 75% falling between November and April (Figure 1).

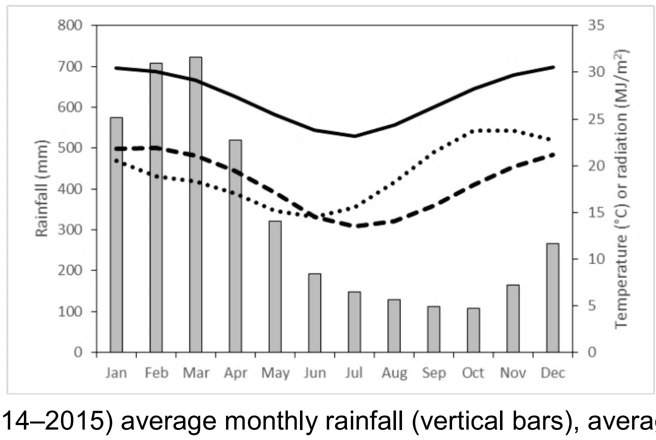

Fig. 1—Historical (1914–2015) average monthly rainfall (vertical bars), average monthly maximum temperature (continuous line), average monthly minimum temperature (dashed line) and average monthly solar radiation (dotted line).

Verification simulated yield levels

The simulated yields were reflective of historical district yield levels (Figure 2a). They also exhibited strong seasonal variability, and showed higher yield levels for the longer season plant crops compared with the ratoon crops (Figure 2b). There were also small differences in the yield distributions between the early and late scenarios.

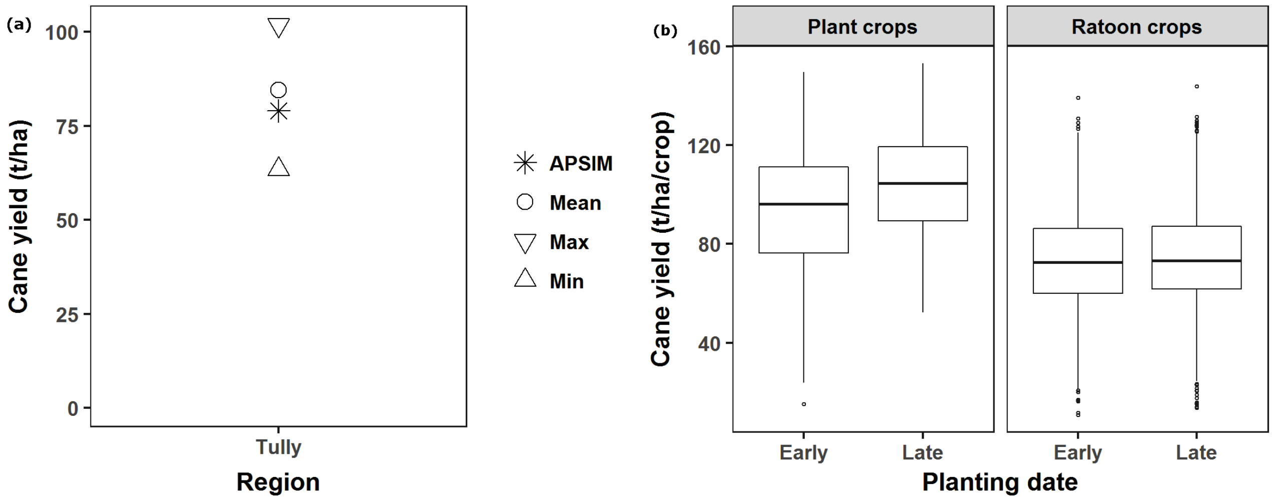

Fig. 2—(a) Average simulated cane yield across planting date and crop class at 150 kg N/ha fertiliser application compared with the mean and range of historical data (Source: ABS 7321.3, Crops and Pastures, Queensland, various editions; ABS 7113.3, Agriculture, Queensland, various editions; ABS 7113.0, Agriculture, Australia, various editions; ABS 7121.0, Agricultural Commodities, Australia, various editions.); (b) distribution of simulated cane yield by crop class and planting date.

Simulated results

The APSIM-Sugar simulation model can provide a wide range of model outputs – predictions of yield and N loss outcomes, but also other, intermediate variables that can help explain these outcomes. The simulation results are, therefore, organised around the questions listed in the introduction section of this paper.

What are the benefits of CRFs?

