WHY BENEFITS FROM CONTROLLED RELEASE FERTILISERS CAN BE LOWER THAN EXPECTED ON SOME SOILS

By

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Abstract

CONTROLLED RELEASE FERTILISERS (CRFs) have received increased interest by the Australian sugarcane industry as part of efforts to evaluate the use of enhanced efficiency fertilisers to reduce nitrogen (N) losses and improve N use efficiency. Experimental results and simulations, here and abroad, have shown that benefits from CRFs are dependent on soil and management conditions and are highly seasonally variable. Understanding the causes of this variability may better define where and when benefits can be expected from the use of CRFs. Here we use simulation analysis to quantify and explain the effects of soil type on agronomic and environmental benefits from CRF use for a case study in Tully, Queensland. The simulation results indicate that CRFs can reduce N loss via both denitrification and deep drainage (leaching). The reduced N losses do, however, not always translate into agronomic benefits, these being an increase in yield and/or a decrease in the optimal rate of N. Agronomic benefits are dependent on the inherent N responsiveness of the system and the seasonal yield potential. For example, on some soils the conditions that give rise to large N losses (e.g. prolonged waterlogging) can also limit crop growth and yield potential. As a consequence the agronomic benefits from CRF may not always be realized on these soils and even some of the environmental benefits may be transient.

Introduction

Controlled release fertilisers (CRFs) are promoted as a means to reduce nitrogen (N) losses and allow lower N fertiliser application rates in sugarcane production systems. Experimental trials evaluating their use, both in Australia and abroad, have shown benefits of variable magnitude (Chen *et al*., 2008; Verburg *et al*., 2014; 2016). This variability has been attributed to CRF effectiveness being affected by a complex set of interacting soil, crop, climate and management factors (Chen *et al.,* 2008; Verburg *et al*., 2014).

While numerous field trials, meta-analyses and pot-trials have been carried out and continue to be undertaken, that complexity has not yet been unraveled. The general expectation is, however, that positive responses to the use of CRF are more commonly obtained in environments that are conducive to N loss (Verburg *et al.*, 2016). For example, combinations of high rainfall with coarse textured soils (N leaching) or soils that remain waterlogged for a considerable period (denitrification). It raises the question whether CRF effectiveness is affected by N loss pathway.

Using simulation analysis, Verburg *et al*. (2017a) studied the agronomic and environmental benefits for a case study of a rainfed sugarcane system in Tully, Queensland. The use of CRF increased yield at lower N rates, but did not increase the maximum yield, except in a small percentage of years. Agronomic benefits from CRF use mainly came about from reductions in agronomic optimum N rate (Nopt), which was defined as the amount of N required to reach 95% of maximum yield. The magnitude of these reductions in Nopt were, however, highly seasonally variable.

Repeating the analysis for a variety of other combinations of soil, climate and irrigation management, Verburg *et al.* (2017b) found the magnitude and seasonal variability of benefits to vary considerably between these scenarios, including between two Tully soils. In order to better define where and when benefits can be expected we need to gain an understanding of the causes of this variability.

Unlike experimental trials, simulations allow us to go back and study more closely the fertiliser, soil, crop and weather interactions during the simulations, on a day by day basis if needed. By monitoring different system variables over time we can gain an understanding of the system's dynamics that may be responsible for benefits or preventing these from being realised.

This paper presents a simulation analysis that explores in more detail the question whether and how soil type affects agronomic and environmental benefits from CRFs. It builds on the analysis of Verburg *et al*. (2017a) and focusses on a rainfed sugarcane system experiencing the wet climate of Tully, Queensland. The two soils that are compared are common in the area, but have different properties that affect both N loss pathway and crop performance.

Methodology

The simulation analysis was carried out using the APSIM-Sugar model (Keating *et al*., 1999; Thorburn *et al*., 2005; Holzworth *et al*., 2014) using historical climate data from Tully Sugar Mill (station 032042, 1902–2015; obtained from SILO Point Patch Data; Jeffrey *et al*., 2001) and two local soils from the Tully region: a granitic colluvial fan soil classified as Yellow Dermosol or Thorpe series (Cannon *et al*., 1992) and an alluvial clay soil classified as a Brown Dermosol or Coom series (Cannon *et al*., 1992). The parameterisation of these soils has previously been used and verified by Thorburn *et al*. (2011). That of the Coom soil was also used by Verburg *et al*. (2017a).

The simulated scenarios represented a rainfed cropping system with a fixed, six year cycle that consisted of a 15 month plant crop, three 12 month ratoon crops, a 13.5 month fourth ratoon and a 7.5 month bare fallow. In reality the length of ratoon seasons will vary within a cycle and the fallow is probably a little shorter, but this design allowed for consistent comparison of different ratoons as well as early and late scenarios.

These were achieved by planting either on 1 May (early plant) or 1 August (late plant) and for the plant and first three ratoon crops harvesting on 1 August (early ratoon) or 1 November (late ratoon) respectively. The last ratoon (fourth) was harvested in mid-September.

The model captures soil water and N dynamics, residue decomposition, crop growth and N uptake, including responses to environmental conditions (solar radiation, temperature, water and N stress), and management actions such as planting, ratooning, irrigation and N fertilisation. In the case of water-logging, the proportion of the root system exposed to soil water conditions at saturation or near saturation was calculated and used to calculate a water logging stress factor, based on work by Biggs *et al.* (2013).

