
CONTROLLED RELEASE FERTILISERS—LESSONS FROM A REVIEW AND EARLY RESULTS CHARACTERISING RELEASE, SYNCHRONY AND NITROGEN LOSSES

By

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Abstract

THE RECENT INTEREST in the use of controlled release fertilisers to reduce nitrogen (N) loss and increase N use efficiency in sugarcane systems warrants a closer look at the understanding and lessons gained from experimental trials to date. This paper presents lessons from a review of the available, published evidence. It also presents early results from SRA project 2014/011 characterising N release from a range of controlled release fertiliser products and uses modelling to explore N uptake patterns and N loss pathways. The modelling also provides insights into how yield or fertiliser N use efficiency benefits will likely occur.

Introduction

The Australian sugarcane industry is under pressure to reduce nitrogen (N) losses and increase N use efficiency (Bell, 2014). This has prompted an interest in the use of so-called enhanced efficiency fertilisers (State of Queensland, 2013; Bell, 2014). These fertilisers release the N more slowly than conventional fertilisers (controlled release fertilisers) or temporarily stabilise it in a form less susceptible to losses (e.g. in urea form through addition of a urease inhibitor or in ammonium form through addition of a nitrification inhibitor).

The aim is to provide the N in a form or at a rate which minimises losses but also ensures crop uptake is not limited (Hauck, 1985). Improved synchrony of N supply (from fertiliser and soil) and crop N demand is seen as a key to improving N use efficiency and reducing N losses (Bell and Moody, 2014).

While these in-principle advantages of enhanced efficiency fertilisers are understood, there remain many practical questions for farmers and advisors. For example: How much improvement in yield or N use efficiency can these fertilisers achieve and will it justify their higher cost? To what extent is their efficacy dependent on soil type, location (climate) and management system? What about season-to-season variability? Will the benefits be consistent across seasons or highly variable? Which type of enhanced efficiency fertiliser to choose or does that depend on soil, location or management? Does blending with urea still provide benefits, or is that in fact needed to ensure early N supply? Finding answers to these questions is pertinent as the higher cost of these fertilisers will generally require achievement of higher yields for the same N rates or achievement of similar yields for lower N rates.

Field trials have been the primary mechanism to evaluate enhanced efficiency fertiliser products. Internationally and across industries, experimentation dates back at least 40–50 years. In the Australian sugarcane industry, enhanced efficiency fertilisers were first trialled in the early 1990s.

Recent renewed interest has prompted a dramatic increase in the number of field trials, with the results of some studies published (e.g. Di Bella *et al.*, 2013, 2014; Wang *et al.*, 2008, 2012, 2014). We have reviewed this body of experimental evidence from sugarcane and other industries internationally (Verburg *et al.*, 2014).

Lessons from the review include the need to consider more closely the longevity of inhibitor action of stabilised fertilisers and the degree of synchrony between N release and crop N demand achieved by controlled release fertilisers. The review also suggests that the magnitude and timing of N loss, as a function of soil, climate and management, needs to be better understood in order to predict the benefits from enhanced efficiency fertilisers.

An SRA funded project (2014/011) is currently having a closer look at controlled release fertilisers. The slower release of N is typically achieved by coating the fertiliser. Control over the release pattern is achieved through the composition or design of the coating, which determines the release mechanism as well as its sensitivity to environmental factors like temperature and moisture. The available evidence suggests a wide range of release patterns between products exists. Consequently, there is a need for a more systematic study of release characteristics and linking these to coating properties.

Accomplishing synchrony between N supply and demand also requires an understanding of crop N demand patterns. Experimental data on crop N uptake patterns are limited and specific to the conditions of the trials in which they are obtained. Modelling is therefore being employed, in SRA project 2014/011, to extrapolate experimental data and assess seasonal variability in uptake patterns.

Modelling is also used to gain a better understanding of typical N loss magnitudes, patterns and their seasonal variability as this could inform the required longevity of inhibitor action of stabilised fertilisers and determine the likely effectiveness of controlled release fertilisers.