Simulated N response curves for yield and N loss from a single urea application or from a more gradual release of urea-N from the linear CRF are shown in Figures 3 and 4, respectively, for a selection of four different first ratoon seasons. The simulated first ratoon harvested in 1982 (early scenario) showed increases of up to 12.5 t/ha in yield at N rates below the agronomic optimum N where crop yield in the urea scenario was limited by N (Figure 3a).

At N rates at which the plateau of the N response curve had already been reached there was no further improvement of yield as the crop was no longer N responsive. The reduction in N loss was considerable in this year (Figure 4aFig. 4) leading to a much lower Nopt 95% (99 kg N/ha compared with 182 kg N/ha). Reaching the yield plateau at a lower N rate implies that the maximum yield could be achieved with a lower N application rate, *i.e.* with increased NUE.

While substantial effects, as in 1982, were seen in several seasons, other seasons were characterised by small benefits or none at all. Sometimes these were seasons with limited N response (not shown) and in other cases, like 2014 (Figure 3b), there was a strong yield response to N but limited N losses (Figure 4b). In some seasons, mainly in the late ratooning scenarios, yield benefits were seen across the full range of N rates (e.g. first ratoon harvested 2009, Figure 3c).

The use of CRF did not, however, always lead to benefits. For example, during the first ratoon harvested in 1962 (early scenario, Figure 3d) yield at the lower N rates was slightly higher for the urea scenario than the CRF scenario. This was not due to differential N loss, as there was little N loss that season and the urea scenario lost more (Figure 4d).

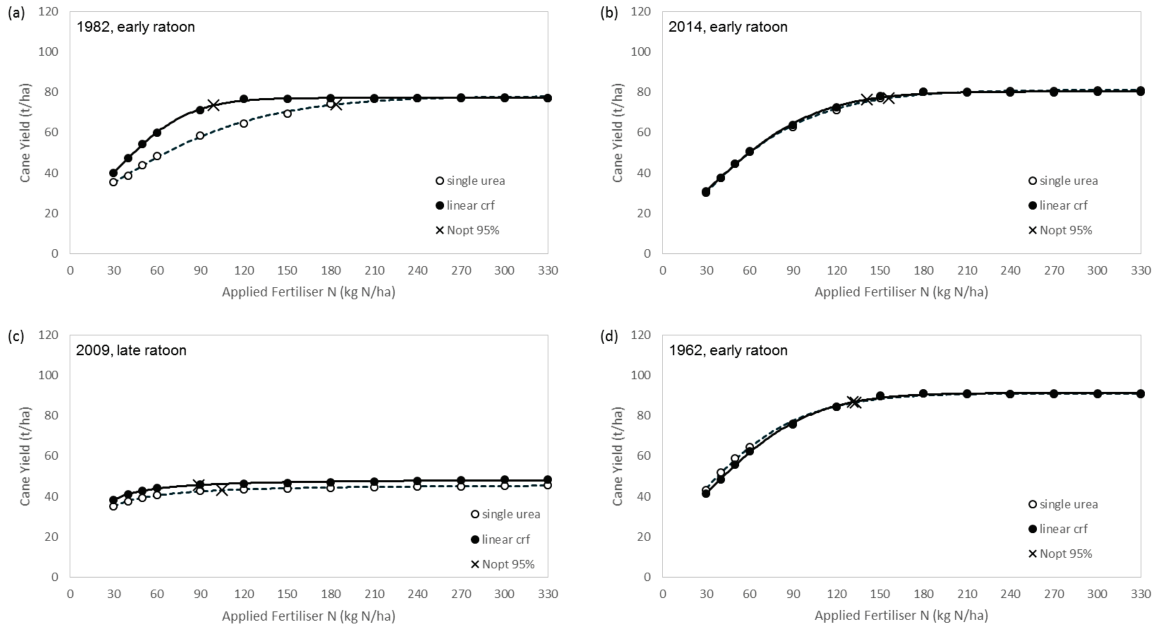

Fig. 3—Simulated N response curves for yield from a single urea application (open symbols) or linear CRF product (closed symbols) in four first ratoon crop seasons (early or late scenario as indicated). The agronomic Nopt 95% (see Methodology) for each fitted response curve is indicated by a X.