This factor reduced photosynthetic activity via a temporary effect on radiation use efficiency. The rule for radiation use efficiency reductions following lodging used by Verburg *et al.* (2017a), which was dependent on rainfall size, soil wetness and crop size, was found to create unrealistic treatment differences at times. It was replaced by a rule based on leaf number ensuring, as before, simulation of district yield levels.

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

Full N response curves were simulated by modelling scenarios with different N application rates (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 a 'linear release' CRF product that exhibited linear release until 50% of the N was released and first order declining release thereafter

The linear release product was parameterised based on literature data for the 'Meister10' product (Trenkel, 2010) and had a release period similar to some of the products used in experimental trials in sugarcane. The release responded to temperature with a Q_{10} = 2.5 (rate increase of 2.5 times for a 10 °C increase in temperature). It was assumed soil moisture did not affect the release rate.

Soil water and mineral N levels were re-set at every harvest to ensure that the effectiveness of different fertiliser products could be evaluated in individual years without being confounded by carry-over effects. For each scenario six parallel runs were started in 1902 through to 1907 to ensure each phase of the cropping cycle was represented in each year. Data from 1914 to 2015 were used in the analyses. Because benefits from CRF in plant crops were shown to be small (Verburg *et al.* 2017a) and the model did not simulate significant differences between ratoon crops, we only report on the results for the first ratoon crop seasons (early and late ratoons grown on two soils).

Simulated yield N response data were fitted using the Weibull model. Due to the close spacing of N rates near the inflection point, the Weibull model provided good fits of the data, and was found to be one of the better models, in particular in the region of the inflection point. The fitted functions were used to calculate an agronomic 'optimum' fertiliser N rate, Nopt, for each response curve. It was defined as 95% of the maximum yield.

As the Weibull function is an asymptotic model, Nopt could not be defined as the N rate at which the slope of the response curve becomes zero. For practical purposes 95% of maximum yield is often chosen as Nopt (e.g. Schroeder *et al*., 2014), although often in conjunction with other fitting functions. A local smoothing function (Locally Weighted Scatterplot Smoothing) was fitted to the N loss N response curves. This model was then used to predict the amount of N lost at Nopt.

Examples of simulated N response are shown in Figure 1. The 1998 season shown was relatively wet, which limited yield on the Coom soil. Simulated yields were reflective of historical district yield levels (Verburg *et al*., 2017a).

With a similar model set-up cane yields from an experiment on the Coom soil were also well simulated (Thorburn *et al.*, 2018). The Weibull model successfully fitted the N response despite the response curve shape varying in response to the conditions of the scenario (management, soil) and season.

Comparing Nopt of the response curves for urea and CRF use provided a good reflection of agronomic benefits, except where the maximum yield using CRF was increased by more than 2–3 t/ha above that obtained with urea. This situation could result in an increase in Nopt if the N response was flat.

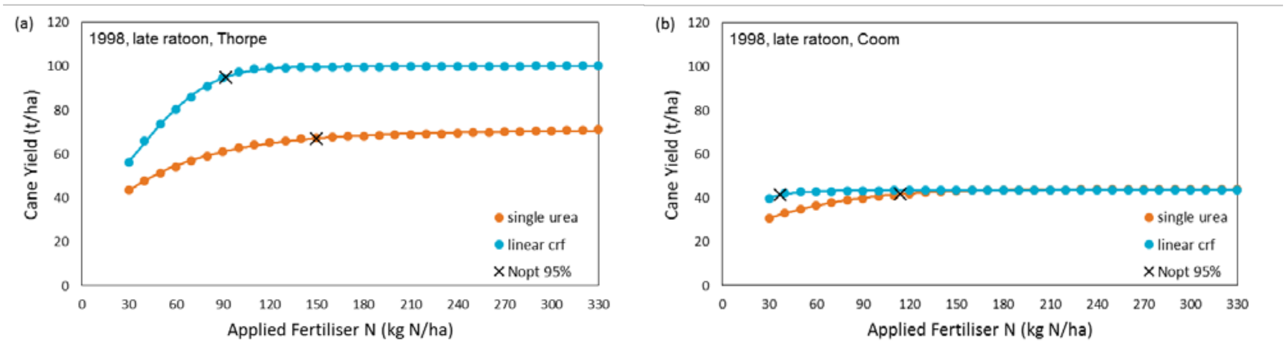

Fig. 1—Simulated N response curves for yield from a single urea application (orange symbols) or linear CRF (blue symbols) in a late first ratoon crop grown on (a) Thorpe and (b) Coom soil and harvested in 1998. The agronomic Nopt for each fitted response curve is indicated by a X.

Results

Yield benefits

In the simulations, increases in maximum (plateau) yield from CRF use were limited in both magnitude and frequency (Table 1 and Figure 2), except for late ratoons on the Thorpe soil. In that scenario the average maximum yield increased by 3 t/ha with increases of more than 3 t/ha experienced in 25% of seasons (including 1998 shown in Figure 1) and a maximum increase of 36 t/ha. In the other scenarios the average maximum yield increased by 1 t/ha or less, increases of more than 3 t/ha were obtained in less than 4% of years and were at most 7 t/ha.

Benefits from reduction in optimum N rate

Both Nopt and the reductions in Nopt due to CRF use were seasonally variable, as previously noted by Verburg *et al*. (2017a). Use of CRF on the Thorpe soil reduced the average Nopt and variability in Nopt considerably (see Table 1, Figure 3).

Reductions of more than 40 kg N/ha were achieved in 17% and 41% of early and late first ratoon seasons, respectively. Use of CRF on the Coom soil also reduced Nopt in many seasons, but the effect was not as marked, in part as the level and variability in Nopt was already much lower (Table 1, Figure 3).

