2014-12-01T01:01:00Z

A review of nitrogen use efficiency in sugarcane

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Sugar Research
Australia

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December 2014

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The report has been coordinated by SRA for the Australian Government through funding from the Australian Government Reef Programme.

ISBN: 978-0-949678-36-2

Acknowledgements

The report has been coordinated by SRA for the Australian Government through funding from the Australian Government Reef Programme.

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Contents

List of Figures

List of Tables

Executive Summary

MJ Bell

Background

The Great Barrier Reef (GBR) is the world's largest coral reef ecosystem, providing both substantial economic benefit to Australia and significant international ecological value. The health of the GBR is under pressure from sediments, pesticides and nutrients (especially nitrogen) discharged from nearby catchments. Discharge of nitrogen is of particular concern as it stimulates outbreaks of the Crown of Thorns Starfish, a major predator of GBR corals. Recent research has shown that the amount of nitrogen fertiliser applied in excess of crop uptake is an important determinant of nitrogen discharge from catchments, so increasing the efficiency of nitrogen use in cropping systems is an important step in protecting the economic and ecological benefits provided by the GBR. Importantly, an increase in nitrogen use efficiency (NUE) also offers opportunities to improve productivity and profitability of agricultural industries, with such benefits a major incentive for industry adoption and practice change.

The Australian sugarcane industry is a significant contributor to the anthropogenic loads of nitrogen entering the Great Barrier Reef lagoon, with recent estimates in the Reef Water Quality Protection Plan (2013) suggesting it contributes 18% and 56% of particulate and inorganic nitrogen loads, respectively. A focus on improving NUE in the Australian sugar industry to reduce these loads wherever possible is a logical outcome from these statistics. While the relative impact of dissolved inorganic nitrogen (DIN) and particulate nitrogen (PN) is still uncertain, recent NUE forums in the sugar industry in 2014 identified clear target reductions in DIN that would be needed in order to significantly improve water quality in line with Reef Plan (2013-18) targets. The forum also identified a clear need for a joint industry-government funded research program to improve NUE in sugarcane cropping systems.

The review conducted for this report was commissioned and funded by the Australian Government Reef Programme to provide a foundation for this joint NUE research program. The review was tasked with providing an improved understanding of past and current research effort and available field trial information (both published and unpublished) relating to nitrogen management in the sugar industry. From this perspective the review was then tasked with identifying research gaps and opportunities for future research projects and field trials that would collectively contribute to improving NUE from both agronomic and production perspectives as well as delivering significant reductions in nitrogen lost to waterways and the Great Barrier Reef lagoon.

It is widely recognized that in any crop, the demand for N is determined by the size of the crop and the fundamental efficiency with which that crop produces a unit of biomass or harvested product from a kg of acquired N (N use efficiency – NUE). Therefore a good understanding of yield potential at the spatial scale of the productivity unit (i.e., farm, several blocks of similar productivity, individual blocks or within-block) about which N fertilizer management decisions (rate, form, placement, timing) are made is required, along with an understanding of how that yield potential varies with seasonal conditions. Collectively, this could be called seasonal 'block' (or productivity zone) yield potential, and it will produce a crop N demand that may vary from year to year. The sugar industry is

currently operating at the district level (generally comprising several thousand cropped hectares across variable soil types and landscapes), and basing N demand for all growers in the district on the best farm yield ever achieved over a 20 year time frame. It is apparent that overall NUE could be improved by basing N fertiliser inputs on the seasonal yield potential of the productivity unit.

Review structure

The review consists of an introductory chapter, six independently written chapters addressing different aspects of crop production and N fertilizer management at both crop and farming systems scales, and a concluding chapter providing an overarching synthesis of key issues and an identification of future research priorities. Briefly, the content of each chapter is outlined below :

- **Chapter 1** – a background to the issues surrounding N management in the sugar industry and an analysis of trends in N fertilizer use over the period 1996-2012 crop seasons (A Wood and M Bell).

- **Chapter 2** – a chapter detailing the evolution of decision support frameworks and the SIX EASY STEPS program that currently support N management in the sugar industry, including presentation of experimental results from which the current N fertilizer rate recommendations are derived (B Schroeder *et al*.). The chapter describes the circumstances that have prompted the need for an N management system aimed at sustainability – profitable sugarcane production in combination with environmental responsibility and the processes of validating and determining the economic impacts for growers. The SIX EASY STEPS program forms the basis of current industry best management practice. The program sets district-specific nutrient guidelines and a well-developed delivery mechanism that can be further fine-tuned to deliver enhancements.

- **Chapter 3** – a broad overview of published and unpublished information relating to the source of N accumulated in cane crops, crop demand for N at different critical growth stages, the fate of N inputs (fertilizers, legumes and amendments) in the soil-crop continuum and a re-examination of frameworks for quantifying efficiency of N use. The current industry approach of calculating N fertilizer requirements based on an aspirational district yield potential, without reference to site specific management factors or seasonal forecasts, is a significant constraint to making improvements in N use efficiency (NUE). Similarly, adoption of improved terminology and experimental protocols to quantify fertilizer NUE by taking into account background soil N supply and crop recovery of applied N would allow a much clearer focus on fertilizer N management improvement (M Bell *et al*.).

- **Chapter 4** – an exploration of opportunities to improve NUE through exploitation of genetic variation in the efficiency with which N is captured by the crop and utilized to produce both biomass and harvestable yield. This chapter explores advances and approaches used in other crop species and contrasts that with the limited data available for sugarcane and potential future opportunities for improvement (N Robinson *et al*.).

- **Chapter 5** – this chapter explores the potential use of remote and proximal sensing as a means of accurately determining crop N status and facilitating in-season management responses, as well as a means of retrospective analysis of crop and genotypic performance in response to spatial and seasonal variables. It overviews a variety of sensor types and platforms, looks at application in other industries and identifies potential applications in the sugar industry. On the basis of this synthesis, some strategies for the possible application of proximal sensing to measuring foliar nitrogen concentration in sugarcane are proposed. Additionally, remote sensing offers a number of 'value adding' benefits for improving the monitoring of seasonal and spatial variation in crop yield over time (A Robson *et al*.).

- **Chapter 6** – a broader scale exploration of crop N use at a cropping systems scale, applying the latest simulation capability to explore spatial and temporal variability in crop productivity, NUE and environmental losses due to various pathways (atmospheric as well as into receiving waters) in response to different N sources and management strategies. This chapter also demonstrates the value of this simulation capability to explore the potential benefits of different management interventions on NUE and environmental losses at local and regional scales (P Thorburn *et al*.).

- **Chapter 7 Part I –** provides an overview of the development and relative effectiveness of different products and methodologies collectively described as Enhanced Efficiency Fertilizers (EEFs), and assesses their potential role for improving NUE in the sugar industry. Most of these products endeavour to better synchronise the supply of plant-available nitrogen with demand by the crop, either by slowing the release or inhibiting the formation of forms of nitrogen vulnerable to losses. The results from limited trials in Australia suggest that EEFs may have agronomic and environmental benefits in at least some situations. The effectiveness of products is affected by a complex set of interacting soil, crop, climate and management factors. Season and site variability contribute to inconsistent performance suggesting that more in depth investigations are warranted. The economic and management implications of using different approaches are discussed (K Verburg *et al*.)

- **Chapter 7 Part II –** this chapter provides a commercial context to the use of EEFs in the Australian sugar industry, covering issues such as the available products, pricing relative to traditional fertilizer N sources and current industry experiences with their use (J Kraak *et al*.).

- **Chapter 8** – this is an overview chapter that collectively considers data and issues covered in the specialist chapters, undertakes further analysis where appropriate and develops unifying themes upon which future advances in NUE could be based. This chapter also identifies major knowledge gaps under key themes and identifies research methodology or approaches that should be followed in some instances. (M Bell and P Moody).

Review findings

The review recognizes that the Australian sugar industry operates in challenging environments, with high rainfall and variable soil types contributing to difficult conditions in which to efficiently manage a mobile nutrient like nitrogen. This is exacerbated by traditional N fertilizer formulations that do not release N in a synchronous manner with crop demand. The combination of these factors poses a major challenge to achieving large improvements in N use efficiency. That said, the review has clearly identified strengths and weaknesses relating to the current approach to nitrogen management in the industry, as well as suggesting promising areas for research and exploration that could deliver improvements in NUE.

The *imperative* for industry change is driven by the need for the following outcomes:

- Improved sustainability and environmental outcomes
- Improved productivity and profitability
- Continued social license to farm

These outcomes will be delivered by improving NUE.

The review findings can be summarised as follows –

(i) A need for an improved framework for both researching and benchmarking NUE

The current approaches used by the industry to determine fertilizer N requirements must be improved to better benchmark current N use and also to quantify improvements in fertilizer use efficiency. The industry currently uses inappropriate methods for benchmarking fertilizer N use efficiency which do not identify the source of crop N (i.e., from indigenous soil reserves, amendments like mill mud or legume residues, or applied fertilizers), or indeed how much of the applied N has actually been accumulated by the crop.

There is a need to adopt benchmarks commonly used in other cropping systems that allow the cane and sugar yield response to be expressed as *additional* productivity/kg N applied (i.e. above and beyond that derived from either an unfertilized reference plot or from lower rates of applied N), rather than simply total production/kg N applied. There is also a need to be able to quantify the amount of additional crop N uptake needed to deliver any productivity gains, thereby allowing true efficiencies of nitrogen uptake and utilization to be derived. When derived in well-designed experiments with appropriate soil and plant sampling strategies, these benchmarks will allow clear and transparent measures of sugarcane NUE to be compared between seasons and geographic regions.

These benchmarks will allow exploration of the trade-offs associated with the current focus on application of the fertilizer N rate that achieves >95% of the seasonal yield potential, both in terms of the amount of fertilizer N actually acquired by the crop and the fate of the rest of the applied N. An increased focus across the industry on the fate of applied N and how to improve fertilizer N recovery by the soil-crop system will be required in order for the industry to embrace the need for changes to management practices.

(ii) Promising opportunities for improving NUE through targeted R and D

The review has clearly identified opportunities for improving NUE under three key themes – Improved decision support systems and diagnostics designed to better define the appropriate N rate to meet yield expectations for an individual crop class, field or farm; Improved fertilizer products and optimized management approaches for these new products; and identified crop genetics that will deliver varieties with both an improved ability to recover applied N and to use it efficiently to produce biomass and sucrose.

Improved decision support systems and diagnostics to define the appropriate N rate - While fertilizer N demand is currently based on an estimate of a target yield, the scale at which that target is set (typically a district comprising thousands of hectares) and the method of setting the target (20% above the best district average yield obtained in the last 20 years) will consistently result in over-application of N by most growers in most years. Attention needs to be devoted to identifying targets that reflect yield potential at a finer spatial scale (sub-district, farm or block) based on historical productivity, and the potential for seasonal weather forecasting to scale yield expectations should be explored.

While there is recognition in the current industry frameworks of the contribution of soil organic N reserves to crop N budgets (through some generalized fertilizer rate discounts based on soil organic matter content), this system will need considerable refinement (to soil types and climatic zones) by more intensive laboratory research supported by an extensive field research program. The latter will necessarily also need to develop an understanding of the amount and fate of N retained in below - ground plant parts (roots and stools) as well as the fraction of crop N returned to the soil in the trash. Collectively this information will allow the development of more appropriate fertilizer rate discounts based on expected contributions from indigenous N sources.