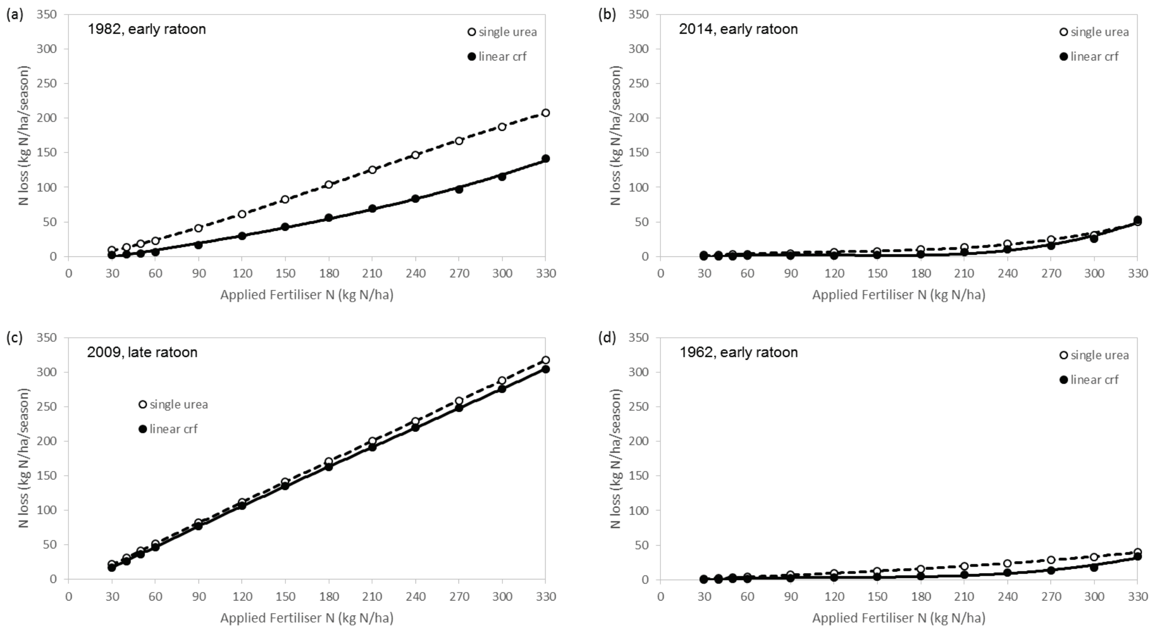

Fig. 4—Simulated N response curves for total N loss (denitrification and nitrate leaching) from a single urea application (open symbols) or linear CRF product (closed symbols) in four first ratoon crop seasons (early or late scenario as indicated).

What is the expected magnitude of agronomic benefits?

Comparison of the long-term average response curves for single urea and linear CRF scenarios demonstrate that the long-term average yield improvement is small (Figure 5). In plant crops the mineralisation and accumulation of mineral N over the fallow reduces the

N responsiveness of the system, despite the higher average yield, which is driven by its (assumed) longer season. For the ratoon crops, large effects, as seen in 1982 are diluted by seasons with smaller or no effect of fertiliser product. In addition, seasonal variability in the position of Nopt also attenuates the average effect.