Table 1—Simulated average (standard deviation) maximum yield, Nopt and total seasonal N loss at Nopt for single urea or CRF use on early or late first ratoons grown on Thorpe or Coom soil.

	Thorpe				Coom			
	Early		Late		Early		Late	
	Urea	CRF	Urea	CRF	Urea	CRF	Urea	CRF
Max. yield (t/ha)	99 (18)	100 (17)	104 (19)	107 (18)	72 (20)	72 (20)	64 (21)	64 (21)
Nopt (kg N/ha)	126 (45)	100 (24)	134 (42)	88 (14)	109 (32)	(96) 28	80 (31)	60 (20)
N loss (kg N/ha)	24 (40)	3 (4)	56 (52)	8 (13)	17 (17)	5 (5)	36 (32)	14 (23)

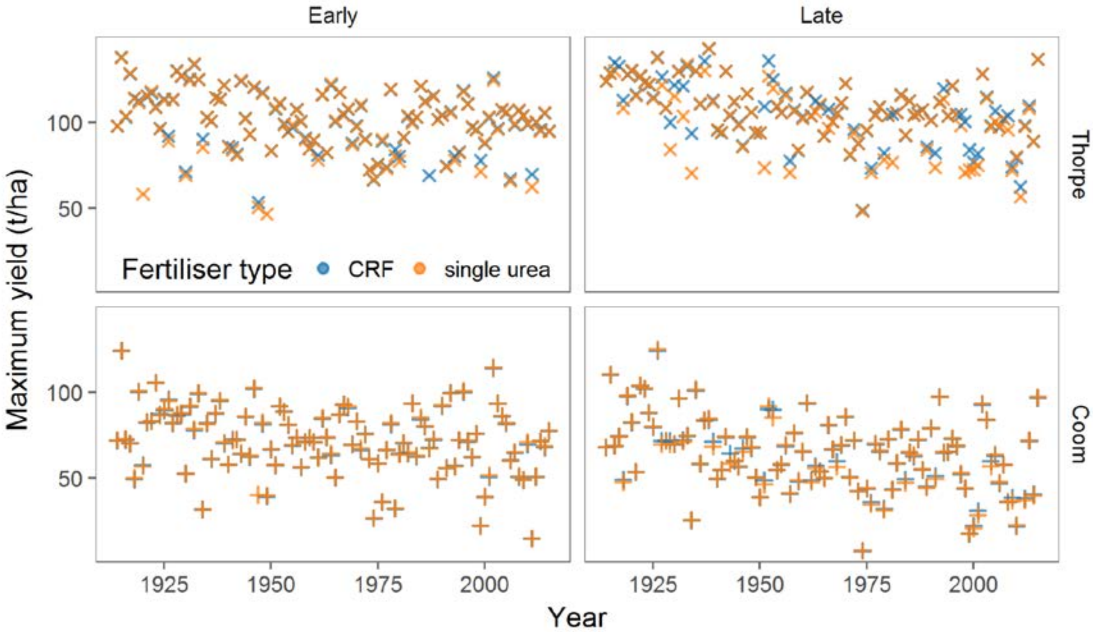

Fig. 2—Simulated maximum yield from 1914 to 2015 for early and late ratoons grown on Thorpe soil (x) and on Coom soil (+) using a single urea application (orange symbols) or linear CRF (blue symbols); note brown are overlapping symbols.

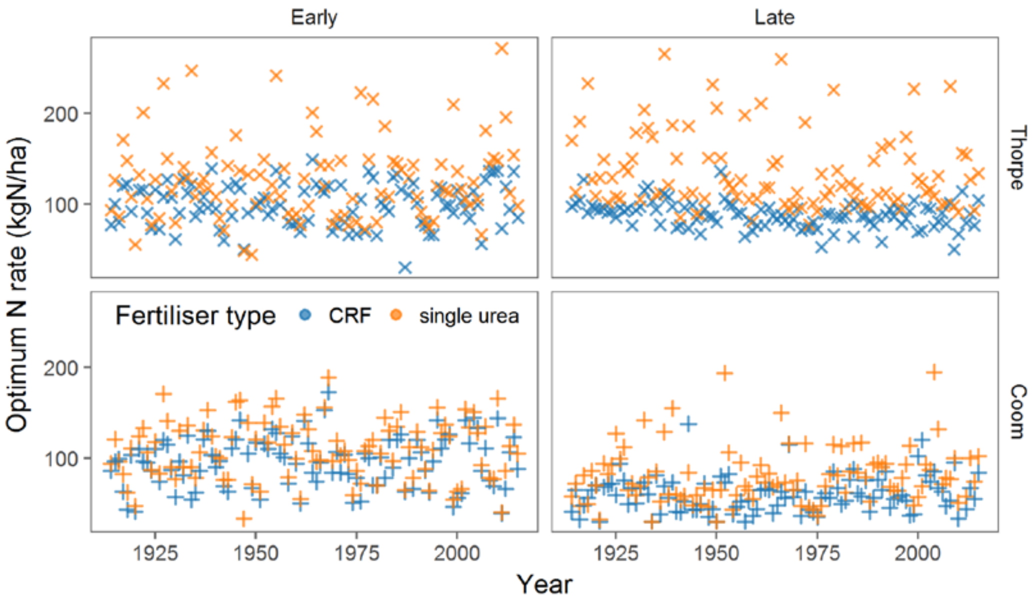

Fig. 3—Simulated reductions in Nopt from 1914 to 2015 for early and late ratoons grown on Thorpe soil (x) and on Coom soil (+) using a single urea application (orange symbols) or linear CRF (blue symbols).