This paper presents lessons from the review (Verburg *et al.* 2014), both in terms of understanding gained and recommendations for design and interpretation of field trials. It also presents the early results characterising N release, synchrony and N losses from SRA project 2014/011 to provide some initial guidance for farmers, advisors and researchers interested in using or trialling controlled release fertilisers.

Methodology

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. As it is impossible to present the full set of review findings in this paper, only a summary and key lessons are provided and the reader is referred to the original publication for further details (Verburg *et al.*, 2014).

Simulations of N uptake by sugarcane and N losses from the sugarcane system were performed with the APSIM model (Holzworth *et al.*, 2014). 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 (e.g. Thorburn *et al.*, 2014).

Simulations of crop N uptake were built on a set of experimental data sets quantifying N uptake patterns in a number of trials at different sites in Queensland (Keating *et al.*, 1999). Simulations of N loss were performed for a variety of soil-climate conditions representative of different sugarcane growing areas in Queensland. Historical climate data were from the SILO climate data archive (Jeffrey *et al.*, 2001).

Review of experimental findings

Evaluation in Australian sugarcane

Early enhanced efficiency fertiliser trials in sugarcane focussed on reducing ammonia volatilisation (Prammanee, 1991; Obcemea, 1994), which had been found to cause considerable N losses from surface applied urea in trash blanketed systems (Denmead *et al.*, 1990; Wood *et al.*, 1990; Freney *et al.*, 1994).

While some successes were noted (see Verburg *et al.*, 2014 for details) a change in industry practice to subsurface application from the mid-1990s onwards reduced ammonia volatilisation losses dramatically without the need for different fertiliser forms. Two SRDC funded trials carried out around this time (Myers and Vallis, 1994; Randall *et al.*, n.d.) found no yield benefits from controlled release fertilisers and nitrification inhibitors, dampening the enthusiasm for research into enhanced efficiency fertilisers for about a decade.

In the mid-2000s concerns over N losses (to the Great Barrier Reef Lagoon or as nitrous oxide emissions) prompted a renewed interest in enhanced efficiency fertilisers, encouraged by reviews by Chen *et al.* (2008) and Wood *et al.* (2010). Published trials include agronomic N efficiency trials by Di Bella *et al.* (2013, 2014) and experiments measuring impacts of enhanced efficiency fertilisers on nitrous oxide emissions by Wang *et al.* (2008, 2012, 2014). Details of these and other trials are included in Verburg *et al.* (2014). Some trials showed encouraging, statistically significant benefits from enhanced efficiency fertilisers (e.g. a reduction in N₂O emission in a trial by Wang *et al.* (2012) and increased cane yields for the same N rate in trials by Di Bella *et al.* (2013; paired sites, across N rates), Di Bella *et al.* (2014; paired sites, at highest two N rates) and Dowie (2013a; highest N rate)).

Other trials did not achieve statistically significant differences, especially where yield benefits were concerned. A number of these trials (e.g. intermediate N rate of Dowie (2013a); Salter *et al.* (2013); some of the blended trials of Farmacist (2013); and some treatments of Wang *et al.* (2014)) did show increased yields for controlled release fertiliser and/or nitrification inhibitor coated fertiliser compared with urea applied at the same rate, but the results were not statistically significant at the 95% confidence level tested. This was also true for a number of trials reported on-line since the review (Deambrosis, 2014; Dowie, 2014; Farmacist, 2014). A pooled analysis (two-way ANOVA site x treatment; Charlie Walker pers. comm.) of normalised data (relative to urea treatments) from seven trials that themselves did not show statistically significant treatment effects did result in statistically significant ($p < 0.05$) predicted average increases in cane and sugar yields (IPF, 2014). Several other trials are currently underway, including one that is systematically testing products across soil types, application time, N rate and (hopefully) a variety of seasonal conditions (J Dowie pers. comm.).

As the measurements were often limited to harvest yield and CCS, the reasons for the lack of statistically significant effects could not be explored. In some trials lack of N response was observed and a number of trials received below average rainfall or experienced relatively dry periods after fertilisation. This may have reduced N loss and hence the potential for the enhanced efficiency fertiliser products to show a difference. 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.

