



# FINAL REPORT 2014/011

## Role of controlled release fertilizer in Australian sugarcane systems: final report 2014/011

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## ABSTRACT

Controlled release fertilisers (CRFs) are promoted as a means to optimise the productivity achieved per unit of fertiliser nitrogen (N) input and lower environmental impacts from N leaching, runoff and emission losses. Through review of experimental results, characterisation of N release patterns of commercially-available CRF products, and modelling to assess environmental, agronomic and economic benefits this project has confirmed that CRFs can play a role in Australian sugarcane systems. They can reduce N losses and provide agronomic benefits in the form of reduced N application rates and under some circumstances increased yield. The agronomic benefits are, however, highly variable from season to season. The percentage of seasons that result in measurable benefits is affected by climate, soil, crop class and timing of fertiliser application. As a consequence CRFs do not provide a consistent economic advantage over conventional fertilisers across all soil, management and climate conditions. This can be improved when the cost of environmental benefits is included or use of CRF can be targeted to those seasons where agronomic benefits are most likely. Commercially-available CRF products have different N release patterns and temperature responses. These need to be taken into account when designing fertiliser management (product choice, application and timing) in order to maximise the benefits. Development of regional decision support for growers and advisors, based on an understanding of the dynamics of local soils and cropping systems as well as seasonal climate and CRF product response to these, will be important for the successful adoption of CRFs.

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## EXECUTIVE SUMMARY

Controlled release fertilisers (CRFs) are promoted as a means to optimise the productivity achieved per unit of fertiliser nitrogen (N) input and lower environmental impacts from N leaching, runoff and emission losses. 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 and make more N available to the crop. This project aimed to provide the Australian sugarcane industry with a deep and critical understanding of how, when and where CRFs work best, and what characteristics and specifications the CRFs need to have to provide reliable benefits in the face of crop-soil system interactions and seasonal climate variability.

The project consisted of five coordinated activities: (1) review of experimental findings, (2) characterisation of N release patterns of commercially-available CRF products, (3) materials science characterisation of these CRFs to help explain the N release patterns and factors of influence, (4) model simulation analyses to assess agronomic and environmental benefits as well as quantify N uptake and N release patterns as a function of climate, soil, management and seasonal conditions, and (5) associated economics analyses. The multi-disciplinary team from CSIRO working on these activities discussed project methodology and results with representatives and researchers from the sugarcane industry and the fertiliser industry throughout the project, including at two project workshops. The fertiliser industry provided samples of the CRF products. The project team also collaborated with HCPSSL in Ingham on an experiment of characterising N release in the field using buried mesh bags.

Project outputs focussed on delivery of information to growers, advisors and researchers on the effective use and experimental trialling of CRFs and exchange of knowledge with the fertiliser industry to identify opportunities to improve CRF products and their management. In addition to the discussions with industry representatives, research findings were presented to industry at the 2016 and 2017 ASSCT conferences and at a number of forums for growers and advisors. The outputs also include a written review of enhanced efficiency fertilisers, three ASSCT papers and two posters, six journal publications (published or in review) and two reports associated with the project workshops.

Based on the review of experimental evidence and results of the simulation analyses the project has confirmed that CRFs can play a role in Australian sugarcane systems. They can reduce N losses and provide agronomic benefits in the form of increased fertiliser N use efficiency. This allows reduced N application rates and under some circumstances increases in yield can be obtained. The agronomic benefits are, however, highly variable from season to season. The percentage of seasons that result in measurable benefits is affected by climate, soil, crop class and timing of fertiliser application. Other yield limiting factors may limit the agronomic benefits that can be obtained from CRF use. As a consequence of the variable agronomic benefits, CRFs do not provide a consistent economic advantage over conventional fertilisers across all soil, management and climate conditions. This can be improved when the cost of environmental benefits is included or use of CRFs can be targeted in those seasons where agronomic benefits are most likely.

Commercially-available CRF products were found to exhibit different N release patterns that were also strongly sensitive to temperature. This can affect the ability of the CRF to synchronise with sugarcane N demand under different conditions. Differences in coating integrity and composition as well as manufacturing quality resulted in three types of release patterns: Type I products that release a considerable amount of N within the first days; Type II products which have a short lag period (< 1 week) followed by a relatively linear release period up to approximately 60% release; and Type III products which have an extended lag period after which release gradually increases to form a sigmoidal release pattern. The different N release patterns and their temperature responses need to be considered when designing fertiliser management (product choice, application and timing) in order to synchronise with sugarcane N demand and maximise the benefits.

The project findings provide a basis for cost-effective, informed adoption of CRFs in Australian sugarcane systems. This will maximise the likelihood of its success in decreasing release of dissolved inorganic nitrogen into waterways of catchments draining into the Great Barrier Reef Lagoon and/or decreasing nitrous oxide emissions. Development of regional decision support for growers and advisors will be important to deliver these environmental benefits as well as economic returns for growers. It will need to be based on an understanding of the dynamics of local soils and cropping systems as well as seasonal climate and CRF product response to these. Simulation analysis methodology developed by the project provide a means to obtain this understanding. Information generated by the project also supports the design of experimental and demonstration trials and interpretation of their results.

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## 1. BACKGROUND

The sugarcane industry is under pressure to reduce the amount of dissolved inorganic nitrogen (DIN) in waterways of catchments draining into the Great Barrier Reef Lagoon (Reef Water Quality Protection Plan by State of Queensland, 2013). The use of enhanced efficiency fertilisers (EEF), including both controlled release fertilisers (CRF) and fertilisers with nitrification inhibitors (NI), has been proposed as one means of reducing nitrogen (N) losses and, in combination with lower application rates, increase N use efficiency (Brodie et al., 2013; Bell and Moody, 2014; State of Queensland, 2016). The use of CRF aims to better synchronise N release with crop N uptake, which along with consideration of N supply by the soil, is seen as a key to improving N use efficiency and reducing the risk of N loss by leaching, runoff or emission pathways (Bell and Moody, 2014).

At the time this project was proposed (2014), a number of experimental trials had demonstrated increased fertiliser N use efficiency, reduced nitrate leaching and/or reduced nitrous oxide emissions using CRF (see e.g. studies cited by Chen et al., 2008) including for sugarcane in Queensland (Di Bella et al., 2013). However, findings were not consistent across seasons, soils, cropping systems and management practices (Chen et al., 2008; Venterea et al., 2012).

These inconsistencies raised a set of research questions for this project:

- How, when and where will CRF reduce N losses and optimise sugarcane productivity achieved per unit of fertiliser input?
- Can negative yield impacts arise and how can these be avoided?
- When and where will CRF provide an economic solution to increase N use efficiency and reduce losses?
- What specifications do CRF products need to provide reliable benefits?
- Do commercially-available CRF products meet the specifications required?
- What additional improvements (e.g. to CRF or their management) are required to achieve (more) reliable benefits?

The variable experimental trial results were due to complex interactions between patterns of CRF N release and crop N uptake as well as soil water and soil N dynamics including timing of N loss. Because these aspects are influenced by soil, seasonal conditions and crop management, it was considered too difficult to capture the interactions and answer the above questions experimentally. This project was, therefore, designed to incorporate a cropping systems modelling approach. Agricultural systems modelling, e.g. with the APSIM model (Keating et al., 2003; Holzworth et al., 2014), has often proven useful to explore management options in a holistic manner (Thorburn et al., 2014). In addition, a new capability to use the APSIM model to simulate the release of N from polymer coated CRF (Verburg et al., 2013) provided an opportunity to explain and extrapolate experimental findings relating to benefits from CRF and explore the complex system interactions.

As the product information accompanying commercially-available CRFs is usually limited to an indication of approximate total release time only, the project also set out to obtain detailed knowledge about the N release patterns of different CRF products and how these depend on environmental factors (temperature, soil water) as well as their material characteristics. It was anticipated that in conjunction with modelling information about optimal matching of fertiliser N release to crop N demand this information could inform CRF product selection and management. Recent advancements in material science and technology could also provide opportunities for the development of new or improved products that would provide a better and more reliable synchrony with crop N demand and therefore provide a real and robust solution to minimising DIN in waterways.

## 2. PROJECT OBJECTIVES

### 2.1. Overall project objective

To provide the Australian sugarcane industry with a deep and critical understanding of how, when and where controlled release fertilisers work best, and what characteristics and specifications the controlled release fertiliser products need to have to provide reliable benefits in the face of crop-soil system interactions and seasonal climate variability.

### 2.2. Specific project objectives

Specifically, the project will:

- Review experimental evidence;
- Establish the release characteristics of existing controlled release fertiliser products and factors of influence, linking these to the properties and assembly methods of the different controlled release fertiliser types;
- Analyse through simulation modelling the sugarcane system's interactions that determine how, when and where controlled release fertilisers work best;
- Simulate field trials (published and current trials already funded through Paddock to Reef 2) to provide field level model verification and an interpretation and extrapolation of experimental data;
- Determine the design specifications for controlled release fertiliser products that will synchronise release with sugarcane crop nitrogen demand and develop a strategy for the development of improved products based on an understanding of material properties and assembly methods; and
- Provide an economic benefit: cost analysis to quantify the on-farm financial impacts of adopting controlled release fertilisers.

### 3. OUTPUTS, OUTCOMES AND IMPLICATIONS

#### 3.1. Outputs

The project set out to deliver:

- i) Information to support decision-making by growers and industry on the effective use and experimental trialling of CRFs, resulting from communication strategies developed by the project and the PEC unit.
- ii) Information to form the basis for an exchange of knowledge with the fertiliser industry to allow new products to be developed (after the end of this project).

The target audience for (i) were sugarcane industry researchers and fertiliser company representatives engaged in experimental and demonstration trials of CRFs as well as the growers and advisors. Many of these people were reached through workshops and meetings organised by the project, through meetings organised by the SRA N Use Efficiency program and a range of other invited presentations (e.g. WTSIP Extension Officers Information Workshop in Innisfail in May 2016, HCPSL/SRA Grower forums in the Herbert catchment in September 2016, SRA Central Growers Update in Mackay March 2017 and the Agronomy community conference 'Tropical systems' in Townsville in June 2017). In addition information about the project and some of its findings was provided through articles in CaneConnection (August 2015, November 2016).

The target audience for (ii) were the fertiliser companies. We interacted with six of them throughout the course of the project. We shared our experimental protocols, early and final results on N release and materials characterisations and discussed issues relating to quality control and transport and storage issues. Several of the fertiliser companies also attended our mid-term and final project workshops. Representatives from Fertilizer Australia and the International Plant Nutrition Institute also attended the final project workshop and some of the other earlier presentations.

The project outputs (see below and in Section 4) provided information on:

- the different types of EEFs and how they work to provide environmental and agronomic benefits;
- the outcomes from experimental trials with EEFs and their interpretation;
- suggested improvements of experimental trial design including choice of control treatment and a method to measure timing of N release from CRF within experimental trials using buried mesh bags;
- the variation in N release characteristics of commercially-available CRF products in relation to material properties of the coatings of these products;
- the effect of soil temperature on N release patterns, including likely variability in the resulting N release patterns across the industry and as affected by time of application;
- the effect of soil water on N release patterns;
- the expected crop N uptake patterns as affected by location, crop class and timing of planting or ratooning;
- the predicted impacts of CRF use on yield improvement, on reduction of optimum N application and on reduction of N loss, including the effect of N release pattern, timing of rainfall, soil type, crop class and timing of ratooning;
- the large predicted seasonal variability in agronomic benefits and its implications for adoption and quantification of benefits using experimental trials; and
- the predicted economic net returns for a selection of case studies to demonstrate dependence on location, soil type, and seasonal conditions as well as to highlight the improved attractiveness when the costs of N loss to the environment are taken into consideration.

Adoption of the project outputs would be demonstrated by an increase in informed use of CRFs by growers, effective trialling of CRFs by researchers, advisers and growers as well as development of new CRF products and improved CRF management practices. While informed use of CRFs by growers will require further support (see below), the project has seen some evidence of early adoption of its outputs.

Over the course of the project we saw increased interest from the sugarcane industry in EEFs and we noticed improved understanding of differences between the types of EEF by the audience at workshops and presentations. We also saw increased recognition of the need for correct use of control treatments in trials of EEF. In the review undertaken during 2014 we identified at least four trials that had compared 'urea at a higher N rate' with 'CRF at a lower N rate' without a control 'urea at a N lower rate' to verify if an equal yield response was due to the CRF or due to a lack of N response. While these early trials were demonstration trials performed with a limited budget, correct choice of the control treatment (including urea at the lower N rate) was a strong message in several of our presentations during 2015 and 2016. We have had feedback that these presentations have provided corroboration for some of the subsequent trial designs. The 60 on-farm demonstration trials of Reef Trust IV will include urea at the lower rate as a control providing reinforcement of our message.

The idea of measuring N release in buried mesh bags during a trial to provide supporting data to assist with result interpretation was suggested in the review (Verburg et al., 2014). After presenting this idea at an SRA meeting in 2015 this led to a request by HCPSL to trial this method (see Section 5.3.3). The approach has since been adopted in three other trials.

The classification of N release patterns of CRF products into three types (I for early release, II for linear release and III for sigmoidal release, see Section 6.2.1) introduced by this project has facilitated discussion around N release patterns and their implications for synchrony with N demand patterns. For example, one of the productivity services contacted us after a presentation wanting to include a Type III release product in their trial. Wider adoption of this classification and how product specific release information can best be communicated will be explored with Fertilizer Australia.

The project findings that predicted N release patterns as well as N uptake patterns vary strongly as a function of location (climate) and timing of application, planting or ratooning have been discussed with researchers and representatives of the sugarcane and fertiliser industry. As these findings imply that optimal synchrony between N release and N uptake requires product, region and time of season specific advice, the project outputs still need to be translated into a useful extendable context to support decision-making by growers. The high seasonal variability in agronomic benefits identified by the project (see Section 6.4) also suggests that decision-making by growers and advisers will need more condition specific information. Extension of these messages is best done by region. A follow-up project will explore the development of decision logic that can fit into decision support tools for N management. The work will initially focus on the Herbert River catchment.

On the fertiliser industry side, the information has been welcomed by the fertiliser company representatives with our results adding to their own understanding of the products. One company which had not previously targeted the sugarcane industry has expressed interest in trialling their product. Another has indicated that the project outcomes may help to influence future development and improvements and that the project's development of novel testing methods to check product integrity and performance could potentially be used when testing new product ideas or to assess batch quality.

As per project proposal the key project outputs included:

- A paper and presentation (ASSCT) reviewing experimental findings.

The review of experimental findings was first delivered as part of a large review of nitrogen use efficiency in sugarcane:

- Verburg, K, Harvey, TG, Muster, TH, Brennan McKellar, LE, Thorburn, PJ, Biggs, JS, Di Bella, LP, & Wang, W 2014, 'Use of enhanced efficiency fertilisers to increase fertiliser nitrogen use efficiency in sugarcane', Chapter 7 Part I, in Bell MJ (ed.), *A review of nitrogen use efficiency in sugarcane*, Research Report, Sugar Research Australia, pp. 226-292.

An updated summary of the review was presented at the ASSCT conference in Mackay in May 2016:

- Verburg, K, Zhao, Z, Biggs, JS & Thorburn, PJ 2016, 'Controlled release fertilisers – Lessons from a review and early results characterising release, synchrony and nitrogen losses', *Proceedings of the Australian Society of Sugar Cane Technologists* 38, 159-169.

This paper was also selected for reprinting in the International Sugar Journal:

- Verburg, K, Zhao, Z, Biggs, JS & Thorburn, PJ 2016, 'Controlled release fertilisers – Lessons from a review and early results characterising release, synchrony and nitrogen losses', *International Sugar Journal*, vol. 118, no. 1414, pp. 764-770.

- A critique on different release mechanisms of controlled release products.

This output was incorporated into the nitrogen use efficiency review chapter:

- Verburg, K, Harvey, TG, Muster, TH, Brennan McKellar, LE, Thorburn, PJ, Biggs, JS, Di Bella, LP, & Wang, W 2014, 'Use of enhanced efficiency fertilisers to increase fertiliser nitrogen use efficiency in sugarcane', Chapter 7 Part I, in Bell MJ (ed.), *A review of nitrogen use efficiency in sugarcane*, Research Report, Sugar Research Australia, pp. 226-292.

- A report and paper documenting and explaining N release characteristics of controlled release fertiliser products.

This output was turned into three journal papers, which were summarised in a report provided as background material for the final project workshop:

- Muster, TH, Mardel, JI, Poole, J, Wittwer-Schmid, K, Verburg, K, Wong, MFT, Zhao, Z, McLachlan, G, Bristow, KL 2017, 'Understanding the release of nitrogen from commercially-available controlled release fertilisers' To be submitted to *Soil Science Society of America Journal*.
- Verburg, K, Bristow, KL, McLachlan, G, et al 2017, 'Towards improved understanding of soil water effects on nitrogen release from controlled release fertilisers' To be submitted to *Soil Science Society of America Journal*.
- Zhao, Z, Verburg, K, McLachlan, G, Bristow, KL, Wittwer-Schmid, K, Muster, T, Wong, MTF & Di Bella, LD 2017, 'A modelling approach to assess the effects of climate and management on nitrogen release patterns of controlled release fertiliser' To be submitted to *Agriculture Ecosystems and Environment*.
- Verburg, K, Muster, TH, Zhao, Z, Biggs, JS, Thorburn, PJ, Kandulu, J, Wittwer-Schmid, K, McLachlan, G, Bristow, KL, Poole, J, Wong, MFT & Mardel JI 2017, *Role of controlled release fertilizer in Australian sugarcane systems. Background information accompanying the final workshop of SRA project 2014/011*, CSIRO, Australia.

Over the course of the project results were also presented at various industry workshops, in one-on-one discussions with fertiliser companies and at the Australian Fertilizer Industry Conference in Cairns in September 2016 (see Section 4.1).

- A report, papers and presentations (conference and ASSCT) communicating understanding of how, when and where controlled release fertilisers offer N benefits, impact yield and loss pathways based on simulation analyses.

This output was presented at the ASSCT conference in Cairns in May 2017:

- Verburg, K, Biggs, JS, Zhao, Z & Thorburn, PJ 2017, 'Potential production and environmental benefits from controlled release fertilisers – Lessons from a simulation analysis', *Proceedings of the Australian Society of Sugar Cane Technologists* 39, 239-250.

A report summarising the findings was provided as background material at the final project workshop in August 2017:

- Verburg, K, Muster, TH, Zhao, Z, Biggs, JS, Thorburn, PJ, Kandulu, J, Wittwer-Schmid, K, McLachlan, G, Bristow, KL, Poole, J, Wong, MFT & Mardel JI 2017, *Role of controlled release fertilizer in Australian sugarcane systems. Background information accompanying the final workshop of SRA project 2014/011*, CSIRO, Australia.

A further one or two papers are planned. Throughout the project results were also presented at a range of industry workshops (see sections 4.1 and 7).

- A report and paper documenting the economic analysis.

An economic risk framework was first developed for assessing economic and environmental impacts of N management strategies taking into account variable climatic and economic conditions:

- Kandulu, J, Thorburn, PJ, Biggs, JS & Verburg, K, 2017, 'Estimating economic and environmental impacts of nitrogen in agricultural systems: an economic risk analysis', Submitted to *Journal of Environmental Management*.

The output relating to an economic analysis of CRF was presented as a case study at the ASSCT conference in Cairns in May 2017:

- Kandulu, J, Thorburn, PJ, Biggs, JS & Verburg, K 2017, 'Estimating economic impacts of controlled release fertilisers in sugarcane systems: An economic risk case study analysis', *Proceedings of the Australian Society of Sugar Cane Technologists* 39, 251-262.

A more elaborate analysis is being written up as a journal paper, the key results of which were summarised in the background materials for the final project workshop:

- Kandulu, J, Verburg, K, Biggs, JS & Thorburn, PJ, 2017, 'Evaluating the trade-off between potential economic and environmental benefits of controlled release fertilisers in sugarcane systems: an economic risk analysis' (in preparation)
- Verburg, K, Muster, TH, Zhao, Z, Biggs, JS, Thorburn, PJ, Kandulu, J, Wittwer-Schmid, K, McLachlan, G, Bristow, KL, Poole, J, Wong, MFT & Mardel JI 2017, *Role of controlled release fertilizer in Australian sugarcane systems. Background information accompanying the final workshop of SRA project 2014/011*, CSIRO, Australia.

## 3.2. Outcomes and Implications

Controlled release N fertilisers have the potential to optimise the productivity achieved per unit of fertiliser N input and lower environmental impacts from N leaching, runoff and emission losses. To support their successful implementation in the sugarcane industry this project has delivered information that has improved the understanding of how, when and where they work best, and what characteristics and specifications the CRF products need to have to provide reliable benefits in the face of seasonal variability. The project has shown how CRFs can provide agronomic, economic and environmental benefits. It has presented the variation in N release patterns of different commercially-available CRF products and quantified sugarcane N uptake patterns to inform required N release patterns. In addition it has demonstrated the large effects of seasonal climate variability, location (climate), soil and management (e.g. time of planting, ratooning and fertilisation) on both the benefits likely to be obtained and the required N release patterns.

This knowledge provides a basis for cost-effective, informed adoption of CRFs in Australian sugarcane systems that will maximise the likelihood of its success in decreasing DIN release into waterways of catchments draining into the Great Barrier Reef Lagoon and/or decreasing nitrous oxide emissions. The information delivered by the project also supports the design of ongoing experimental and demonstration trials with CRFs and interpretation of their results. Due to the high variability in benefits and required N release patterns to maximise them, application of the project outputs to support decision making by growers will likely require a regional approach that links decisions to specific conditions. The project provides a methodology to analyse these conditions and support development of decision tools that will assist in more widespread adoption of CRFs and EEFs in general.

The high variability in benefits and their dependency on soil, climate, management, choice of CRF and seasonal conditions make it difficult to estimate the potential impacts from CRF across industry. The simulations for a selection of climate x soil combinations analysed in this project suggest agronomic benefits in the form of a reduction in optimum N rate of at least 15 kg N/ha could vary from occurring in less than 5% of seasons to in more than 70% of seasons, depending on soil, climate, timing of ratooning and fertiliser management. Yield benefits where the maximum yield increases by more than 3 t/ha are likely to be less common, but could under some conditions occur in more than 20% of seasons. Environmental benefits in the form of reduction in N loss can, however, occur even when agronomic benefits are small or absent. The climate x soil combinations analysed in this project suggest long-term average reductions in total N loss ranging from less than 5% to more than 40% may be possible depending again on soil, climate, timing of ratooning and fertiliser management, but also on how well the total N requirement for the crop is estimated.

### 3.2.1. Recommendations and Future Industry Needs

The findings and learnings from this project lead to the following recommendations:

- Experimental evidence and simulation analyses confirm that CRFs can play a role in Australian sugarcane systems. The CRFs can be used to reduce N losses to the environment and provide agronomic benefits in the form of increased fertiliser N use efficiency, increased yield and/or the option to reduce N application rates. However, as the benefits from CRFs as well as their optimal management have been shown in this project to be highly condition specific, further investment into research and extension is required to develop region and condition specific advice to support decision making by growers (when to use CRF, another EEF or urea; the type of CRF to use; and the timing of its application).
- The simulation analyses indicate that environmental benefits from CRF are more consistent than agronomic benefits (across seasons, between soils and sites and across N rates). The magnitude of N loss is, however, strongly influenced by the total N supply relative to total N demand by the crop. With the simulation results indicating that the optimum agronomic N

rate is highly variable from season to season, better prediction of seasonal N requirements will be critical for achieving N loss reductions.

- The economic analysis in this project indicates that the CRFs will not provide a consistent economic advantage over urea across all soil, management and climate conditions, but that this can be improved when cost of environmental benefits is included. This suggests that other mechanisms may be required in regions where the environmental benefits are desired, but the farm economics would be insufficient to drive adoption.
- Experimental trials that attempt to provide decision support on when and where to use EEF need to use complementary simulation analyses to capture a wider range of seasonal, soil and management conditions and to provide an insight into the likely place of the experimental conditions within these.
- Experimental trials that evaluate whether similar yield/economic outcomes can be achieved with a reduced N rate for EEF should include a control treatment of urea at the same reduced rate to allow an assessment whether the similar yield was due to the benefits of EEF or absence of N response.
- Experimental trials that attempt to quantify the magnitude of the N rate reduction for EEF need to measure the full N response curve, because otherwise effects may be missed or underestimated.

The project findings also suggest further research would be warranted in the following areas:

- A similar model evaluation quantifying benefits and frequency of benefits from the use of nitrification inhibitors (NIs), another popular type of EEFs, as a function of seasonal climate conditions, time of application and soil type. As NIs keep the N in ammonium form, this requires testing of the parameterisation of a model that allows both nitrate and ammonium uptake by crops.
- Evaluation whether climate forecasting (for the first 2-3 months of the season) can be used to predict those seasons where EEF will provide the biggest benefits.
- Testing whether the higher agronomic benefits from CRF use predicted for some soils in Tully and the Burdekin Delta relate to loss pathway, frequency of large N loss events and/or their higher yield potential. As well as an investigation of what limited agronomic benefits in some of the other soil x climate combinations that did achieve reductions in N loss.
- Further quantification of the precise coating properties that affect soil water effects on N release from CRF, in order to predict likely sensitivity of other and new CRF products.
- Quantification of early N demand by ratoon crops and improved understanding of root dynamics following harvest. This is still poorly understood and not captured well enough in the model to conclude with certainty that little N is required until the rapid growth stage.
- Evaluation whether there may be varietal differences in N uptake patterns. These were not considered in this project due to the limited availability of experimental data comparing N accumulation by multiple varieties under identical conditions. The limited data to-date (Wood et al. 1996, Connellan and Deutschenbaur 2016) suggest differences in N accumulation are small during the first 100-150 days after planting or ratooning, but this would warrant confirmation.
- Evaluation whether timing of N supply, as distinct from total amount of N supply, can affect CCS and, if so, whether that should be taken into account in decisions on CRF N release patterns for crops designated for early harvest.