N loss reduction benefits

Simulated N losses increased with N rate, but were generally lower when CRF was used (see example in Figure 4 for a season with relatively high N loss

To compare N loss and N loss reduction benefits across seasons and scenarios (soil, management) the benefits were expressed as the reduction in N loss at Nopt for the given scenario (Figures 5 and 6).

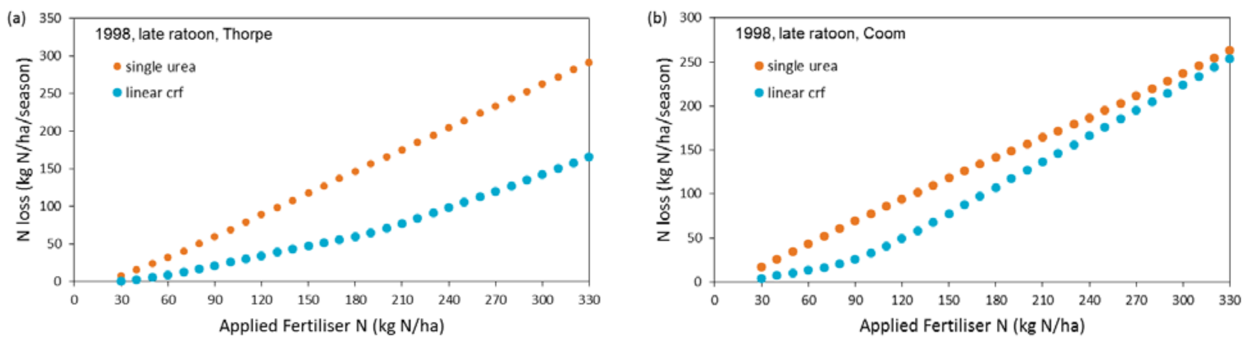

Fig. 4—Simulated N response curves for total N loss from a single urea application (orange symbols) or linear CRF (blue symbols) in a late first ratoon crop grown on (a) Thorpe and (b) Coom soil and harvested in 1998.

On the Thorpe soil N loss was dominated by leaching, with leaching considerably lower in the early ratoon scenario than the late ratoon scenario (Figure 5). On the Coom soil more N was lost via denitrification, especially in the early ratoon scenario, although considerable leaching losses were also experienced in the late ratoon scenario (Figure 6).

Simulated loss of N in surface runoff was small relative to the other two loss pathways for both soils. The use of CRF was effective at reducing N loss for the Thorpe soil, with both the average N loss at Nopt and its variability reduced considerably (Table 1).

On the Coom soil the use of CRF did reduce the level of N loss, but in the late scenario the losses remained quite variable (Table 1).

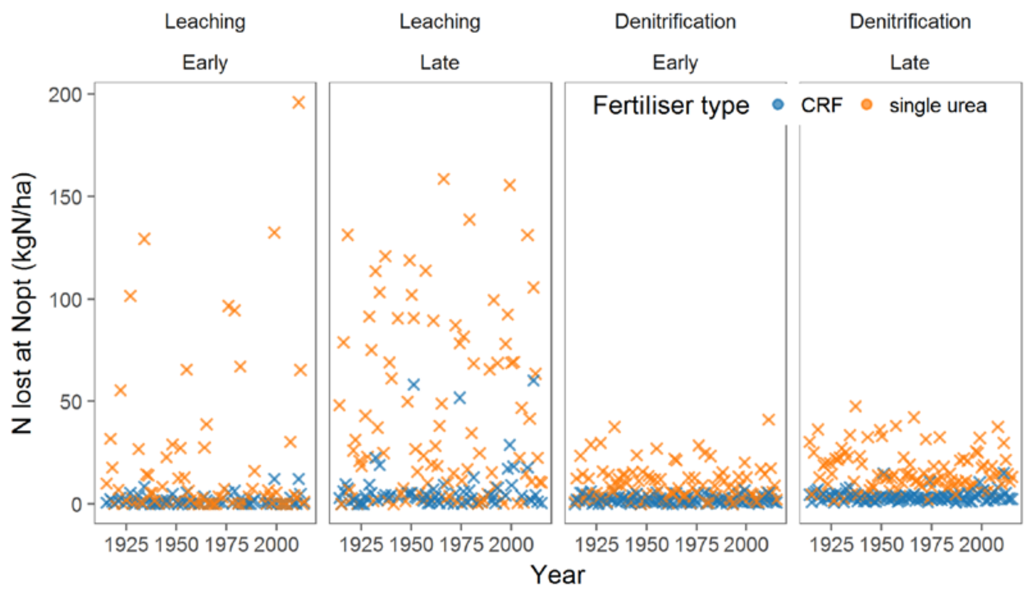

Fig. 5—Simulated reductions in N loss at Nopt from 1914 to 2015 for N loss via leaching or denitrification for early and late first ratoons grown on Thorpe soil; orange = single urea, blue = CRF.