There are opportunities to explore the potential for precision agriculture techniques to further refine N management within defined productivity zones. This would involve combinations of remotely sensed productivity zones based on yield stability maps to determine likely crop N demand, combined with opportunities to use remotely sensed in-season canopy assessment of crop N status to deploy variable rate fertilizer applications before the crop reaches out-of-hand stage.

Fertilizer technology and management - recent advances in fertilizer technology that are delivering enhanced efficiency fertilizer (EEF) formulations that better match N release to crop N demand have considerable potential to deliver a step change in NUE in many sugarcane producing regions – especially in environments with high rainfall during periods of crop N acquisition. There are currently commercial products available with two different modes of N release, so there is a clear need for a broad research program to assess the performance of these products in different environments and soil types, and to develop fertilizer management strategies that can capture the opportunities for better crop N recovery, reduced environmental losses and lower fertilizer N application rates without compromising productivity.

Improved crop genetics delivering improved recovery and use of applied N - The industry currently does not have a good understanding of how efficiently existing genotypes can recover and use N to produce biomass and sucrose. If these benchmarks can be developed for existing genotypes, the opportunity then exists to develop methodologies to routinely benchmark material emerging from

the breeding program for attributes contributing to improved NUE. While a longer term objective, such genetic approaches to improving NUE are being widely adopted in other industries.

(iii) Maintaining a focus on extension, communication and industry engagement

The industry is well served by a Decision Support System like SIX EASY STEPS (6ES), which is a framework into which information addressing the knowledge gaps and technology developments outlined above can be incorporated. Continuous updating of the interpretive guidelines of the 6ES framework provides industry with a vehicle for implementing improved N use efficiency, and the extension framework developed around 6ES offers the potential for rapid dissemination of new information and approaches to industry.

There is also a need for the industry to develop a communication strategy to convey the complexity and economic realities of improving NUE to the broader community. This will involve quantifying the risks from economic as well as environmental perspectives of applying an additional increment of N, and conversely the economic cost and environmental benefits of reduced N applications.

With NUE issues now identified, there is an opportunity to facilitate the better coordination and communication of industry and government research, investment and extension activities. There is considerable merit and interest in forming an NUE Steering Group to provide coordination and structured governance into the future, to enhance linkage between industry needs and R, D&E objectives, and to influence the development of government policy and plans to realise environmental management targets.

Development of a roadmap to determine future research priorities and strategies

In response to the review findings, a roadmap outlining possible future Actions, Outputs and Outcomes for improved N management in the Australian sugar industry has been developed by SRA with input from the review team. This document outlines a strategy for addressing the key issues identified in the review and, after a consultation process with industry and key stakeholders, could form the basis for developing a consensus path to improving NUE in the Australian sugar industry.

GOAL

Optimise Nitrogen use efficiency in sugarcane to maintain crop productivity, improve profitability and produce environmentally sustainable outcomes for the industry and community benefit. Industry targets; 50% reduction in DIN by 2017/18 and 80% reduction in DIN by 2025 in environmentally sensitivities regions.

OUTCOMES

- Implementation of seasonal block/ management zone yield potential and application of N fertiliser at optimal rates.
- Understanding the economic impacts of implementation of the various NUE strategies on farm/enterprise profitability
- 6ES guidelines developed for precision agriculture that take into account spatial variability and address the temporal needs of the crop.

- Delivery of N-efficient varieties to industry to meet stringent environmental targets which cannot be met by BMP strategies alone.
- Core breeding program geared to screening and breeding for N-efficient varieties adapted to specific soil types/environments

- Improved understanding through monitoring of temporal and spatial variation of crop performance relative to N fertiliser use and availability
- Growers can refine N fertiliser practices for better outcomes
- Reduced reliance on anticipatory (pre-season) strategies in favour of rapid in-crop diagnostics and in-season N monitoring and N applications

- Improved synchrony of N supply to crop demand through better accounting for all sources of N and appropriate use of EEF or CR fertilisers
- Technologies and tools to determine the most effective combination of application strategies and EEF to mitigate risk in response to the size of the crop and climatic conditions.
- Economic implications for industry of EEF products and product mixes for different seasonal and site conditions

OUTPUTS

Refinement and continuous updating of industry DSS; 6ES, NutriCalc, SafeGauge, SmartCane BMP modules: vehicles and extension framework for implementing NUE

Realistic measures for seasonal block/ management zone yield potential based on productivity data, seasonal weather, crop age and stage.

Integration of seasonal climate forecasting into N fertiliser management using appropriate DS system; 'Yield Prophet' tool for sugarcane growers

Improve definition of N uptake efficiency - benchmarks for fertiliser NUE expressed as additional productivity/kg applied N, after accounting for other sources of N and unavoidable losses

Surrogate markers available to accelerate genetic gain and facilitate integration into the core breeding program

Development of a business case for core breeding program on N-efficient varieties; understanding of how efficiently the crop can use N to produce biomass and sucrose.

Maps indicating temporal and spatial trends in N removal and industry N use; NIR technology installed at all mills

Integrated spatial information layers used to optimise crop inputs for strategic planning at a regional level where consistent high and low performing cane is identified.

Grower use of on ground sensors to deliver variable rate 'on-the-go' N rates – with-in season risk mitigation

Vegetation Index foliar N maps at crop / region scale –independent of cultivar and seasonal conditions.

DS frame work that allows growers to match the most effective EEF's and conventional fertilisers with a given season, soil type, and management system; integration of the DS framework into NutriCalc and SafeGauge

DS tool to inform appropriate management of residues and fallow legumes to enhance synchrony of N benefits and management of N losses under site and seasonal conditions

Overarching conceptual model for a DS framework and publicly available information for the selection of EEF products and their economics that can inform industry BMP and SafeGauge tools

ACTIONS

Develop industry tools and strategies to assess the economic outcomes of improving NUE

Refine 6ES to more accurately account for the contribution of indigenous sources of N and yield potential at appropriate spatial scales using crop class, age and seasonal conditions..

Development of N mineralisation index to account for indigenous sources of N from soil, crop residues above and below ground and amendments.

Develop N management and accounting strategies for different crop classes, older ratoons and time-of-harvest impacts on the yield potential of subsequent crops; develop strategies for better temporal management of N applications

Understand yield potential at the spatial scale of the production unit using performance data sourced from trials, farm and mill records, and remote sensing technology

Evaluate the impact of climate variability and seasonal forecasting on cane yield in a wide range of soil types.

Better understanding of root health and the impact of sub-soil constraints on crop vigour and N accumulation

Improve understanding of genetic variation of NUE in local germplasm and crop-specific N physiology including below ground attributes, N regulation, use, storage and remobilisation of N

Develop surrogate markers for breeding and selection for NUE in sugarcane. Such markers may include shoot and root vigour traits.as well as N partitioning between canopy components and between above and below ground parts.

Explore transgenic and marker assisted improvement of N-efficient varieties through collaborative research with multi-nationals or other institutions.

Establish protocols and experimental locations where screening of sugarcane genotypes for yield under contrasting N input conditions can identify differences in NUE unconfounded by environmental losses.

NIR monitoring of N concentrations in harvest cane at mills to measure N removal. Develop area /regional maps linking NIR monitoring and mill GIS data with crop boundary layers to calibrate remote sensing data.

Use remote sensing to develop spatial layers for yield variation; integrate with soil maps to define temporal and spatial orientation of production zones.

Develop a standardised fertiliser response index using limited and non-limited N reference strips as the basis for calibrating commercial sensors used to indicate likely crop N status.

Identify spectral wavelengths that correlate with leaf N concentration

Development of variable rate fertiliser application equipment guidelines for growers

Explore the interactions between irrigation management/WUE and NUE in high risk environments like the Wet Tropics and Burdekin to mitigate potential N loss pathways

Intensive investigation of the effectiveness of different CR/EE fertilisers and product combinations for their effectiveness in better synchronising N availability with crop demand.; assess the impact of seasonal effects, soil type, topography and crop management on effectiveness on N losses and the potential benefits of CR/EE fertilisers.

N response trials that include zero N treatments to allow for assessment of N supplied by soil/ carried over from previous season, to more accurately gauge N responsiveness

Improve understanding of dynamics of N release from crop residues and fallow legumes; develop residue management strategies that deliver N release patterns better synchronized with crop N demand

Improvements to parameterising APSIM for sugarcane, including variety-specific traits, to enhance simulation capability, interpretation and extrapolation of results.

1. Introduction and trends in nitrogen fertiliser use

MJ Bell, A Wood and P Moody

1.1 Introduction

The Australian sugarcane industry is predominantly situated in coastal catchments adjacent to the Great Barrier Reef (GBR), and while occupying only ~1.3% of the total GBR catchment areas, is deemed to be responsible for contributing an estimated 6%, 18% and 18% of the average annual anthropogenic loads of Total Suspended Solids (TSS), Particulate Phosphorus (PP) and Particulate Nitrogen (PN) delivered to the GBR lagoon (Australian Government 2014). It is also deemed to contribute an estimated 56% of the Dissolved Inorganic Nitrogen (DIN). The discharge of Nitrogen (N) is of particular concern as it stimulates outbreaks of the Crown of Thorn Starfish, a major predator of GBR corals (De'arth *et al*. 2012). At the same time, these losses of N represent an inefficient or wasted investment by sugarcane growers in costly fertilizers, as well as a potential lowering of crop productivity, so improvements to N use efficiency in the sugarcane industry represent an opportunity to achieve a rare win-win situation for both the environment and industry productivity and profitability

The Australian and Queensland governments established the Reef Water Quality Protection Plan in 2003 to halt and reverse the decline in the quality of water entering the GBR lagoon. Investments by government and industry/growers in recent years to improve agricultural management practices have resulted in significant practice change and predictions of a 6-15% reduction in key pollutants (State of Queensland 2013b). However scenario analyses conducted for the 3rd Reef Plan Report Card (State of Queensland 2013C) suggest that even wholescale adoption of current A (Aspirational or cutting edge) class nutrient management practices may not achieve the Reef Plan 2009 water quality targets for DIN reduction, and that other options to improve NUE and/or reduce N inputs need to be investigated.

Improving the management of N used in sugarcane production to mitigate the impacts of run off of dissolved inorganic nitrogen (DIN) and poor water quality on the Great Barrier Reef is a complex issue. There are differing views and expectations on the impact of N on the reef, fertiliser rates used by growers, programs to determine N requirements of sugarcane, N loss pathways, the drivers and influence of DIN on COTS initiation sites, the targets needed to meet water quality and how best to achieve those targets. At the CANEGROWERS Nitrogen Forum held in Townsville in February 2014, research from the Wet Tropics based on catchment, paddock and stream monitoring between 1986-2009 notionally identified the need for DIN losses to the environment to be reduced by approximately 10 kg of DIN per hectare of cane in order to have a significant effect on water quality and to meet Reef Plan targets of a 50% reduction in DIN. This comment provided common ground; growers, researchers and extension officers alike responded positively to this approach as it provided an aspirational target that is achievable, supported by research and able to be met with a suite of strategies and not just a reduction in rate of N fertiliser. However it was also clear that there were significant gaps and uncertainties around the identification, development and implementation of any such strategies, and that there was a clear need for a joint industry-government funded research program to improve NUE in sugarcane.