## 4. INDUSTRY COMMUNICATION AND ENGAGEMENT

### 4.1. Industry engagement during course of project

The project team engaged with both the sugarcane and fertiliser industry over the course of the project. This included presentations at ASSCT in Mackay (2015) and Cairns (2016), at SRA organised workshops for N management related projects, at grower updates or forums, at extension oriented workshops, at the Australian Fertilizer Industry Conference and at scientific conferences. We also held two project workshops (mid-term and end-of-project) that brought together representatives and researchers from the sugarcane industry and the fertiliser industry. At these meetings we presented project results and the workshops discussed implications and future directions. In addition we had discussions directly with small groups or individuals in the sugarcane and fertiliser industry.

David Calcino from the SRA PEC unit attended a number of these presentations and was kept informed of progress, but as so many opportunities for communication already presented themselves through connections with SRA, collaborators and others in the industry we did not approach the PEC Unit for further assistance. While we have presented at grower updates and forums in the Herbert and Mackay regions as well as at an agronomy community conference in Townsville, there may be benefit in extending these grower focussed presentations to other regions. Assistance was also provided for articles in CaneConnection (Winter 2015, Spring 2016).

Industry communication and presentations carried out during the course of the project and their main topics are listed below. Adoption of project outputs to-date has been discussed in Section 3.1. Examples of the key communications that influenced the early adoption of project outputs include the presentation at the SRA NUE Meeting in Brisbane in July 2015 (prompting the mesh bag trial with HCPSL), discussion of laboratory protocols for characterisation of CRF products with the fertiliser industry (consideration of use as quality or batch-to-batch consistency tests), presentation at ASSCT conference in Mackay in May 2016 (correct controls in EEF trials, choice of trial conditions conducive to N loss, value of mesh bag N release measurement), mid-term project workshop in Townsville in May 2016 (implications of different N release patterns, need for decision support leading to the proposal for a new project, outside fertiliser company stimulated to start trials), presentation at ASSCT conference in Cairns in May 2017 (implications of seasonal variability for experimental trials and need for decision support), presentation at Agronomy community conference in Townsville in June 2017 (classification of N release patterns and one of the productivity service seeking out a particular N release pattern), and final project workshop (fertiliser industry considering ways to improve communication of CRF N release characteristics).

Industry presentations, workshops, meetings and discussions (publications are listed in Section 7):

- NUE Review in Brisbane, Sep 2014: presentation of early review findings, literature evidence of N release patterns, early simulations on agronomic and environmental benefits
- SRA NUE Meeting in Brisbane, Jul 2015: presentation of project objectives, methodology, expected outcomes, connections
- Article in CaneConnection Winter 2015, Aug 2015: project introduction
- Meetings with Fertiliser Companies in Sydney, Melbourne and by phone, Aug 2015: presentation of project overview, experimental and modelling methodologies
- Discussion of laboratory protocols for characterisation of CRF and N release, Aug 2015: detailed description of protocols for information and comment of fertiliser companies
- SRA EHP Meeting in Brisbane, Sep 2015: presentation of project overview, early modelling results and modelling plans for discussion

- Meeting with Herbert catchment farmer group in Ingham, Sep 2015: presentations introducing EEF, project overview, early modelling results and modelling and economic analysis plans for discussion
- MODSIM2015 conference at Gold Coast, Dec 2015: presentation of modelling analyses extrapolating from field trials to determine variability in N uptake patterns
- ASSCT 2016 Conference in Mackay, May 2016: presentation introducing EEF, review findings, reasons for lack of experimental treatment effects, and early project results on N release patterns of CRF products and modelling of benefits
- ASSCT 2016 Conference in Mackay, May 2016: poster and presentation on CRF N release patterns and temperature effects
- ASSCT 2016 Conference in Mackay, May 2016: poster and presentation on N uptake and N release patterns as a function of climate, time of planting/ratooning or fertilisation and seasonal variability
- N management workshop in Townsville, May 2016: presentation introducing EEF, review findings, project overview and early results on CRF N release patterns and temperature effects, and on modelling of agronomic benefits and implications for trials (choice of control treatment)
- WTSIP Extension Officers Information Workshop in Innisfail, May 2016: presentation introducing EEF, interpretation of experimental results and statistical significance, review findings, role of EEF, reasons for lack of experimental treatment effects, overview of project and early results on CRF N release patterns and on modelling of agronomic benefits and implications for trials (choice of control treatment)
- Project workshop for fertiliser and sugar industry in Townsville, May 2016: presentations introducing EEF, review findings, role of EEF, possible reasons for lack of treatment effects, project overview, CRF N release patterns and temperature effects, model analyses of N uptake and N release as a function of location (climate), management and seasonal variability, modelling of agronomic benefits and possible improvements from better synchrony; industry presentations and discussions, report summarising workshop findings.
- Australian Fertilizer Industry Conference 2016 in Cairns, Sep 2016: presentation introducing EEF, review findings, example simulated agronomic benefits and implications experimental design (choice of control treatments), characterisation of CRF N release and material properties affecting N release
- HCPSL/SRA Grower forums in the Herbert catchment, Sep 2016: five presentations in different parts of the catchment introducing EEF, role of EEF, interpreting experimental results, review findings, project N release characterisation and modelling activities
- SRA NUE meeting in Brisbane, Oct 2016: presentation of intended project outputs and outcomes
- Article in CaneConnection Spring 2016, Nov 2016: early results on N release and N response
- Meeting with advisors in Townsville, Jan 2017: presentation introducing EEF, role of EEF, review findings, modelling of agronomic benefits for Tully case study and large seasonal variability in optimum N reductions, discussion on decision support needs
- SRA Central Growers Update in Mackay, Mar 2017: presentation introducing EEF, role of EEF, review findings, CRF N release patterns and temperature effects, modelling of agronomic benefits for Mackay case study and seasonal variability in optimum N reductions
- ASSCT 2017 Conference in Cairns, May 2017: presentation introducing CRF, role CRF, experimental N release patterns, modelling of agronomic and environmental benefits Tully case study, quantification of magnitude and seasonal variability in benefits (optimum N reductions), drivers determining benefits, implications for experimental design (choice of control treatments for experimental assessments, likelihood of missing effects due to seasonal variability in N response), opportunities for improving benefits

- ASSCT 2017 Conference in Cairns, May 2017: presentation of a Tully case study of economic benefits from CRF
- Agronomy community conference 'Tropical systems' in Townsville, Jun 2017: presentation of CRF N release characteristics and material properties explaining them
- 3rd International Conference on Agricultural and Biological Sciences in Qingdao, Shandong, China, Jun 2017: presentation of modelling analysis of N uptake to inform required N release patterns
- Meeting at Controlled Release Fertiliser innovation centre in Shandong, Jul 2017: discussion of CRF products, N release patterns and temperature effects, experimental and modelling methodologies, project overview and potential collaborations
- Meeting with Fertiliser Researchers in Beijing, Jul 2017: discussion of project, CRF N release patterns, field experimental data and possible future collaborations on modelling of field experiment data
- Phone meetings with fertiliser companies, Jul 2017: presentation of N release and characterisation results for individual products
- Final project workshop for fertiliser and sugar industry, Brisbane, Sep 2017: presentations providing an overview of all project findings, presentations from other EEF projects and the fertiliser industry and discussions on future directions.

## 4.2. Industry communication messages

The key messages presented by the project, grouped by theme, are:

### *Benefits from CRF*

- Experimental evidence and simulation analyses confirm that CRFs can play a role in Australian sugarcane systems. They can reduce N losses and provide agronomic benefits in the form of increased fertiliser N use efficiency, increased yield and/or reduced N application rates that achieve a similar yield as higher rates of conventional fertiliser.
- The agronomic benefits are, however, highly variable from season to season. The percentage of seasons that result in measurable benefits is affected by climate, soil, crop class and timing of fertiliser application. Other yield limiting factors may limit the agronomic benefits that can be obtained from CRF use.
- As a consequence of the variable agronomic benefits, CRFs do not provide a consistent economic advantage over conventional fertilisers across all soil, management and climate conditions. This can be improved when the cost of environmental benefits is included or use of CRFs can be targeted to those seasons where agronomic benefits are most likely.
- Yield increases or reductions in optimum N rate need to be considerable to overcome the higher cost of CRF relative to urea and this reduces the economic benefits. Production processes and location as well as model of transport affect the cost of CRF products and hence the economics of their use. To some extent these are driven by demand.
- Development of regional guidance for informed decisions, e.g. a decision tool based on an understanding of the dynamics of local soils and cropping systems as well as seasonal climate and climate variability and CRF product response to these will be important for the successful implementation of CRFs.
- Yield benefits are typically limited to the slope of the N response curve (below the agronomic optimum N rate), except in situations where almost complete loss of urea fertiliser N occurs, which is more likely to happen with late ratooned crops grown in wet climates on soils susceptible to large N loss events.

- The ability to reduce N application rates while maintaining yield (and hence increase N use efficiency) will be the more common agronomic benefit of using CRFs, but the magnitude of the reduction in optimum N rate and the optimum N rate itself are seasonally variable.
- Agronomic benefits are obtained more often with late ratoon crops compared with plant crops and early ratoon crops due to the increased risk of N loss in the period before crop N uptake.
- Environmental benefits in the form of reduction in N loss can occur even when agronomic and economic benefits are small or absent. This strengthens the environmental drivers for promoting the use of CRFs, but adoption in these circumstances may require additional mechanisms.
- As the magnitude of N supply relative to crop N demand has a large effect on magnitude of N loss, effective use of CRF requires that N application levels are matched to the demand by the crop and that the higher efficiency of CRFs is taken into account and used to lower N application rates.

#### *Lessons from and for experimental trials with CRFs*

- Experimental trials with CRFs and other EEFs in Australian sugarcane have shown neutral to positive effects, but only some of the studies achieved statistically significant treatment effects.
- Lack of statistically significant treatment responses can be linked to (1) a lack of reduction in N loss due to insufficient N loss or timing of N loss, (2) an absence of yield response by the crop due to total N supply being too high, other factors limiting yield or N release not being matched with demand, and (3) spatial variability resulting in low precision of observed yields and treatment yield difference not being large enough.
- Experimental trials that test whether a lower rate of EEF can achieve a similar yield as a higher rate of urea-N need to include a control treatment of urea-N at the lower rate to distinguish between the effect of the EEF and lack of N response.
- The large season-to-season variability in agronomic benefits from CRF makes it difficult to generalise from the results of experimental trials and provide advice on likely yield benefits or magnitude of reductions in optimum N, unless the conditions of the trials have been put in context, e.g. using simulation analysis.

#### *Characteristics of commercially-available CRF products*

- Commercially-available CRF products exhibit different N release patterns that are also strongly sensitive to temperature, which can affect the ability of the CRF to synchronise with sugarcane N demand under different conditions.
- Differences in coating integrity and composition as well as manufacturing quality result in three types of N release patterns: Type I products that release a considerable amount of N within the first days; Type II products which have a short lag period (< 1 week) followed by a relatively linear release period up to approximately 60% release; and Type III products which have an extended lag period after which release gradually increases to form a sigmoidal release pattern.
- Soil water can affect N release from CRF at soil matric potentials between field capacity and the crop wilting point. Release can be delayed under drier soil conditions, but the magnitude of the effect is CRF product specific and may under typical field conditions experienced in many sugarcane systems not be of practical significance.

- Within product variations in granule size, coating thickness and integrity can affect the N release pattern as well as reducing precision in laboratory experiments that use small samples of CRF granules.

#### *Opportunities for improved synchrony and CRF product improvements*

- It is important to understand the required N release patterns to achieve synchrony between N release and crop N demand to maximise benefits and avoid negative crop yield impacts.
- Agronomic and environmental benefits from CRF use are sensitive to the synchrony achieved between N release and crop N demand. Blends are not as effective, but may provide some buffer against negative crop yield impacts.
- The different N release patterns of commercially-available CRF products and their temperature responses need to be considered when designing fertiliser management (product choice, application and timing) in order to synchronise with sugarcane N demand.
- The large season-to-season variability in agronomic and economic benefits and their dependence on climate, soil type and cropping system management strongly suggests that tactical use of CRFs supported by decision support tools for growers should be the route to sustained adoption.
- While seasonal variability in N release appears limited, the strong temperature response of CRFs results in release times that can vary considerably depending on location and time of application with release faster in warmer climates and with later applications.
- Simulated N uptake patterns for sugarcane show an initial, well-defined lag period with little N uptake (on average < 17 kg N/ha), followed by a relatively sudden transition to a rapid and approximately linear uptake period, after which N uptake continues at a slower rate, but with increasing seasonal variation.
- Simulations indicate that both the lag period (55-137 days) and linear uptake rate are affected in large by location, crop class and management effects although seasonal variability only affected the N uptake rate.
- Simulated total N uptake showed considerable seasonal variability. While luxury N uptake may have contributed to this it highlights that there is a need for better forecasting of seasonal N requirements otherwise the benefits of CRF may be negated by over or under supply of N.
- Simulations can provide guidance around desired lag time and maximum release rate, but the temperature and soil water response of the CRF product as well as the seasonal N requirement need to be considered to determine optimal fertiliser management for local conditions.
- As a consequence of temperature dependence of both N release and N uptake patterns, optimal synchrony may not be able to be achieved with a "one size fits all" CRF given Australian sugarcane is produced in a large range of climates and with a wide spread in planting / ratooning dates.
- The early demand for N by ratoon crops remains uncertain as the root dynamics following harvest are still poorly understood and is hence not captured well enough in the model to conclude with certainty that little N is required until the rapid growth stage.
- CRF coating characteristics, including N release pattern type, temperature and soil water response can be modified through variation of the coating composition, use of fillers or use of multiple coating layers with different properties.
- Quality control and assurance of CRF products, e.g. in relation to batch to batch consistency, will be important for increased adoption as is more detailed information on release patterns.

## 5. METHODOLOGY

### 5.1. Overview of project activities

The project consisted of five coordinated activities:

- Review of experimental findings
- Characterisation of N release patterns of commercially-available CRF products
- Materials science characterisation of commercially-available CRF products
- Model simulation analyses to assess agronomic and environmental benefits
- Economics analyses

The aim of the materials science characterisation of the commercially-available CRF products was to help explain the N release patterns and effects of temperature and soil water. It was also included to inform design parameters for possible improvement of CRF products.

### 5.2. Review of experimental findings

A review of types of EEF products and experimental findings of their use in sugarcane and other agricultural industries was undertaken as part of a larger review of nitrogen use efficiency in sugarcane (Verburg et al., 2014, chapter 7 in Bell, 2014). The review considered more than 240 sources and focussed primarily on published (peer reviewed) results, but also included other evidence publicly available on the Internet. The review was updated with additional new evidence for a summary presented at ASSCT (Verburg et al., 2016).

### 5.3. Characterisation of N release patterns of commercially-available CRF products

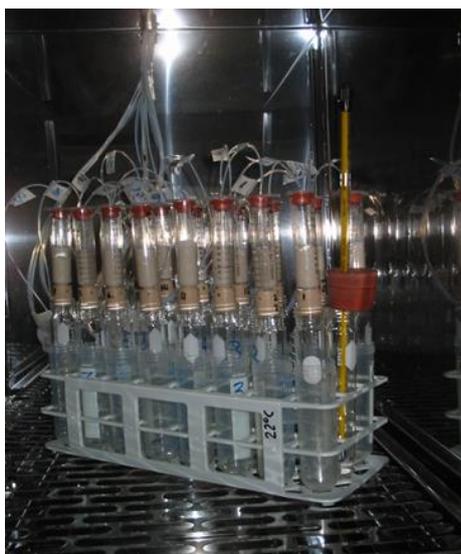
The characterisation of N release patterns consisted of two types of laboratory release experiments, a range of measurements and experiments to characterise the material properties of the CRF granules, and measurement of N release in the field. The characterisation was aimed at providing information to the sugarcane industry in Australia on product types and their N release characteristics.

In addition, the data was intended to provide a basis for parameterisation of fertiliser N release in the Agricultural Production Systems Simulator (APSIM) model (Keating et al., 2003; Holzworth et al., 2014), which was used in the simulation analyses (Section 5.4). This latter aim contributed to the inclusion of two types of N release experiments. Incubation leaching columns were used to characterise the N release patterns and their dependency on temperature. Separately, small intact soil cores were used to study the effect of soil water. Separation of the temperature and water factors allows them to be modelled using multiplicative factors that modify a set N release pattern. This is similar to approaches used to simulate other soil N dynamics processes, e.g. mineralisation and nitrification (Probert et al., 1997).

The experiments and measurements are briefly described below, but further details can be found in Muster et al. (2017), Verburg et al. (2017b) and Zhao et al. (2017b). They involved subsets of a range of CRF products that were either polymer coated urea (PCU) or polymer sulfur coated urea (PSCU). The PSCU products are sulfur coated fertilisers with an additional thin layer of an organic polymer intended to improve the attrition resistance of the coated granules (Shaviv, 2001). The PCU products have coatings made of a variety of organic polymers, sometimes consisting of mixtures of low and high permeability polymers or including inorganic fillers (Shaviv, 2001; Muster et al. 2017). Both composition and thickness of the coating can control the release rate and its temperature response. The products were obtained from different fertiliser companies and were selected to capture a range of different coating types. At the time of their selection, only some of the products were being trialled in the Australian sugarcane industry.

### 5.3.1. Incubation leaching columns

Incubation leaching experiments were used to characterise N release as a function of temperature for nine CRF products, of which seven were PCU and two were PSCU. The methodology is based on exposing a soil-fertiliser mixture to intermittent leaching (every 2 hours) to remove and collect the N as soon as it is released. This allows the release pattern to be established as a function of time for a single sample (Figure 1). The method used biologically-active soil to allow for all modes of degradation (chemical, physical and microbial) to occur. Using a compact set-up that fitted within incubators, the experiments could be performed at controlled temperatures and multiple samples to be analysed concurrently.



**Figure 1: Incubation leaching columns for determining N release as a function of time and temperature.**

All tests were conducted using a silty clay soil taken at a depth of 10 cm from a sugarcane farm near Ingham Qld (pH 4.6, 51% clay, 2.1 % total C). The soil was mixed with 0.5 g of the CRF. The mixture of soil plus CRF represented an application of 200 – 230 kg N/ha applied as a uniform 5 cm band in furrows spaced at 1.5 m in the field. This rate of CRF, while higher than commonly applied rates of 120-180 kg N/ha was chosen to ensure that the population of fertiliser granules would be better reflected in the samples. The soil-fertiliser mixture was placed in 25 ml syringes giving a soil height of approximately 2 cm. The bottom of each syringe was pre-lined with a double layer of glass fibre filter paper and then moistened <75  $\mu\text{m}$  silica flour (3.0 g dry weight equivalent) to act as a filter bed. The top of each soil was covered with a layer of glass fibre filter paper. Three replicates were used for each soil-CRF mix along with three control soil replicates with no CRF.

The soil-fertiliser mixture was exposed to daily leaching with a 10 mM  $\text{CaCl}_2$  solution, which passed through the soil-fertiliser bed and was collected for analysis. Use of a  $\text{CaCl}_2$  solution minimised soil dispersion. The daily leaching rate of 40-50 ml per day was applied as 12 aliquots every 2 hours using a programmable power timer to control the pump. Each aliquot of 3.3 to 4.2 ml was equivalent to about 1 pore volume of solution entrained in the soil. Hence, the soil-fertiliser mix was effectively leached with the equivalent of 12 pore volumes of solution to ensure that the daily amounts of N released were removed from the soil. The output solution drained into 250 ml plastic bottles. Leachate volumes were measured by weight. The concentrations of urea, ammonium and nitrate N were measured and N released at each sampling interval calculated from output solution volume and concentration. The experiments were performed at three temperature levels (approximately 15°C, 28°C and 36°C; see Muster et al. (2017) for details).

### 5.3.2. Soil core studies

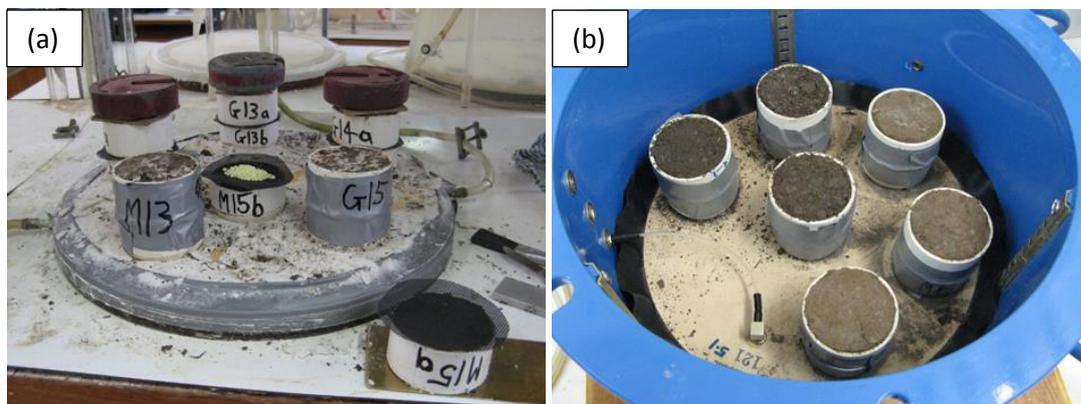
Two CRF products, a PSCU and PCU product used in the incubation leaching columns (Section 5.3.1) and in the mesh bag field N release study (Section 5.3.3 below), were used to explore the effects of soil water on N release. The experiment consisted of monitoring the release of N from CRF granules placed in the middle of undisturbed soil cores equilibrated at different soil matric potentials using soil physics-equipment in the laboratory.

Soil matric potential rather than soil water content was chosen as the independent variable, because three previously identified processes by which soil water could affect N release were all controlled by the soil matric potential rather than the soil water content (see Verburg et al. (2017b) for details). The soil matric potential, which determines the force with which water is being held by the soil particles and controls the thickness of the water films around the soil particles, could affect (1) the ease with which water moves into the CRF granules (water absorption stage prior to release), (2) the rate at which urea-N moves out of and diffuses away from the CRF granules (release stage), and (3) for sulfur coated CRFs the microbial dynamics responsible for degradation of the sulfur coatings. Expressing the soil water effect as a function of matric potential also allows learnings to be applied across a range of soils.

Soil cores were obtained from two different sugarcane paddocks near Ingham Qld and represented a sandy loam soil (pH 5.5, 10% clay, 0.7 % total C) and a silty clay soil (pH 4.6, 51 % clay, 2.1 % total C; same as in Section 5.3.1) with contrasting relationships between soil matric potential and soil water content.

The CRF N release measurements were made at four different soil matric potentials in the range between 'field capacity' and 'crop wilting point' in a constant temperature environment (21°C): at -100 cm and -600 cm using ceramic suction plates and hanging water columns (Figure 2a) and at -5,000 cm and -10,000 cm (Figure 2b) using pressure plates. The CRF granules (approximately 2 g) were inserted in the cores by cutting the cores in half and lining with a mesh (1.8 mm by 1.2 mm) to aid with retrieval of the granules after set equilibration times (5, 30, 45 or 60 days).

Upon retrieval the granules were counted and weighed, after which half were analysed for the amount of remaining urea and the other half were photographed using stereomicroscopy. The amount of urea remaining (i.e. not released) was determined rather than the amount released as the latter would be more difficult to capture and be affected by soil variability. Three replicate measurements were made for each combination of matric suction and equilibration time, product and soil type.

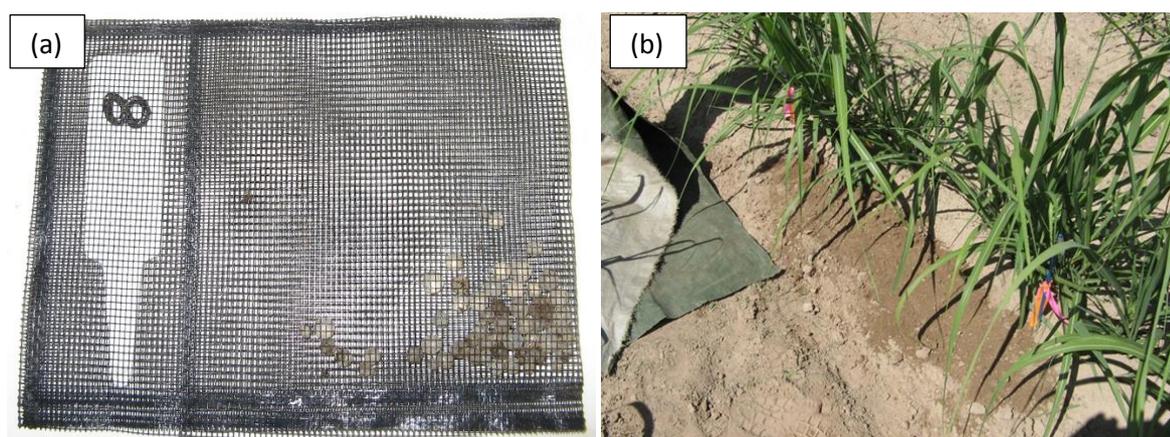


**Figure 2: Use of (a) ceramic suction plates and hanging water columns (-100 and -600 cm) and (b) pressure plate equipment (-5000 and -10,000 cm) to allow N release to occur at controlled soil matric potentials.**

### 5.3.3. Mesh bag field N release

Release of N under field conditions was tested during the 2015-16 season for two CRF products, a PCU and a PSCU, in a sugarcane field with an alluvial sandy loam soil near Ingham Qld (same soil as in Section 5.3.2). Mesh bags (10 cm x 10 cm) made of a pliable PVC coated fibreglass yarn with apertures of 1.8 mm x 2.0 mm (fibreglass insect screen) were filled with 2.09 g urea, 2.23 g PCU or 2.53 g PSCU (representing an application of 160 kg N/ha for a row spacing of 1.8 m) and buried at 10 cm below the soil surface in the hill of the sugarcane row (Figure 3). At the time of application the soil surface was drying out, but there was some moisture at depth. Seven mesh bags of each type of fertiliser were buried in each of 6 replicate plots 98 days after planting of the sugarcane crop with one bag retrieved at each sampling time. The late application was to avoid interference from the 'hilling up' performed at 79 days. The bags were sampled sequentially, one bag of each type of fertiliser per replicate plot 21, 49, 99, 153, 229 and 272 days after application. Upon retrieval the granules were briefly dried with a tissue and gently brushed to remove water and soil and stored in the fridge prior to transport to an interstate laboratory. During some of the later samplings the retrieved samples were very muddy and were left to air-dry before being brushed. At the last sampling rinsing in ice water was trialled with the 7<sup>th</sup> bag. In the laboratory the granules were counted and weighed, after which half was analysed for the amount of remaining urea inside and the other half was photographed using stereomicroscopy.