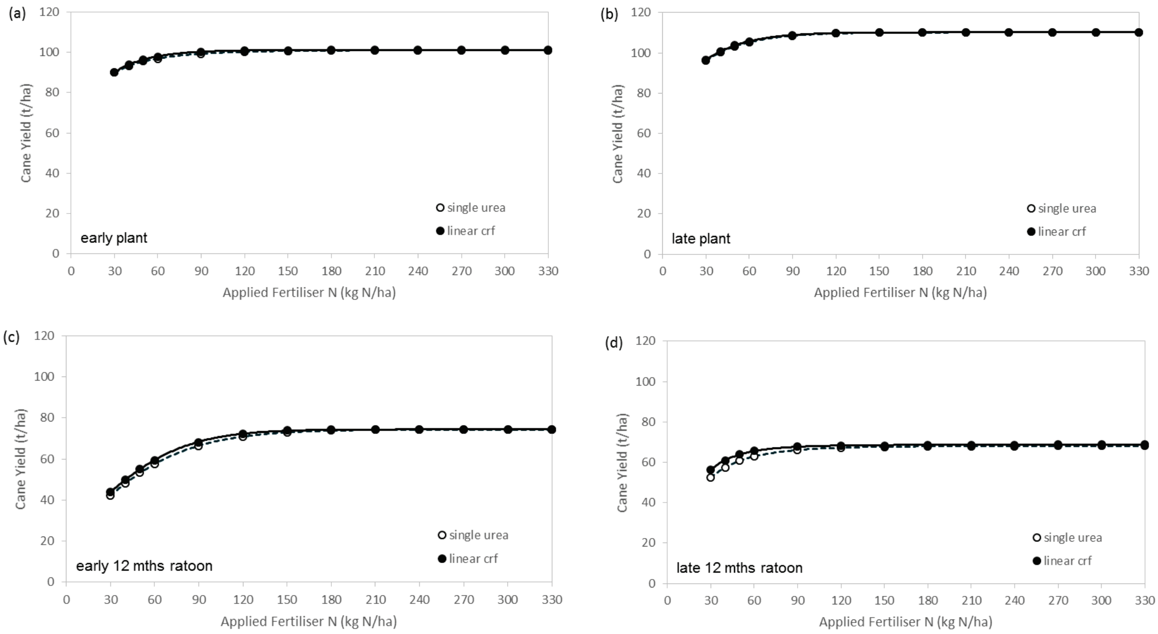

Fig. 5—Simulated average cane yield N response curves for (a) early (1 May) and (b) late (1 August) plant crops, and (c) early (1 August) and (d) late (1 November) 12-month ratoon crops.

Given that maximum yield is often the production aim, the reduction in N rate that a shift in Nopt can provide is of greater interest. The distribution of Nopt 95% for early and late ratoon crops and comparing single urea with linear CRF is shown in Figure 6a and c.

The distribution of changes in Nopt 95% are shown alongside (Figure 6b and d). The Nopt 95% are lower for the late ratoon scenario than the early ratoon scenario, as was also reflected in the shape of the average response curves above.

In both cases, the use of CRF shifted the distributions of Nopt to lower N rate. In the majority of seasons the reductions in Nopt 95% were, however, small, with only 30% of seasons in the early scenario and 31% of season in the late scenario showing reductions in Nopt 95% of more than 15 kg N/ha.

In the late ratooning scenario there was, however, an additional 10% of seasons in which there was a yield benefit of 3 t/ha or more across the full N rate range studied (listed as a separate category * in Figure 6b and d as Nopt 95% does not capture these benefits).

What is the expected magnitude of environmental benefits?

While yield benefits from CRF are mainly seen at the lower N rates, reductions in N loss are across a wider fertiliser range (Figure 7). On average across all seasons and crop classes the reduction (for this particular Tully and Coom soil scenario) was up to 16 kg N/ha/season.

The magnitude of this average N loss reduction is affected by the level of N accumulation during the fallow prior to the plant crop and hence dependent on fallow management. At higher N rates the simulated N loss and N loss benefits may be overestimated.

Due to the resetting of the simulations any unused N is not carried over into the next season, where it could contribute to next season's crop N uptake or N loss. There was also significant seasonal variability. For example, at the rate of 150 kg N/ha fertiliser application the simulated N loss reductions in individual seasons reached up to 50 kg N/ha/season for early ratoons and up to 60 kg N/ha/season for late ratoons.