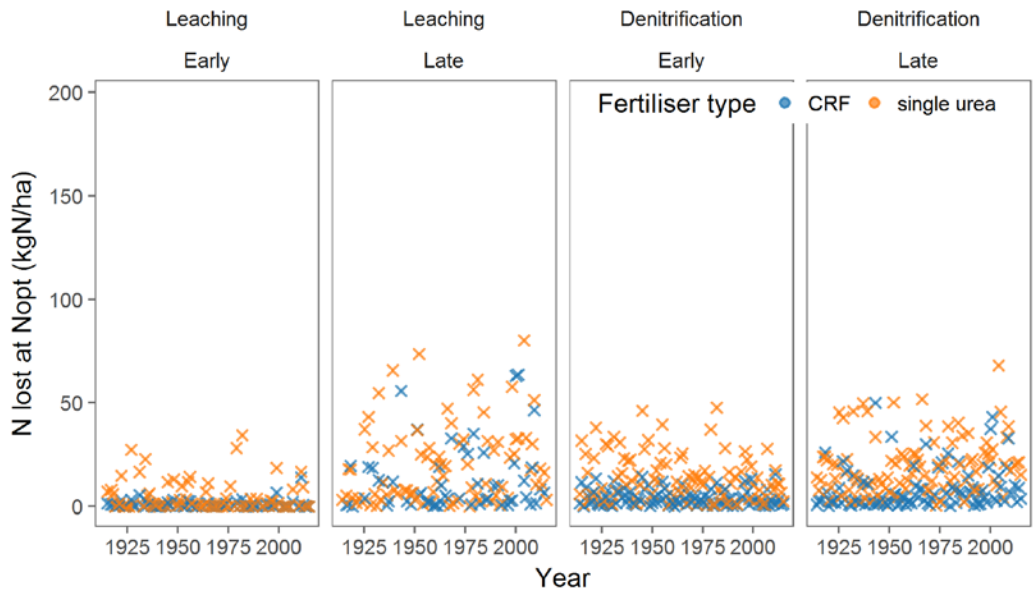

Fig. 6—Simulated reductions in N loss at Nopt from 1914 to 2015 for N loss via leaching or denitrification for early and late first ratoons grown on Coom soil; orange = single urea, blue = CRF.

Discussion

Differences in simulated benefits between the two soils

The simulation results clearly indicate that benefits from CRF are larger and more likely obtained on the permeable, coarser textured Thorpe soil compared with the poorly drained alluvial Coom soil.

Both the reductions in N loss and in optimum N rate were larger for the Thorpe soil than the Coom soil, albeit helped by the fact that the N losses and optimum N rates were larger in the first place. In addition, late ratoon crops on the Thorpe soil could achieve increases in maximum yield of more than 3 t/ha in 25% of seasons, whereas this was not the case for crops grown on the Coom soil.

In experimental field trials soil differences have not been as pronounced. This is likely influenced by the fact that it has often proven difficult to obtain statistically significant treatment effects (Verburg *et al.*, 2016). Di Bella *et al*. (2013; 2014) obtained similar cane yield increases from CRF use on both clay and solodic soils in their trials in the Herbert catchment harvested in 2012 and 2013.

Enhanced efficiency fertiliser (EEF) trials in the Burdekin as part of project Catalyst, which specifically included soil type as a factor, have not found any effects either (2015 and 2016 harvests; Dowie *et al.,* 2018). Further trials comparing soil types are currently underway.

Internationally, a meta-analysis by Akiyama *et al*. (2010) of experimental field results on the effect of EEF on N_2O emissions found that CRFs were most effective on imperfectly drained Gleysol grasslands and least effective on well-drained Andosol 'upland fields'.

In another meta-analysis focused on yield and N use efficiency effects, larger responses were obtained in coarse-textured soils (Abalos *et al*., 2014). Neither study was in a position to explain the effects.

Dynamics responsible for benefits – Thorpe soil

As indicated in the Introduction, the simulations can be used to explore the system's responses to CRF in more detail by looking at system variables over time.

This provides us with a better understanding of how benefits develop in response to the seasonal conditions. For example, by following how N is released, when N is lost to deep drainage (leaching) or denitrification following rainfall or is taken up by the crop.

As well as monitoring the various stresses that affect crop growth (oxygen deficit stress from saturated soil or stresses from insufficient N or water).

For the 1998 late ratoon season on the Thorpe soil, we see what one could call a 'classic response' to CRF. The CRF releases the N more slowly (Figure 7a).

In response the soil nitrate content increases more slowly (Figure 7b), which means that less N is lost with the large rainfall event between 57 and 77 days, both for denitrification (Figure 7c) and N loss in deep drainage (Figure 7d).

As the nitrate continues to be released after this event in the CRF treatment, this increases nitrate content slightly above that of the urea treatment (Figure 7b).

The reduced losses mean that the crop can take up more N (Figure 7e) and experience less N stress (Figure 7f). As water stress and oxygen deficit stresses are similar for the CRF and urea treatments (Figure 7g and Figure 7h), biomass increases more quickly in the CRF treatment (Figure 7i) with an increased cane yield as a consequence (Figure 7j).

As the 100 kg N/ha rate used in this simulation was below the Nopt, there is still some N stress and yield is below the maximum possible yield (cf. Figure 1).

Dynamics responsible for benefits – Coom soil

For the 1998 late ratoon season on the Coom soil the response is similar, including the reduction in N loss with the large rainfall event between 57 and 77 days (denitrification Figure 8c; N loss in deep drainage Figure 8d).

Compared with the Thorpe soil, the N uptake increases slightly later (*cf*. Figure 8e and Figure 7e) due to more oxygen deficit stress in this poorly drained soil (*cf*. Figure 8h and Figure 7h).