Temperature loggers were buried at 10 cm depth alongside the mesh bags in three of the plots and also at 20 cm depth in one of the plots. Soil temperatures were recorded at 30 min intervals for the duration of the experiment.



**Figure 3: (a) Mesh bag retrieved from the field after a set release time, with separate pocket for identification label, (b) seven bags of each type of fertiliser were buried in the hill of the sugarcane row of each of 6 replicate plots for sequential removal over the course of the season.**

### 5.3.4. Material science characterisation

The seven urea CRF product types, which included a number of product variations (e.g. with a thicker or thinner coating, or an earlier version of the product) were characterised using the following measurements and experiments:

1. *Fourier Transform Infra-Red (FTIR) spectroscopy and solvent dissolution*: information on chemical bonding and thermoplastic versus thermosetting characteristics of the coating to provide a general understanding of the coating used. Classification of thermoplastic versus thermosetting was also supported by evaluation of polymer dissolution in organic solvents;

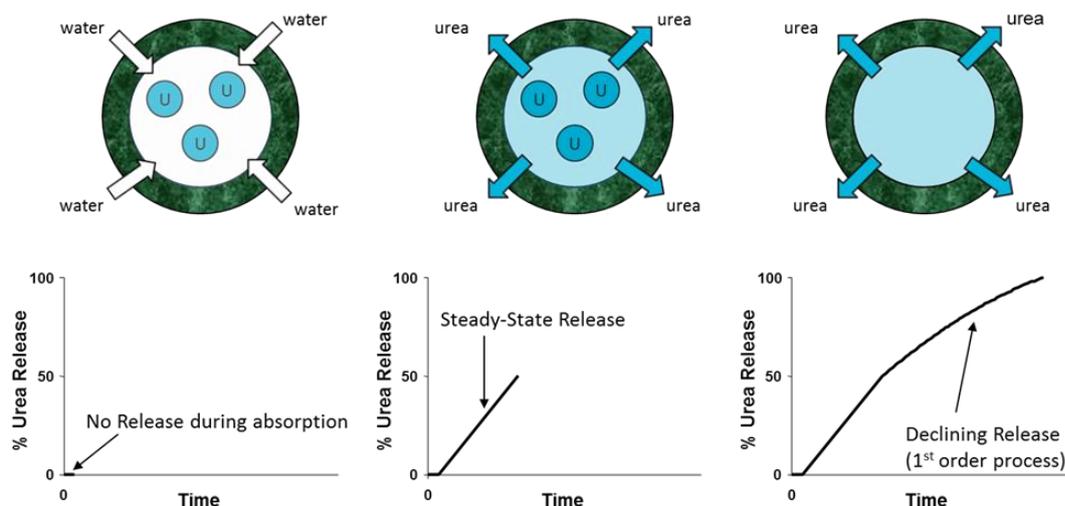
2. *Optical microscopy*: To visualise coating defects and changes over time, CRF granules were viewed using an optical stereo microscope and photographed using 10x magnification before and after release;
3. *Coating integrity test 1*: to test the initial integrity of the coatings of PCU granules they were monitored over a 5-day immersion in water. Based on the density of urea ( $1.32 \text{ g/cm}^3$ ) and that of the polymer coatings ( $< 1 \text{ g/cm}^3$ ), a 'full' granule sinks in water whilst an 'empty' granule will float. 100 granules of each PCU product were tested and the percentage floating recorded over time. Due to sulfur possessing a density  $> 2 \text{ g/cm}^3$ , this test was not performed with PSCU products;
4. *Coating integrity test 2*: In a second integrity test applicable to all types of coating, individual CRF granules were placed in each well of a 96 well plate. A test solution comprised of jack bean urease and phenolphthalein was added to provide colorimetric evidence of release of any urea ( $>$  approximately 1%). This method was also used to test for coating integrity following impact testing of the CRF products, where 96 granules of each product were selected at random and dropped down a 10.7 m high tower;
5. *Compression testing*: to provide a measure of resistance of granules to deformation or fracture under pressure, which is of interest in estimating the expected handling and storage properties of a granular material (Walker et al., 1997, 2003). Individual fertiliser granules were placed on a flat metal surface and pressure applied by a flat-end rod attached to the compression test load cell to measure maximum load and crush strength that avoided rupture. The experiment was done with dry original samples as well as water saturated samples from the water uptake experiment;
6. *Granule size distribution*: A series of stainless-steel sieves with square mesh was used to grade the relative number of granules in the size ranges of  $< 1.5 \text{ mm}$ ,  $1.5 \text{ mm} < x < 2.5 \text{ mm}$ ,  $2.5 \text{ mm} < x < 3.0 \text{ mm}$ ,  $3.0 \text{ mm} < x < 4.0 \text{ mm}$ , and  $> 4 \text{ mm}$ ;
7. *Nitrogen content evaluation*: Coatings of CRF granules were carefully pierced using a scalpel and the mass of the dry granules was recorded prior to dissolving the urea from the granules through the addition of milli-Q water over a period of 48 hours. The remaining coatings were rinsed with milli-Q water, dried in a vacuum oven at  $40^\circ\text{C}$  overnight and weighed to calculate the percentage weight of the coating and N content;
8. *Hydrophobicity*: to provide a measure of how easily the granules are wet by water. Hydrophilic surfaces are easily wet by water whereas hydrophobic surfaces repel moisture and would prefer to remain in contact with other hydrophobic surfaces or surrounding air. Relative hydrophobicity was assessed by monitoring the ability of the CRF granules to be suspended on the surface of water/ethanol mixtures of varied surface tension. Ten granules (sized  $2 \text{ mm} < x < 2.5 \text{ mm}$ ) were gently rolled onto the surface of water-ethanol mixtures of varying ratio and the number of granules remaining suspended on the air-water interface after one minute recorded;
9. *Rate of water (vapour) uptake*: 1 g of each fertiliser was placed into an open sample vial, weighed and recorded. The vials were then placed in a petri dish on a raised stand in a 20 L bucket with 2 L of saturated potassium sulphate solution and sealed with a lid. This allowed measurement of water uptake through vapour flow (measured over time for up to 56 days by weight difference) in an environment of 97% relative humidity.

## 5.4. Model simulation analyses

Simulations were performed with the APSIM model (Keating et al., 2003; Holzworth et al., 2014) configured with a sugarcane model (Keating et al., 1999). APSIM captures crop growth, soil water and N dynamics, as well as interactions between these and management. APSIM has been tested extensively in sugarcane and a variety of other crops (see e.g. Thorburn et al., 2014).

The model was also configured with a custom management script that described the controlled release of N using a three-stage conceptual model (Figure 4) often associated with polymer-coated fertiliser granules in which release is only dependent on time and temperature (Shaviv, 2001): (1) a water absorption stage without release; (2) a linear release stage (to 50%); and (3) a (first order) declining release stage. This model was first used by Verburg et al. (2013) and is described in more detail in Zhao et al. (2017b).

The analyses included simulations of crop N uptake and CRF N release as a function of climate, crop class and management as well as simulations of agronomic and environmental benefits in response to different levels and types of fertiliser N. The latter were performed for a variety of soil, climate and management conditions representative of different sugarcane growing areas in Queensland. Historical climate data were obtained from the SILO climate data archive (Jeffrey et al., 2001).



**Figure 4: Conceptual three-stage process for release from controlled release polymer coated fertilisers.**

### 5.4.1. N uptake patterns

The analyses of N uptake patterns used measured data on biomass N accumulation as its starting point taken from literature detailing the development of the APSIM Sugarcane model (Keating et al., 1999). These data sets included biomass and biomass N accumulation from a variety of experiments across the Australian sugarcane industry. In a first simulation analysis ten of these experiments with high water and N input were simulated using the APSIM model version 7.7 and extrapolated in time by *virtually* repeating these experiments in an additional 55 seasons (1958–2014) using the same management (Zhao and Verburg, 2015).

This initial analysis highlighted significant effects from differences in climate as well as planting and ratooning times in the different experiments. Consequently, a follow-up analysis took a more systematic approach to evaluate N uptake patterns as affected by climate (5 sites, 56 seasons, 1958–2014), crop class (plant and ratoon), early and late planting (1 May, 1 August) or ratooning (1 August, 1 November). Nitrogen uptake patterns were studied for N and water unlimited conditions, but also for region specific irrigation management or rainfed conditions (based on the work by Biggs et al.

(2013) and Thorburn et al. (2011)) along with a still generous, but limited N application of 300 kg N/ha. The five sites and the parameterisation of their soils were based on Keating et al. (1999) and included: Ingham (I), Ayr (A), Bundaberg (B), Harwood (H) and Grafton (G). See Zhao et al. (2017a) for further details.

The simulated N uptake patterns were compared to the conceptual three-stage CRF release pattern described above (Figure 4). This allowed quantification of the variations in uptake patterns to be expressed in terms that related to the required timing of N supply, namely the lag to the rapid N uptake period, the rate of uptake during this period and the amount of N required during the lag.

#### 5.4.2. N release patterns

A similar systematic analysis was used to explore the effects of climate and time of application on the N release patterns, due to the observation that the release is highly sensitive to temperature (Section 6.2.2). Starting point for these simulations was the parameterisation of the 3-stage CRF release model using the incubation leaching column N release data (Section 6.2.1) and temperature response (Section 6.2.2) of the PCU product used in the field N release mesh bag experiment. The temperature response was captured by a  $Q_{10}$  factor, which indicates the factor by which the release rate increases for a 10°C increase in temperature. For example a  $Q_{10} = 2$  results in the halving of the stage 1 lag and a doubling of release rates during stages 2 and 3 for every 10°C increase in temperature. The data from this field trial (Section 6.2.4) along with soil temperature measurements were used to verify the model.

Nitrogen release patterns for this product were then predicted at four locations (Innisfail, Ingham, Bundaberg, Harwood), for three application times (1 May, 1 August, 1 November) and 112 seasons of historical climate data (1902–2014). For more details see Zhao et al. (2017b).

#### 5.4.3. Yield and N loss response to CRF

Over the course of the project several simulation analyses were performed to illustrate crop responses to CRF or to explore particular questions for industry presentations. For example, they were used to illustrate the principles behind benefits from CRF, to explain the type of control treatments required in experimental trials and to demonstrate effects of improved synchrony and timing of fertiliser application. A final large simulation analysis quantifying climate x soil effects on predicted benefits incorporated most aspects of the earlier analyses and is described here.

The simulation analysis was carried out using the APSIM-Sugar model (Keating et al., 1999; Thorburn et al., 2005; Holzworth et al., 2014) version 7.8. The simulations included climatic conditions reflecting the districts of Bundaberg, Mackay, Burdekin River Irrigation Area, Burdekin River delta, Herbert, and Tully (historical climate data obtained from SILO Point Patch Data; Jeffrey et al., 2001). For each region simulations included a number of locally relevant and contrasting soil types for which model parameterisations have been tested in past work (Table 1).

As the scenario analysis focussed on the 'where and when', it used a relatively simple design of the cropping system that nevertheless resulted in a set of 22,770 simulations. The simulated scenarios represented a 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. Six parallel, continuous simulations of 18 six-year cropping cycles were used to represent each phase in each year of the climate data set.

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.

**Table 1: Climate, irrigation management and soils used in the large climate x soil simulation analysis**

Region	Climate	Irrigation	Soil code	Soil description	Reference
Wet Tropics	Tully Sugar Mill station 032042	Rainfed	tu-02	Brown Dermosol	(Cannon et al., 1992)
			tu-03	Yellow Dermosol	(Cannon et al., 1992)
Herbert	Ingham Composite station 032078	Rainfed, except for small amounts of irrigation where crops would otherwise have failed (< 1% of years)	hr-01	Fine sandy loam	(Keating et al. 1999 and references therein)
			hr-03	Alluvial silty loam	(Thorburn et al., 1999)
Burdekin DELTA	Burdekin Shire Council station 033001	110 mm per irrigation, delays for rainfall and a dry down of 60 days.	bk-03	Silty clay loam / light clay	(Thorburn et al., 2011a)
			bk-04	Silty clay / coarse sand	(Stewart et al., 2006)
Burdekin BRIA	Clare station 033122	110 mm per irrigation, delays for rainfall and soil specific dry down (42-60 days)	bh-01	Medium Clay	(Thorburn et al., 2011a)
			bh-02	Medium clay	(Thorburn et al., 2011a)
Mackay	Mackay Aero station 033045	42.5 mm per irrigation. Timing is based on soil moisture, delays for rainfall, and a dry down 28 days. Maximum allocation of 100 mm	mk-01	Loam	(Robertson and Thorburn, 2007; Thorburn et al., 2001)
			mk-02	Cracking clay	(Thorburn et al., 2010; Weier, 1998)
Bundaberg	Burnett Heads Niell St station 039017	37.5 mm per irrigation. Timing is based on soil moisture, delays for rainfall, and a dry down 98 days. Maximum allocation of 375 mm	bu-11	Red Kandosol	(Dawes et al., 2003)
			bu-13	Redoxic Hydrosol	(Dawes et al., 2003)

A single sugarcane variety was used with rooting depth dictated by soil characteristics/experimental experience. The systems were rain-fed or received region specific irrigation (Table 1). Full N response curves were simulated by ‘applying’ between 30 and 330 kg N/ha fertiliser in 10 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 (Type II) and sigmoidal (Type III) release CRF products as well as a 50% blend of urea and the linear release product (Type II) (see Section 6.2.1 for an explanation of release type patterns). The linear release product was modelled on Meister10 (Trenkel, 2010) and the sigmoidal release product was optimised against the N uptake patterns for the sites (100 kg N/ha urea treatment) to provide optimal synchrony. Simulated yield N response data were fitted with the Weibull model. This allowed the agronomic ‘optimum’ fertiliser N rate,  $N_{opt}$ , to be calculated for each response curve, defined as 95% of the maximum yield. See Verburg et al. (2017a) for further details.

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. 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.

## 5.5. Economics analyses

Assessing the economic benefits of CRFs included as a first step the development of an economic risk framework for assessing economic and environmental impacts of N management strategies, taking into account variable climatic and economic conditions. The framework was underpinned by a modelling platform that integrated APSIM, probability theory, Monte Carlo simulation, and financial-risk analysis techniques (see Kandulu et al. (2017a) for details). This framework was applied to a case study in Tully. Economic and environmental costs and benefits were compared for switching from N rates under three private optimization objectives based on grower risk profiles to the socially optimum N rate. The three grower risk profiles considered were: 1) risk averse growers minimizing expected extreme losses, 2) risk neutral grower seeking to maximise average private net returns, and 3) risk taking grower with the objective of maximising on high profits in good years. The socially optimum N rate maximized net returns taking DIN loss and  $N_2O$  emissions into account.

This initial study was followed by an application evaluating the impact of adopting CRFs on profitability of the sugarcane enterprise. This analysis used the same modelling approach, building on the results from the APSIM simulations described above that assessed the agronomic and environmental benefits of CRF (Section 5.4.3). The economic analysis focussed on three scenarios with different water management systems (an irrigated system in the Burdekin Delta vs. a rain-fed system at Tully) and soil types with different leaching potentials (TU-02 vs. TU-03, and BK-04; see Table 1). In addition, we assessed the potential for profitable adoption of CRF for a subset of the one-in-three seasons with the largest agronomic benefits from CRF in the Tully & TU-02 scenario to understand the extent to which seasonal variability can affect the potential for profitable CRF use. The economic analysis compared urea, a linear (Type II) CRF, and a 50:50 blend of urea and linear CRF, with net returns calculated with and without environmental costs.

Net returns,  $NR_i$ , under various N application rates,  $N_i$ , were calculated as:

$$NR_i = (Y_i \times CPF) - (C_N \times N_i) - (C_H \times Y_i) \quad (1)$$

for the case without environmental cost, or

$$NR_i = (Y_i \times CPF) - (C_N \times N_i) - (C_H \times Y_i) - (N_i \times D \times C_A) - (N_i \times E \times P_C) \quad (2)$$

for the case with environmental costs, where  $Y_i$  is the APSIM simulated cane yield (t/ha) and  $CPF$  is the cane payment formula used to allocate net income from sugar sales between farmers and millers calculated as (Di Bella, 2014):

$$CPF = (P_s \times 0.009 \times (CCS - 4)) + 0.662 \quad (3)$$

$P_s$  is the market price of sugar,  $CCS$  is the sugar content in sugarcane at harvest,  $C_N$  is the cost of N (\$/t) and  $C_H$  is the cost of harvesting (\$/t cane/ha). The cost of CRF was estimated at between 1.5 and 2 times the cost of urea  $C_U$ , with the cost of the 50:50 urea-CRF blend intermediate between the two.  $D$  is the proportion of N applied that is lost as DIN from fields through runoff and deep drainage and exported from Great Barrier Reef catchments.  $E$  is the proportion of applied N lost as  $N_2O$  emissions in  $CO_2$  equivalent and  $P_C$  the cost of its abatement. For the CRF and blend scenarios the environmental costs were scaled according to the predicted N losses in drainage and runoff and as  $N_2O$  emissions relative to those of the urea scenarios. To reflect uncertainty in these parameters, they were sampled from approximately normal distributions based on the data in Table 2.

**Table 2: Variable costs and prices used in the economic analysis.**

$C_U$	Cost of urea fertiliser	\$/t	103-570	World Bank (2015) ( <a href="http://www.indexmundi.com/commodities/?commodity=sugar&amp;months=360&amp;currency=aud">http://www.indexmundi.com/commodities/?commodity=sugar&amp;months=360&amp;currency=aud</a> )
CRF multiplier	Cost of CRF relative to urea	-	1.5-2	Lammel (2005); Gagnon et al. (2012); Di Bella (2014)
$C_H$	Harvesting cost paid to contractors	\$/t	6-7.5	Mallawaarachchi and Quiggin (2001); Di Bella et al. (2014)
$P_s$	Market price of sugar	\$/t	213-498	Data from the World Bank ( <a href="http://www.indexmundi.com/commodities/?commodity=sugar&amp;months=360&amp;currency=aud">http://www.indexmundi.com/commodities/?commodity=sugar&amp;months=360&amp;currency=aud</a> )
$CCS$	Commercial Cane Sugar, a measure of recoverable sugar in the cane.	%	10-15	FAO, 2015
$D$	The proportion of N applied lost from fields and discharged at the end of the catchment		0.07-0.22	Thorburn et al. (2013)
$C_A$	Nitrogen abatement cost in the Wet Tropics catchment	\$/kg	0.91-34	van Grieken et al. (2013); Rolfe and Windle (2016)
$E$	The proportion of N applied lost as $N_2O$ emissions from soils in $CO_2$ equivalent ( $CO_2e$ )		0.03-0.05	Thorburn et al. (2010)
$P_C$	Average cost of $CO_2$ abatement	\$/t	10.23-13.95	<a href="http://www.cleanenergyregulator.gov.au/ERF/Auctions-results/april-2016">http://www.cleanenergyregulator.gov.au/ERF/Auctions-results/april-2016</a>

\*Sampled from an approximately normal distribution which gives more weight to values in the middle of the range.

## 6. RESULTS AND DISCUSSION

### 6.1. Review of experimental evidence

The review of experimental findings of EEF use in sugarcane and other agricultural industries (Verburg et al., 2014, 2016) used the classification in Figure 5 to illustrate the differences between the main types of EEF of interest to the sugarcane industry. While the focus in this project was on the coated CRFs, the review of experimental evidence also captured that of nitrification inhibitors (NI), which aim to keep the fertiliser N in the ammonium form for longer than when applied as urea.

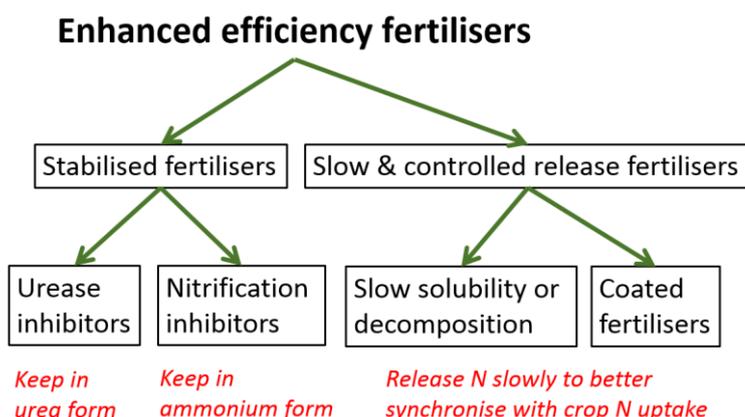


Figure 5: Diagram outlining the main types of EEF (see Verburg et al., 2014 for a more elaborate diagram).

Both the CRF and the NI aim to keep the concentration of nitrate, the more labile form of soil N, low in order to reduce the risk of N loss in runoff, through leaching or denitrification. A reduction in N loss, makes more N available to the crop. If the crop can use and respond to this ‘saved’ N it can lead to a yield increase (provided there are no other limiting factors). Otherwise it may be possible to reduce the N application rate and obtain the same yield with a higher N use efficiency from the fertiliser application (Figure 6).

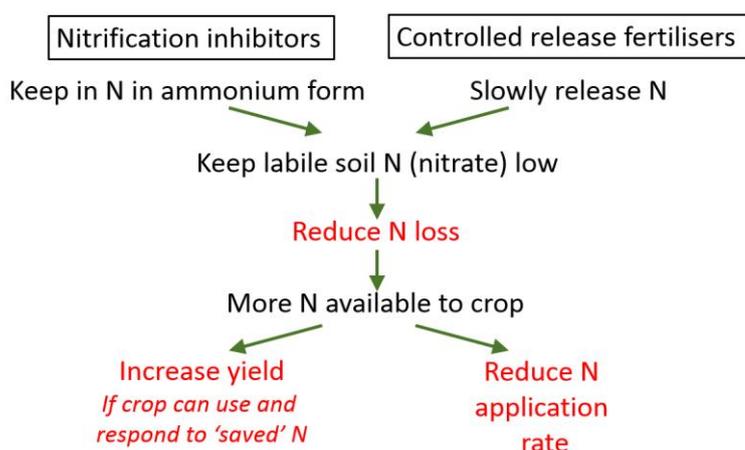


Figure 6: How EEF work to provide benefits

*Observed effects of EEF*

Both CRF and NI have been evaluated in experimental trials across the Australian sugarcane industry. Details of the various trial findings from experiments in Australian sugarcane with published results up to late 2015 were captured in reviews by the project (Verburg et al., 2014, 2016) and the references contained therein. In summary:

- Some studies showed with 95% confidence positive effects
- Quite a few studies showed an increase in average yield, but not with 95% confidence
- A few studies had no increase in average yield
- No studies showed with 95% confidence negative effects

The experience in other industries was similar. Meta-analyses which pooled data from several experiments (Akiyama et al., 2010; Halverson et al., 2014; Abalos et al., 2014; IPF, 2014) showed on average positive effects, but the regular occurrence of obtaining no statistically significant treatment effects reinforces the importance of working out where, when and why benefits can be expected – one of the aims of this project.

In some of the sugarcane trials a lack of an N response was observed. Additionally, a number of trials received below average rainfall or experienced relatively dry periods after fertilisation. Low rainfall reduces the potential for N losses and hence the potential for the EEF to have an effect. Wet conditions and waterlogging not long after fertilisation have been noted in trials with larger treatment effects. Spatial variability in yield may have masked smaller effect sizes due to insufficient replicates. Following the logic presented in Figure 6, possible reasons for lack of treatment effects are listed in the slide of Figure 7.

The difficulty with many of the trials, both here and overseas, is that measurements were usually limited to yield or one N loss pathway and contained too few supporting measurements to explain the results, whether these were positive or negative. For CRF the measurement of N release at key times during the season (e.g. before the rapid N uptake period, before a wet period) would be helpful, hence the development of the field N release method using mesh bags (Section 5.3.3).

Some trials have compared urea applications at standard rates with applications of EEF at lower rates, representing a likely scenario for the use of these fertilisers. Results that show EEF at the lower rate achieve the same yield as urea at a higher rate are, however, inconclusive as to the benefits of these fertilisers unless it is demonstrated that urea at the lower rate performed worse. Hence, for validation purposes, yield increases due to EEF at the lower N rate need to be demonstrated through inclusion of a urea control at that rate. We alerted to this in our reviews and presentations and the designs of more recent trials have improved on this.