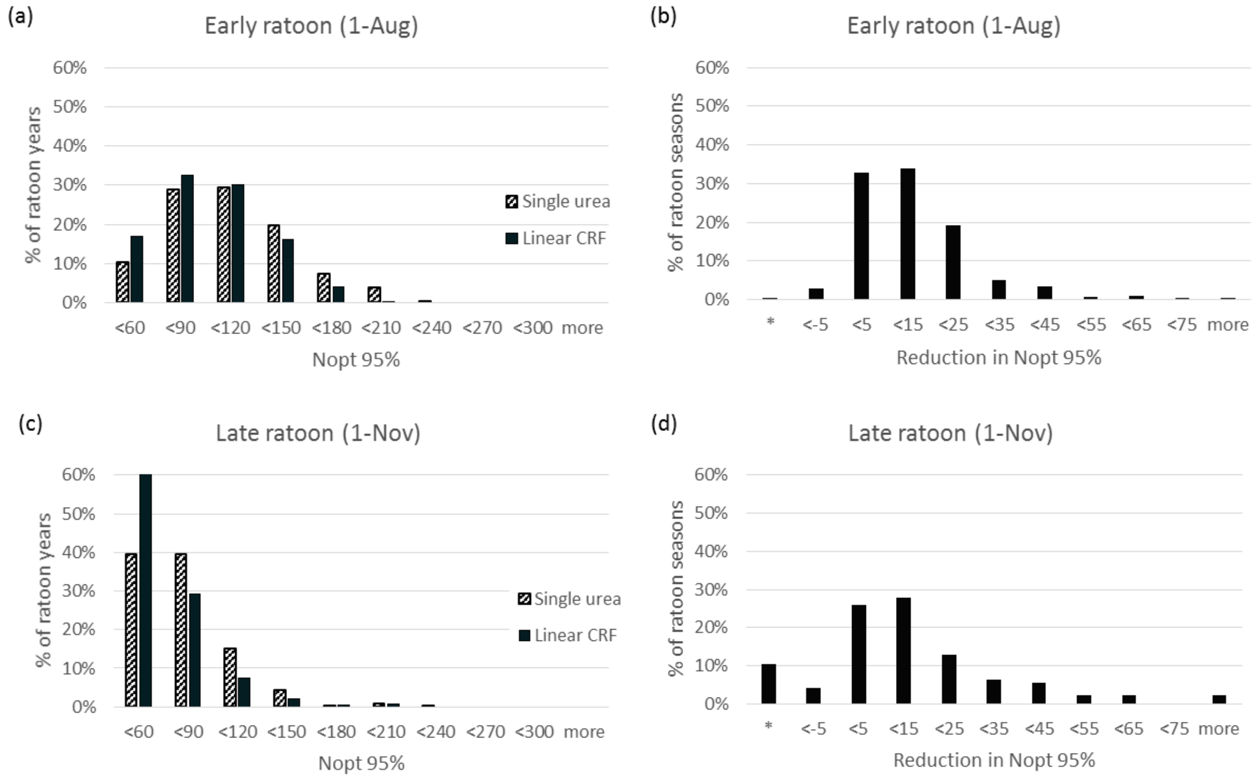

Fig. 6—Distribution of simulated Nopt 95% for scenarios with a single urea application or a linear CRF product and early (a) or late (c) ratooning; along with (b,d) the distribution of simulated change in Nopt 95% due to the use of linear controlled release product instead of a single urea application. Category * refers to the percentage of seasons where the CRF scenario had a maximum yield that was at least 3 t/ha or more than that of the urea scenario. These seasons were not included in the calculation of change in Nopt 95%.

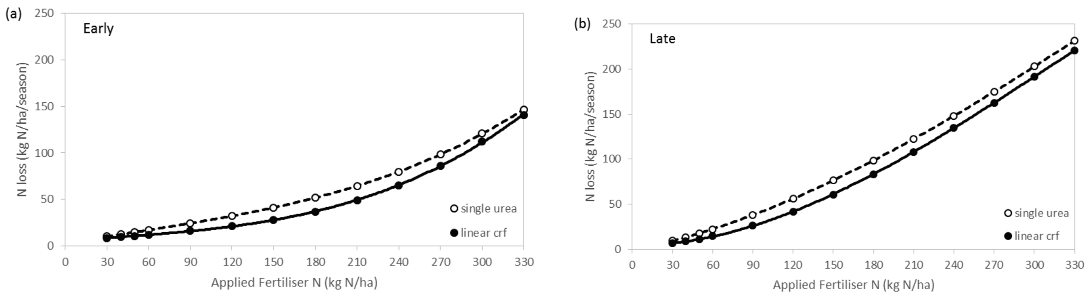

Fig. 7—Simulated average N loss (denitrification and nitrate leaching) response curves (across all seasons and crop classes) for (a) early and (b) late planting dates.

What determines the magnitude of benefits?

The first ratoon crops harvested in 1982 and 2014 of the early ratooning scenario showed contrasting effects of CRF on yield (Figure 3a and b).

Seasonal rainfall for the crop harvested in 1982 (3 907 mm) was in fact lower than that of the crop harvest in 2014 (4 383 mm), but the different distribution (above average rainfall in first two months after fertilisation in 1982 and rainfall concentrated in the second half of the 2014 season) contributed to the differences in N loss and N loss reduction (Figure 4a and b) and resulting crop N stress reductions as illustrated in the time series of the 90 kg N/ha fertiliser scenario shown in Figure 8.

The 2009 late ratoon season was characterised by very high rainfall during January and February (Figure 9, left). While the linear CRF provided some protection, almost all the fertiliser N was lost in this period, leading to the linear N loss curves (Figure 4c) and low yield plateau where the urea scenario cannot 'catch up' on the controlled release treatment (Figure 3c). These two examples illustrate the role of amount and timing of rainfall and N loss events.