As a consequence soil nitrate content after the rain increases more strongly (Figure 8b) causing some continued N loss in the CRF treatment following smaller subsequent rainfall events (Figure 8c and Figure 8d). The reduced losses do mean that the crop can take up more N (Figure 8e) and experience less N stress (Figure 8f). As water and oxygen deficit stresses are similar for the CRF and urea treatments (Figure 8g and Figure 8h), biomass increases more quickly in the CRF treatment (Figure 8i) with a slightly increased cane yield as a consequence (Figure 8j).

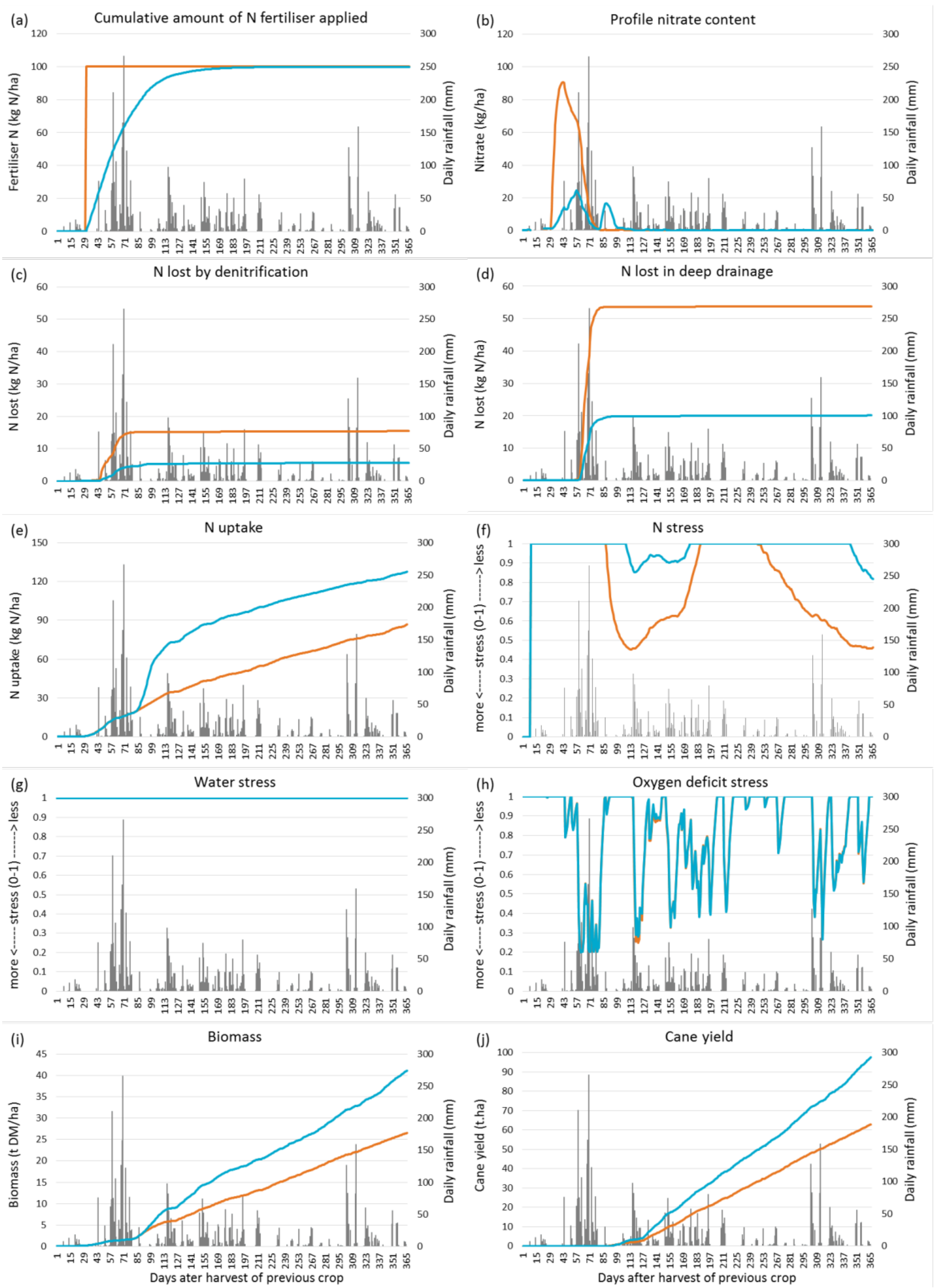

Fig. 7—Time series of simulated system variables during the season of a late first ratoon grown on a Thorpe soil harvested in 1998 using a 100 kg N/ha application of urea (orange) or linear CRF (blue); rainfall in grey.