These developments prompted the Australian Government Reef Programme to commission and fund this review of N use in the Australian sugar industry.

1.2 Scope of the review

The review team was charged with delivering the following outputs

- Foundational activities for increasing Nitrogen Use Efficiency (NUE) in sugarcane to ensure N rates are better matched to crop requirements.
- Review and synthesis of published and (where available) unpublished ('grey literature') field trial data relating to NUE in the sugarcane industry within the GBR catchments.
- Identification of knowledge gaps and provision of recommendations for a further structured program of research required to optimise NUE according to regional and local cane production systems whilst delivering significant reductions in N lost to waterways from cane lands.

1.3 Background information on N fertilizer use in the Australian sugar industry

Application rates of nitrogen fertiliser in the Australian sugar industry rose steadily from very low levels in the early 1900s, around 60 kg N/ha in the 1940s, 160-180 kg N/ha in the 1970s and up to 200 kg N/ha by the 1990s (Keating et al, 1997; Johnson 1997). Since the mid -1990s there is evidence to show that application rates have declined.

Each year for the last 17 years, Incitec Pivot Fertilisers have released a document "Nitrogen and Phosphorus Rates in Sugarcane" which documents average N and P application rates for each sugarcane region (Wet Tropics, Herbert, Burdekin, Central Queensland, Southern Queensland and New South Wales) and for the whole industry. The data are compiled using fertiliser sales figures for each region, separating sugarcane from other crops, calculating areas treated and the % market share held by Incitec Pivot (Rob Dwyer, personal communication).

In some regions such as the Herbert, Productivity Boards have also been collecting data on fertiliser use rates in sugarcane as well as farm productivity data. Wood et al (2008) compared HCPSL survey data on fertiliser application rates for the 1996, 1998, 2000, 2002, 2004 and 2006 crops with those from Incitec Pivot, and found good agreement between the two datasets.

In a later paper, which explored opportunities for improving nitrogen use efficiency in the Australian sugar industry, Wood et al (2010) presented data on average N fertiliser application rates (kg/ha N applied) and fertiliser N use efficiency (tonnes cane/kg N fertiliser applied) for the period 1997-2009. The main purpose of this document is to extend the analysis up to 2013, explore some of the factors which may have influenced these trends and examine possible implications for crop production.

Figure 1.1 shows average N fertiliser application rates for Queensland for 1997-2013. Data for N application rates have been related to the year in which the fertilised crop has been harvested so that it is possible to examine trends in fertiliser N use efficiency and the impact on crop yields. Application rates of N fertiliser declined steadily from 206 kg N/ha for the 1997 crop to 164 kg N/ha for the 2008 crop. Sharp rises and falls occurred over the next 4 years but with a similar overall rate of decline. The application rate for the 2012 crop was the same as that for the 2008 crop.

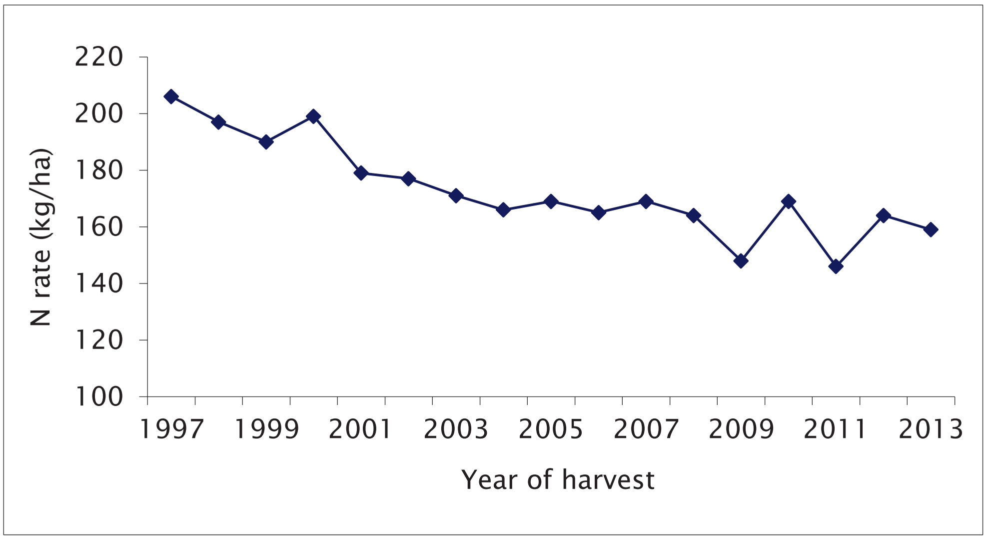

Figure 1.1. Average N Fertiliser application rates for sugarcane in eastern Australia 1997-2013

Figure 1.2 shows urea prices adjusted to 2011 Australian dollars from 1997 to 2011. Clearly the extremely high urea prices in 2008-09 have contributed to a more rapid rate of decline in N rates during this period. Sugar prices, when adjusted to present dollars, are very low from 1999 onwards ($300-$500) when compared with prices in the 1970s (>$1000), 1980s (>$600) and 1990s (>$500). It is therefore not surprising that expenditure on fertilisers has reduced in real terms as part of the 'belt tightening' to accommodate income levels now less than half what they were 40 years ago.

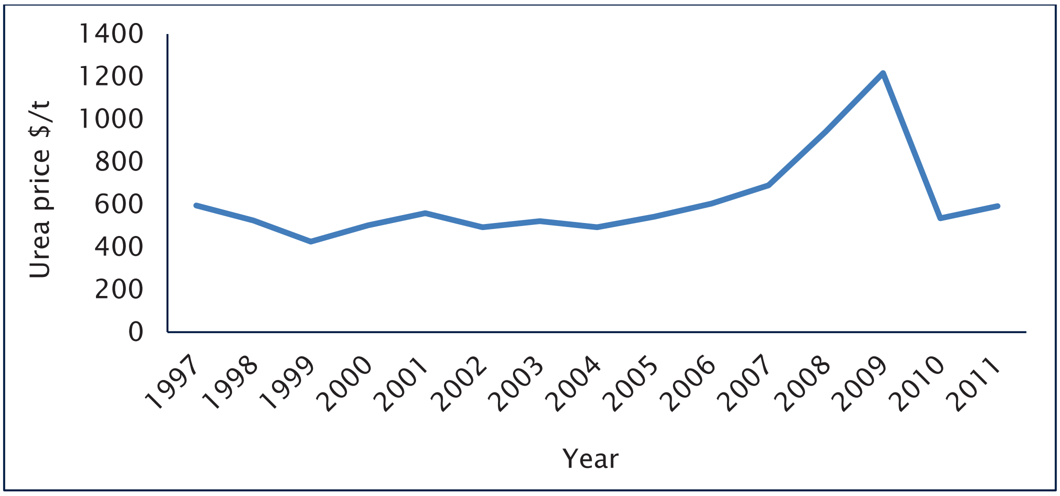

Figure 1.2. Average 1 tonne bag price of urea adjusted to 2011 dollars

During the period under investigation there has been an overall decline in cane yields in all districts (Figure 1.4), with the decline most pronounced in the Central district (Figure 1.5). Co-incidentally, the Central district has also seen the greatest decline in N fertilizer application rates, and there is some concern being expressed in the industry that the two factors are linked – i.e. declining productivity is a result of too large a decline in fertilizer N rates.

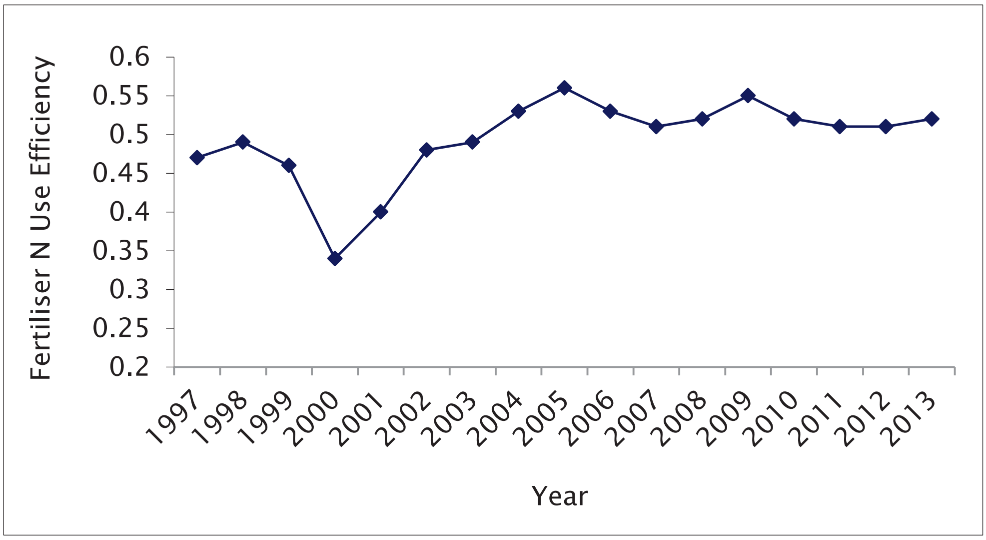

Figure 1.3. Fertiliser N use efficiency 1(tonnes cane/ kg N) for sugarcane production in eastern Australia 1997 - 2013