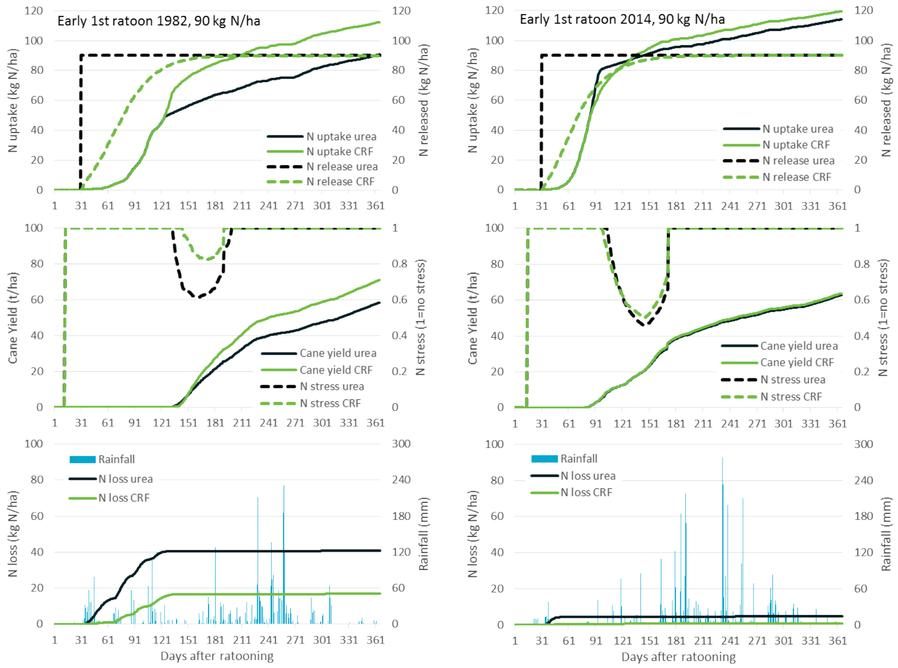

Fig. 8—Simulated time series (top) N uptake and N release, (middle) cane yield and N stress, (bottom) rainfall and N loss for urea and linear CRF during the early 1st ratoons receiving 90 kg N/ha and harvested in 1982 (left) and 2014 (right).

The negative impact on yield from the use of CRF compared with urea in the 1962 season (Figure 3d) highlights another factor of influence, as the time series in Figure 9 demonstrates that the yield reduction was due to the N being released too late compared with crop demand in this particular season.

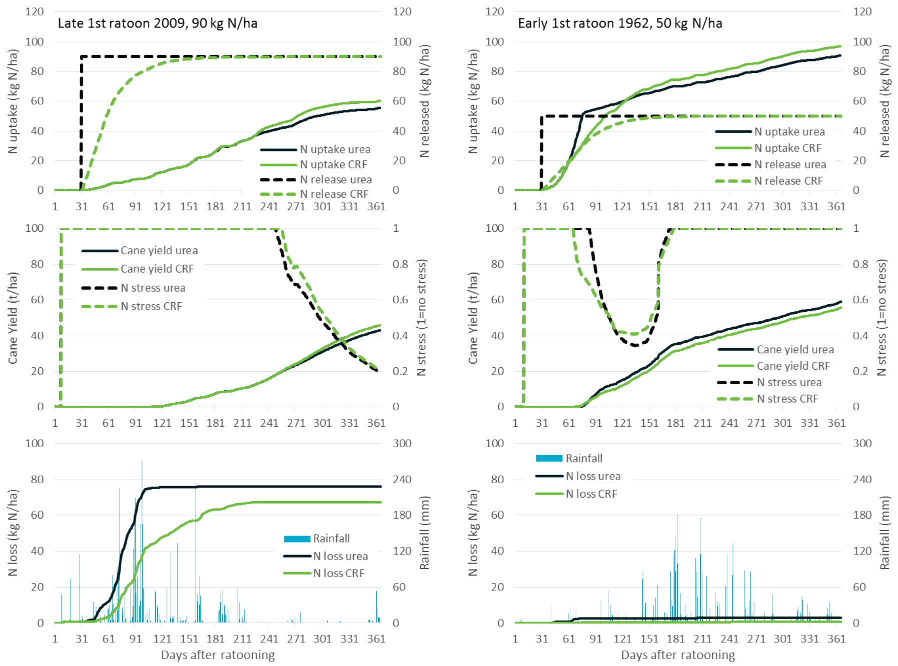

Fig. 9—Simulated time series (top) N uptake and N release, (middle) cane yield and N stress, (bottom) rainfall and N loss for urea and linear CRF during the late 1st ratoon harvested in 2009 receiving 90 kg N/ha (left) and early 1st ratoon harvest harvested in 1962 receiving 50 kg N/ha (right).