*Lack of reduction in N loss*

- N loss absent or small
- N loss occurring after the release period
- Leaching event insufficiently large
- Release too fast (poor synchrony with crop N uptake)

*Lack of N response*

- Total N supply greater than N demand
- Yield reductions negating any potential or achieved benefits
- Potential benefits off-set by yield reductions if release is too slow (poor synchrony)
  - e.g. early vigour problems, insufficient N release during peak uptake period, or reduction of CCS.

**Figure 7: Slide demonstrating possible reasons for lack of treatment effects**

## 6.2. Characterisation of N release patterns of commercially-available CRF products

The results describing the N release patterns, temperature and soil water effects and materials characterisations that explain them are summarised below. Further details can be found in Muster et al. (2017), Verburg et al. (2017b) and Zhao et al. (2017b).

### 6.2.1. Release patterns

The shape of the N release patterns for nine CRF products of different coating nature varied considerably (Figure 8). They can broadly be grouped into three types:

- Type I products that release a considerable amount of N early, >5% within the first 24 hours and >10% within the first five days at 28°C;
- Type II products that have a short lag period (< one week) to allow for water absorption into the granule, and thereafter urea is released at its maximum rate, giving rise to a relatively linear release period up until approximately 60% of N has been released. Following the linear release, the internal concentration of N within the granule is decreased, in agreement with common understanding of 'linear-release' products (Shaviv, 2001), and release is slowed thereafter;
- Type III products that have a lag period of greater than one week and, in the case of the samples tested here, up to 6-8 weeks (at 28°C). Following the extended lag period these products gradually increase their release rate (as opposed to immediately releasing at their maximum rate like Type II products) leading to patterns that are more sigmoidal in character.

### 6.2.2. Temperature effects

The N release patterns were also strongly affected by temperature, with release accelerated considerably at the higher temperatures (Figure 8). Further to the variations in release patterns, each of the CRFs was found to be responsive to temperature in varied ways. The Type I products showed the least temperature response. The two Type III products showed the strongest temperature response, especially for the early release (to 10%). See Muster et al. (2017) for further details.

Implications of the strong and variable temperature effects are that the same CRF product may release N according to different patterns in different locations within the sugarcane industry and that the differences or trends may not be the same for each product. This is explored in Section 6.3.2.

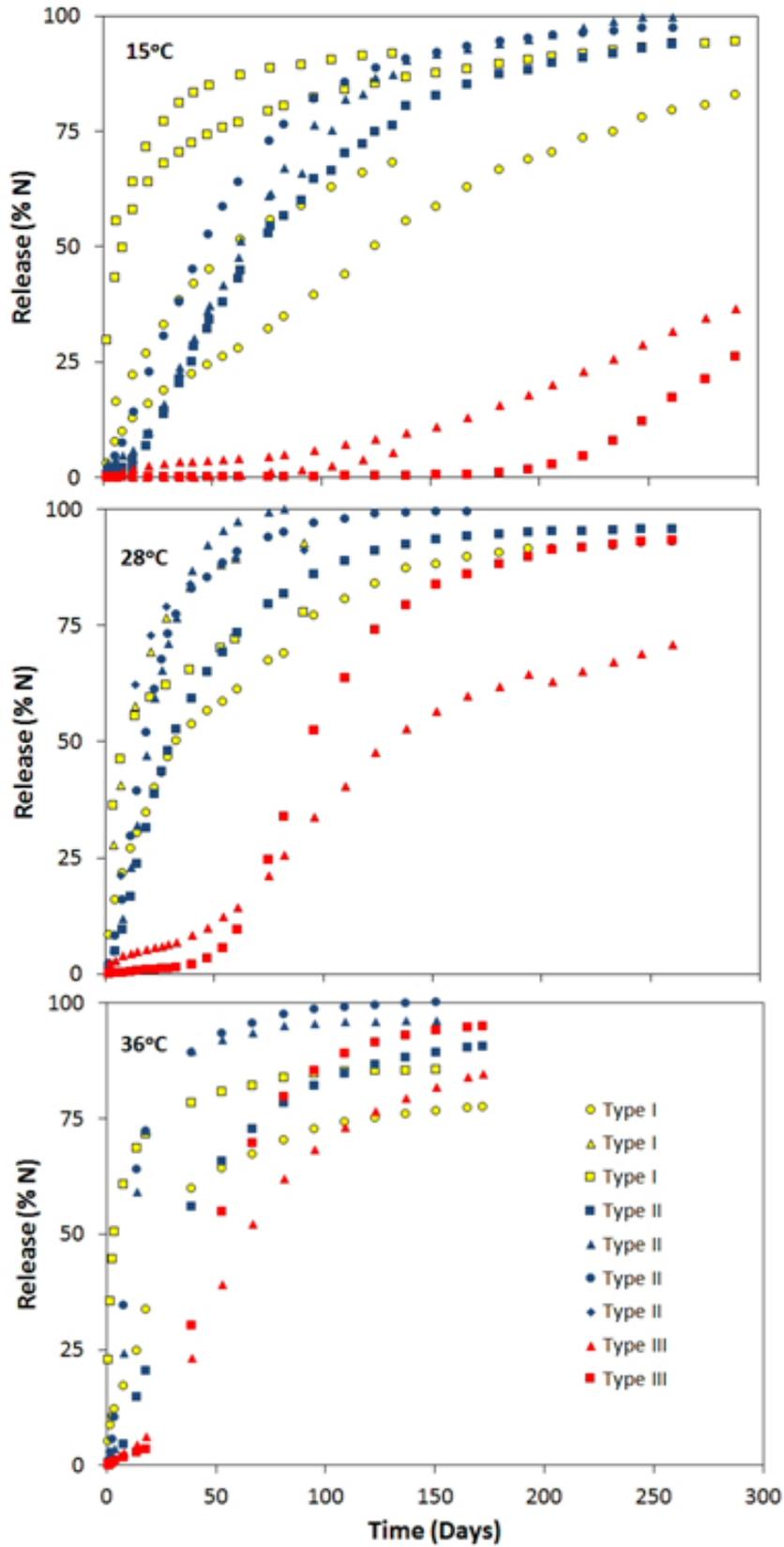
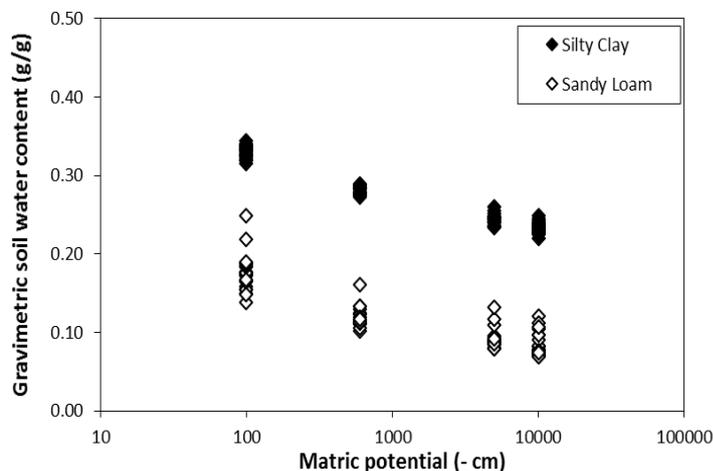


Figure 8: Cumulative N release from nine different CRF as measured in the incubation leaching columns as a function of time at fixed temperatures of 15°C, 28°C and 36°C.

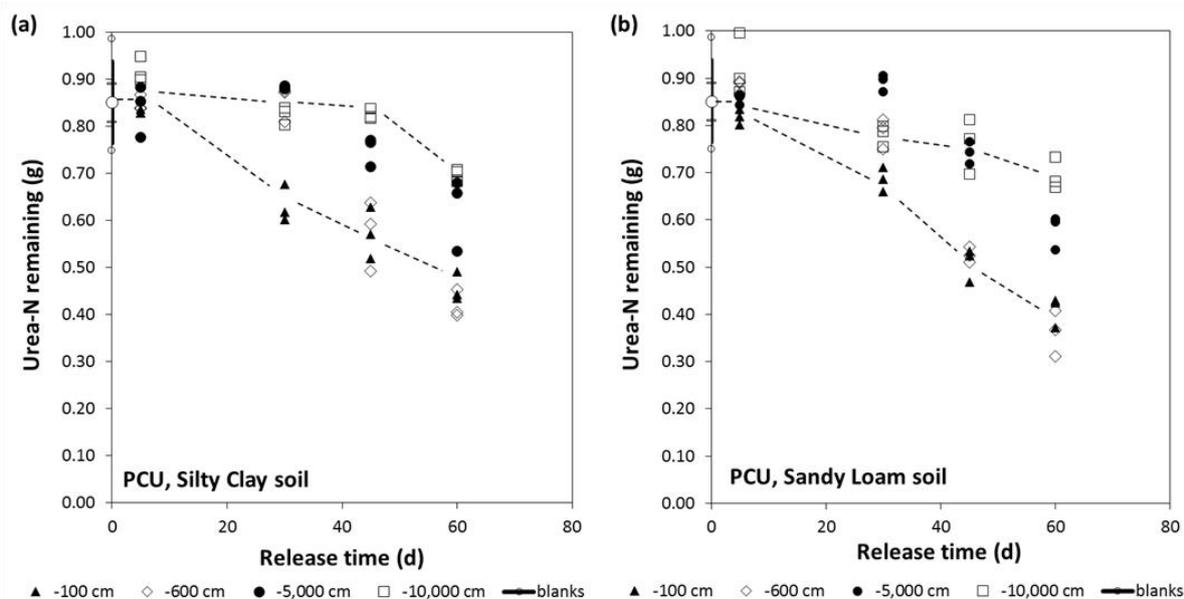
### 6.2.3. Soil water effects

The gravimetric water contents obtained during the course of the N release experiments showed no overlap in soil water contents between the two soils across the range of soil matric potentials used (Figure 9). As expected on the basis of soil texture the silty clay soil held more water than the sandy loam soil. At the same matric potential a clay soil can hold more soil water than a sandy soil, due to the larger proportion of small clay particles that have a large surface area.

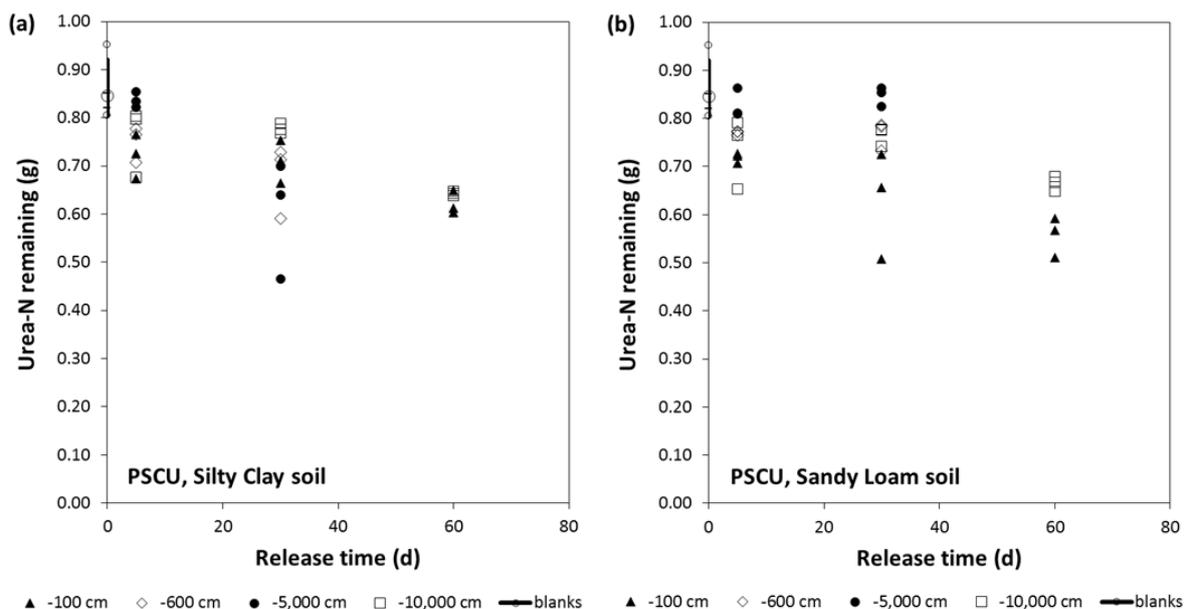


**Figure 9: Gravimetric water content obtained in the two soil types as a function of applied matric potential; based on sampling of soil cores used in the various N release experiments (two CRF products, four soil matric potentials and four release times).**

The different gravimetric water contents did, however, not affect the N release patterns, which were very similar for the two soils (Figure 10 for the PCU product and Figure 11 for the PSCU product), confirming that it is indeed not about the amount of water contained in the soil, but the thickness of the water films determined by the soil matric potential. This provides the opportunity to incorporate a soil water effect into release models via a function based on soil matric potential.



**Figure 10: Urea-N remaining (i.e. not released) in PCU as a function of release time and different soil matric potentials in (a) a silty clay and (b) a sandy loam. Initial content represented by range open circle mean, tick marks 25 and 75% and ends of bar 5 and 95% percentiles, small open circles minimum and maximum. Dashed straight lines ‘connecting’ -100 cm and -10,000 cm data shown for visual guidance only.**



**Figure 11: Urea-N remaining (i.e. not released) in PSCU as a function of release time and different soil matric potentials in (a) a silty clay and (b) a sandy loam. Initial content represented by range open circle mean, tick marks 25 and 75% and ends of bar 5 and 95% percentiles, small open circles minimum and maximum.**

The effect of soil water on N release from the PSCU product was unresolved due to the high variability in the release data. There was early release of some urea-N, which corresponds with the Type I release pattern of the PSCU product (see Section 6.2.1), but an effect of soil water, if present, was overwhelmed by the variability between replicate measurements. This was in part due to the more variable nature of the PSCU granule population, but also due to at least some of its release occurring through holes in the coating (Figure 12), rather than only by diffusion through the coating.

For the PCU product the soil matric potential had a marked effect on N release, with the start of release clearly delayed in drier soil with more negative matric potentials where the water films would be a lot thinner. There was, however, considerable variability between replicates. This was due to the population nature of the CRF granules, which also led to uncertainty in the amount of N contained in the samples before release. The microscope photographs (Figure 13) did, however, confirm the soil water effect. At more negative soil matric potentials it took a lot longer for the CRF granules to absorb water, which needs to happen before release can start.



**Figure 12: Selected stereo microscope photographs of samples of PSCU after 0, 5 and 60 days (left to right) of release demonstrating at least part of the N release over time is occurring through breakdown of coating. White bar bottom right in each photo indicates 100 µm.**



**Figure 13: Representative stereo microscope photographs of replicate samples of PCU after 0, 5, 30, 45 and 60 days of release in the clay soil at matric potentials of -100 cm, -600 cm, -5,000 cm, and -10,000 cm. White bar bottom right in each photo indicates 100  $\mu$ m. (A) granule containing solid urea, (B) granule containing liquid urea, (C) granule containing solid urea and saturated urea solution.**

Other studies testing the water effect on N release have obtained mixed results. Christianson (1988) observed that the initial wetting was affected. The delays in N release in that study were, however, considerably smaller than the results obtained here. The particular coating properties of the PCU product used in this study may have affected its larger soil water effect as it was found to have one of the more hydrophobic coatings (Muster et al., 2017; Verburg et al., 2017b). This suggests that water effect on N release will be CRF product specific and would hence need to be tested for each product. If we can identify the exact coating properties that contribute to a smaller or larger soil water effect, then this may speed up testing.

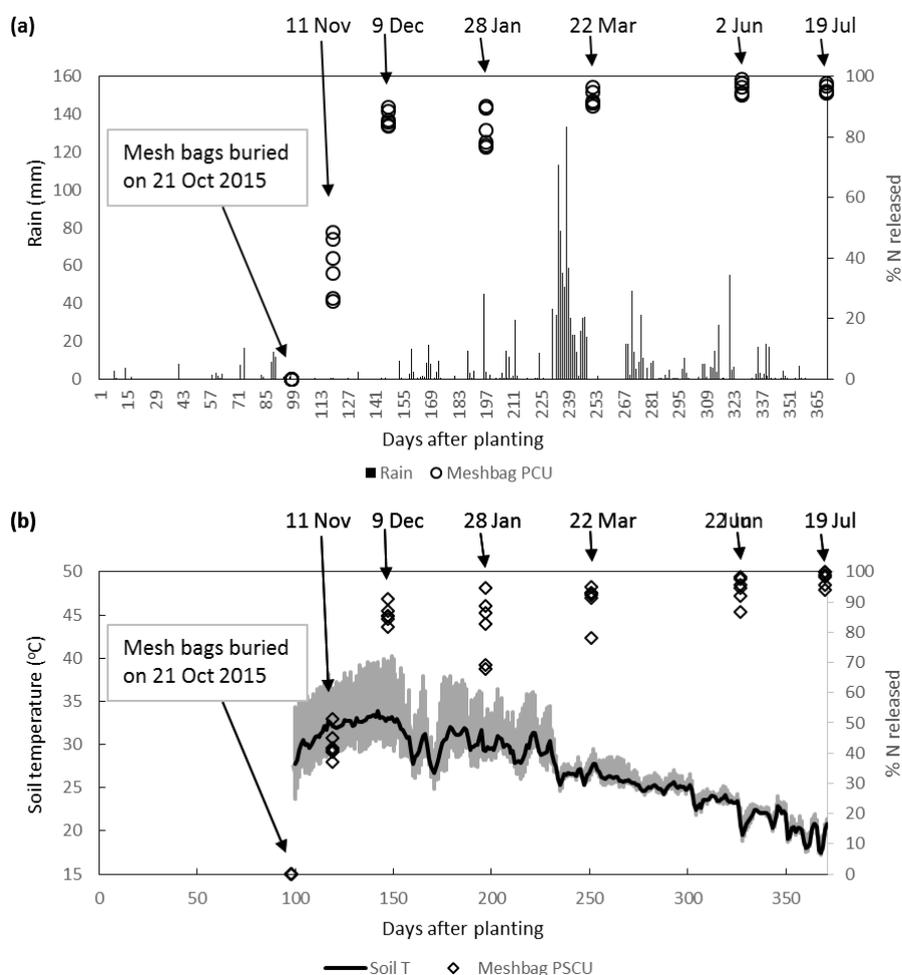
The variability in the data and the limited number of equilibration times, did not allow us to assess whether N release once commenced was unaffected by matric potential. Other literature studies detailing experiments with intermittent drying after the initial absorption of water found no effect on N release (Christianson, 1988).

Based on the presented data and literature evidence, the main implication of a soil water effect on CRF N release would appear to be the possible delay to the start of release in cropping systems that experience a lack of rainfall or irrigation in the first 1-2 months after fertiliser application. In the mesh bag field N release trial (Section 6.2.4) release did, however, not appear inhibited, despite receiving less than 2 mm rainfall during the first 3 weeks after application. There was, however, 7 mm of rain in the week preceding application and 35 mm during an event 10-12 days earlier. At the first sampling, 3 weeks after application, on average 37% of the urea-N of the PCU had been released. While this was at a higher temperature than the core experiment reported here (average 26°C over this period), it does indicate that small amounts of intermittent rainfall and an initial soil matric potential at or near field capacity were sufficient to ensure water absorption by the granules and allow release to start.

### 6.2.4. Release under field conditions

The mesh bag field N release experiment was initially set-up to evaluate whether the methodology could be used in CRF trials as a simple method to establish the amount of CRF N released at key points in time. For example, relative to crop development stages or before and after large rainfall events in order to help interpret the presence or absence of treatment effects. The method proved reasonably straight forward to implement, with mesh bags prepared using easily accessible materials (e.g. fly screen mesh). The only complications included field operations like hilling up potentially interfering with the bags and bags sampled during wet conditions requiring additional steps to remove soil from the mesh bags (reported separately). It also proved a good dataset for model verification (see Section 6.3.2).

At the first sampling, 21 days after fertiliser application and 120 days after planting, cumulative N release from the PCU was on average 37% and that of PSCU slightly higher at 43% (Figure 14). Release of N occurred despite these three weeks coinciding with a dry period. On average over 80% of N was released from both CRF products at 49 days after application. At the end of season, 229 days after CRF application, cumulative N release was over 95%. The rapid release of >80% of the N in just 49 days relates to the high soil temperatures achieved during this period (Figure 14b).

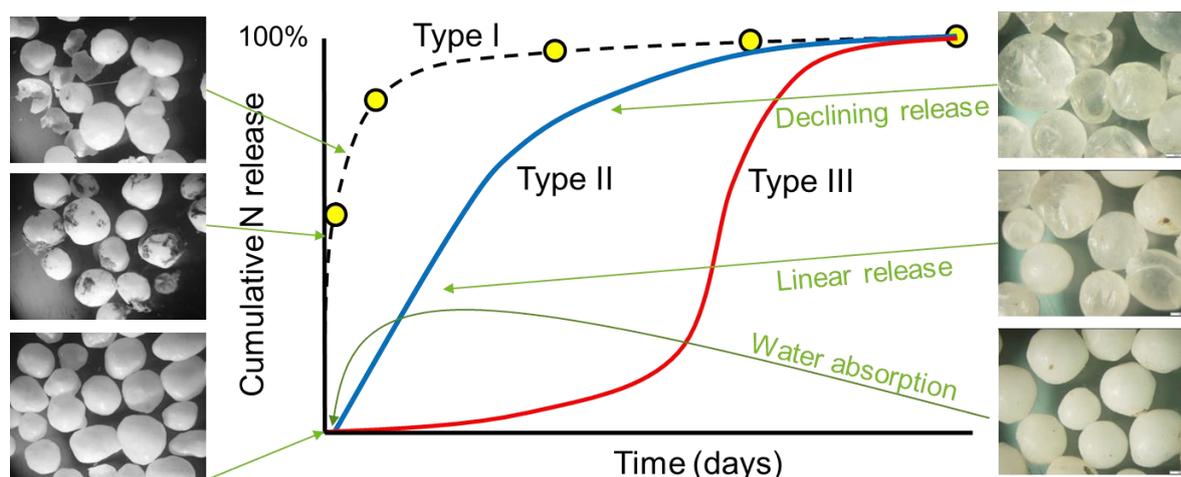


**Figure 14: (a) Nitrogen release from PCU (circles) as measured in buried mesh bags and daily rainfall; (b) N release from PSCU (diamonds) and soil temperature at 10 cm depth in one of the plots (grey 30 min data, black daily average).**

### 6.2.5. Explaining N release patterns using material science

The results of the material science characterisation of the CRF products are described in detail in Muster et al. (2017). The various measurements contributed to an understanding of how the material properties lead to the different N release patterns (Type I, II and III; Figure 15) and how modification of coating properties could allow transition from one type to another.

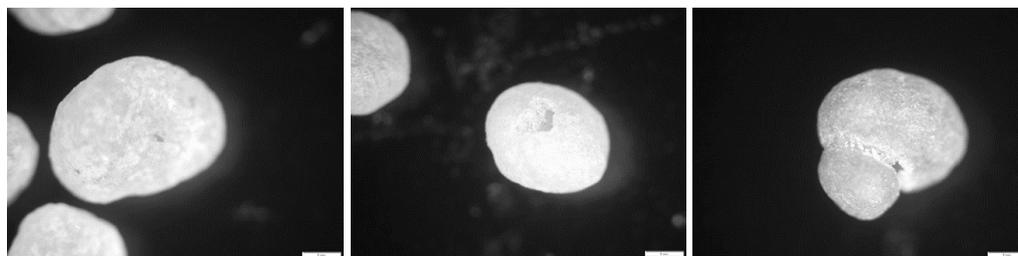
The CRFs included two PSCU (polymer sulfur coated urea) and a variety of PCU (polymer coated urea) with different coating compositions, some with a wax-like coating or inclusion of inorganic fillers. Some of these CRF products had identical composition with different coating thickness.



**Figure 15: Schematic N release patterns for Type I, II, and III CRF products with on left microscope pictures of rapid degradation of Type I granules, and on right microscope pictures confirming the 3-stage release process of Type II granules (Shaviv 2001; Figure 4).**

Optical microscopy proved useful to visualise the N release mechanisms (Figure 15). For the Type I products early release was associated with rapid degradation and disintegration of the coatings of a relatively large number of the granules. For Type II products optical microscopy confirmed the three-stage release process described by Shaviv (2001), which includes a water absorption stage during which there is no release, a linear release stage during which the urea concentration inside the granules is constant and in equilibrium with the remaining solid urea, and a declining release stage in which urea inside the granules is being depleted.

The Type II and III can, however, also suffer from defects, such as illustrated in Figure 16. Both types of coating integrity tests (Section 5.3.4) confirmed that some products had considerable variation in coating consistency leading to early release of N. This happened especially in Type I products, but also in some Type II products. It was less common in the Type III products.