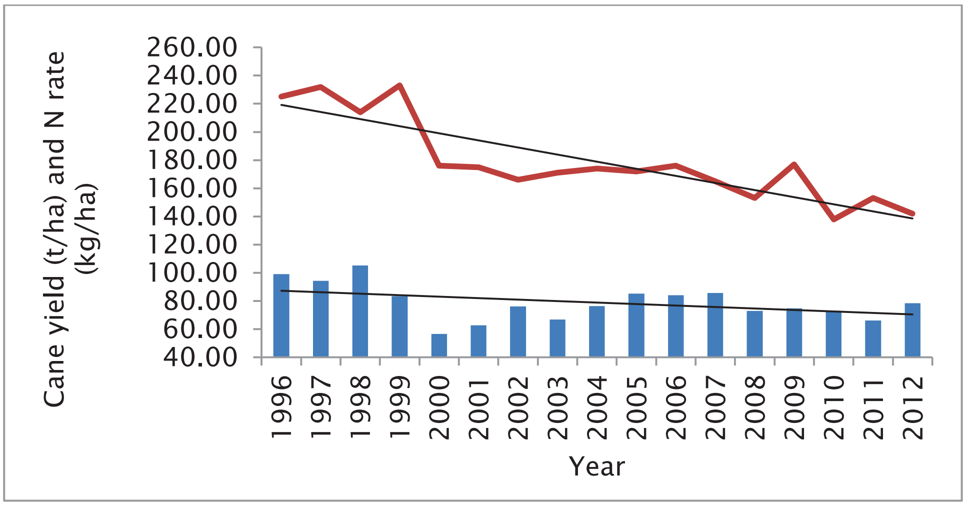

Figure 1.4. Cane yields and N rates for eastern Australia

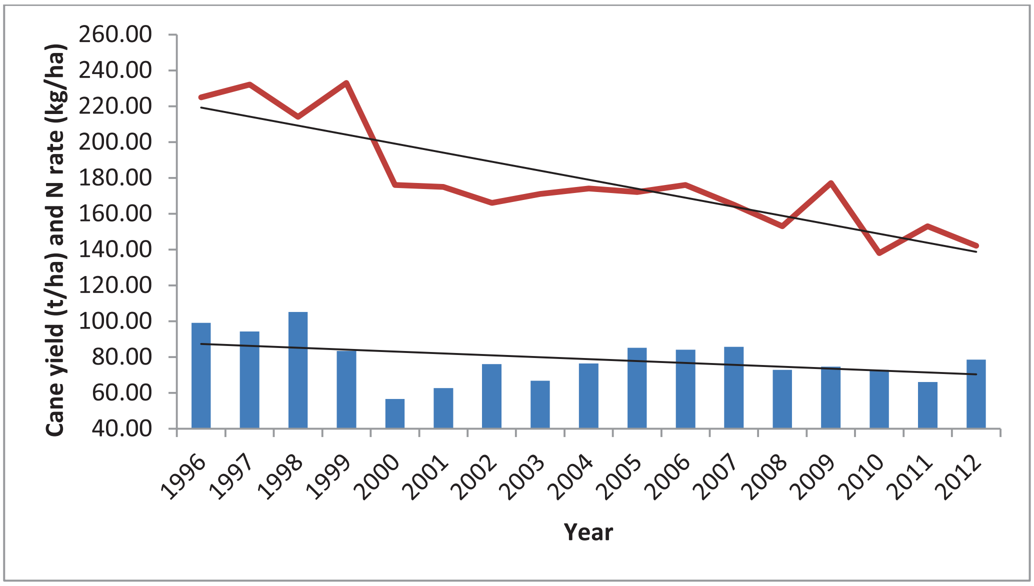

Figure 1.5. Cane yields and N rates for Central district

While there is recognition that productivity will be affected if there is insufficient nitrogen available to the crop, there is no definitive evidence that the lower recent productivity in Central district is related to reduced N use. Declining productivity at a district level can be caused by a variety of climatic, soil health, plant disease, genetic and crop management factors, as was demonstrated by the Sugar Yield Decline Joint Venture. To assess whether there is a causal relationship between lower yields and declining N fertilizer use would require a substantial new research effort.

Future data on N fertiliser application rates from Incitec Pivot are unlikely to be made available due to a significant reduction in field sales staff. The lack of staff in the field will make the gathering of market intelligence on fertiliser sales much more difficult. It is hoped that some of the Productivity Service companies will continue to gather data on grower practices, such as fertiliser usage so that monitoring of long-term trends can continue.

1.4 Acknowledgements

The provision of fertiliser application rate data by Incitec Pivot through Rob Dwyer is gratefully acknowledged as is the provision of data on cane yields, urea prices and sugar prices by ASMC through Jim Crane.

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2. Evolving nature of nitrogen management in the Australian sugar industry

BL Schroeder, B Salter, PW Moody, DM Skocaj and PJ Thorburn

2.1 Abstract

Nitrogen (N) management within the sugarcane production systems in Australia continues to evolve as grower and industry needs, and government and environmental pressures, change with time. In this chapter we describe the importance of N as an essential crop nutrient within the production system, and the forms and loss pathways of N in soil. We then consider past approaches to N management and describe the changing circumstances that prompted the need for an N management system aimed at sustainability – profitable sugarcane production in combination with environmental responsibility. The genesis and basic principles of recently developed N management systems (SIX EASY STEPS and N Replacement N) are described, as are the processes of validating and determining the economic value of the two systems. We recognise that on-going developments (since the early 1900s) have ensured continuing improvements in target and actual N-use efficiencies (NUEs), and the economic effectiveness of N inputs.

In particular, the SIX EASY STEPS program forms the basis of current industry best management practice (BMP). The program contains sets of district-specific nutrient (including N) guidelines, and a well-developed delivery mechanism. It also enables further fine-tuning through an evolutionary process.

The delivery of the SIX EASY STEPS N management package to industry is described. Current enhancements and refinements are highlighted. Future needs are identified in terms of current and predicted circumstances, with the following considered the most important N management R&D topics in the short to medium term:

- Understanding the impact of climate variability on cane yield and N management. Improvements in NUE should be evaluated for a wide range of soil types and sugarcane growing districts.
- Any changes to the "district yield potential" used within the SIX EASY STEPS program to calculate N fertiliser requirements should be well-researched. Focus should not only be based on historical yields, but also aim at determining yield potentials for the forthcoming season.
- Development of SIX EASY STEPS guidelines for Precision Agriculture (PA) to target in-field variability.
- Addressing the temporal N needs of sugarcane by matching N supply to crop N usage.

We recognise that it is vital that the most appropriate N inputs are used within the sugarcane production system in Australia. To this end, the combination of the SIX EASY STEPS program and the integrated framework that underpins the program provides a suitable mechanism for future RD&E in nutrient management. Sustainable (profitable and environmentally responsible) N inputs will contribute to the prosperity of sugarcane communities of regional Queensland and the survival of the World Heritage-listed Great Barrier Reef.

2.2 Introduction

The Australian sugar industry has continued to recognise the important role of nutrient management in sugarcane production since the inception of the Bureau of Sugar Experiment Stations (BSES) in 1900. In particular, N has been the subject of ongoing RD&E, with a large number of trials and investigations conducted by the former BSES/BSES Limited. During the 1990s, the industry recognised the need for nutrient management that aimed at sustainable sugarcane production. Much effort went into better understanding the factors that controlled losses and uptake of N. Due to a concerted effort within the Cooperative Centre for Sustainable Sugarcane Production (CRC Sugar) in the late 1990s and early 2000s, a need was established for nutrient guidelines to be based on soil properties and processes, and the interaction of nutrients with soils. Such developments led to two new approaches to N management - the SIX EASY STEPS nutrient management principles and program, and the N-Replacement concept.

The SIX EASY STEPS program was developed using a logically-based 'systems' framework that enables further evolution as additional research results emerge. The initial R&D and evaluation phases of the program were extensive. It has been delivered to industry through various mechanisms, including a widely run short-course program, ongoing development of district-specific soil/nutrient management booklets, and an on-line nutrient management package.

The N-Replacement concept is more environmentally focused than the SIX EASY STEPS. However, with its reduced N-input strategy, maintenance of sugarcane productivity and profitability is less well-tested than SIX EASY STEPS. As such, it cannot be considered as a generally applicable system at this time.

2.3 Nitrogen – an essential crop nutrient

Although nitrogen (N), existing as N_2, makes up about 80% of Earth's current atmosphere, it is relatively unavailable for plant uptake. Plants can only access N once it has been converted through fixation processes into reactive forms such as ammonium (NH_4^+) and nitrate (NO_3^-). These processes involve free-living or symbiotic organisms (e.g. bacteria, fungi, etc), naturally occurring high-intensity phenomena such as lightning strikes, and/or anthropogenic activities associated with fertiliser manufacture. Urea [$CO(NH_2)_2$] is a commonly manufactured product that is applied to many agricultural crops, including sugarcane. It is synthetically produced from ammonia (NH_3) and carbon dioxide (CO_2) and its production relies largely on energy and carbon from hydrocarbons such as oil, coal and natural gas.

Nitrogen is one of the 16 essential plant nutrients (Figure 2.1) and required in relatively large quantities (60 – 200 kg/ha) by crops such as sugarcane (Calcino, 1994) that produce large amounts of biomass. The group of so-called macronutrients also include phosphorus (P), potassium (K), calcium (Ca), sulphur (S) and magnesium (Mg). Micronutrients [iron (Fe), copper (Cu), zinc (Zn), molybdenum (Mo), manganese (Mn), boron (B), and for some crops sodium (Na)] are required in relatively small amounts (less than 10 kg/ha/crop). Silicon (Si) is considered a beneficial nutrient although its direct benefit to crop production is not yet fully understood. Silicon-containing material is usually applied in fairly large quantities, similar in rates to ameliorants such as lime (applied to ameliorate soil acidity) or gypsum (applied to ameliorate soil sodicity). All of these nutrients are

potentially available in most soils, with some soils being able to supply more of a particular nutrient than others. Fertilisers and soil ameliorants are used to supplement these supplies of nutrients and prevent the mining of nutrients from soil reserves.

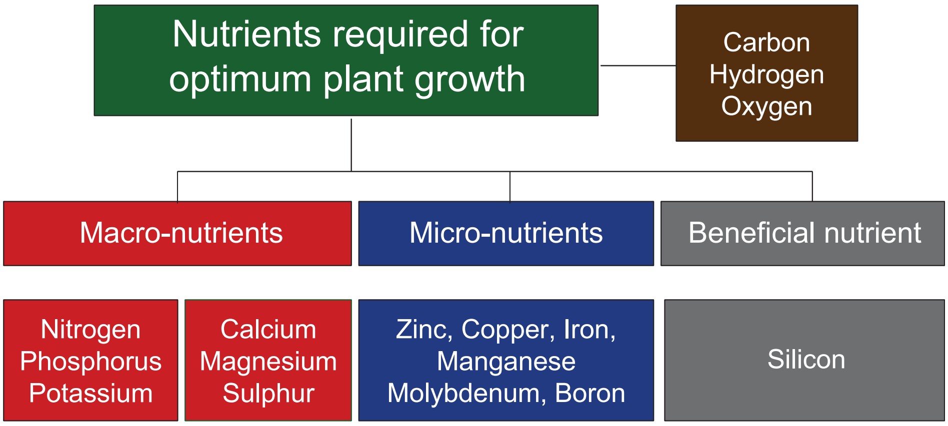


Figure 2.1. Macro, micro and beneficial nutrients used by crops.

Role of N in sugarcane crops

Nitrogen is involved in the following plant processes:

- Plant growth, expansion of green leaves, and tiller (Das, 1936; Wood, 1968) and sucker (Stanford, 1963; Salter and Bonnet, 2000) production.
- Formation of plant proteins - it is essential for photosynthesis (Anderson and Bowen, 1990).

Deficiency symptoms in sugarcane

When N is deficient, the whole plant is affected showing stunted growth (Figure 2.2a), reduced stooling and low yields. Yellowing of leaves occurs from the base of plant upward with die-back of the leaf tips and edges of the leaves (Figure 2.2b).

(a) (b)

Figure 2.2. Nitrogen deficiency affects the whole plant – stunted growth and yellowing of leaves from the base of the plant upward (a). There is often die-back of the leaf tips and edges (b).

Consequences of excess N in sugarcane

Excess N can lead to prolonged vegetative growth and reduced sucrose concentration (sucrose % fresh mass) mainly due to increased moisture in stalks (Muchow and Robertson, 1994). High N can also lead to increased amounts of the reducing sugars (glucose and fructose) in juice (Das, 1936) particularly in the early part of the harvest season. These reducing sugars may react with any excess N stored in stalks as amino acids such as asparagine (Chapman *et al*., 1996; Keating *et al*., 1999) to produce phenolic compounds during the milling process. These compounds contribute to darker juice colour which adds to the complexity of the refining process (Keating *et al*., 1999).