A number of trials with controlled release fertilisers used blends with conventional urea. While blends reduce the cost and ensure early N supply, they may also be less effective in reducing N loss due to rapid availability of the urea component.

Some trials have compared urea applications at standard rates with applications of enhanced efficiency fertilisers at lower rates, representing a likely scenario for the use of these fertilisers. Results that show enhanced efficiency fertiliser at the lower rate achieve the same yield as urea at the standard 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 at the same (lower) N rate need to be demonstrated.

Evaluation elsewhere

In sugarcane internationally, controlled release fertilisers are popular on sandy soils (>97% sand and <2% organic matter) in Florida, USA, due to the poor water and nutrient retention capacities of these soils and their potential to leach N to ground water. Published results for sugarcane appear limited to a conference abstract (Morgan, 2007), but suggested positive results.

Controlled release fertilisers have been trialled in a range of other industries, nationally and internationally. In a few industries controlled release fertilisers are widely adopted (lawns, golf courses, fruit trees and vegetables; Shaviv, 2001), suggesting (more) consistent benefits. In other industries, adoption is low and the trials (of which an increasing number are published) have demonstrated mixed results. This conclusion is highlighted by papers in a recent special issue of the *Agronomy Journal* (Vol 106, Issue 2, Mar-Apr 2014).

The difficulty with many of these international trials, as with Australian sugarcane trials, was that the studies usually contained too few supporting measurements (e.g. soil N, fertiliser N release) to explain the results, whether these were positive or negative. This makes it difficult to draw general conclusions about the effectiveness of enhanced efficiency fertilisers.

A number of meta-analyses have attempted to identify patterns across multiple studies (Akiyama *et al.*, 2010; Halverson *et al.*, 2014; Abalos *et al.*, 2014). The positive 'overall' effects seen in these studies across the various environments, systems, and products are encouraging and provide a balance to the mixed results mentioned above.

Meta analyses can have some drawbacks (see Verburg *et al.* (2014) for a discussion), including that one needs to watch for publication bias (lower rate of publication of trials with no response) and an even representation of environments if one tries to identify cropping systems, soils and climates with larger or smaller treatment effects.

Some observations that can be made on the basis of the collected evidence include:

- Positive responses to the use of enhanced efficiency fertilisers are more commonly obtained in environments that are conducive to N loss, e.g. high rainfall environments, especially when concentrated in a short season or large events, coarse textured soils (N leaching) or soils that are waterlogged for a considerable period (N denitrification).
- Understanding the key drivers for N loss, as well as pathways and timing of N loss is important. Potential benefits of enhanced efficiency fertilisers are maximised where the in-season N losses are significant and beyond control of the grower (Hartz and Smith, 2009), e.g. N losses from large rainfall events and/or inability to delay N application.
- Reduction of N loss via one pathway may increase that of another (Venterea *et al.*, 2012; Prammanee, 1991). This needs to be kept in mind when interpreting trial results that measure only one loss pathway.
- Initial effectiveness in reduction of N loss can often be demonstrated for the period immediately following application, but rainfall patterns during the rest of the season determine overall efficacy (Hatfield and Venterea, 2014).
- Reductions in N loss will not necessarily translate into yield benefits. A response to the improved N supply is a necessity (further discussed below).
- The limited data on N release and sugarcane N uptake patterns suggest that the synchrony could be improved.
- Field trials should ideally compare multiple products, comprise of multiple N rates to test N response, include an assessment of N release time and an understanding of loss pathways. The number of replicates needs to be high to capture field variability.

Characterising N loss

Nitrogen can be lost from the cropping system to the environment via leaching beyond the root zone, in runoff water and as gaseous losses. Additionally, N is lost from the system in harvested products and when residue is removed or burnt. The focus of reductions in N losses here is on leaching, runoff and denitrification.