**Figure 16: Optical microscopy images of Type II and III coatings, demonstrating common manufacturing defects: (a) thin coating with pinholes; (b) thick coating with defect resulting from contact between granules during the coating process; (c) inability of the coating to seal at the joint between two merged granules.**

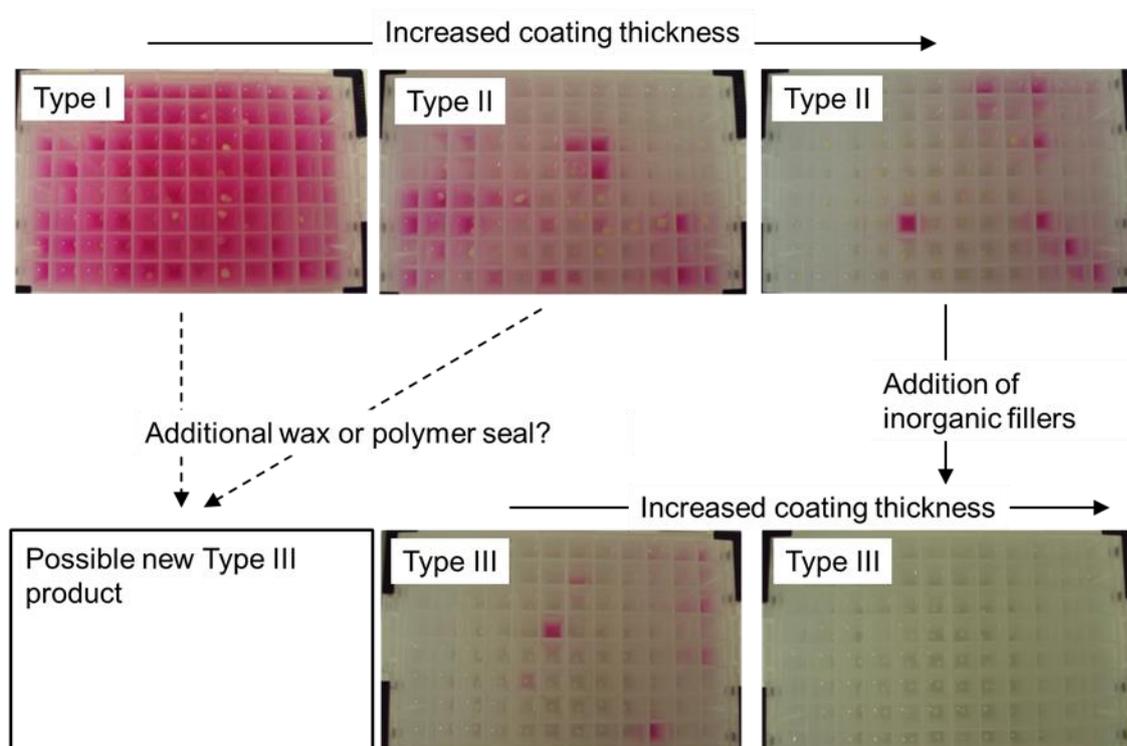
The different CRF products varied in granule size and distribution. A broader spread in particle size is likely to reduce coating consistency and lead to a product with increased variability in N release.

Compression testing, relevant for estimating the expected handling and storage properties of the granules, showed the Type I products had lower crushing strength than the Type II and Type III products, with those Type II and Type III products containing fillers having the highest crushing strength due to the fillers adding rigidity to the polymers.

The N content of products, expressed on a weight basis, was reduced for CRFs with sulfur coatings and coatings with fillers. For a given polymer composition, products with a thicker coating (and longer release time) have lower N content.

The measurements of relative hydrophobicity indicated that products possessing inorganic fillers (Type III and one Type II product) tended to be more hydrophilic in nature, whereas those with a wax or sulfur coating tended to have more hydrophobic characteristics. In general the rate of vapour water uptake was highest for the Type I products and lowest for Type III, despite their hydrophilic nature. Chemistry and morphology of the polymer coating as well as its thickness were found to affect the water permeation into the granule. In the case of the Type III products, the fillers in the coating may have created more tortuous paths for water uptake. We are still collecting more data to confirm whether the nature of these fillers changes over time (e.g. breakdown of polymer bonds or gradual dissolution) in order to produce the longer lag times and sigmoidal release patterns.

The understanding of how material properties affect the N release patterns was used to indicate in a schematic how modifications in the preparation of CRFs can be made in order to change the type of release patterns (Type I to Type II, Type II to Type III) (Figure 17). The key control parameters for manufacturers being coating thickness, the addition of inorganic fillers and the use of secondary coatings to increase release lag times.



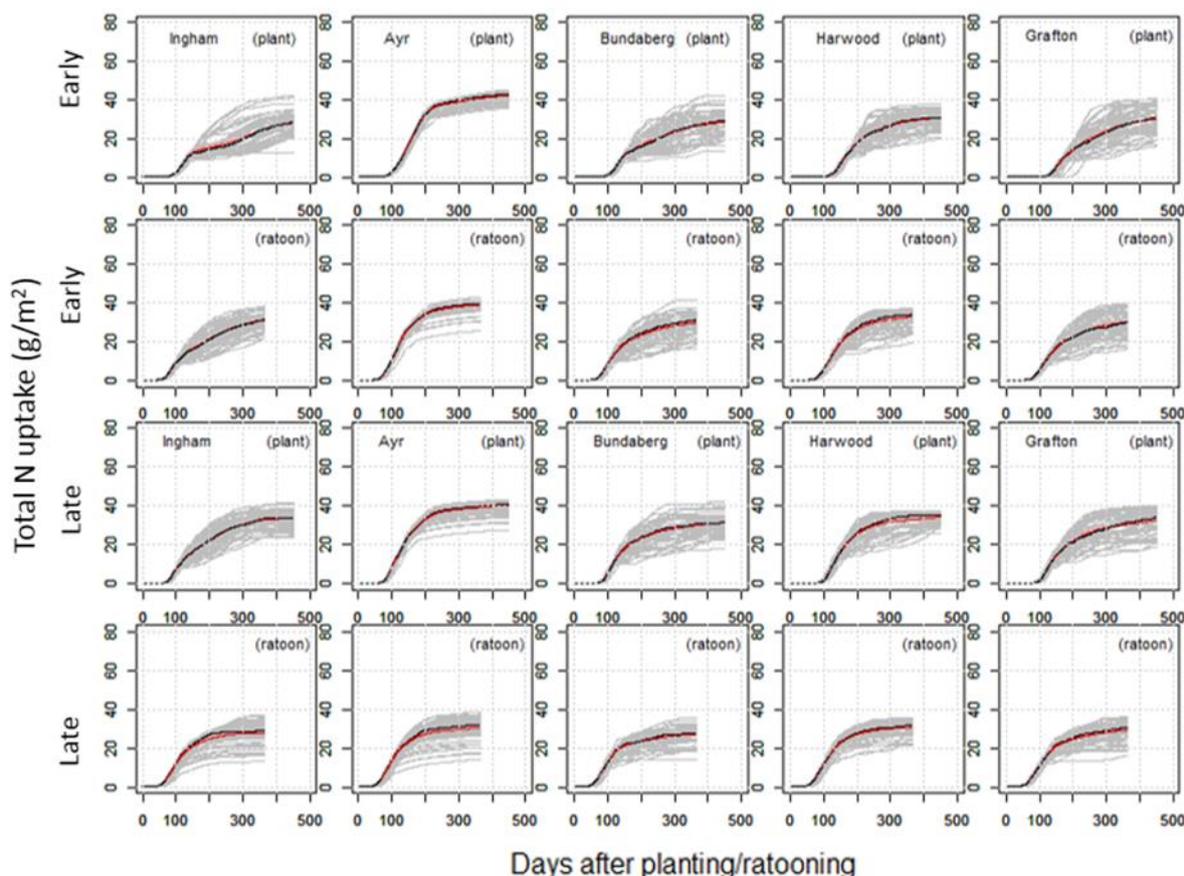
**Figure 17: Schematic demonstrating routes of transition between the various types of CRF, pictures demonstrate the early N release (pink when >1% of a single granule urea content released) as measured in the colorimetric coating integrity measurements.**

### 6.3. Modelling to explore synchrony and inform CRF design and choice

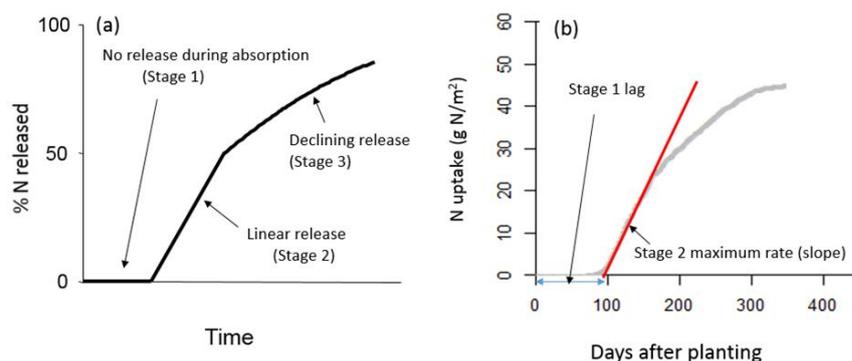
Achieving synchrony between N release and N demand requires an understanding of N uptake patterns and how these may vary in response to climate, seasonal conditions, and management, including time of planting or ratooning, as well as an understanding how the N release patterns may vary due to the temperature dependence of release. Soil water dependence was not considered here as there was insufficient data to fully parameterise this effect and the mesh bag trial suggested the effect may be negligible in practice. A summary of the simulation results are presented below. Further details can be found in Zhao et al. (2017a,b).

#### 6.3.1. N uptake patterns

The simulated N uptake patterns (Figure 18) confirmed that N uptake in sugarcane can be characterised by a 2-3 month lag period during which the crop requires relatively little N, followed by a period of 80-120 days of rapid N uptake and a declining N uptake rate after that. While there was considerable variation in crop N uptake patterns across seasons, the lag and the slope of the initially linear, rapid uptake period were well defined. This allowed the uptake patterns to be compared with the 3-stage release model introduced in Section 5.4. By synchronising the linear stage 2 with the maximum initial slope of the N uptake curve (Figure 19), the variability in stage 1 lag duration, stage 2 uptake rate and the small N requirement during stage 1 could be quantified (Figure 20).

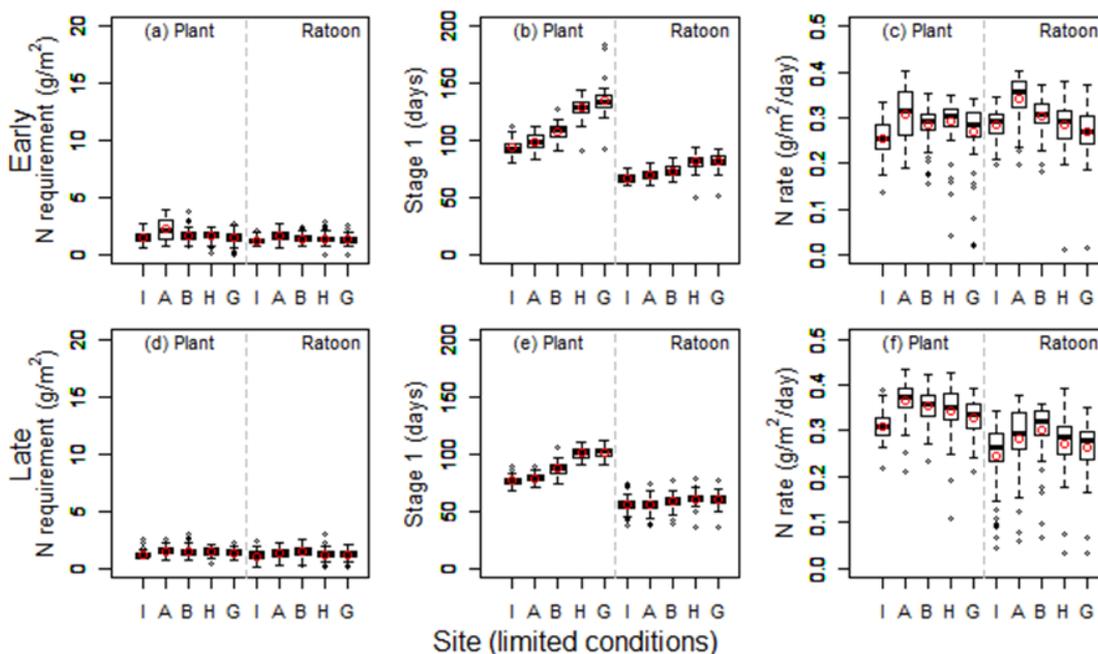


**Figure 18: Simulated N uptake patterns at 5 sites for early and late plant and ratoon crops under region specific irrigation management or rainfed conditions (based on the work by Biggs et al. 2013 and Thorburn et al. 2011) and an N application of 300 kg N/ha; in grey patterns from 56 different seasons (1958 – 2013), with the average and median value at each site shown by a red and a black line, respectively.**



**Figure 19: (a) Conceptual three-stage process for N release from polymer coated CRF (as in Figure 4); (b) derivation of parameters describing Stage 1 lag and linear Stage 2 maximum rate of release from a conceptual 3-stage model (red line matching linear Stage 2) synchronised with predicted N uptake (grey).**

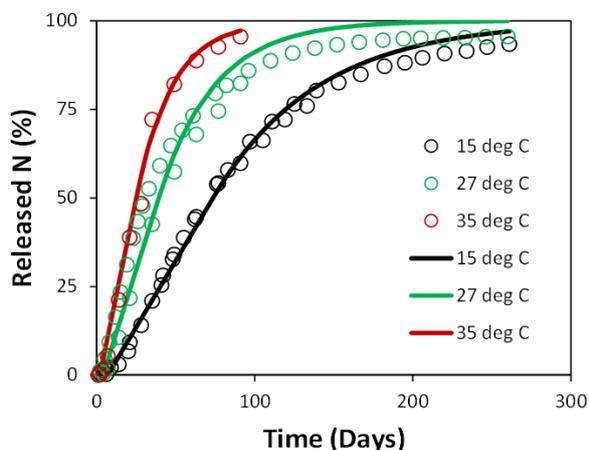
The simulation showed large location (climate) and management effects on the stage 1 lag and stage 2 linear N uptake rate, although seasonal variability only affected the N uptake rate. The predicted average lag periods ranged from 55 days to 137 days. The average lag period was shorter for the ratoon crops (55–83 days) as compared to that for the plant crops (79–137 days) and shorter for later planted or ratooned crops that experienced warmer temperatures in the first months of their growth. Temperature also contributed to a location effect, which was particularly strong for plant crops where, for example, the average lag period for early plant crops ranged from 102 days for the most northern tropical site to 137 days for the most southern subtropical site. The predicted average maximum linear N uptake rate ranged from 0.25 to 0.38 g N/m<sup>2</sup>/day and was driven by direct and indirect effects of solar radiation input. The N requirement during the stage 1 lag was small and consistent across sites and seasons.



**Figure 20: Simulated average and range of (a and d) the amount of early N uptake during stage 1 lag, (b and e) the stage 1 lag duration (see Figure 1b for definition), and (c and f) the stage 2 maximum linear N uptake rate. Early plant and ratoon crops represented in (a, b, c) and late plant and ratoon crops in (d, e, f). All scenarios reflect limited water and N supply conditions. The box boundaries indicate the 75 and 25% quartiles, and the whisker caps indicate the 95th and 5th percentiles, with the average shown by a red circle. The black circles are the outliers. I = Ingham, A = Ayr, B = Bundaberg, H = Harwood, G = Grafton.**

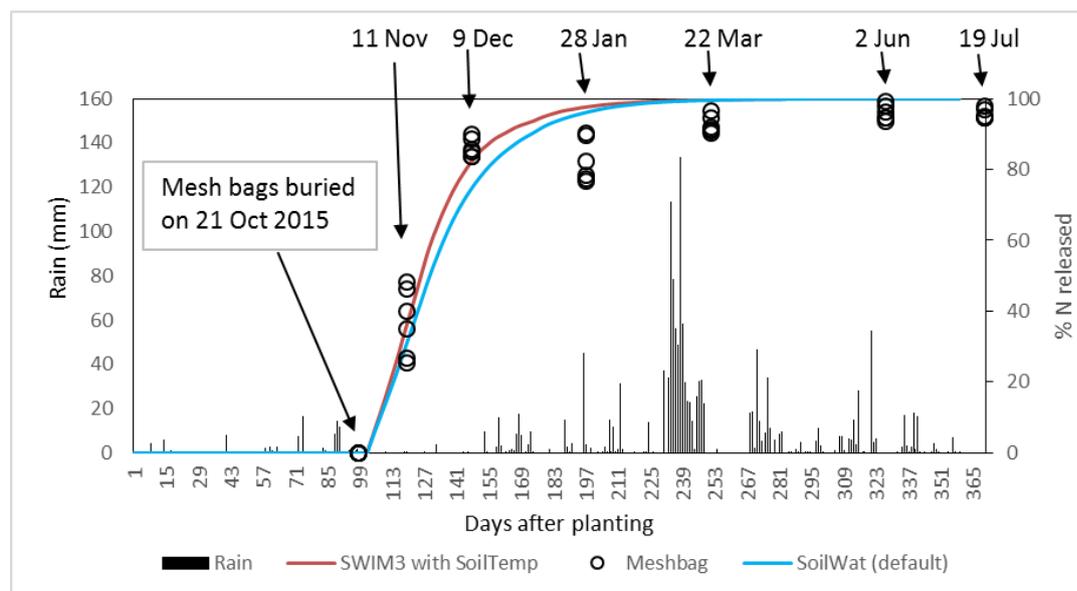
### 6.3.2. Nitrogen release patterns

The conceptual 3-stage model was successfully parameterised for the PCU product using the N release data from the leaching column incubation study (Figure 21).

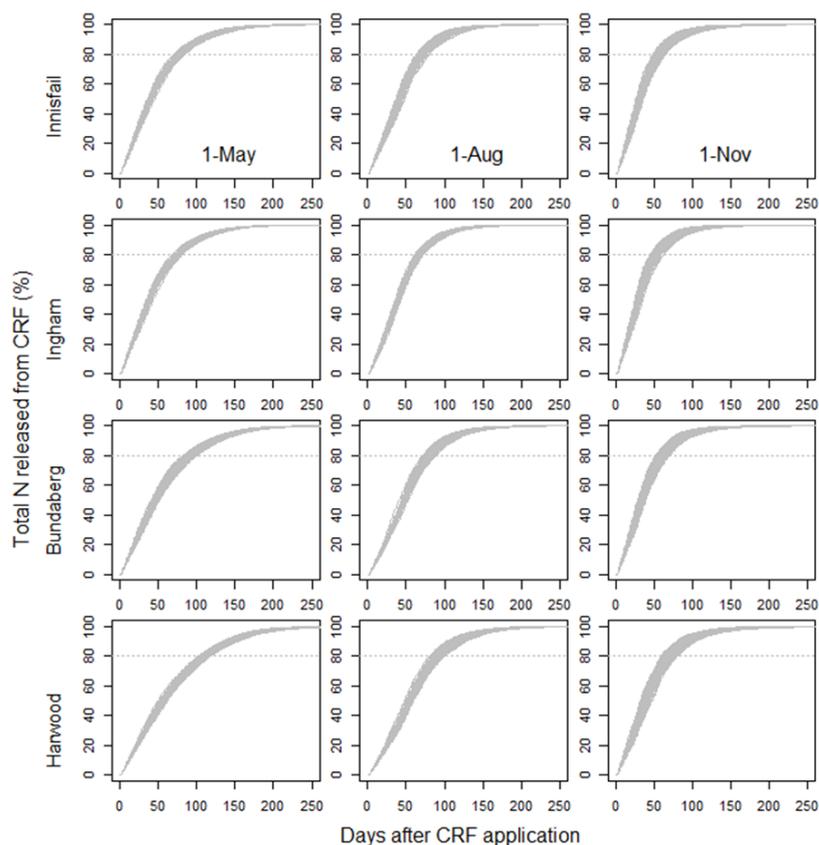


**Figure 21: Model predictions (lines) of N release from the PCU product at fixed temperatures parameterised using the laboratory incubation data (open circles; Section 6.2.1).**

The model was then successfully used to simulate the N release from the same product measured under field conditions and variable temperatures using mesh bags (Section 6.2.4). The two model configurations gave slightly different predictions, with the combination of the SWIM3 water balance model and APSIM’s Soil Temperature module providing the best prediction of both temperature (not shown, see Zhao et al., 2017b) and N release (Figure 22). This model configuration was used for the subsequent simulation analysis exploring climate, seasonal and time of application effects on the N release patterns.



**Figure 22: Observed and predicted N release from PCU in the mesh bag trial near Ingham; simulations used either the SWIM3 water balance model and a dedicated soil temperature model (red) or the SoilWat water balance model and APSIM’s default soil temperature model.**

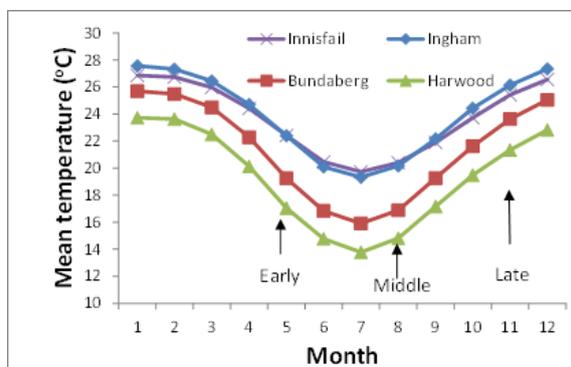


**Figure 23: Predicted seasonal N release patterns (multiple grey curves) using historical climate data (1902-2013, 112 years) with early (1-May), mid (1-Aug) and late (1-Nov) CRF application times at four sites across the Australian sugarcane region.**

The predicted season-to-season variation of the N release patterns was small at all four sites (Figure 23). Fertiliser N release was faster at Innisfail and Ingham compared with Bundaberg and Harwood, as judged from the average time it took to release 80% of the N (Table 3). The differences were greater for the early application (May) when temperature differences between the sites were largest (Figure 24). Compared to the effect of site (climate), the time of application had a greater effect on the N release patterns. Due to the change in temperature throughout the year (Figure 24), N release from late application was considerably faster than that from early application.

**Table 3. Simulated time to 80% of total N released**

Site	Days after application (mean ± stdev)		
	1-May	1-Aug	1-Nov
Innisfail	79 ± 3	72 ± 3	56 ± 4
Ingham	76 ± 3	68 ± 2	52 ± 4
Bundaberg	93 ± 4	81 ± 4	60 ± 4
Harwood	111 ± 4	93 ± 4	69 ± 4



**Figure 24: Monthly mean temperature at the 4 study sites from 1902 to 2013. Application times indicated by vertical arrows.**

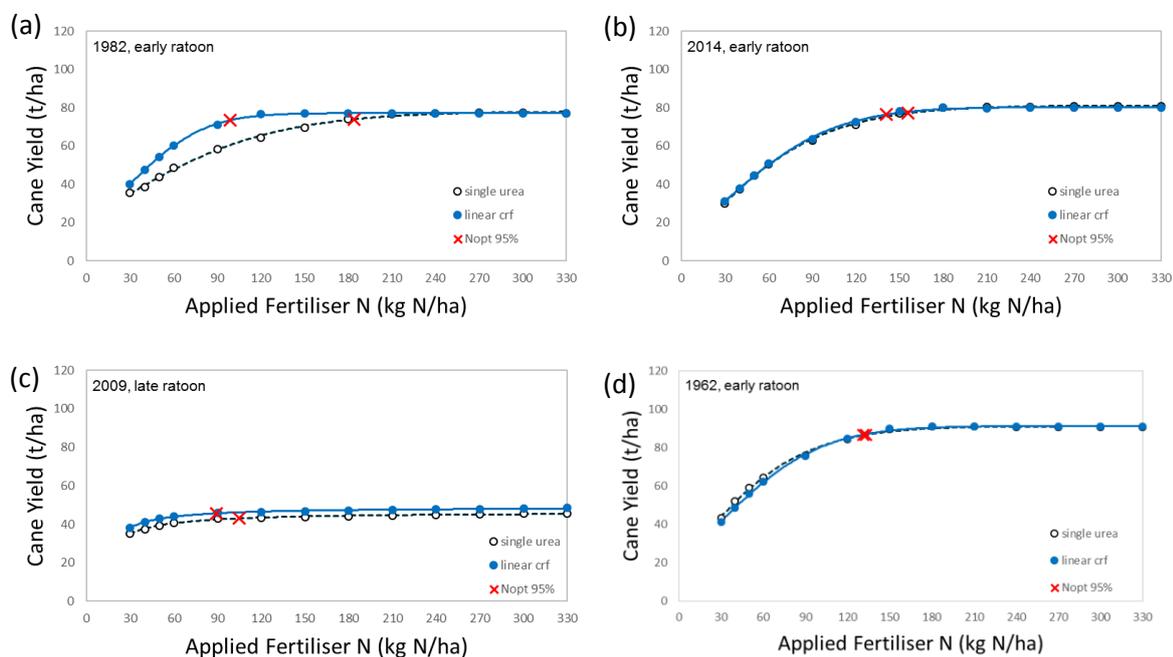
## 6.4. Modelling to assess benefits from CRF

The cropping system simulations of agronomic and environmental benefits from CRF provided not only information on the relative magnitude of benefits across climates and soils, but also helped clarify how and when benefits are obtained. Below we first illustrate that for one case study for a rainfed system at Tully on an alluvial clay soil (Brown Dermosol, Coom series, TU-02 in Table 1).