2.4 Nitrogen in soil

Forms of N in soil

The different forms of N in soil, and the processes and transformations of these forms of N are well recognized, and illustrated in the N cycle (Figure 2.3). Although N may be added in various forms, it is also subject to various losses. Understanding the transformation processes and loss pathways enables the identification of management options to ensure effective use of the various sources of N for crop production and the minimization of losses (Wood *et al*., 2010). Mineral N in soil essentially exists in two forms, namely NO_3^- and NH_4^+. This mineral N is the main form of plant available N and its occurrence is often associated with fertiliser N (often urea in the sugar industry, as indicated earlier). Direct or indirect atmospheric sources are also possible. Nitrogen within sugarcane crop residues (particularly trash, roots and mill by-products) is returned to the soil in the organic form. This organic N becomes available for plant uptake once the organic matter has broken down (mineralised) and the N has been transformed into the mineral forms. Apart from being removed by the crop, mineral N can be lost from soil through various pathways.

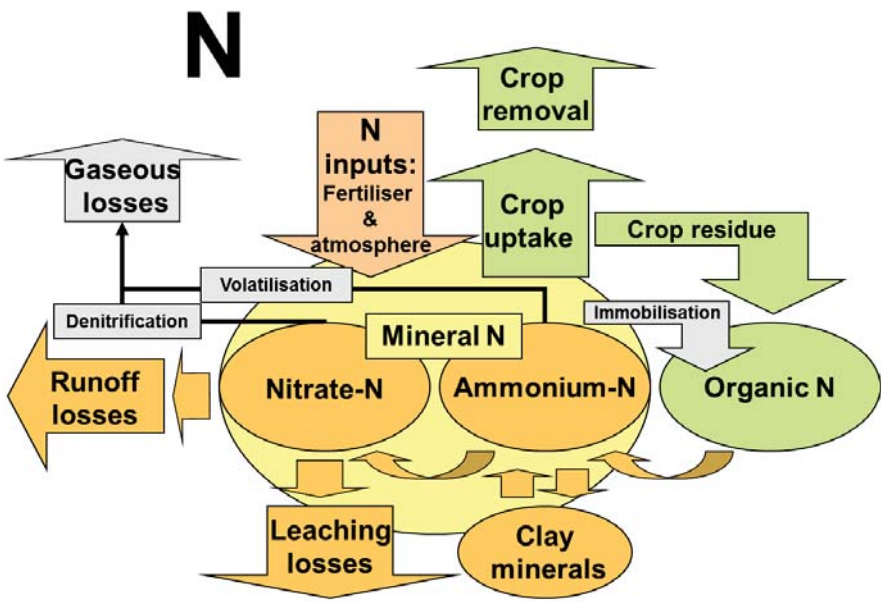


Figure 2.3. N cycle within a sugarcane cropping system showing additions, transformations losses and recycled forms.

Losses of N from soil

Nitrate-N can be lost in runoff water, and/or by leaching. Leaching is defined as the downward movement of water through the soil, together with the accompanied movement of soluble nutrients and suspended clay particles. Nitrate can also be lost through the process of denitrification. This occurs when soils are waterlogged and anaerobic conditions exist (Weier *et al*., 1996). Such circumstances, in combination with a ready source of organic carbon, will enable certain micro-organisms to convert nitrate to gaseous forms of N (such as nitrous oxide) that are able to escape from the soil surface.

Ammonium-N, on the other hand, can be lost from soil by the process of volatilisation. This loss mechanism is particularly associated with urea. Urease (a naturally occurring enzyme) is responsible for converting urea to ammonium and subsequently to ammonia (which is easily lost to the atmosphere). The risk of this type of loss increases when urea is applied to the surface of a sugarcane trash blanket that often contains substantial amounts of urease (Prammanee *et al*., 1989; Denmead *et al*., 1990). Volatilisation losses can also increase if urea is surface applied to alkaline soils (soil pH_{water} > 7.5).

Appropriate management options for minimising N volatilisation losses from applied urea include the following:

- Application of urea in the soil below the trash – this substantially reduces the risk of N loss by volatilisation. However, this strategy could increase the risk of N loss by denitrification if soils become waterlogged (Weier *et al*., 1996). Where this is a potential problem, urea should be applied to cane planted in mounded rows.

- If it is necessary to apply urea to the surface of a trash blanket, it should be done immediately prior to rainfall or irrigation events. Past research has indicated that at least 20 mm of rainfall or irrigation is needed to wash urea through the trash blanket and into the soil to minimize such volatilisation losses (Freney *et al*., 1992). The risk of volatilisation increases with cyclical wetting and drying.

- Delaying application until a cane canopy has developed will enable uptake of some of the escaping ammonia through the leaves (Freney, *et al*., 1991).

2.5 Past approaches to N management in sugarcane production in Australia

A review of the basis for fertiliser recommendations in the Australian sugar industry was undertaken in the late 1990s (Schroeder *et al*., 1998) as part of the activities of CRC Sugar. The existing nutritional norms (at that time) were re-evaluated due to a change in focus by the industry and other stakeholders to sustainable sugarcane production (Kingston and Lawn, 2003). Despite ongoing research into various aspects of nutrient management in sugarcane, growers were adopting their own approaches to nutrient management (Johnston, 1995; Webster *et al*., 1996). They tended to apply nutrients, particularly N, in excess of recommendations (Kingston and Linedale, 1987; Wood, 1992) because of their conservative approach to risk (Wegener, 1990).

Early developments

Very early researchers working within the former BSES established the need for 'balanced nutrition' in sugarcane production (Maxwell, 1901) and recognised the importance of linking fertiliser inputs to soil properties (Maxwell, 1902). During the 1930s a comprehensive set of calibration trials were conducted and used to establish N guidelines based on production functions, and soil test procedures and critical values for P and K (Kerr and von Stieglitz, 1938). Investigations conducted during the 1950s and 1960s revealed that sugarcane yields were unaffected by the choice of N carrier (urea or ammonium sulphate) as long as the fertiliser was buried (Leverington, 1964). Urea was found to be less efficient if surface applied. High rates of N caused increased concentration of N in juice causing decreased P concentration and subsequent sugar clarification difficulties (Leverington *et al*., 1964), and depressed sugar yields across the harvest season (Yates, 1965).

By the end of the 1960s, modifications had been made to the original P and K critical values. Nitrogen input rates continued to be determined from general production functions, but with account taken of economic factors and time of harvest ((Chapman, 1968).

During the 1970s and 1980s, a relatively large number of N, P and K calibration trials (110 in total) within two distinct series were conducted across the industry to establish, confirm and/or modify soil analytical methods, nutrient critical values and recommended nutrient input rates (Chapman, 1971). Unfortunately the trials were of limited value because of the trial design (incomplete factorial) and inappropriate selection of trial sites (Chapman, 1982). An apparent lack of supporting data and information made it difficult to use the results other than for providing general production functions (Chapman, 1994) for use across regions and soils (Schroeder *et al*., 1998). The short duration of most of these trials (often one year) made it difficult to assess the longer-term validity of N inputs and, in particular, the effectiveness and efficiency of different N strategies.

With trash retention gaining wide acceptance by the early 1990s (the exceptions being the Burdekin district and New South Wales), research into NUE was primarily aimed at understanding the factors controlling losses of N particularly from urea applied to cane grown in green cane trash blanketed (GCTB) systems. It was found that N losses from urea

- applied below the soil surface were less than that from urea broadcast to bare soil or onto the trash surface (Prammanee *et al*., 1989);
- banded on the surface was greater than the N losses from broadcast applications (Freney *et al*., 1991);
- applied to the surface of a trash blanket could be as much as 30 to 40% of applied N (Denmead *et al*., 1990). In contrast, minimal loss occurred when N was applied as ammonium sulphate, irrespective of the method of application;
- were reduced when applications were delayed until canopy development (Freney *et al*., 1991); and
- could be controlled by irrigation or rainfall occurring soon after application (Freney *et al*., 1994).

Although previous anecdotal evidence had suggested that N uptake by sugarcane was relatively low, Vallis *et al*. (1996a) found that the recovery of N by the crop following fertiliser application was between 20 – 40% of the N applied in the season of application. Muchow *et al*. (1996) found that

there were opportunities to manipulate the N supply to sugarcane in order to allow for optimal sucrose accumulation and maximising economic return.

2.6 Changing circumstances and the need for sustainable nutrient management

The farming system generally used across the Australian sugar industry has changed over the years. It appears to have evolved according to the following progression (Schroeder *et al.*, 2009c):

- The 'historical approach' of the 1960s and 1970s – sugarcane grown as a plant crop and two ratoons with a fallow period between crop cycles and burning of cane prior to harvest.

- So-called 'cane-on-cane' period of the 1980s and 1990s – sugarcane grown as a plant crop and three ratoons, using replant (plant crop established soon after harvest of the last ratoon) with limited bare fallow areas. GCTB started to replace the burnt system towards the end of the 1980s.

- The 'improved' system of the 2000s – sugarcane grown as a plant crop and four ratoons with break crops grown between sugarcane crop cycles. Green-cane trash retention widely used in most areas, with the exceptions continuing to be the Burdekin region and northern New South Wales.

During the 'cane-on-cane' period, N inputs increased substantially from an average 115 kg N/ha for plant cane and 120 kg N/ha for ratoon cane, to 150 kg N/ha for plant cane and 170 kg N/ha for ratoon cane (Schroeder *et al*, 2009a). This trend occurred despite the existence of the rather 'generous' N rates based on the BSES-derived production functions (herein referred to as the 'BSES' or 'traditional' N rates) contained in the Australian Sugarcane Nutritional Manual (Calcino, 1994). These guidelines (Table 2.1) were general in nature, with only 'richland' soils separated from all other soils, and the Burdekin region having separate recommendations to the other regions (Chapman, 1994). A distinction in N rates was made between fallow plant cane versus replant/ratoon cane. Growers appeared to favour applying higher N rates and adopting their own N management strategies to mitigate against productivity losses (Thorburn *et al*., 2003a). Unfortunately this gave rise to widespread over-use of N fertiliser. It was estimated from surveys that 80% of growers applied N to plant crops (following a fallow) in excess of the BSES N rates, 45% applied N to replant cane in excess of the recommendations, and 44% applied N to ratoon cane in excess of the recommendations (Schroeder *et al*., 2002, Calcino *et al*., 2010).

Table 2.1. BSES / traditional N rates that were based on general production functions (Calcino, 1994)

Soil	Crop	Nitrogen fertiliser recommendations (kg N/ha)	
		Burdekin	All other regions
All soil types	Fallow plant	135 -150	120 – 150
	Replant and ratoons	210 - 250	160 – 200
		All regions	
Richland	Fallow plant	80	
	Replant and ratoons	120	

The grower-developed approaches to N management also gave rise to many symptoms of inefficiency (Schroeder *et al*., 2006a). These included:

- A perception that all soils were are similar (and therefore no justification for varying N inputs according to soil type).
- An assumption that all nutrients reacted with soils in similar ways once they are applied.
- A belief that more fertiliser was better than less, and the extra did little harm anyway.
- A lack of understanding of nutrient losses, their causes and effects.
- Use of generalised fertiliser recommendations across regions.
- Generalised fertiliser applications on the farm – targeting the worst soil and fertilising the whole farm according to that requirement.
- Infrequent use of soil and leaf testing.
- Over application of some nutrients (N and P) and under application of others (K, S and others).
- No check on the adequacy of fertiliser inputs.
- Ongoing questions about nutrient management.
- Few or poorly kept records.
- Little modification of nutrient inputs.
- No adjustment of fertiliser application rates after mill by-products were applied.
- Nitrogen applications not reduced after legume fallow crops.