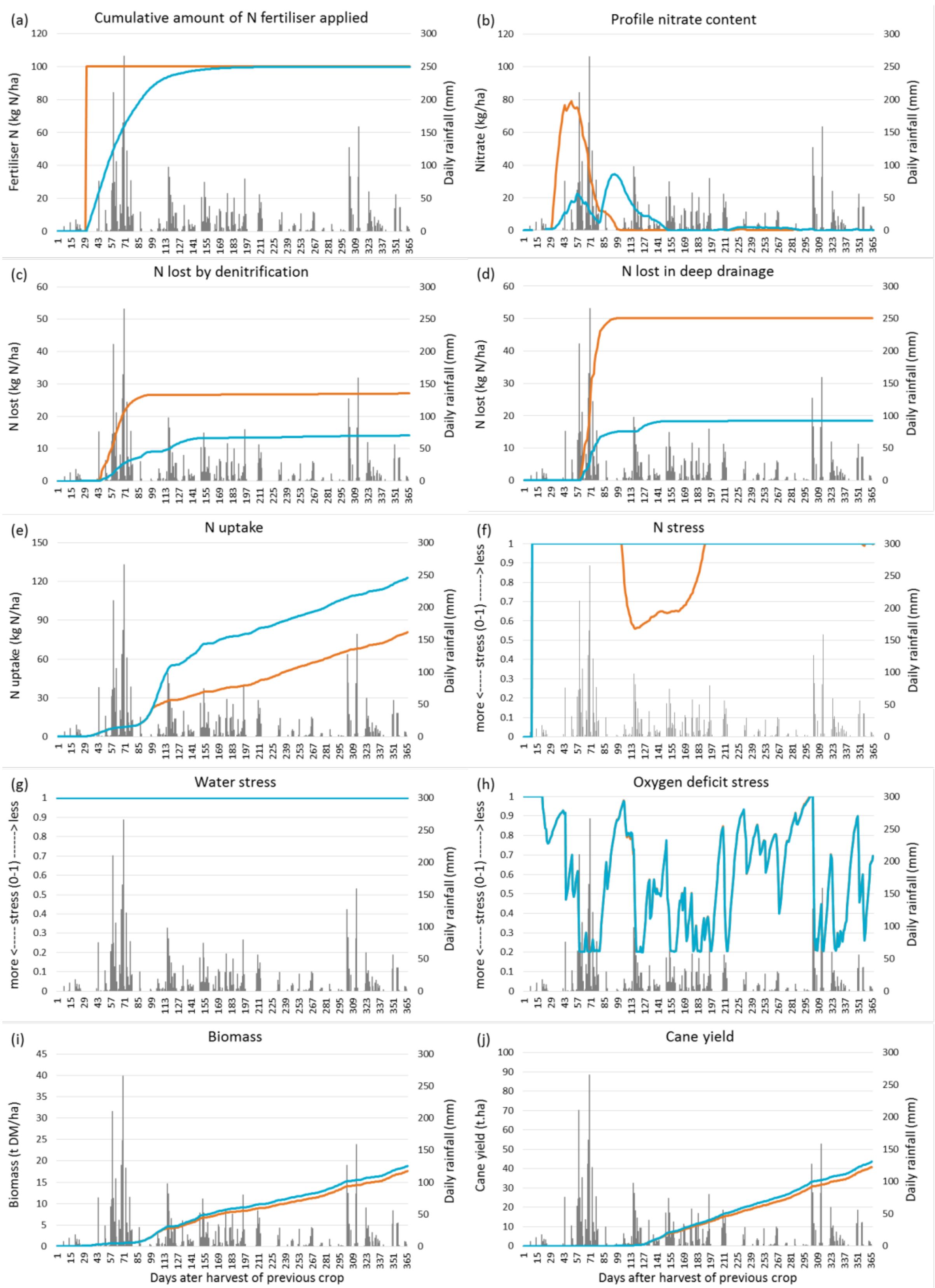

Fig. 8—Time series of simulated system variables during the season of a late first ratoon grown on a Coom soil harvested in 1998 using a 100 kg N/ha application of urea (orange) or linear CRF (blue); rainfall in grey.

The 2000 late ratoon season shows different dynamics. As in 1998, the slower release of N in the CRF treatment results in a slowed increase in soil nitrate content (Figure 9b) and reduces the N loss caused by the first and second large rainfall events after fertiliser application (at 50 and

100 days after harvest; Figure 9c and Figure 9d). In contrast to 1998, this does not lead to increased N uptake (Figure 9e), as crop growth is severely limited by oxygen deficit stress (Figure 9h) due to the continued wet conditions.

As the 'saved' N is not used by the crop it remains in the soil and is lost during the subsequent rainfall events (Figure 9c and Figure 9d), all but negating the initial environmental benefits. The oxygen deficit stresses induced by the waterlogged conditions (Figure 9h) reduced the crop's growth potential, meaning there is little or no N and water stress (Figure 9f and Figure 9g), resulting in similar biomass and cane yield (Figure 9i and Figure 9j).