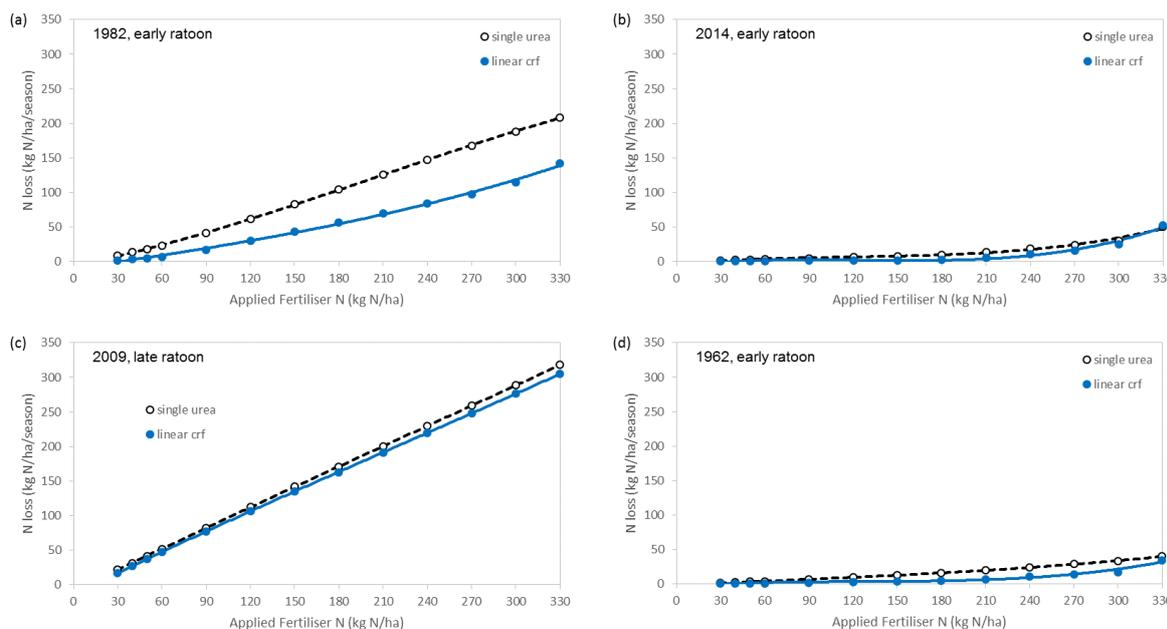
### 6.4.1. Yield and N loss response

Simulated N response curves for yield and N loss varied strongly from season to season. Figure 25 and Figure 26 provide a selection of the type of responses comparing a single urea application and Type II CRF ('linear CRF'). Some seasons, like the simulated ratoon harvested in 1982 in Figure 25a showed considerable increases in yield at N rates below the agronomic optimum N where crop yield in the urea scenario was limited by N. 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. This was often accompanied by considerable reduction in N loss (Figure 26a) leading to a reduction in Nopt 95% (red X in Figure 25a) and hence an increase in N use efficiency.

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 in 2014 (Figure 25b), there was a strong yield response to N but limited N losses (Figure 26b). In some seasons, mainly in the late ratooning scenarios, N response was limited but with small yield benefits from CRF across the full range of N rates (e.g. ratoon harvested 2009, Figure 25c). These were due to large loss events that caused most of the applied N to be lost, except for what had not yet been released by the CRF. In a few seasons the use of CRF resulted in slightly lower yield at the lower N rates (e.g. ratoon harvested in 1962, Figure 25d). While the CRF did reduce N loss in that season (Figure 26d), a more rapid development of the crop resulted in early N stress due to the N being released too late.

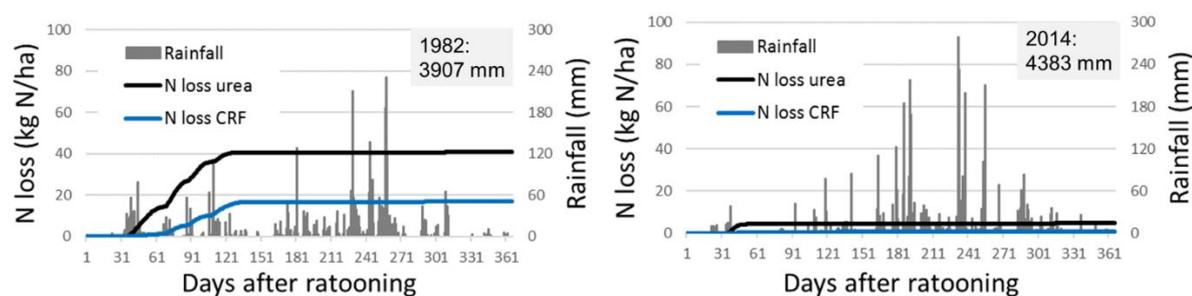


**Figure 25: Simulated N response curves for yield from a single urea application (open symbols) or linear (Type II) CRF product (closed symbols) in four first ratoon crop seasons (early or late scenario as indicated). The agronomic Nopt 95% for each fitted response curve is indicated by a red X (Tully, TU-02 scenario).**



**Figure 26: Simulated N response curves for total N loss (denitrification, runoff and nitrate leaching) from a single urea application (open symbols) or linear Type II CRF product (closed symbols) in four first ratoon crop seasons (early or late scenario as indicated) (Tully, TU-02 scenario).**

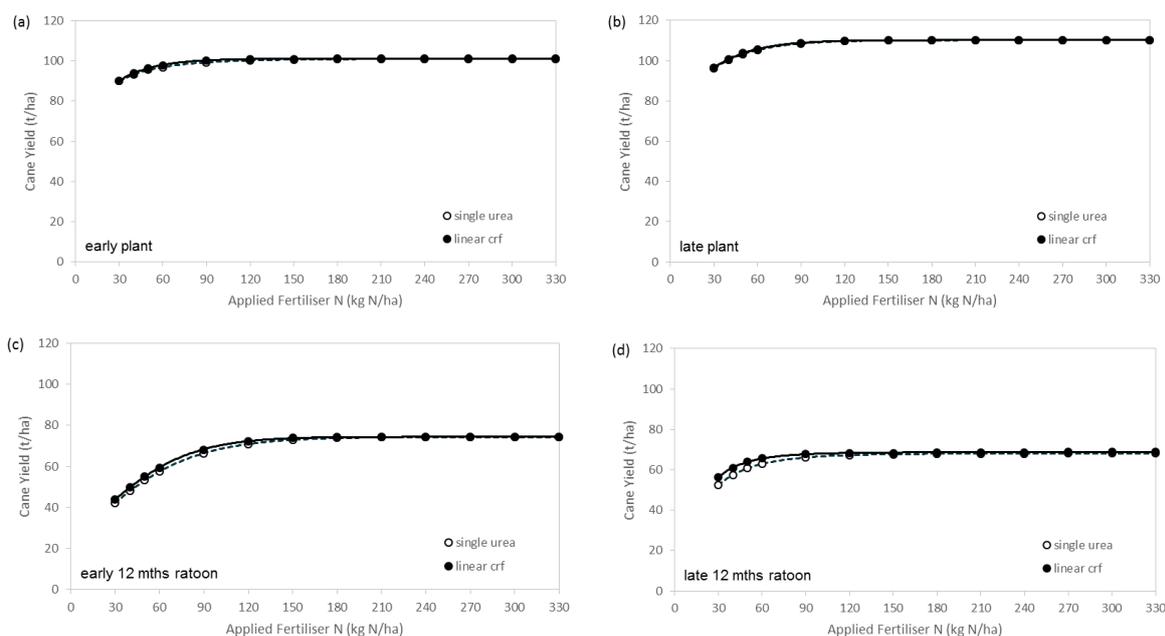
Detailed analysis of crop biomass development, timing of N and water stresses, and timing of N release and N loss in response to rainfall, temperature and solar radiation in individual seasons (see e.g. Verburg et al. 2017a) highlights that the many system interactions give rise to many different outcomes. An example is the contrast in simulated benefits from CRF between the two first ratoon crops harvest in 1982 and 2014. Seasonal rainfall was above average in both seasons, lower in 1982 than in 2014 (3907 vs. 4383 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 differences in N loss and N loss reduction (Figure 27). The absence of a significant N loss reduction in 2014 meant there was no effect of CRF on yield.



**Figure 27: Simulated time series rainfall and N loss for urea and linear (Type II) CRF during the early 1st ratoons receiving 90 kg N/ha and harvested in 1982 (left) and 2014 (right) (Tully, TU-02 scenario).**

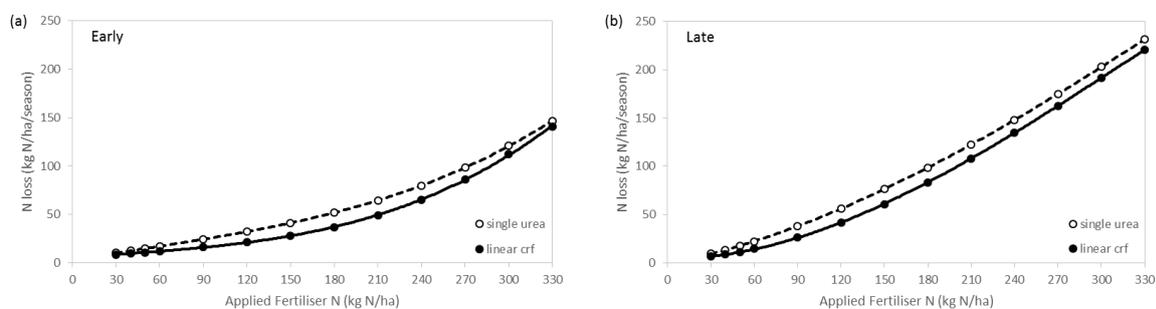
### 6.4.2. Average magnitude of benefits

The average yield N response curves show very limited long-term average yield improvement from CRF. This contrasts with the benefits we see in seasons like the 1982 first ratoon season in Section 6.4.1. Due to the season-to-season variation in N response curve shape as well as the N rates at which CRF provides yield benefits, these long-term average present a ‘diluted’ picture of the benefits. It does, however, highlight that there is no consistent benefit across seasons at least not in this particular scenario (Tully climate, TU-02 soil). It also shows that benefits are on average larger for ratoon crops than for plant crops and also higher for late ratoon crops compared with early ratoon crops. The latter relates to the timing of the larger rainfall events that cause N loss, which are more likely to happen soon after fertilisation in the late scenario. 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.



**Figure 28: 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 (Tully, TU-02 scenario).**

While yield benefits from CRF are mainly seen at the lower N rates, reductions in N loss are across a wider fertiliser range (Figure 29). Environmental benefits are achieved more often than yield benefits, because reductions in N loss can be present even in seasons where this did not translate into yield benefits due to lack of N response by the crop.

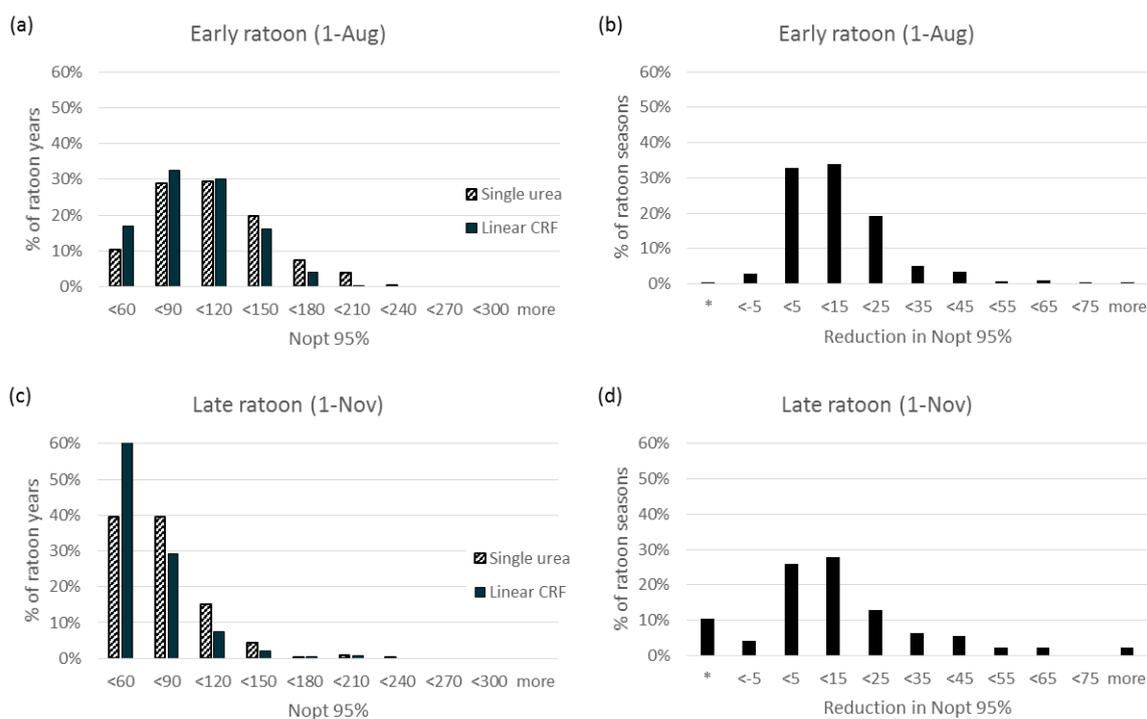


**Figure 29: Simulated average N loss (denitrification and nitrate leaching) response curves (across all seasons and crop classes) for (a) early and (b) late planting dates (Tully, TU-02 scenario).**

### 6.4.3. Frequency of agronomic benefits

As yield increases due to use of CRF occur at N rates below the Nopt, the reduction in N rate that a shift in Nopt can provide will often be of greater interest to the farmer than increasing yield at sub-optimal N rates. The exception are those years, like in Figure 25c, where yield is increased across the range of N rates. Agronomic benefits may, hence, be better expressed in terms of the reductions in Nopt.

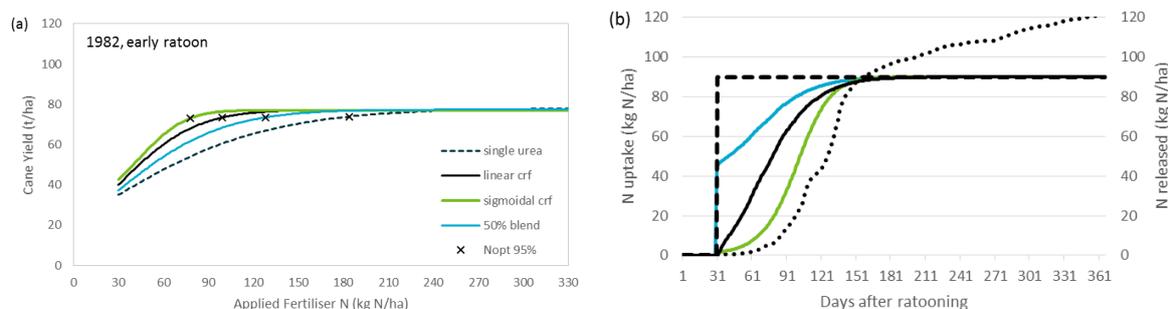
As an illustration, the distributions of Nopt for early and late ratoon crops of the Tully, TU-02 scenario are shown in Figure 30a,c, comparing single urea with linear CRF. The distributions of reductions in Nopt that are caused by switching from urea to CRF are shown alongside (Figure 30b,d). The Nopt are lower for the late ratoon scenario than the early ratoon scenario, as was also reflected in the shape of the average response curves (Figure 28). 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 were, however, small, with only 30% of seasons in the early scenario and 31% of season in the late scenario showing reductions in Nopt 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 30b,d because Nopt defined as 95% of maximum yield does not capture the benefits in these situations).



**Figure 30: Distribution of simulated Nopt 95% for scenarios with a single urea application or a linear(Type II) 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 CRF 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 (as in Figure 25c). These seasons were not included in the calculation of change in Nopt 95% (Tully, TU-02 scenario).**

#### 6.4.4. Benefits from improved synchrony

Comparing the simulations for different CRF products (linear Type II CRF, a hypothetical, optimised sigmoidal Type III product and a urea-CRF blend) indicates that improving the synchrony between N release and crop N uptake can increase the benefits, as shown for the early ratoon in 1982 in Figure 31. Our experience with the simulations of the hypothetical optimised, sigmoidal release product was, however, that the crop was very sensitive to any small early N stress if the N release was just slightly too late, with effects persisting for the remainder of the cropping season. It is not clear whether the real cropping system would be equally sensitive.



**Figure 31: (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 X. (b) Predicted N release patterns of the four fertilisers compared with simulated crop N uptake in the sigmoidal CRF scenario (dotted line).**

#### 6.4.5. Benefits across soil, climate and systems

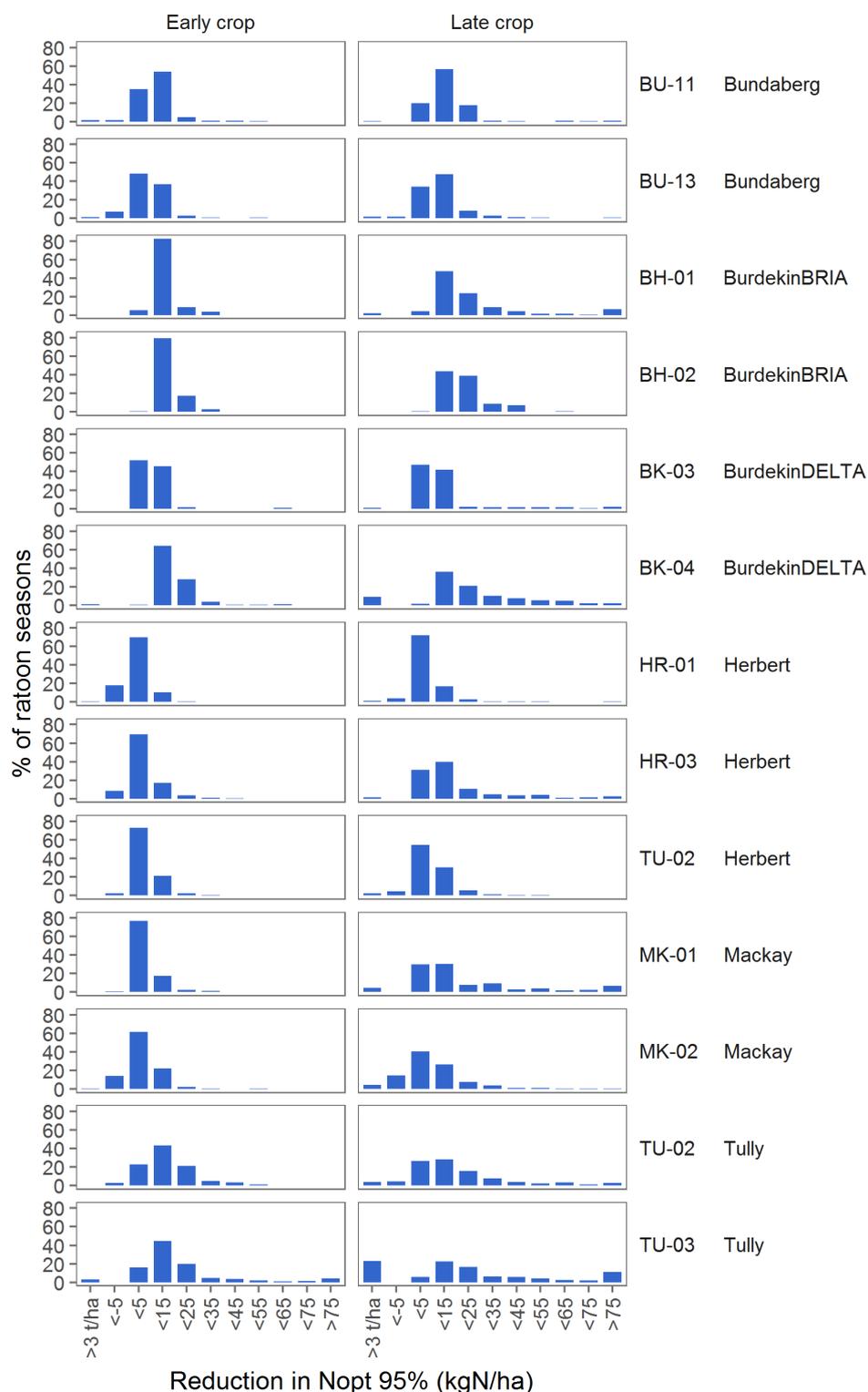
Repeating the analysis of quantifying the potential benefits of reductions in Nopt for the other regions and soils, highlights that the distributions of Nopt reductions do vary in response to timing of ratooning, soil properties and 'system' differences driven by the combination of climate and irrigation management (Figure 32). Use of CRF on late ratoon crops results in a higher proportion of larger reductions in Nopt, consistently across all the regions and soils.

The high seasonal rainfall and large rainfall events experienced in the two Tully scenarios contribute to their larger benefits, for both the early and late scenarios. Three of the four Burdekin scenarios (BH-01, BH-02, BK-04) also showed considerable benefits. Compared with the Tully sites these were also more consistent as N reductions of at least 5 kg N/ha were achieved in almost all seasons. This may relate to the higher yield potentials. In Tully the wet seasons that have the most potential for benefit from CRF often have a reduced yield potential due to the lower solar radiation input in wet seasons, negating some of the benefits that CRF may have provided.

Soil differences were also shown to have considerable impact. Compare e.g. the Nopt distributions for TU-02 and TU-03 in Tully, BK-03 and BK-04 in the Burdekin Delta, and MK-01 and MK-02 in Mackay (Figure 32). Of these pairs, the soils with a higher proportion of larger benefits also had a larger proportion of N loss occur via leaching (Figure 33). Others have also suggested CRF was particularly useful to reduce leaching losses (Di Bella et al. 2017). However, Figure 37 also shows that N loss reductions can be of the similar magnitude for leaching and denitrification pathways (compare e.g. BH-02 and BK-04). Reasons for the different agronomic responses in the presence of similar N loss reductions are still being explored. They may relate to timing or magnitude of N loss events, or crop yield potential.

There were a few scenarios where CRF was simulated to have a negative impact (increase in Nopt) in a proportion of years (e.g. MK-02 in Mackay). We have not yet been able to establish the reasons for

this. In some seasons of the MK-02 scenario it seemed related to small amounts of early N stress which, at least in the simulations, resulted in crop biomass differences that persisted throughout the cropping season. The same sensitivity to small amounts in early N stress may have affected some of the sigmoidal CRF scenarios.