The circumstances described above necessitated modifications to nutrient management in the industry and opportunities for more precise targeting of inputs (Wood *et al*., 1997). A major prerequisite, however, was the need for sustainability i.e. profitable cane production in combination with environmental responsibility (Schroeder *et al*., 1998). In particular, this led to the development of two new approaches to N management i.e. the SIX EASY STEPS nutrient management principles and program, and the N-Replacement concept. The background and development of these two approaches will be described in the next sections of this chapter. It will include supporting data, experimental results and pertinent information.

2.7 SIX EASY STEPS N management system

The SIX EASY STEPS program was developed using an integrated 'systems' framework (Table 2.2) to refine the BSES/traditional guidelines into soil-specific nutrient management guidelines for each of the major sugarcane producing areas in Australia (Schroeder *et al*., 2006b). The framework was initially applied to the Herbert and Bundaberg districts and progressively introduced across the industry (Queensland Wet Tropics to northern New South Wales). Much attention was focussed on re-assessing the previous N fertiliser recommendations and developing modified guidelines using the 'framework' approach (Schroeder and Wood, 2001; Schroeder *et al*., 2005).

Table 2.2. Steps within the framework for developing soil-specific management guidelines (Schroeder *et al*., 2006b).

Step	Activity	Explanation
1	General assessment	A general review of the existing situation, scientific papers, technical reports and semi-technical publications. Identification of pertinent available resources (data, information, maps, local expertise, etc).
2	Identify major soil types used for sugarcane production	Identification of the major soil types used for sugarcane production by utilising pre-existing soil maps / soil mapping information in conjunction with maps of cane blocks, preferably in a GIS. The more detailed the mapping, the more appropriate the information for establishing soil/site specific nutrient management strategies. Cross-referencing of local soil names to the Great Soil Group and Australian Soil Classification Systems aid in comparisons across regions.
3	Establish soil reference sites	Comprehensive assessments of major soil types present to determine differences in the morphological, chemical and physical properties. Comparison of the basic soil chemical and physical data with expected ranges, medians or means (from soil mapping data / available data bases) ensures that the reference sites are representative of soil types. Information such as the geographic location, position in the landscape, visual qualities needs to be recorded.
4	Consider and review current information	Review of existing information relating to specific nutrients. Data from past trials and investigations considered to gain an understanding of the current status and existing guidelines. Priority issues established.
5	Conduct glasshouse and / or laboratory experiments	Pot experiments and /or appropriate laboratory investigations conducted using selected soil types covering a range of pertinent soil properties. The information obtained is important to discriminate nutrient availability in contrasting soil types and to determine relative responses to applied nutrients (or amendments).
6	Infer nutrient management strategies	Preliminary nutrient management guidelines developed from the soils information (morphological, chemical and physical properties), reference sites and mapping information, the results of the investigative pot experiments, and any data, including historical commercial soil analysis results, or reviews of data from past investigations (if available).
7	Develop tools to support these strategies	Tools such as soil testing, leaf analysis and integrated nutrient-management approaches are developed to ensure that growers can make informed decisions about nutrient inputs. Not only is it important that growers have access to such tools, but it is equally important that guidelines for interpreting the analytical data are scientifically based and updated and/or modified when appropriate.
8	Validate the strategies	Further glasshouse or laboratory investigations are conducted and replicated small-plot field trials are established. The results are used to validate the nutrient-management strategies that were inferred from the original pot experiments and soil data, and to update the guidelines used for interpreting nutritional data. The information gained from the field experiments will help to identify further research needs.
9	Present the nutrient management package to users	Information about the system, the reason for its development, its basis and outcomes are communicated to the industry via 'train-the-trainer' short courses, workshops, posters, grower meetings, scientific papers and semi-technical articles, etc., to ensure that the latest information can be utilised by stakeholders. Refresher presentations should be given on a regular basis.
10	Demonstrate advantages of the nutrient management strategies	On-farm participative strip trials and/or replicated small plot trials are used to demonstrate the advantages of improved nutrient-management practices. A combination of visual qualitative differences and statistical data is important in conveying the messages to the grower community and instilling confidence in the modified guidelines.
11	Identify innovative approaches to enhance the system	The series of preceding steps are used to identify deficiencies in current diagnostic and predictive capability. Innovative approaches are identified and possible modifications postulated. This step provides a feed-back loop to (5) Conduct pertinent glasshouse and laboratory investigations, and/or (6) Infer nutrient management strategies.

As a result of the investigative work associated with the use of the framework described above, the N guidelines within the SIX EASY STEPS program are based on a combination of district yield potential (DYP) that determine the baseline N application rate for each district, and a soil N mineralisation index to take account of soil type (Schroeder *et al*., 2005). Discounts are applicable for various other sources of N within the sugarcane cropping system.

District yield potential

The DYP was determined from the best possible yield averaged over all soil types within a district over the period of 1990 to 2008. It is defined as the estimated highest average annual district yield (EHAADY) multiplied by a factor of 1.2 (Schroeder *et al*., 2010a). The multiplier accounts for the fact that some farms/blocks yield higher than EHAADY particularly in seasons characterised by favourable/well-distributed rainfall patterns.

The mill statistics indicated that the EHAADY value for most districts within the Queensland sugarcane industry (Northern Tropics (Mossman and Mulgrave), Wet Tropics (South Johnstone, former Babinda and Mourilyan mills and Tully), Herbert (Victoria and Macknade) and Bundaberg (Millaquin, Bingera and the former Fairymead) was most appropriately set at 100 t cane/ha (as indicated by the horizontal line in Figures 2.4, 2.5, 2.6 and 2.7). The EHAADY for the Proserpine and Mackay districts was set at 110 t cane/ha (Figure 2.8). When the SIX EASY STEPS program was initially developed for the Burdekin region, the EHAADY value was set at 125 t cane/ha (Figure2. 9). However, local expertise and individual farm data suggested that higher average annual yields were possible in some sub-districts / farms in the Burdekin district. Two EHAADY values (125 and 150 t cane/ha) were therefore established for the Burdekin region. The EHAADY and DYP values for the Queensland sugar industry are shown in Table 2.3. It should be note that since 1999, the average annual district yield for Proserpine and Mackay has been lower than in previous years, suggesting that EHAADY should be reassessed from time to time (probably using a rolling 20-year period). In contrast to the decrease in average annual district yield observed in Proserpine/Mackay in recent years, the Burdekin yields have remained more or less stable (Figure 2.9).

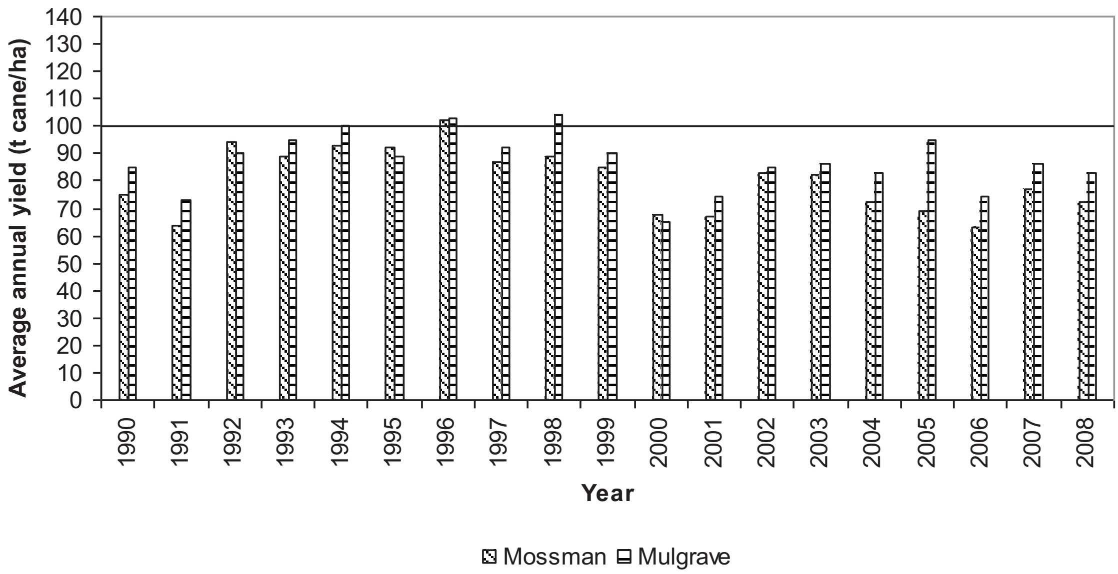


Figure 2.4. Average annual district yields for Mossman and Mulgrave mill areas within the Northern Tropics: 1990 to 2008 (Schroeder *et al.*, 2010a).

The horizontal line indicates the estimated highest average annual district yield (EHAADY) = 100 t cane/ha.

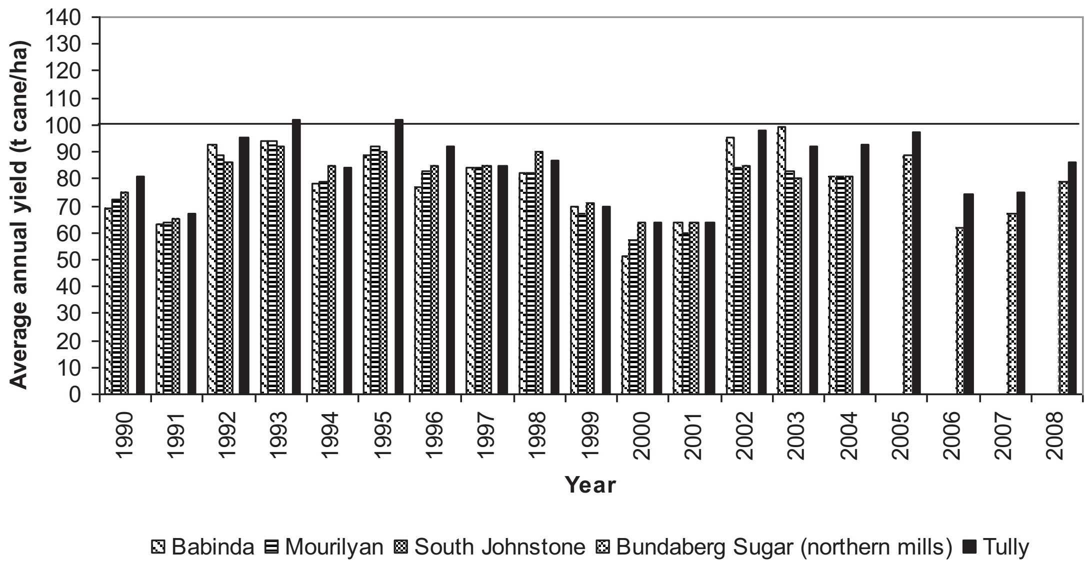


Figure 2.5. Average annual district yields for Babinda, former Mourilyan, South Johnstone and Bundaberg Sugar (northern mills) mill areas within the Wet Tropics: 1990 to 2008 (Schroeder *et al.*, 2010a).