Measuring these N losses is challenging and most studies focus on just one or two of the pathways. As season-to-season variability is large, modelling approaches have been employed to

extrapolate from experimental data and to explore simulation ‘scenarios’ to increase our understanding (Verburg *et al.*, 1998; Stewart *et al.*, 2006; Thorburn *et al.*, 2010, 2011; Biggs *et al.*, 2013). Nitrogen loss magnitude and timing influences the potential benefits from enhanced efficiency fertilisers. SRA project 2014/011 is, therefore, characterising the magnitude and pathways of N loss from sugarcane systems as a function of climate, soil and management.

Preliminary simulated results highlight the different distributions of the three pathways (Figure 1), which is strongly affected by soil type. For example, in coarse textured soils, leaching dominates (e.g. TU-03), in fine textured soils denitrification becomes more important (e.g. TU-02) or even dominates (e.g. MK-02 BH-02). Further work is underway to characterise the timing of these N losses.

Simulated average annual total N loss was not as variable as one might expect considering the variation in annual rainfall and/or irrigation input and soil type. While in short-term, single season assessments these factors do drive the magnitude of losses, over the long-term N losses are related to N removed from the system in harvested products or burning of residue relative to the amount of N fertiliser applied (Thorburn and Wilkinson, 2013).

Any excess N not taken up by the crop and not lost one season, will carry-over into the subsequent season and be liable to loss another season (Verburg *et al.*, 1998), unless fertiliser rates are adjusted for available soil N. A corollary of this finding is that enhanced efficiency fertilisers will only reduce N loss to leaching, runoff or denitrification in the long run, if the ‘saved’ N is taken up by the crop. Correctly estimating N demand is hence still important.

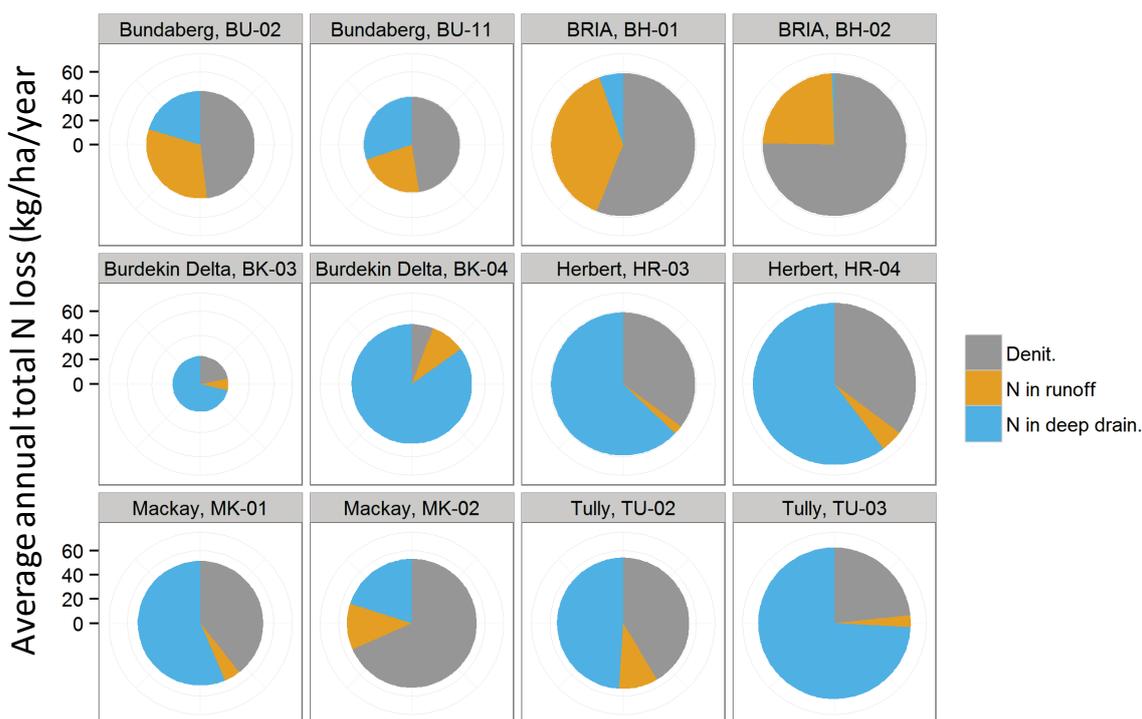


Fig. 1—Simulated (60–80 years) average annual total N loss (magnitude of circles) and proportion of loss pathways from sugarcane systems in six locations for contrasting soil types. Simulations were for a fixed cropping cycle consisting of a fallow, plant crop and three to four ratoons. Management of surface residues, tillage, irrigation and fallows were based on typical practices in each region.