**Figure 32: Distribution of simulated reductions in Nopt stemming from the use of a linear (Type II) CRF product compared with a single urea application 30 days after ratooning for early (1 Aug harvest) and late (1 Nov harvest) ratoon crops by region and soil type (see Table 1).**

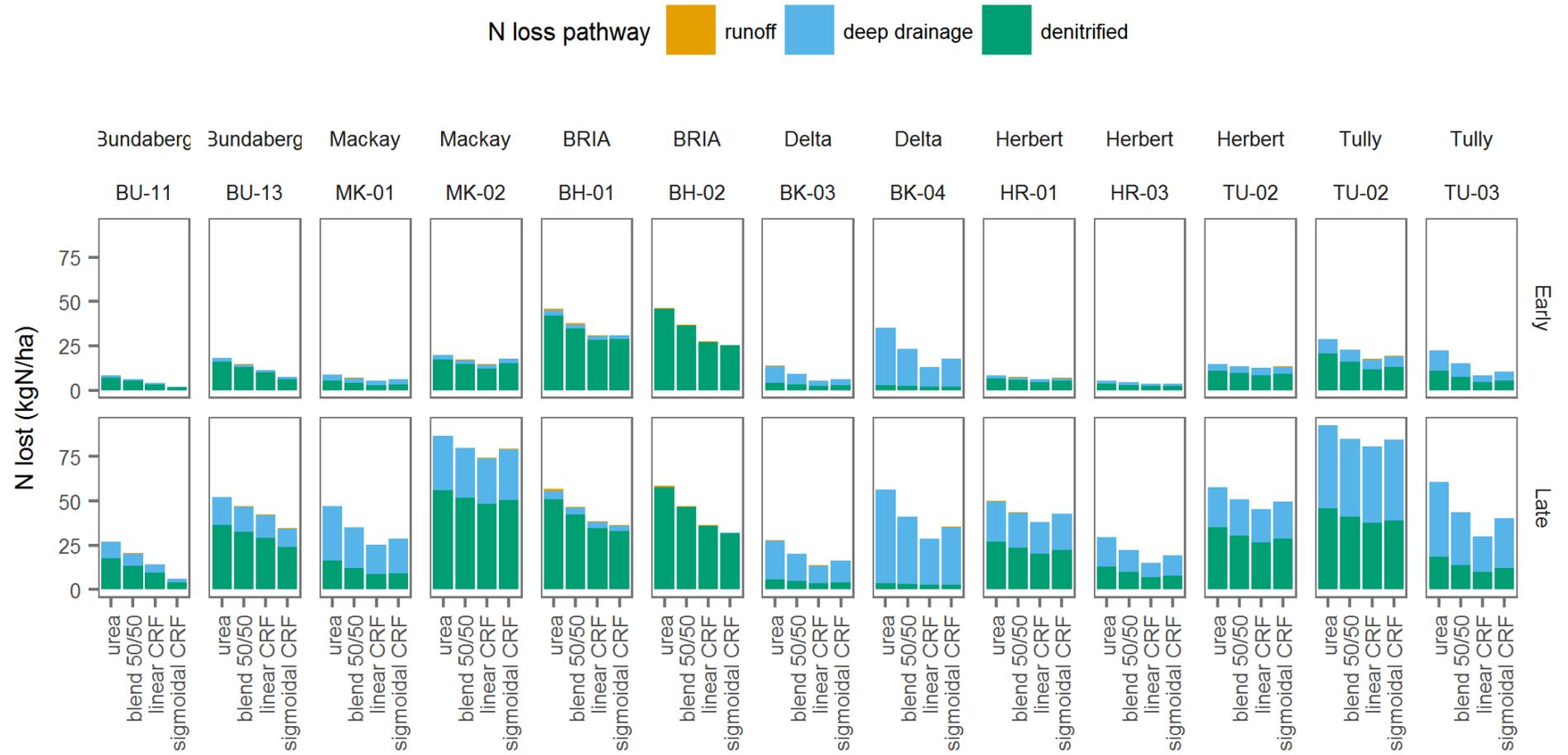


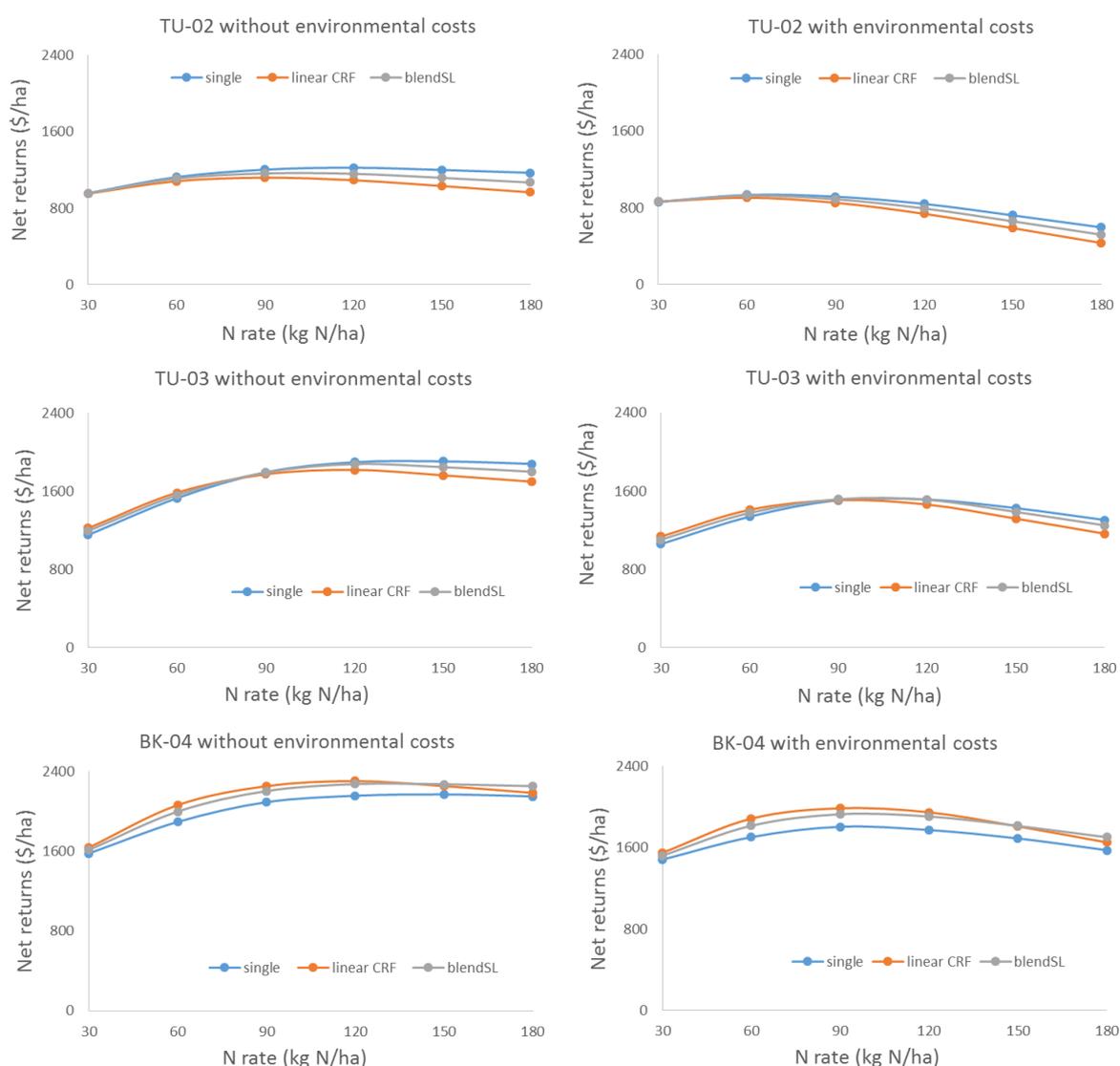
Figure 33: Predicted N loss by pathway for the different region x soil x fertiliser type scenarios and early (1-Aug) and late (1-Nov) ratoon crops at N rates of 150 kg N/ha.

### 6.5. Economics

The economic analysis focussed on three of the simulation scenarios that showed the largest agronomic benefits (Figure 32): late ratoons of the TU-02 and TU-03 soils in Tully and the BK-04 soil in the Burdekin. Results from economic analysis of mean expected net returns for these scenarios are shown in Figure 34 with and without environmental costs under six N rates between 30 and 180 kg N /ha of urea, linear (Type II) CRF and a 50:50 blend of urea and CRF.

While the agronomic simulations demonstrated equal or improved yield for the CRF across this range of N rates in all scenarios, the mean net return for CRF was lower than that of urea for the TU-02 scenario, which relates to its higher cost. For the TU-03 and BK-04 scenarios it was possible to obtain higher mean net returns at some of the N rates, including achieving the highest mean net return in the BK-04 scenario.

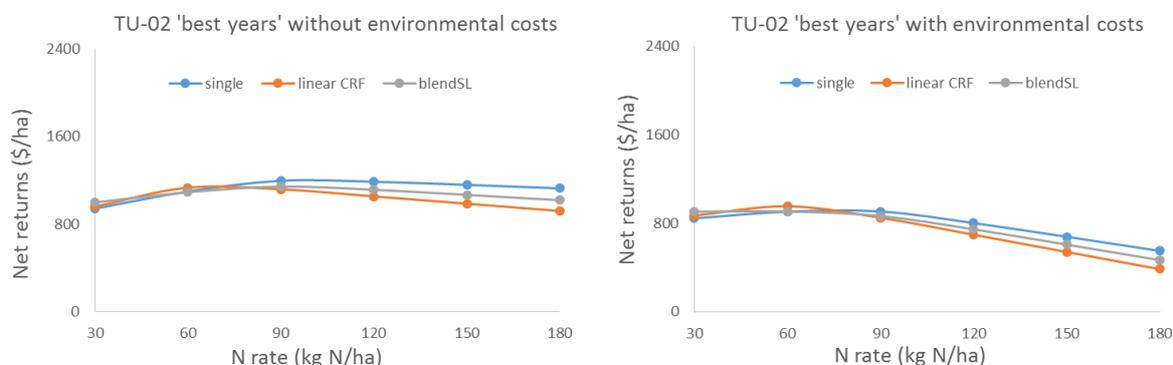
The comparison between the two Tully scenarios, TU-02 and TU-03 which only differ in soil type, show that the benefits from CRF use are soil dependent with TU-02 showing no benefit from CRF use in mean net return and TU-03 showing benefit of switching to CRF at the lower rates.



**Figure 34: Mean net returns with and without environmental costs under six N rates between 30 and 180 kg N/ha for urea (blue), linear (Type II) CRF (orange), and a 50:50 urea and CRF blend (grey).**

Including environmental impacts makes a big difference in relative attractiveness of CRF vs urea (compare left and right columns in Figure 34). The higher benefits shown by the BK04 scenario (Burdekin) compared with the TU-03 (Tully) scenario are still being explored further, but may relate to a higher and less variable yield potential (higher and less variable plateau yields in the N response curves).

The results of the simulation analysis of agronomic and environmental benefits (Section 6.4) highlighted the high season-to-season variability in benefits. Therefore, while the mean net returns for CRF do not always show a clear benefit over urea, the situation in individual seasons can be different. We repeated the analysis for the Tully TU-02 scenario for those years that showed a reduction in  $N_{opt}$  of more than 15 kg N/ha (Figure 30). These are the years expected to show the greatest benefit from CRF. Results of the mean net returns with and without environmental costs for TU-02 show that if CRF are used tactically in years where benefits are more likely, then there was potential for CRF to outperform urea, in particular when environmental costs are taken into account (Figure 35). Without environmental costs the highest average net return was still obtained using urea.



**Figure 35: Mean net returns with and without environmental costs for urea (blue), linear (Type II) CRF (orange) and a 50:50 urea and CRF blend (grey) and for TU-02 for one in three years with the best climatic conditions.**

The effect of seasonal variability is also highlighted in Figure 36, which shows frequency distributions of net returns including environmental costs for BK-04 at 90 kg N/ha, close to the optimal N rate, under urea and CRF. The shift in the distribution indicates there is considerable potential to mitigating economic risk through CRF adoption with a lower likelihood for getting low net returns under CRF than under urea.

Prices for CRF are subject to change over time, e.g. in response to market forces and volumes traded. For example, the price premium for ESN CRF products in the US and Canada has recently been reported to be in the range of 15-30% higher than traditional fertilizers (Gagnon et al., 2012). A lower cost multiplier (current analysis assumed CRF was 1.5-2.5 times more expensive) would improve the net returns.

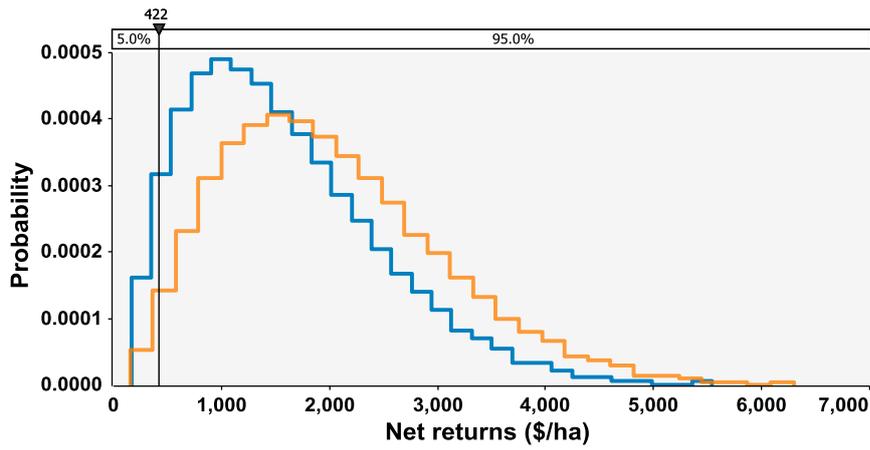


Figure 36: Frequency distributions of net returns including environmental costs for BK-04 at 90 kg N / ha under urea (red line) and linear (Type II) CRF.

## 6.6. Discussion

### 6.6.1. Lessons for experimental trials

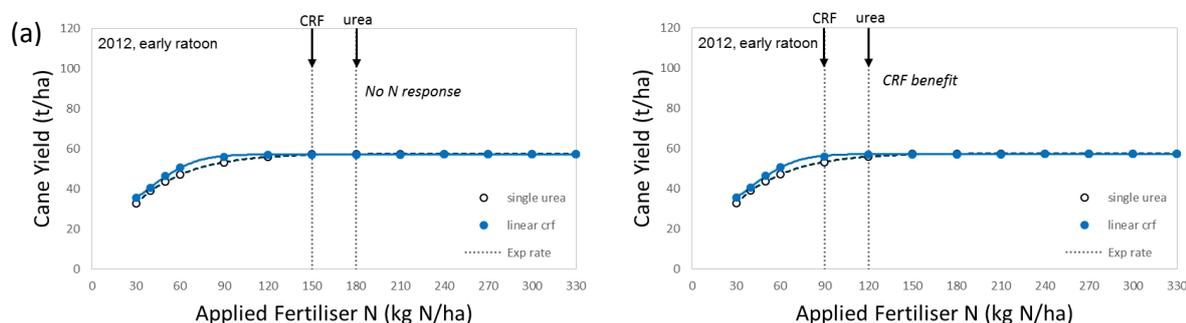
The findings of the review of experimental evidence, the results of the characterisation of N release from commercially-available CRF products as well as the insights provided by the simulation analyses provide a number of key lessons for experimental trials. Here we touch on three of these lessons.

#### *Prediction of N release in a trial or measurement using mesh bag method*

The N release characterisations and simulations extrapolating them indicate that not only do the N release patterns of CRF products differ inherently, the temperatures experienced in an experimental trial can modify the actual N release pattern even further. If the release characteristics of a product are known, the expected N release patterns can be predicted for a trial, given local climate data and time of application. In the light of the review finding that it would be beneficial to verify whether presence or absence of measured treatment differences (N loss or yield) is linked to the slow release of N by the CRF, another approach may be to evaluate N release of the chosen product within the trial itself using the mesh bag method.

#### *Importance of including a urea control at the lower N rate*

As highlighted in both literature reviews (Verburg et al., 2014, 2016), it is important that experimental trials which evaluate whether it is possible to maintain yield with CRF applied at a lower N rate compared with urea applied at a higher rate also include a urea control at the lower rate. If this control treatment is not included or if the control treatment is a zero N rate, then a result of yields that are not statistically significantly different could be due to lack of N response (Figure 37a) or be a true effect of the CRF (Figure 37b). A urea control at the lower rate helps distinguish between these two situations.



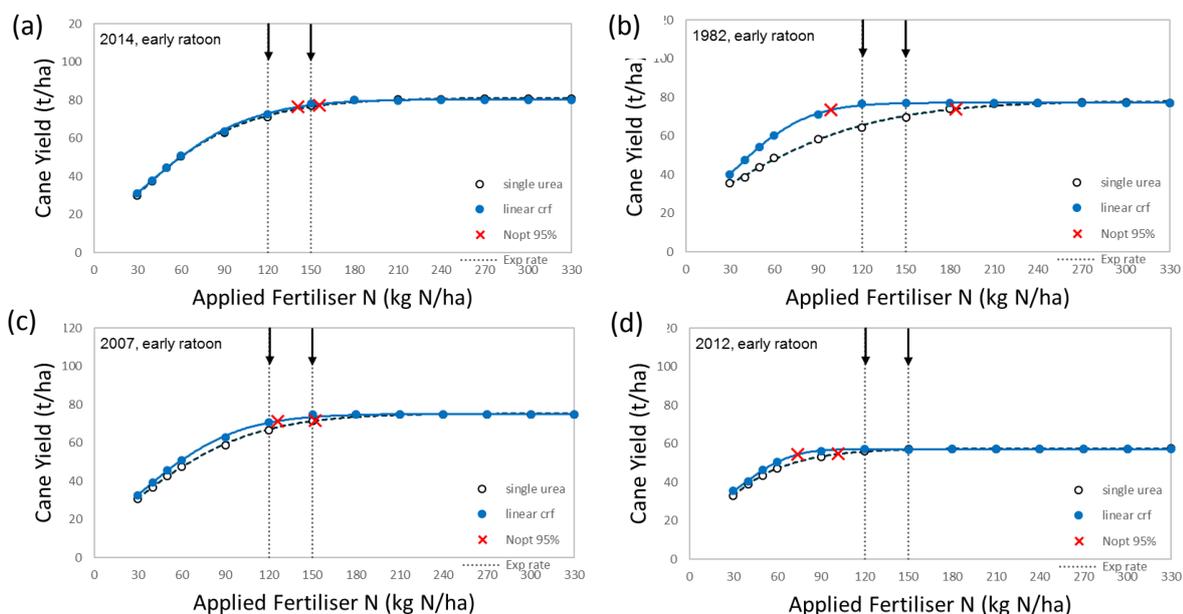
**Figure 37: Simulated N response curves for yield from a single urea application (open symbols) or linear (Type II) CRF product (closed symbols) in a first ratoon crop harvested in 2012. Vertical lines represent set N rates of hypothetical experimental treatments comparing CRF at a lower rate with urea at a higher rate. Including a urea control at the lower rate can distinguish between the two possible reasons for similar yields: (a) lack of N response and (b) CRF benefit.**

#### *Experimentally determining the possible reduction in $N_{opt}$ or frequency of CRF benefits*

We can use the simulated yield N response curves of both urea and CRF from Section 6.4 to explore what the outcomes might have been in different seasons of an experiment that compares treatments of urea at 150 kg N/ha, CRF at a reduced rate of 120 kg N/ha and, as a control, urea at 120 kg N/ha. This design is similar to many of the experimental trials currently used in the Australian sugarcane industry. If we had done this experiment with our virtual early ratoon crop in 2014, as shown in Figure 38a by the two vertical arrows, the results would have detected an N response between the lower and higher rates of N and correctly identified that there was no effect from the use of CRF. If the trial had instead been carried out in 1982 (Figure 38b), it would have confirmed the benefit of CRF over urea, although it would have underestimated the magnitude of the possible

reduction in Nopt. In 2007, the experimental results would have given approximately the right magnitude benefit (Figure 38c). But if these N rates had been trialed in 2012 we would have been unlucky as we would not have detected an effect from CRF use, whereas there was an effect at lower N rate (Figure 38d).

This demonstrates that it is difficult to use experiments to quantify the agronomic benefits and estimate the magnitude of the reduction in N rate that would be achievable across various seasons. In individual seasons this can be achieved by measuring the full N response curve.



**Figure 38: Simulated N response curves for yield from a single urea application (open symbols) or linear CRF product (closed symbols) in four early, first ratoon crop seasons (year of harvest indicated). The agronomic Nopt 95% for each fitted response curve is indicated by a red X. Vertical lines represent set N rates of a hypothetical experiment comparing treatments of urea and CRF at 120 and 150 kg N/ha.**

### 6.6.2. Environmental versus agronomic benefits

In Section 6.4 it was highlighted that agronomic benefits of CRF in the form of yield increase were limited to N rates below the agronomic optimum N rate (Nopt 95%) except in a small percentage of years (denoted by \* in Figure 30b). The magnitude of the benefits in the form of a reduction in Nopt were also found to be highly variable. Environmental benefits were more consistent across the range of N rates as well as from season to season. Reductions in N loss can be obtained without these translating into agronomic benefits (cf. Figure 32 and Figure 33). While the variable agronomic benefits suggest tactical application of CRF in seasons and under conditions where higher benefits can be expected, from an environmental perspective it may be attractive to use CRF more often. Even when there are no agronomic benefits and productivity is similar the N loss reductions that can be achieved may be valuable. Given the challenging economic situation due to CRF products being more expensive than urea (Section 6.5), other mechanisms may need to be considered to increase adoption where the increased N use efficiency of CRF does not result in increased economic net returns.

Correctly predicting the required N rate as a function of soil and management conditions and the upcoming season is also important for ensuring the environmental benefits from CRF are not negated by surplus N leading to an increase in N loss in the current or subsequent season. Nitrogen loss increases rapidly with N rate (Figure 29), which makes application of the right amount of N a critical issue.

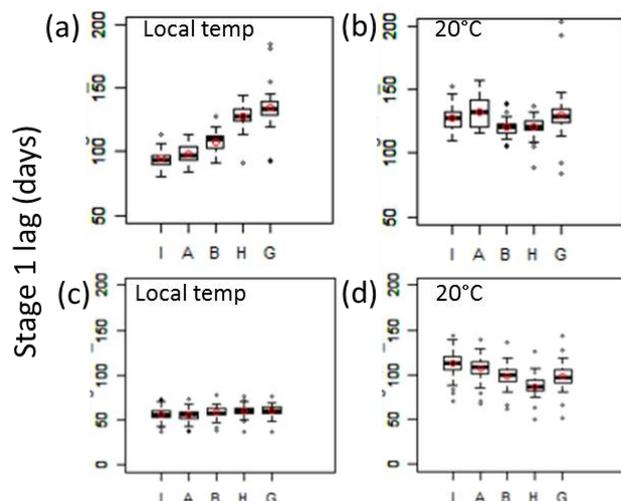
### 6.6.3. Opportunities to improve CRFs and their management

Comparison of the N release patterns of current commercially-available CRF products (Figure 8) and the observed (Keating et al., 1999; Zhao et al., 2017a) and simulated N uptake curves (Figure 18) suggests that there is room to improve the synchrony between N release and crop N demand. This will increase the benefits obtained from CRF use. The predicted crop N uptake patterns show a considerable lag before a period of rapid N uptake. Synchronising N supply with this uptake pattern does, however, not need to imply use of a Type III release product. A Type I or Type II release product can also achieve synchrony as long as the timing of its application can be managed. As this may depend on weather and soil conditions, different N release pattern types may need to be chosen for earlier or later planted or ratooned crops, and for well drained soils vs. those susceptible to waterlogging.

The N uptake simulations also suggest that optimal synchrony may not be able to be achieved with a 'one size fit all' CRF across industry. Australian sugarcane is produced in a large range of climates and with a wide spread in planting/ratooning dates. This resulted in considerable variability in predicted lag time as well as maximum N uptake rate (Figure 20). Water supply (e.g. full versus limited irrigation) also affected the maximum uptake rate, although had less effect on the lag (see Zhao et al. 2017a for details).

In designing CRF products and managing the timing of their application to match the desired lag and maximum uptake rate, the temperature response of the N release needs to be considered as well. The experimental results showed a considerable and varying effect of temperature on N release for the different CRF products (Figure 8). In addition, for a single CRF product the simulations resulted in quite different release rates for different locations and for early vs. late application (Table 3). For both Type II and Type III products we have successfully simulated the experimental temperature response with a  $Q_{10}$  factor, which indicates how much the rate changes for a 10°C increase in temperature (see Section 5.4.2).

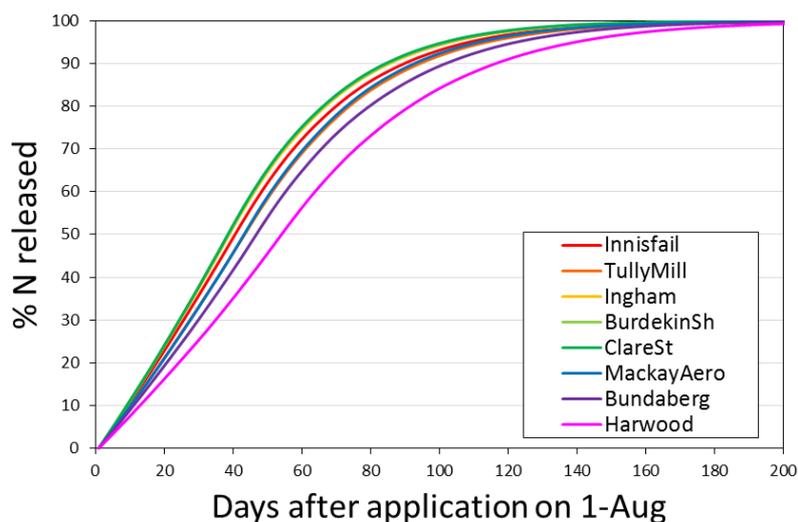
As the N uptake lags and maximum N uptake rates quantified by the simulations presented in Figure 20 reflect the temperatures of the first few months of growth in the different scenarios, their 'translation' using a  $Q_{10}$  factor to the standardised temperatures of a laboratory N release test (e.g. at 20°C) changes the relative magnitudes of the required lags and rates. This is illustrated in Figure 39 for the N uptake lags predicted for the early plant and late ratoon crop scenarios. On the left are the simulated lags at the local temperatures. On the right what they would translate to at 20°C for a CRF product with a  $Q_{10}$  factor of 2. It suggests that a Type III product with a  $Q_{10} = 2$  temperature effect on the duration of the release lag could in fact capture much of the variation in predicted N uptake lag between the different sites for the early plant crop scenario. In a laboratory N release experiment at 20°C it would need to show a lag of on average approximately 126 days. The same CRF product would, however, not provide the correct lag for the late ratoon crops, which required average lags between 87 and 113 days at 20°C.



**Figure 39: Predicted N uptake lags for the (a) early plant crop and (c) late ratoon crop scenarios, along with required N release lags at 20°C for a CRF product with a  $Q_{10} = 2$  temperature factor. The box boundaries indicate the 75 and 25% quartiles, and the whisker caps indicate the 95th and 5th percentiles, with the average shown by a red circle. The black circles are the outliers. I = Ingham, A = Ayr, B = Bundaberg, H = Harwood, G = Grafton.**

These results suggest that the target for CRF design should not be to develop a product for the industry as a whole, but to have a variety of N release patterns available from which a choice can be made for different conditions. That scenario requires that detailed information about the N release patterns of different products and their temperature response is available and can be translated to local temperature conditions (climate and time of application). Release simulations as carried out for this project could be used to develop this information into a decision support tool, e.g. allowing the user to specify the characteristics of a product and the location (climate) of interest and then explore the effect of time of application on timing of N release.

A preliminary exploration suggests that while there are considerable differences in N release patterns between some of the sugarcane growing regions, differences in N release patterns may be small within some of the regions. For example, the N release patterns generated with data from two climate stations within the Burdekin catchment were almost identical (Figure 40). The predicted release pattern using data from the Ingham station was also similar, although that predicted with data from Innisfail and Tully Mill stations suggested a slightly slower release. Within-region differences would need to be tested further. This requires that the temperature records are verified against local experience as many of the climate stations include spatially interpolated data for part of their record when local measurements were not made. Local topography and other conditions in combination with a sparse network of climate stations can make interpolation difficult. As shown in Section 6.3.2 the seasonal differences in N release were predicted to be small and can hence be ignored. Soil water effects would need to be confirmed as would the effect of trash cover for ratoon crops.



**Figure 40: Comparison of predicted average N release patterns for the Type II PCU used in Section 6.3.2 ( $Q_{10} = 1.8$ ) based on historical records from a range of climate stations.**

As shown in the example in Figure 25d, negative yield impacts can occur when N is released too late. Attempting to closely synchronise the release of N with N demand hence poses a risk of getting the timing of N release from CRF wrong. Applying the CRF as a CRF-urea blend with a small percentage of urea may provide some insurance against negative yield impacts. Large percentages of urea will, however, reduce the effectiveness of the product, although may sometimes be more economical (Section 6.5).