Can CRFs or their management be further improved?

The issue of synchrony between N release and crop N uptake can also be exploited to improve the benefits. Yield increases and Nopt 95% reductions (Figure 11a) as well as N loss reductions (not shown) could be further increased by using a better synchronised sigmoidal CRF (Figure 10b). Use of a urea-CRF blend, a practice commonly adopted to reduce cost and provide early N supply, reduces the synchrony and hence provides reduced benefits. The effects on Nopt 95% reductions change accordingly; with further increases for the sigmoidal CRF and decreased effectiveness of the blend (*cf.* Figure 6b and Figure 11).

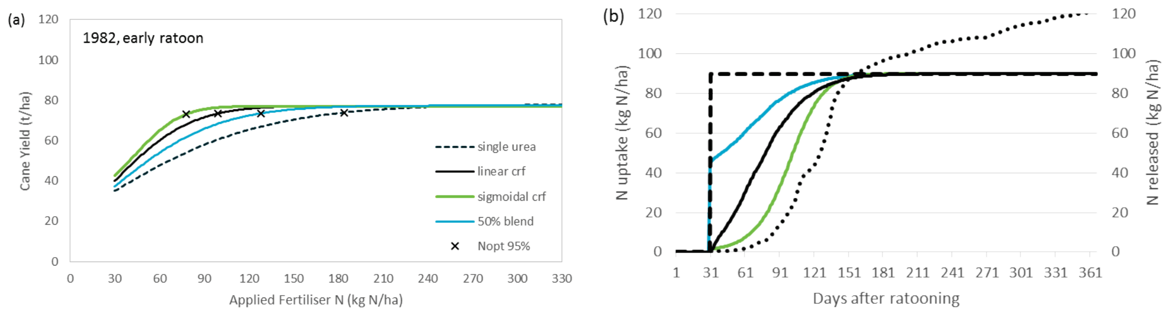

Fig. 10—(a) Fitted N response curves for yield from a single urea application (dashed line), linear CRF product (continuous line) compared with used of a 50% blend (blue line) or sigmoidal CRF (green line) for the first ratoon crop harvested in 1982 (early scenario). The agronomic Nopt 95% (see Methodology) for each fitted response curve is indicated by a X. (b) Release patterns of the four fertilisers compared with crop N uptake in the sigmoidal CRF scenario (dotted line).

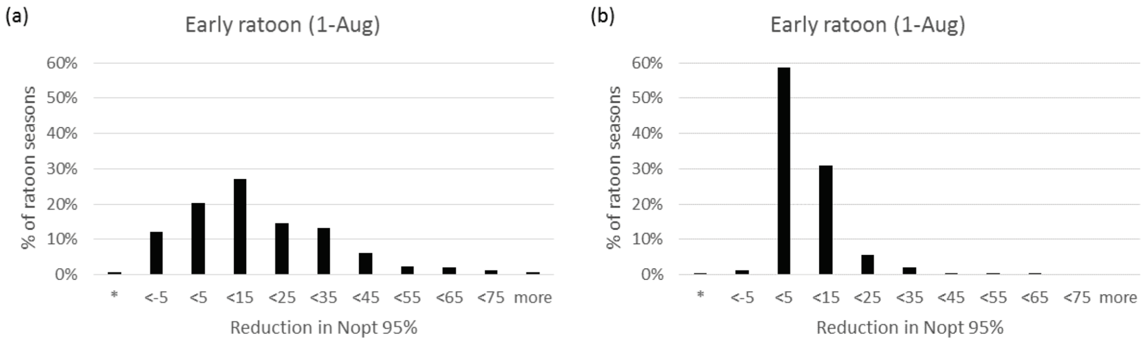

Fig. 11—Distribution of simulated change in Nopt 95% due to the use of (a) sigmoidal CRF or (b) a blend (50% urea – linear CRF) instead of a single urea application.