Understanding N demand

Datasets quantifying N uptake patterns of sugarcane are sparse. A number of time-series measurements of above-ground biomass and biomass N were taken in the early 1990s and used in the Keating *et al.* (1999) paper to parameterise and test the APSIM-Sugar model.

The data came from several experiments in various locations from northern NSW to Ingham, Qld. While these data provide an initial feel for N uptake patterns, they come from short-term experiments carried out under specific conditions.

To explore the seasonal variability in uptake patterns, these individual experiments were extended using modelling and historical climate data (Zhao and Verburg, 2015). The simulations (virtually replicated ‘trials’) showed distinct sigmoidal N accumulation curves which exhibited little range over the first part of the uptake curve (Figure 2), i.e. not affected too much by season-to-season climate differences. Time of planting effects and early N demand of roots in ratoon crops are subjects of further investigation and validation.

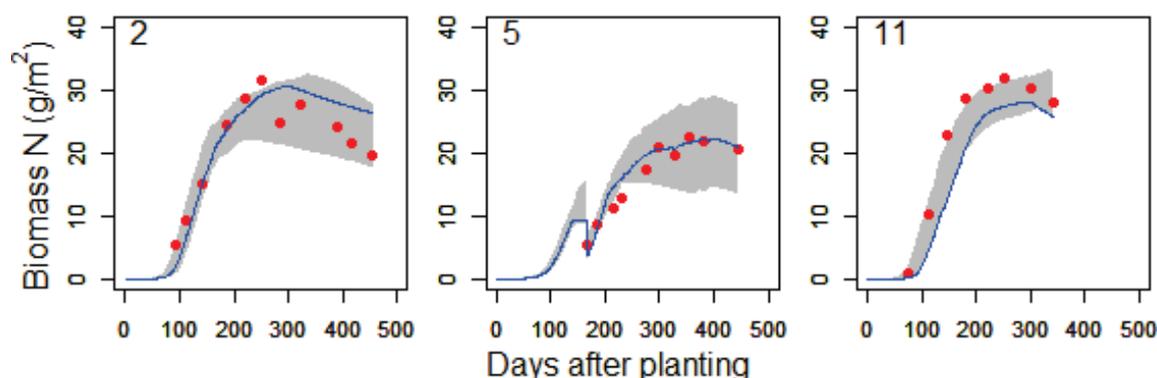


Fig. 2—Simulated ranges (grey bands) of above-ground biomass N accumulation over 56 seasons (1958 – 2013) for three plant crops from Ingham (data set 2), Ayr (set 5) and Grafton (set 11) along with the original data (red symbols) and general rule-based (blue) simulations of the original experiments. Crop at Ayr was subject to hilling up. (Adapted from Zhao *et al.*, 2015).

Characterising N release from controlled release fertilisers

To maximise effectiveness of controlled release fertilisers (and avoid negative impacts) fertiliser release must precede N uptake, but be synchronised as closely as possible. Information provided with products usually only describes the release time, not the release pattern. The review identified a lack of data specific to Australian sugarcane systems. Data on release patterns collected world-wide for a wide range of products showed a variety of release patterns (Verburg *et al.*, 2014).

Many of these release patterns were obtained under laboratory conditions that bear little resemblance to field conditions, e.g. in water and at constant temperature. Depending on the type of coating this may or may not be a good approximation. In order to predict the release under variable (temperature and soil water) conditions we need to understand and quantify the effect of these factors.

SRA project 2014/011 is currently determining release patterns and quantifying temperature and soil moisture effects for a range of products that are currently used in sugarcane or could suit the sugarcane environment given their release period. Characterisations of the coatings (composition and breakdown) are also performed to provide an understanding of the release characteristics and allow them to be captured in a model. This would allow an investigation of the seasonal variability in release and effects of time of application in response to changing soil temperature and soil water.