The large season to season variations in agronomic and economic benefits suggest that decisions should not only consider the type of N release pattern and time of its application, but also whether CRF is the best choice in a given season. Tactical use of CRF may be a more realistic adoption goal, but will require development of decision tools to assist farmers and advisors. This should include forecasting of early season weather, as this drives the likelihood of large N loss events. Development of appropriate decision logic is best done by region so that climatic conditions and irrigation practices are more similar and can be captured by two to three scenarios. This would also allow reference to local soil types.

A pre-requisite for improving management of CRFs to achieve better synchrony between N release and crop N demand is that N release patterns of products are reported, including temperature response and any dependence on soil water. With the CRF products undergoing continuous improvement and new products entering the market, information from studies like the characterisations performed in this project may be quickly out-of-date. This suggests that the fertiliser industry needs to be proactive in ensuring that information about N release patterns is made available.

Whilst the N release patterns will determine the likely effectiveness of the product, there are also a number of other aspects that need to be considered, such as consistency of the product in terms of the population of granules (distribution in granule size, thickness and integrity of coating) and resistance to damage during transport. Improvement of CRF products should hence not only be focussed on the required lags, maximum release rates or desired temperature response, but also focus on consistency of the product: less variability within the granule population; reduced coating imperfections, and products that are resistant to damage during handling. In addition, the mid-term workshop with industry (see Verburg 2016) identified that degradability of the polymer coatings needs to be considered in order not to introduce other environmental issues (e.g. micro-plastics).

## 7. PUBLICATIONS

The various written publications prepared over the course of the project are listed below, grouped by type.

### 7.1.1. Papers, abstracts, posters and presentations at ASSCT conferences

- Kandulu, J, Thorburn, PJ, Biggs, JS & Verburg, K 2017, 'Estimating economic impacts of controlled release fertilisers in sugarcane systems: An economic risk case study analysis', *Proceedings of the Australian Society of Sugar Cane Technologists* 39, 251-262. (paper and presentation)
- Muster, T, Verburg, K, Mardel, J, Wittwer-Schmid, K, Wong, M, Bristow, K, McLachlan, G & Zhao, Z 2016, 'Understanding nitrogen release from controlled-release fertilisers', *Proceedings of the Australian Society of Sugar Cane Technologists* 38, 146. (abstract, poster and short presentation)
- Verburg, K, Zhao, Z, Biggs, JS & Thorburn, PJ 2016, 'Controlled release fertilisers – Lessons from a review and early results characterising release, synchrony and nitrogen losses', *Proceedings of the Australian Society of Sugar Cane Technologists* 38, 159–169. (paper and presentation)
- Verburg, K, Biggs, JS, Zhao, Z & Thorburn, PJ 2017, 'Potential production and environmental benefits from controlled release fertilisers – Lessons from a simulation analysis', *Proceedings of the Australian Society of Sugar Cane Technologists* 39, 239-250. (paper and presentation)
- Zhao, Z & Verburg, K 2016, 'Modelling nitrogen release from controlled-release fertilisers in Australian sugar systems', *Proceedings of the Australian Society of Sugar Cane Technologists* 38, 145. (abstract, poster and short presentation)

### 7.1.2. Other conference papers, abstracts and presentations

- Muster, T, Verburg, K, Zhao, Z, Wittwer-Schmid, K, Poole, J, McLachlan, G, Bristow, K, Wong, M & Mardel, J 2016, 'The practicalities of using controlled release fertilisers', *Australian Fertilizer Industry Conference 2016*, 13-15 September 2016, Cairns, Fertilizer Australia. (<http://www.fertilizer.org.au/Publications-and-Events/Conference-Proceedings-2016-Cairns>) (presentation)
- Muster, T, Verburg, K, Poole, J, Zhao, Z, Wittwer-Schmid, K & Bristow, K 2017, 'Characterisation of commercially-available nitrogen controlled release fertilisers', *Agronomy community conference 'Tropical systems'*, 8 June 2017, Townsville
- Zhao, Z & Verburg, K 2015, 'Modelling nitrogen uptake by sugarcane crops to inform synchrony of N supply from controlled release fertiliser', In Weber T, McPhee MJ and Anderssen RS (eds.) *MODSIM2015, 21st International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2015, pp. 420–426. ISBN: 978-0-9872143-5-5. (<http://www.mssanz.org.au/modsim2015/B3/zhao.pdf>) (paper and presentation)
- Zhao, Z & Verburg, K 2017, 'Modelling to synchronise nitrogen uptake by sugarcane crops with N supply from controlled release fertiliser', *3rd International Conference on Agricultural and Biological Sciences (ABS2017)*. 26-29 June 2017, Qingdao, Shandong, China (abstract and presentation)

### 7.1.3. Journal publications and web-published reports

- Kandulu, J, Thorburn, PJ, Biggs, JS & Verburg, K 2017, 'Estimating economic and environmental impacts of nitrogen in agricultural systems: an economic risk analysis', Submitted to *Journal of Environmental Management*.
- Kandulu, J, Verburg, K, Biggs, J & Thorburn, P, 2017, 'Evaluating the trade-off between potential economic and environmental benefits of controlled release fertilisers in sugarcane systems: an economic risk analysis' (in preparation).
- Muster, TH, Mardel, J, Poole, J, Wittwer-Schmid, K, Verburg, K, Wong, MFT, Zhao, Z, McLachlan, G, Bristow, KL 2017, 'Understanding the release of nitrogen from commercially-available controlled release fertilisers'. To be submitted to *Soil Science Society of America Journal*.
- Verburg, K, Harvey, TG, Muster, TH, Brennan McKellar, LE, Thorburn, PJ, Biggs, JS, Di Bella, LP, & Wang, W 2014, 'Use of enhanced efficiency fertilisers to increase fertiliser nitrogen use efficiency in sugarcane', Chapter 7 Part I, in Bell MJ (ed.), *A review of nitrogen use efficiency in sugarcane*, Research Report, Sugar Research Australia , pp. 226-292.
- Verburg, K, Zhao, Z, Biggs, JS & Thorburn, PJ 2016, 'Controlled release fertilisers – Lessons from a review and early results characterising release, synchrony and nitrogen losses', *International Sugar Journal*, vol. 118, no. 1414, pp. 764-770.
- Verburg, K, Bristow, KL, McLachlan, G, et al. 2017, 'Towards improved understanding of soil water effects on nitrogen release from controlled release fertilisers' To be submitted to *Soil Science Society of America Journal*.
- Zhao, Z, Verburg, K & Huth, NI 2017, 'Modelling sugarcane nitrogen uptake patterns to inform design of controlled release fertiliser for synchrony of N supply and demand', *Field Crops Research*, vol. 213, pp. 51-64.
- Zhao, Z, Verburg, K, McLachlan, G, Bristow, KL, Wittwer-Schmid, K, Muster, T, Wong, MTF & Di Bella, LD 2017, 'A modelling approach to assess the effects of climate and management on nitrogen release patterns of controlled release fertiliser' To be submitted to *Agriculture Ecosystems and Environment*.

### 7.1.4. Industry updates

- Pfeffer, B 2016, Controlled –release fertilisers: unravelling the mystery, CaneConnection Spring 2016.
- Power, C 2015, Controlled release fertilisers under the microscope, CaneConnection Winter 2015.

### 7.1.5. Industry collaborator communication

- Biggs, JS & Verburg, K 2014, 'Data requirements for modelling sugarcane systems and experimental trials' *SRA-CRF project industry consultation on simulation of experimental trials*. 5 pp.
- Muster, T 2016, 'Preliminary release data product report, January 2016, Agrocote', 9 pp. (Confidential)
- Muster, T 2016, 'Preliminary release data product report, January 2016, ESN', 6 pp. (Confidential)
- Muster, T 2016, 'Preliminary release data product report, January 2016, IPL', 8 pp. (Confidential)
- Muster, T 2016, 'Preliminary release data product report, January 2016, Meister', 7 pp. (Confidential)
- Muster, T 2016, 'Preliminary release data product report, January 2016, Multicote', 7 pp. (Confidential)
- Muster, T 2016, 'Preliminary release data product report, January 2016, Sumito', 7 pp. (Confidential)

- Verburg, K 2015, 'Role of controlled release fertiliser in Australian sugarcane systems. SRA project is seeking industry input into modelling scenarios', *SRA-CRF project industry consultation on modelling plan*, 6 pp.
- Verburg, K, Muster, T, Bristow, K, Wong, M, Mardel, J, Wittwer-Schmid, K, Harvey, T & McLachlan, G 2015, 'Laboratory protocols developed for the SRA funded project Role of controlled release fertiliser in Australian sugarcane systems', *draft for consultation with industry*, 34 pp.
- Verburg, K 2016, 'Towards improved synchrony for controlled release fertilisers. An interim report by SRA project 2014/011 'Role of controlled release fertiliser in Australian sugarcane systems' following a workshop on Tuesday 24 May 2016 at Townsville Rydges Southbank to gain industry input', 10 pp.
- Verburg, K, Muster, TH, Zhao, Z, Biggs, JS, Thorburn, PJ, Kandulu, J, Wittwer-Schmid, K, McLachlan, G, Bristow, KL, Poole, J, Wong, MFT & Mardel JI 2017b, *Role of controlled release fertilizer in Australian sugarcane systems. Background information accompanying the final workshop of SRA project 2014/011*, CSIRO, Australia.

## 8. REFERENCES

- Abalos, D, Jeffrery, S, Sanz-Cobena, A, Guardia, G & Vallejo, A 2014, 'Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency', *Agriculture, Ecosystems and Environment*, vol. 189, pp. 136-144.
- Akiyama, H, Yan, X & Yagi, K 2010, 'Evaluation of effectiveness of enhanced-efficiency fertilisers as mitigation options for N<sub>2</sub>O and NO emissions from agricultural soils: Meta-analysis', *Global Change Biology*, vol. 16, pp. 1837-1846.
- Ball-Coelho, B, Sampaio, EVSB, Tiessen, H & Stewart, JWB 1992, 'Root dynamics in plant and ratoon crops of sugarcane', *Plant and Soil*, vol. 142, pp. 297-305.
- Bell, MJ (Ed.) 2014, *A review of nitrogen use efficiency in sugarcane*, SRA Research Report, Sugar Research Australia, Brisbane.
- Bell, MJ & Moody, P 2014, 'Fertilizer N use in the sugarcane industry – an overview and future opportunities', in Bell MJ (ed.), *A review of nitrogen use efficiency in sugarcane*, SRA Research Report, Sugar Research Australia, Brisbane, pp. 305-320.
- Biggs, JS, Thorburn, PJ, Crimp, S, Masters, B & Attard, SJ 2013, 'Interactions between climate change and sugarcane management systems for improving water quality leaving farms in the Mackay Whitsunday region', Australia. *Agriculture Ecosystems and Environment*, vol. 180, pp. 79-89.
- Brodie, J, Waterhouse, J, Schaffelke, B, Kroon, F, Thorburn, P, Rolfe, J, Johnson, J, Fabricius, K, Lewis, S, Devlin, M, Warne, M & McKenzie, L 2013, *Scientific consensus statement: Land use impacts on Great Barrier Reef water quality and ecosystem condition*. Reef Water Quality Protection Plan Secretariat, State of Queensland, Brisbane, 12 pp.
- Cannon, M, Smith, C, & Murtha, G 1992, *Soils of the Cardwell-Tully area, north Queensland*, Division of Soils divisional report no. 115, CSIRO Division of Soils, Glen Osmond, 141 pp.
- Chen, D, Suter, H, Islam, A, Edis, R, Freney, JR & Walker, CN 2008, 'Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers', *Australian Journal of Soil Research*, vol. 46, pp. 289-301.
- Christianson, CB 1988, 'Factors affecting N release of urea from reactive layer coated urea', *Fertilizer Research*, vol. 16, pp. 273-284.
- Connellan, JF & Deutschenbaur, J 2016, Nitrogen accumulation in biomass and its partitioning in sugarcane growth in the Burdekin. *Proceedings of the Australian Society of Sugar Cane Technologists*, vol. 38, pp. 72-80.
- Dawes, L, Sweeney, C, Cook, F, Bristow, K, Eldridge, S, Biggs, J & Thorburn, PJ 2003, *Soil hydraulic properties of the Fairymead soils, Bundaberg*, CRC for Sustainable Sugar Production, Townsville.
- Di Bella LP, Stacey SP, Benson A, Royle A & Holzberger G 2013, 'An assessment of controlled release fertiliser in the Herbert cane growing region', *Proceedings of the Australian Society of Sugar Cane Technologists*, vol. 35, pp. 784-788.
- Di Bella, L, Stacey, S, Moody, P, Benson, A, Dowie, J & Sluggett, R 2014, 'An Assessment of Controlled Release Fertilisers in the Australian Sugar Industry', *Proceedings of the Australian Society of Sugar Cane Technology*, vol. 36, pp. 121-131.
- Di Bella, LP, Armour, J, Moody, P, Royle, M, Ibanez, M & Le Bris, M, 2017, 'The assessment of enhanced efficiency fertilisers (EEFs) in a glasshouse experiment to investigate nitrogen loss

pathways in sugarcane', *Proceedings of the Australian Society of Sugar Cane Technology*, vol. 39, pp. 263-273.

FAO, 2015. <http://www.fao.org/es/faodef/fdef03e.HTM>. Food and Agriculture organisation of the United Nations.

Gagnon, B, Ziadi, N & Grant, C 2012, 'Urea fertilizer forms affect grain corn yield and nitrogen use efficiency', *Canadian Journal of Soil Science*, vol. 92, pp. 341-351.

Halvorson, AD, Snyder, CS, Blaylock, AD & Del Grosso, SJ 2014, 'Enhanced efficiency nitrogen fertilizers: Potential role in nitrous oxide emission mitigation', *Agronomy Journal*, vol.106, pp. 715-722.

Holzworth, DP, Huth, NI, de Voil, PG, Zurcher, EJ, Herrmann, NI, McLean, G, Chenu, K, et.al. 2014, 'APSIM—evolution towards a new generation of agricultural systems simulation', *Environmental Modelling & Software*, vol. 62, pp. 327-350.

IPF (2014) *More cane more gain*. Incitec Pivot Fertilisers. Webpage.  
<http://www.incitecpivotfertilisers.com.au/Customers/More%20cane%20more%20gain>

Jeffrey, SJ, Carter, JO, Moodie, KB & Beswick, AR 2001, 'Using spatial interpolation to construct a comprehensive archive of Australian climate data', *Environmental Modelling & Software*, vol. 16, pp. 309-330.

Kandulu, J, Thorburn, PJ, Biggs, JS & Verburg, K 2017a, 'Estimating economic and environmental impacts of nitrogen in agricultural systems: An economic risk analysis', Submitted to *Journal of Environmental Management*.

Kandulu, J, Thorburn, P, Biggs, J & Verburg, K 2017b, 'Estimating economic impacts of controlled release fertilisers in sugarcane systems: An economic risk case study analysis', *Proceedings of the Australian Society of Sugar Cane Technologists* 39, pp. 251-262.

Keating, BA, Robertson, MH, Muchow, RC & Huth, NI 1999, 'Modelling sugarcane production systems I. Development and performance of the sugarcane module', *Field Crops Research*, vol. 61, pp. 253-271.

Keating, BA, Carberry, PS, Hammer, GL, Probert, ME, Robertson, MJ, Holzworth, D, Huth, NI, Hargreaves, JNG, Meinke, H, Hochman, Z, McLean, G, Verburg, K, Snow, V, Dimes, JP, Silburn, M, Wang, E, Brown, S, Bristow, KL, Asseng, S, Chapman, S, McCown, RL, Freebairn, DM & Smith, CJ 2003, 'An overview of APSIM, a model designed for farming systems simulation', *European Journal of Agronomy*, vol. 18, pp. 267-288.

Mallawaarachchi, T & Quiggin, J 2001, 'Modelling socially optimal land allocations for sugar cane growing in North Queensland: a linked mathematical programming and choice modelling study' *Australian Journal of Agricultural and Resource Economics*, vol. 45, pp. 383-409.

Muster, TH, Mardel, J, Poole, J, Wittwer-Schmid, K, Verburg, K, Wong, MFT, Zhao, Z, McLachlan, G & Bristow, KL 2017, 'Understanding the release of nitrogen from commercially-available controlled release fertilisers', To be submitted to *Soil Science Society of America Journal*.

Probert, M, Dimes, J, Keating, B, Dalal, R & Strong, W 1998, 'APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems', *Agricultural Systems*, vol. 56, pp. 1-28.

Rolfe, J & Windle, J 2016, *Benchmarking costs of improving agricultural water management in GBR catchments*, Report to the National Environmental Science Programme, Reef and Rainforest Research Centre Limited, Cairns, 52 pp.

- Shaviv, A 2001, 'Advances in controlled-release fertilizers', *Advances in Agronomy*, vol. 71, pp. 1-49.
- State of Queensland 2013, *Reef Plan Scientific Consensus Statement*. Reef Water Quality Protection Plan Secretariat, Brisbane. 34 pp.
- State of Queensland 2016, *Great Barrier Reef Water Science Taskforce Final Report 2016*. The Great Barrier Reef Water Science Taskforce, and the Office of the Great Barrier Reef, Department of Environment and Heritage Protection, State of Queensland, Brisbane, 94 pp.
- Stewart, LK, Charlesworth, PB, Bristow, KL & Thorburn, PJ 2006, 'Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM', *Agricultural Water Management*, vol. 81, pp. 315–334.
- Thorburn, PJ, Probert, ME, Lisson, SN, Wood, AW & Keating BA 1999, 'Impacts of trash retention on soil nitrogen and water: An example from the Australian sugarcane industry', in: *Proceedings of the South African Sugar Technologists Association*. pp. 75–79.
- Thorburn, PJ, Probert, ME & Robertson, FA 2001, 'Modelling decomposition of sugar cane surface residues with APSIM-Residue' *Field Crops Research*, vol. 70, pp. 223–232.
- Thorburn PJ, Meier EA & Probert ME 2005, 'Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications', *Field Crops Research*, vol. 92, pp. 337–351.
- Thorburn, PJ, Biggs, JS, Collins, K & Probert, ME 2010, 'Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane production systems', *Agriculture Ecosystems and Environment*, vol. 136, pp. 343-350.
- Thorburn, PJ, Biggs, JS, Attard, SJ & Kemei, J 2011, 'Environmental impacts of irrigated sugarcane production: Nitrogen lost through runoff and leaching', *Agriculture, Ecosystems and Environment*, vol. 144, pp. 1-12.
- Thorburn, PJ, Wilkinson, SN & Silburn, DM 2013, 'Water quality in agricultural lands draining to the Great Barrier Reef: A review of causes, management and priorities', *Agriculture Ecosystems and Environment*, vol. 180, pp. 4-20.
- Thorburn, PJ, Biggs JS, Meier, EA, Empson, M, Palmer, J, Verburg, K & Skocaj, DM 2014, 'Increasing nitrogen use efficiency in Australian sugarcane crops: Insights from simulation modelling'. Chapter 6, in Bell MJ (ed.), *A review of nitrogen use efficiency in sugarcane*, SRA Research Report, Sugar Research Australia, Brisbane, pp.180-225
- Trenkel, ME 2010, *Slow- and controlled-release and stabilised fertilisers: An option for enhancing nutrient use efficiency in agriculture*, 2nd ed., International Fertiliser Industry Association (IFA), Paris, France.
- van Grieken, M, Lynam, T, Coggan, A, Whitten, S & Kroon, F 2013, 'Cost effectiveness of design-based water quality improvement regulations in the Great Barrier Reef Catchments', *Agriculture Ecosystems and Environment*, vol. 180, pp. 157-165.
- Venterea, RT, Halvorson, AD, Kitchen, N, Liebig, MA, Cavigelli, MA, et al. 2012, 'Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems', *Frontiers in Ecology and the Environment*, vol. 10, pp. 562-570.
- Verburg, K, McBeath, T, Keating, B, Probert, M, Lisson, S, Botwright Acuna, T & Moore, A, 2013, 'Evaluating controlled release fertiliser for sustainable intensification of agriculture: examples illustrating the value of systems analysis', *4th International Symposium for Farming Systems Design*, 19-22 August 2013 Lanzhou, China.

Verburg, K, Harvey, TG, Muster, TH, Brennan McKellar, LE, Thorburn, PJ, Biggs, JS, Di Bella, LP, & Wang, W 2014, 'Use of enhanced efficiency fertilisers to increase fertiliser nitrogen use efficiency in sugarcane', Chapter 7 Part I, in Bell MJ (ed.), *A review of nitrogen use efficiency in sugarcane*, SRA Research Report, Sugar Research Australia, Brisbane, pp. 226-292.

Verburg, K 2016, *Towards improved synchrony for controlled release fertilisers, Interim report by SRA project 2014/011 'Role of controlled release fertiliser in Australian sugarcane systems' following a workshop on Tuesday 24 May 2016 at Townsville Rydges Southbank to gain industry input*, CSIRO, Canberra, 10 pp.

Verburg, K, Zhao, Z, Biggs, JS & Thorburn, PJ 2016, 'Controlled release fertilisers – Lessons from a review and early results characterising release, synchrony and nitrogen losses', *Proceedings of the Australian Society of Sugar Cane Technologists*, vol. 38, pp. 159–169.

Verburg, K, Biggs, JS, Zhao, Z & Thorburn, PJ 2017a, 'Potential production and environmental benefits from controlled release fertilisers – Lessons from a simulation analysis', *Proceedings of the Australian Society of Sugar Cane Technologists*, vol. 39, pp. 239-250.

Verburg, K, Bristow, KL, McLachlan, G, et al. 2017b, 'Towards improved understanding of soil water effects on nitrogen release from controlled release fertilisers', To be submitted to *Soil Science Society of America Journal*.

Walker, GM, Magee, TRA, Holland, CR, Ahmad, MN, Fox, N & Moffatt, NA 1997, 'Compression testing of granular NPK fertilizers', *Nutrient Cycling in Agroecosystems*, vol. 48, pp. 231-234.

Walker, GM, Moursy, MN, Holland, CR & Ahmad, MN 2003, 'Effect of process parameters on the crush strength of granular fertiliser', *Powder Technology*, vol. 132, pp. 81-84.

Wood, AW, Muchow, RC & Robertson, MJ 1996, Growth of sugarcane under high input conditions in tropical Australia. III Accumulation and partitioning and use of nitrogen. *Field Crops Research*, vol. 48, pp. 223–233.

Weier, K 1998, 'The potential for N losses via denitrification beneath a green cane trash blanket', *Proceedings of the Australian Society of Sugar Cane Technologists*, vol. 20, pp. 169–175.

World Bank, 2015,

<http://www.indexmundi.com/commodities/?commodity=sugar&months=360&currency=aud&commodity=urea>. World Bank.

Zhao, Z & Verburg, K 2015, 'Modelling nitrogen uptake by sugarcane crops to inform synchrony of N supply from controlled release fertiliser', in Weber, T., McPhee MJ & Anderssen RS (eds.) *MODSIM2015, 21st International Congress on Modelling and Simulation*, Modelling and Simulation Society of Australia and New Zealand, December 2015, pp. 420–426. (<http://www.mssanz.org.au/modsim2015/B3/zhao.pdf>)

Zhao, Z, Verburg, K & Huth, NI 2017a, 'Modelling sugarcane nitrogen uptake patterns to inform design of controlled release fertiliser for synchrony of N supply and demand', *Field Crops Research*, vol. 213, pp. 51-64.

Zhao, Z, Verburg, K, McLachlan, G, Bristow, KL, Wittwer-Schmid, K, Muster, T, Wong, MTF & Di Bella, LD 2017b, 'A modelling approach to assess the effects of climate and management on nitrogen release patterns of controlled release fertiliser' To be submitted to *Agriculture Ecosystems and Environment*.

## 9. APPENDIX

### 9.1. Appendix 1 METADATA DISCLOSURE

**Table 4 Metadata disclosure 1**

<b>Data</b>	Datasets of N release from incubation experiments, soil core experiments and field mesh bag experiment and characterisations of CRF products as presented in Verburg et al. (2017b), Muster et al. (2017) and Zhao et al. (2017b) and this Final Report.
<b>Stored Location</b>	CSIRO "\\nexus\projects\Agriculture\SRA Controlled Release Fertiliser\SRA Project 2014-011\Archive files"
<b>Access</b>	The stored location is not publically accessible. Confidentiality requirements require that only the published, anonymized data (not identifying the CRF product) as included in the publications can be made available.
<b>Contact</b>	Dr Kirsten Verburg, CSIRO Agriculture and Food, project leader

**Table 5 Metadata disclosure 2**

<b>Data</b>	Datasets of APSIM simulation results as disclosed in Zhao and Verburg (2015), Verburg et al. (2017a), Zhao et al. (2017a), Zhao et al. (2017b) and Sections 6.4.4, 6.6.1 and 6.6.1 of this Final Report.
<b>Stored Location</b>	CSIRO "\\nexus\projects\Agriculture\SRA Controlled Release Fertiliser\SRA Project 2014-011\Archive files"
<b>Access</b>	The stored location is not publically accessible. Data can be made available upon request.
<b>Contact</b>	Dr Kirsten Verburg, CSIRO Agriculture and Food, project leader

**Table 6 Metadata disclosure 3**

<b>Data</b>	Datasets of economic analysis results as disclosed in Kandulu et al. (2017a), Kandulu et al. (2017b) and Section 6.5 of this Final Report.
<b>Stored Location</b>	CSIRO "\\nexus\projects\Agriculture\SRA Controlled Release Fertiliser\SRA Project 2014-011\Archive files"
<b>Access</b>	The stored location is not publically accessible. Data can be made available upon request.
<b>Contact</b>	Dr Kirsten Verburg, CSIRO Agriculture and Food, project leader