The horizontal line indicates the estimated highest average annual district yield (EHAADY) = 100 t cane/ha.

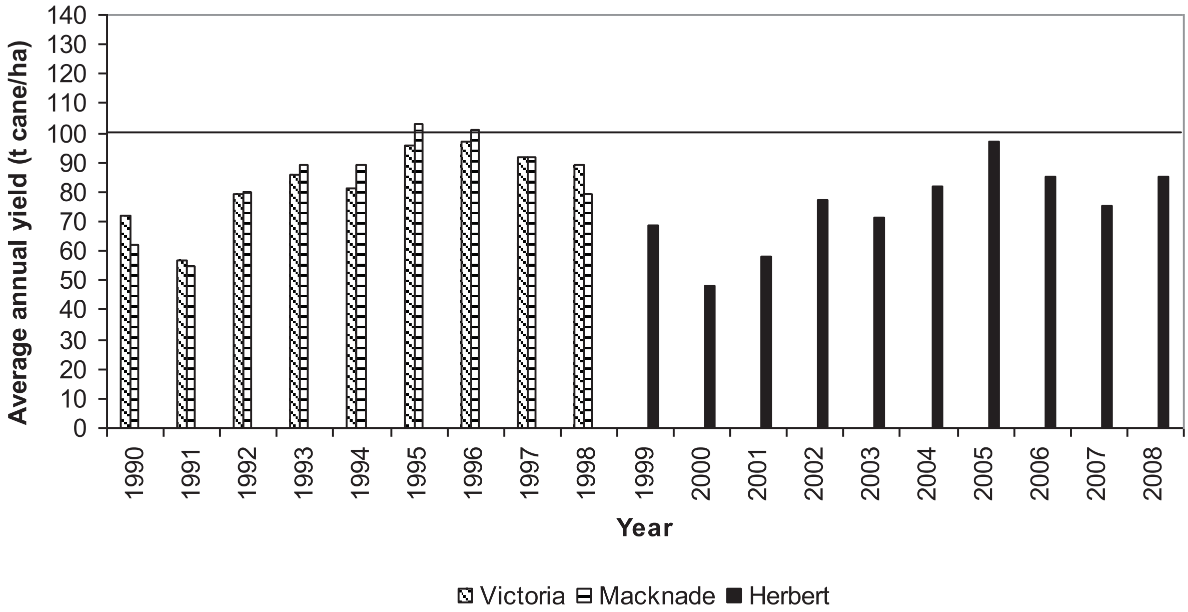


Figure 2.6. Average annual district yields for former Victoria and Macknade mill area within the Herbert district (moist tropics):1990 to 2008 (Schroeder *et al*., 2010a).

The horizontal line indicates the estimated highest average annual district yield (EHAADY) = 100 t cane/ha.

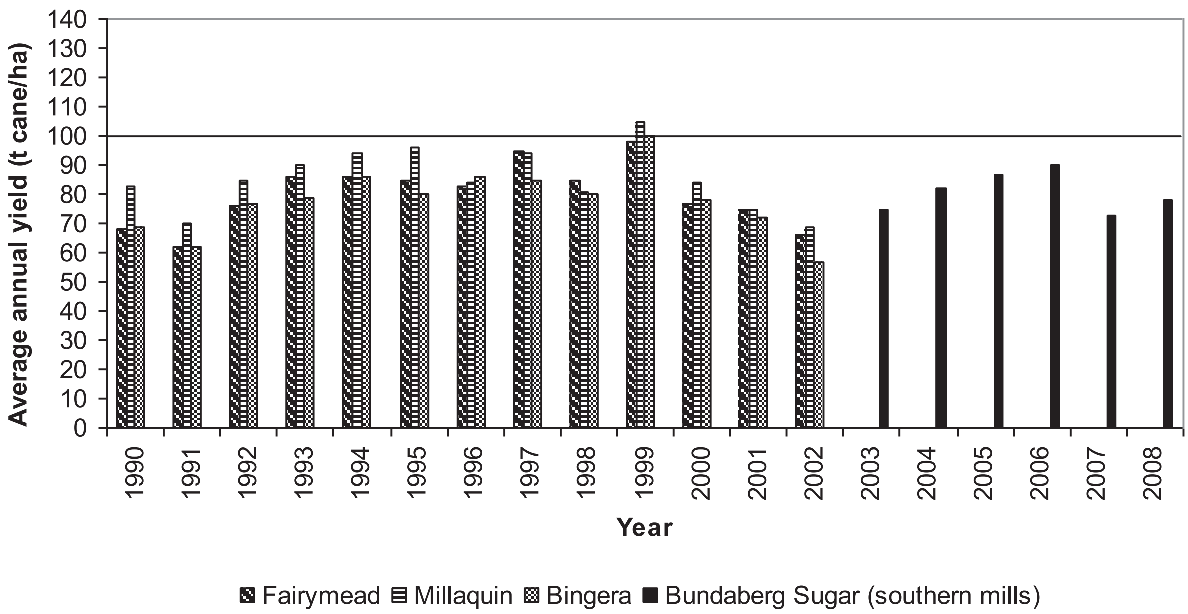


Figure 2.7. Average annual district yields for former Fairymead, Millaquin, Bingera and current Bundaberg Sugar (southern mills) mill areas within the Bundaberg district: 1990 – 2008 (Schroeder *et al*., 2010a).

The horizontal line indicates the estimated highest average annual district yield (EHAADY) = 100 t cane/ha.

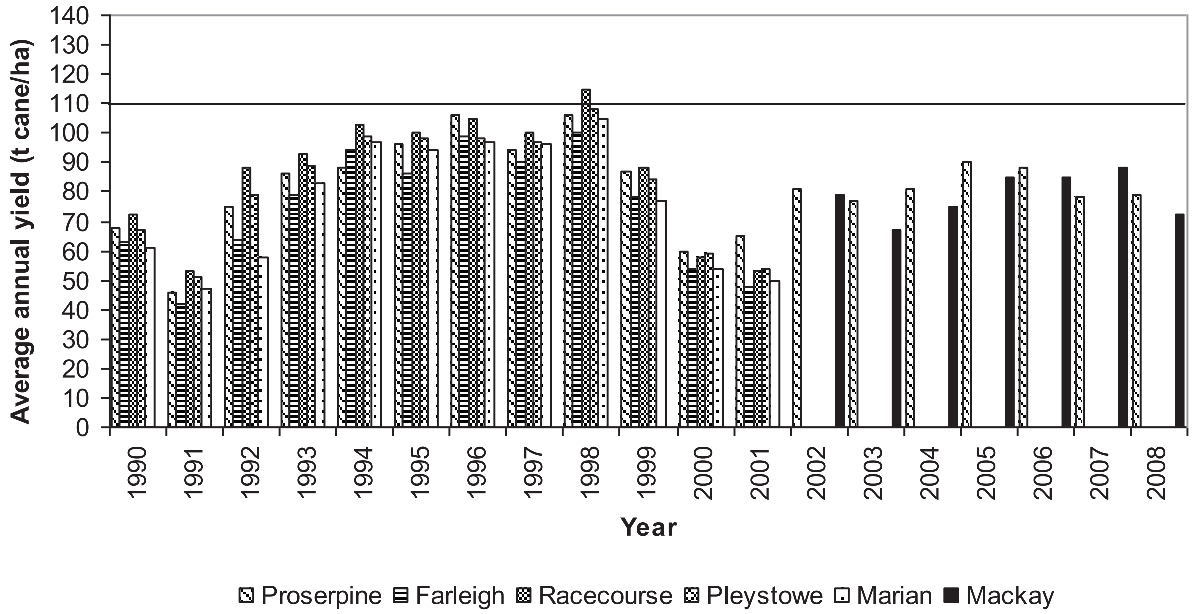


Figure 2.8. Average annual district yields for Proserpine and Mackay (Farleigh, Racecourse, Pleystowe and Marian) mill areas within the Mackay/Whitsundays (Central) region: 1990 – 2008 (Schroeder *et al*., 2010a).

The horizontal line indicates the estimated highest average annual district yield (EHAADY) = 110 t cane/ha.

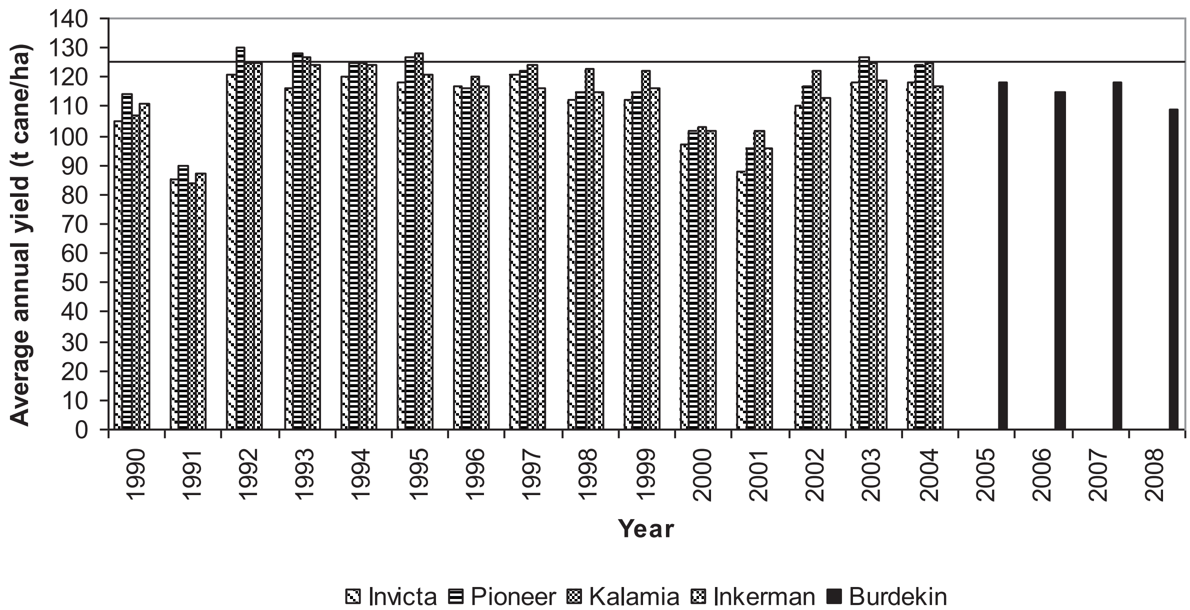


Figure 2.9. Average annual district yields for former Invicta, Pioneer, Kalamia and Inkerman and current CSR Burdekin mill areas within the Burdekin region: 1990 – 2008 (Schroeder *et al*., 2010a).

The horizontal line indicates the estimated highest average annual district yield (EHAADY) = 125 t cane/ha.

Table 2.3. Estimated highest average annual district yields (EHAADY) and district yield potentials (DYP) used within the SIX EASY STEPS program for the different sugarcane producing regions and districts in Queensland (Schroeder *et al*., 2010a).