Preliminary data for seven controlled release products have shown that N release patterns vary considerably and can broadly be grouped into three types: those that start releasing N on day 1 and initially release N rapidly, those with a short lag period (< 1 week) before release starts and those having a long lag period that results in the release being more sigmoidal. Comparison with the biomass N accumulation patterns of Figure 2 suggests that the latter release patterns are needed to

provide better synchrony with N uptake patterns. Temperature affected release, but the response varied between products.

Variability in release was explored using modelling for a hypothetical product parameterised based on published data under the assumption that release was affected by temperature but not by soil water or other factors. Season-to-season variation in response to temperature effects was predicted to be small, but time of application did affect the rate of release due to seasonal changes in temperature (Figure 3). The effect of dry spells is still being explored in the laboratory, but if affecting release it could be important in some systems/locations and likely contribute to more variability.

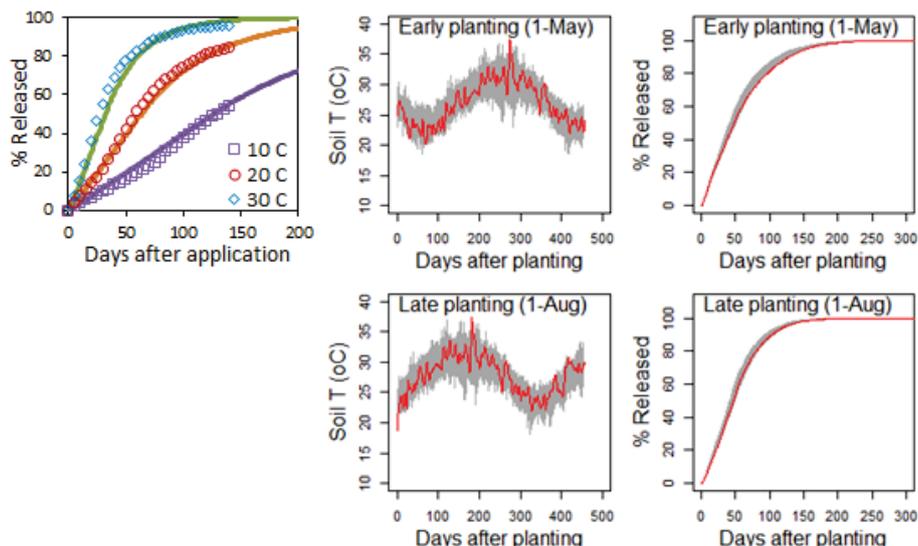


Fig. 3—Top left: Parameterisation of controlled release model to laboratory release data at fixed temperatures (ESN 43% 120-day product; Ellison, 2012). Middle and right: Simulated soil temperature and cumulative N release for the same product during 56 plant crop seasons (grey) of Ingham weather (2012 season in red) on the assumption that release was only affected by temperature.

Possible reasons for lack of treatment effects in field trials

As noted above, a number of the published sugarcane trials failed to demonstrate statistically significant cane or sugar yield effects from application of controlled release fertiliser (Verburg *et al.*, 2014). Anecdotal evidence suggests the results from unpublished studies are similarly mixed. What are the possible reasons for lack of response?

To answer this question we need to consider what is required for the crop to respond differently to the controlled release N fertiliser compared with conventional urea. The slower release of N from controlled release fertilisers is designed to keep the soil N concentration low and reduce the magnitude of any N loss occurring during the release period. The reduction of N loss would ensure that more N is available to the crop. However, this will only turn into a yield benefit if the crop needs this 'saved' N and can use it to increase yield. In other words, a yield response to controlled release fertiliser requires not only a reduction in N loss, but also a yield response to the extra N available.

Absence of a yield response to enhanced efficiency fertilisers could be due to several reasons, some of which could act together:

Lack of reduction in N loss

- N loss absent or small, e.g. due to a relatively dry season
- N loss occurring after the release period of controlled release fertilisers
- Leaching event insufficiently large to leach N beyond the crop rooting depth

- Poor synchrony of release with crop N uptake (too fast) leading to higher soil N concentrations and N loss later compensating for any earlier savings.