Discussion

Models and hence simulations performed with them are a close, but not perfect reflection of reality. The absolute magnitude of effects presented, therefore, need to be treated with caution. The order of magnitude and the relative effects are, however, likely to be correct. The benefits from performing simulation analysis, therefore, stem from the insights that they provide. In the analysis presented here this includes confirmation and clarification of factors of influence, an indication of the magnitudes of benefits as well as their large variability and ways to explore improvement of CRFs and their management.

The large variability in benefits between seasons (and the limited benefits in some) as well as the differences between the early and late scenarios suggest that to maximise the benefits from CRFs and minimise any negative impacts there is a need to develop decision rules that help identify seasons and conditions where CRFs will have a role to play and which release pattern would best suit. Note that these decisions may differ depending on whether they are developed from an N loss or yield perspective, as the simulations show that N loss reductions can still occur even when there are no yield benefits.

The simulations suggest that benefits obtained from urea-CRF blends are less than those from CRF products, although still an improvement on urea alone. Economics will likely affect decisions on blends as well as use of different controlled release patterns if they vary in cost. It is important, however, to consider not just their cost per kg of product, but also take into account their effectiveness (see Kandulu *et al.*, 2017).

Note that the simulations here assumed that any early root demand prior to emergence did not require fertiliser N. Further work on early root N demand is needed and if an early N demand is shown to be present, then blends could be the best way forward, provided the urea amount is tuned to the crop's early N requirements.

Extrapolating the findings from this case study to other soils and climates need to be done with care. The benefits may be larger or smaller; more consistent or more variable. Based on the findings from this case study and reported experimental results (Verburg *et al*., 2016) it is likely, however, that in many situations yield or NUE benefits will not be achieved every season. Controlled release fertiliser release, being sensitive to temperature, leads to different release patterns for the same product depending on location and time of fertilisation (Zhao and Verburg, 2016), which will impact on their effectiveness.

The project is currently performing similar studies for other soils and regions, to capture different N loss and crop growth conditions as well as studying the required synchrony between N release and crop N uptake. Tully was chosen as a first example, as it was expected that the high rainfall and rainfed system would be conducive to large N losses, but these conditions also lowered the yield potential and made the benefits less predictable. The continuing work will look at benefits under higher yielding situations (expected to increase benefits) as well as feedbacks from full and limited irrigation.

Variability in the agronomic Nopt (examples in Figure 3 and spread of Nopt in Figure 6) demonstrate that the shape of the yield N response curves vary considerably from season to season, at least in this scenario for Tully. As too little N will limit yield and too much N will reduce NUE and increase N loss, even with the use of CRF, it is important we develop ways to predict the likely Nopt for a season. This work is currently being undertaken in SRA project 2015/075 (led by Yvette Everingham) on incorporating climate forecasting into N management in the Wet Tropics.

Variability in response curve shape also has implications for the likelihood that experimental trials can demonstrate the benefits. Evaluation of CRF with set N rates (*e.g.* Six Easy Steps equivalent for specific circumstances or 80% thereof) may result in missed effects in years where Nopt is low and the selected rates fall on the yield plateau or vice versa.

Demonstrating that CRF use at a lower rate can achieve the same yield as urea at higher rate while improving on yield from urea at the same lower rate requires the two N rates to straddle the Nopt. In situations where the variability in Nopt is high, as in this case study, this may be difficult to achieve consistently.

Extracting decision rules on the basis of experimental results alone does not, therefore, look feasible. This would be best done in conjunction with modelling, which would allow additional virtual experimentation with endless permutations.

Conclusions

While the findings in this paper cannot be used to draw conclusions about the magnitude of production and environmental benefits from CRFs in general, beyond the current case study, they do provide some early lessons:

- Yield benefits are typically limited to the slope of the response curve, except in situations where almost complete loss of urea fertiliser N occurs, which is more likely to happen in late applications of fertiliser.

- The ability to reduce N applications and increase NUE will be the more common production benefit of using CRFs, but the magnitude of the reduction will be climate, soil and timing specific as well as seasonally variable.
- Development of regional guidance for informed decisions based on an understanding of the dynamics of local soils and cropping systems will be crucial for the successful implementation of CRFs.
- Environmental benefits in the form of reduction in N loss can occur even when production benefits are small or absent.
- Benefits from CRFs are difficult to quantify and characterise using experimentation alone. The variation in simulated benefits help explain the variability in results from experiments. Development of decision support will require complementary simulation analyses.

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