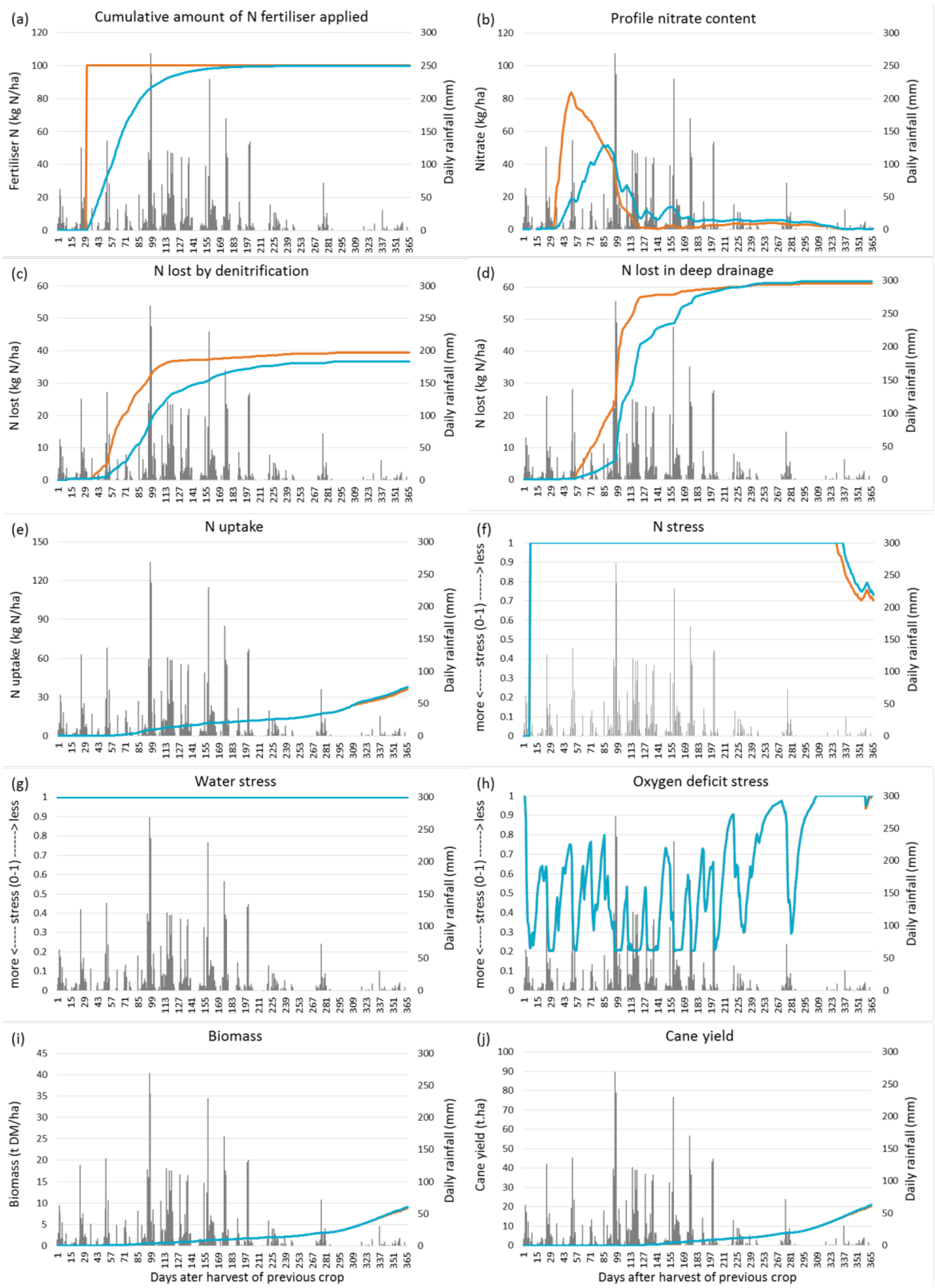

Fig. 9—Time series of simulated system variables during the season of a late first ratoon grown on a Coom soil harvested in 2000 using a 100 kg N/ha application of urea (orange) or linear CRF (blue); rainfall in grey.

Implications

The dynamics shown in Figures. 7, 8 and 9 show that the sugarcane system's response to use of CRF instead of urea is quite complex. The use of CRF achieves reductions in both denitrification and deep drainage N losses, but if these N 'savings' cannot be used by the crop (Coom soil, 2000) or are taken up more slowly (Coom soil, 1998) the agronomic benefits are not fully realised and the environmental benefits can in fact prove transient.

As the dynamics demonstrate the increased N losses seen later in the CRF treatment on the Coom soil are not due to poor performance of the CRF, but a consequence of reduced crop performance. Effectively the N supply is no longer matched nor synchronised with the N demand.

This effect will be more marked on soils that where waterlogging periods last longer due to poor soil drainage. While these soils also have a larger proportion of N loss via denitrification, the reduced benefits are not due to CRF being less effective in reducing denitrification losses.

Some experimental studies have also suggested CRFs may be best suited to soils that experience N loss through leaching, whereas nitrification inhibitors, another type of enhanced efficiency fertilisers, could be more effective for conditions that cause N loss via denitrification (e.g. Di Bella *et al.*, 2017).

The above simulation results suggest that it is unlikely that other EEF, like nitrification inhibitors, would perform better than CRF on the Coom soil, because the crop's response to the waterlogged conditions play such a key role in limiting benefits. These same crop growth limiting factors would be present regardless of type of EEF. The exception would be if the nitrification inhibiting action would last longer than the release period of the CRF.

The wet tropics and especially wet seasons with early rainfall events would appear to provide ideal conditions for getting benefits from CRFs. The results presented here indicated that this potential may not always be realised in soils where the yield potential is affected by the wet conditions, e.g. soils experiencing prolonged waterlogging. And even for the Thorpe soil, the yield potential and hence potential for benefit from CRF will be reduced in very wet seasons due to lower solar radiation input (Muchow *et al.*, 1997; Everingham *et al*., 2016). In these situations Nopt will be relatively low and its upfront prediction will be critical to reduce N loss and maximise N use efficiency (see Thorburn *et al*., 2018).

Conclusions

The findings reported in this paper confirm that soil type affects benefits obtained from CRF use in sugarcane. The effects are, however, strongly influenced by crop-soil system interactions and feedbacks that can override some of the straight CRF effects on N loss. In the wet climate of Tully, the use of CRF can initially be just as effective in reducing N loss from denitrification as from N leaching. However, as conditions leading to denitrification can also affect the crop and limit yield potential, the crop cannot always make the most of these N savings. In turn, that leads to the initial N loss benefits disappearing if the season continues to be wet. Benefits from CRF use will be largest on soils where N loss events (e.g. large or prolonged rainfall events) are not associated with reductions in yield potential.

Acknowledgements

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