Lack of N response

- Total N supply from fertiliser and soil greater than N demand. This could be due to:
 - Initial soil N being high (mainly an issue for plant crops)
 - Soil N supply from mineralisation is high
 - Reduced yield potential due to other factors (e.g. soil water deficit, water logging, low radiation) reducing N demand.
- Yield reductions negating any potential or achieved benefits (e.g. lodging, disease)
- Potential benefits from any extra N (over the season) off-set by yield reductions if release is not sufficiently synchronised (too slow) leading to e.g. early vigour problems, insufficient N release during peak uptake period, or reduction of CCS.

Additionally, spatial variability in cane yields could result in low precision of observed yields, resulting in relatively large differences being required for statistical significance.

The N responsiveness of a system can be established through inclusion of several N rates in the experimental trial design to generate an N response curve. Model simulations of N response in sugarcane systems in which N supply was slowed either through the use of multiple split applications (Verburg *et al.*, 1998, 2014) or by mimicking the release from controlled release fertiliser products (Verburg *et al.*, 2013; Figure 4) have shown that yield benefits are limited to increasing yields that are on the slope of the N response curve and will not raise the yield plateau itself. However, on occasion, the N losses are so high that the yield plateau is not reached until very high N rates (1978 in the example of Figure 4) and controlled release fertiliser improves yields across the board.

Figure 4 does illustrate that the N rate at which this yield plateau is reached is reduced by the use of controlled release fertiliser. The magnitude of the shift is linked to the reduction in N loss achieved and can vary considerably from year to year. Testing the concept of achieving the same yield with a lower rate of enhanced efficiency fertiliser has been the focus of some of the experimental trials in sugarcane. To correctly interpret the results from these trials they need to be accompanied by N response experiments to determine whether the outcome of a similar yield at a lower N rate could indeed be ascribed to reduction of N loss and use of the 'saved N' or is due to being on the yield plateau of the N response curve in which case a reduced rate of urea may have had the same effect.

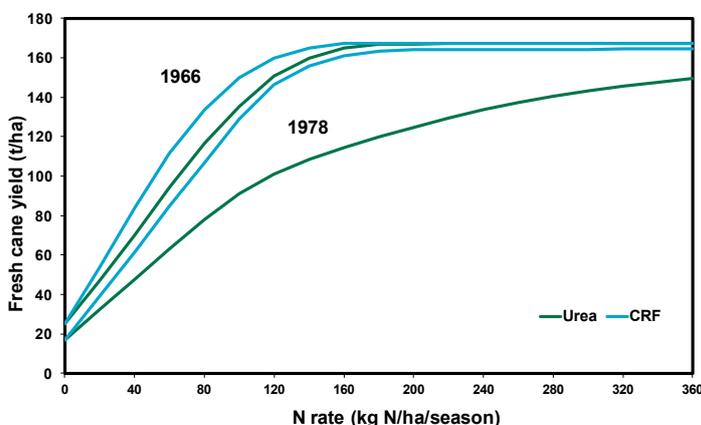


Fig. 4—Preliminary, exploratory simulations of cane yield response to different rates of urea and of a hypothetical controlled release fertiliser product for two individual seasons of Innisfail weather applied to the soil properties of a deep well-drained Red Kandosol soil from Bundaberg.

Conclusions

While there has been a considerable increase in trialling of controlled release fertilisers, both in sugarcane and other crops, questions remain about the magnitude and consistency of benefits in time and space, especially in relation to improving yield. Field trials alone will not be able to answer these questions. They need to be accompanied by an understanding of the release patterns, crop N demand patterns and timing of key N loss periods. Modelling can assist in interpreting and extending experimental results.

The preliminary results presented here already provide an indication of N uptake patterns and their seasonal variability which may inform required N release patterns and of relative magnitude of N loss pathways in response to soil type. The results also suggest that the use of controlled release fertiliser will not increase the yield plateau of an N response curve, but it may raise yields where the crop is N limited and as a consequence lower the N rate at which the yield plateau is reached.

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