Region	District	EHAADY (t cane/ha)	DYP (t cane/ha)
Wet Tropics	Cairns (Mulgrave / Mossman)	100	120
	Innisfail / Babinda and Tully	100	120
Herbert (moist tropics)	Herbert	100	120
Mareeba / Dimbulah	Mareeba / Dimbulah	125	150
Burdekin	Lower yielding areas	125	150
	Higher yielding areas	150	180
Mackay – Whitsundays (Central)	Proserpine	110	130
	Mackay	110	130
	Plane Creek	100	120
Southern	Bundaberg / Isis / Maryborough	100	120

Baseline N application rates for each district

District yield potential is used to determine the baseline N application rate for replant and ratoon cane using a multiplier of 1.4 kg N per tonne of cane up to a cane yield of 100 tonnes and 1.0 kg N per tonne of cane thereafter, as previously suggested by Keating *et al*. (1997). This multiplier was developed as a 'rule of thumb' measure of N requirement based on simulated first ratoon crop yields from a well-drained soil at Ingham over 100 years (1895-1994). The baseline N application rate for districts with a DYP of 120 t cane/ha is therefore (100 x 1.4) + (20 x 1.0) = 160 kg N/ha. This increases to 170 kg N/ha for areas with a DYP of 130 t cane/ha, and 190 kg N/ha to 220 kg N/ha for DYPs of 150 and 180 t cane/ha respectively (Schroeder *et al*., 2010a).

Soil N mineralisation index

Baseline N application rates within the SIX EASY STEPS program are adjusted within each region to take account of soil type. This is done by using an N mineralisation index based on soil organic C as determined using the method of Walkley and Black (1934). The use of an N mineralisation index for modifying N fertiliser guidelines for the Australian sugar industry was initially proposed by Schroeder and Wood (2001). Nitrogen mineralisation potentials were determined for selected soils from the Herbert and Bundaberg districts using incubation studies (Saunders *et al*., 1957) to determine the amounts of easily mineralisable N (14 days incubation at field capacity under aerobic conditions) for each soil. Subsequent to that study, easily mineralisable (aerobic) N values were determined for topsoil samples from the soil reference sites that were established across the industry. Easy mineralisable N was found to be reasonably well correlated with Walkley-Black organic C across several regions (r^2 = 0.61) as shown in Figure 2.10. As Walkley-Black organic C is the routine method used in commercial laboratories servicing the Australian sugar industry, it was deemed an appropriate surrogate measure for easily mineralisable N and a suitable basis for the N mineralisation index (Schroeder *et al*., 2005).

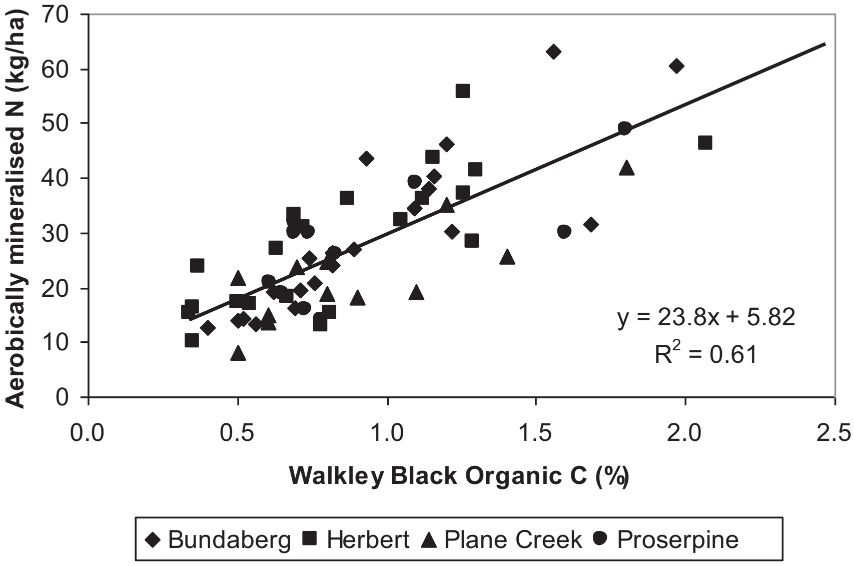


Figure 2.10. Relationship between easily mineralisable (14-day aerobic incubation) N and Walkley-Black organic C (0-25cm sample depth) in four districts in the Australian sugar industry (Schroeder *et al*., 2005).

SIX EASY STEPS N application rates

A combination of the baseline N application rate and the N mineralisation index were then used to determine appropriate N application rates for the areas with a DYP of 120 t cane/ha (Table 2.4). Subsequently the same technique was used to determine N application rates for the other sugarcane districts or regions. Importantly account was also taken of reduced N requirement for plant cane following a bare or grass fallow (Table 2.5).

Table 2.4. Nitrogen guidelines based on the N mineralisation index for areas where the estimated district yield potential is 120 t cane/ha (Schroeder *et al*., 2005).

N mineralisation index	Organic Carbon (%)	Estimate of easily mineralisable (aerobic) N[1] (kg N/ha)	Suggested N rate for ratoons (kg N/ha)
VL	<0.4	<20	160
L	0.41-0.8	20-30	150
ML	0.81-1.2	30-40	140
M	1.21-1.6	40-50	130
MH	1.61-2.0	50-60	120
H	2.01-2.4	60-70	110
VH	>2.4	>70	100

[1]*after Schroeder and Wood (2001)*

Table 2.5. N requirement for plant and ratoon crops (Schroeder *et al*., 2010b).

Crop	Soil organic carbon (%)						
	0 – 0.4	0.4 – 0.8	0.8 – 1.2	1.2 – 1.6	1.6 – 2.0	2.0 – 2.4	> 2.4
Wet Tropics, Herbert, Plane Creek, Bundaberg/Isis, Maryborough (district yield potential = 120 t cane/ha)							
Replant cane and ratoon after replant	160	150	140	130	120	110	100
Plant cane after a grass/bare fallow	140	130	120	110	100	90	80
Proserpine and Mackay (district yield potential = 130 t cane/ha)							
Replant cane and ratoon after replant	170	160	150	140	130	120	110
Plant cane after a grass/bare fallow	150	140	130	120	110	100	90
Burdekin (district yield potential = 150 t cane/ha)							
Replant cane and ratoon after replant	190	180	170	160	150		
Plant cane after a grass/bare fallow	150	140	130	120	110		
Burdekin (district yield potential = 180 t cane/ha)							
Replant cane and ratoon after replant	220	210	200	190	180		
Plant cane after a grass/bare fallow	180	170	160	150	140		

Other sources of N

The SIX EASY STEPS program recognises sources of N other than that supplied by fertiliser applications. These include N from legume fallow / break crops, mill by-products, irrigation water, and residual mineral N remaining after small/vegetable rotational crops (Schroeder *et al*., 2005). The Sugar Yield Decline Joint Venture provided information on how to estimate the amount of N from legume break crops (Garside and Bell, 2001). The amount of N available to the succeeding sugarcane crop is dependent on the type of legume, how well it was grown, and whether the grain was harvested (Table 2.6). The preferred management of leguminous break crops is to leave the stubble standing so that decomposition is slower (with lower rates of N mineralisation) compared with legumes incorporated into the soil as green manures (Bell *et al*., 2003; Garside and Berthelsen, 2004). Incorporation results in large amounts of N being available when the N demand of the establishing plant cane crop is low, resulting in potential loss of the mineralised N by leaching, runoff or denitrification. The amount of N being returned to the soil by a legume crop can be used to adjust the amount of N fertiliser required following different legume fallows. The values shown in **BOLD** in Table 2.6 are used as examples in Table 2.7.

Table 2.6. Calculation of N contribution from a fallow legume based on information from the Sugar Yield Decline Joint Venture (Schroeder *et al.*, 2005).

Legume crop	Fallow crop dry mass (t/ha)	N (% of crop dry mass)	N content above ground (tops)	N content below ground (roots)	Total N contribution	N removed in harvested grain	N contribution if grain harvested
			(kg/ha)				
Soybean	8	3.5	280	80	360	240	120
	6		210	60	270	180	90
	4		140	40	180	120	60
	2		70	20	90	60	30
Cowpea	8	2.8	225	65	290	190	100
	6		170	50	220	145	75
	4		110	35	145	95	50
	2		55	15	70	45	25
Lablab	8	2.3	185	55	240	160	80
	6		140	40	180	120	60
	4		90	30	120	80	40
	2		45	15	60	40	20

Table 2.7. Effect of fallow management on N requirement (Schroeder *et al.*, 2005).

	N application rates in relation to organic C (%) and N mineralisation index categories						
Organic C (%)	<0.4	0.4 - 0.8	0.8 – 1.2	1.2 – 1.6	1.6 – 2.0	2.0 – 2.4	>2.4
N mineralisation index category[1]	VL	L	ML	M	MH	H	VH
Crop							
Replant cane and ratoon after replant	160	150	140	130	120	110	100
Plant cane after a grass/bare fallow	140	130	120	110	100	90	80
Plant cane after a poor legume crop (e.g. 2 t/ha cowpea green manure: N rate minus 70 kg N/ha)	90	80	70	60	50	40	30
Plant cane after a good legume crop (e.g. 6 t/ha soybean: N rate minus 270 kg N/ha)	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Plant cane after a good legume crop harvested for grain (e.g. 6 t/ha soybean: N rate minus 90 kg N/ha)	70	60	50	40	30	20	10
First ratoon after a good legume crop[2]	160	150	140	130	120	110	100
Second ratoon after a good soybean/cowpea crop	160	150	140	130	120	110	100

[1]N mineralisation index categories as indicated in Table 2.4.
[2]Data from the Yield Decline Joint Venture suggest that N applied to the first ratoon sugarcane crop after a good legume crop should follow the normal guidelines and that no reduction be made despite the apparent excess of N being supplied to the plant cane.

Target fertiliser N-use efficiency

The concept of improving NUE is not new to the Australian sugar industry. The information provided thus far in this chapter has illustrated the concepts and developments that have all aimed at improving NUE in various ways. It is widely accepted that from an agronomic viewpoint, nutrient use efficiency should be viewed in terms of yield per unit of nutrient applied. This is also termed Partial Factor Productivity (Dobermann, 2007). It can be considered as the product of recovery and utilisation (Wood and Kingston, 1999) as shown in Equation 1 below:

Yield/unit nutrient applied = (unit nutrient taken up/unit nutrient applied) x (yield/unit nutrient taken up)

i.e. YIELD EFFICIENCY = RECOVERY x UTILISATION) …. *Equation 1*

Yield efficiency should be the objective of any commercial cropping system. Increases in nutrient use efficiency should be viewed as either achieving:

- The same yield with less fertiliser,
- Greater yield with less fertiliser, or,
- Greater yield with the same amount of fertiliser (Wood and Kingston, 1999).

Based on the above, two terms exist for reporting on NUE. These are:

- Fertiliser N-use efficiency factor (t cane/kg N) = yield (t cane/ha) / N applied (kg N/ha), and corresponds to the term "Partial Factor Productivity" mentioned above.
- N fertiliser utilisation index (kg N/t cane produced) = N applied (kg N/ha) / yield (t cane/ha). This is the reciprocal of "Partial Factor Productivity".

In this equation, no account is taken of yield at nil applied N, as is the case in some other agricultural industries. Bell *et al*. (2014) (this review) refer to this index as the "Apparent Agronomic Efficiency of Fertiliser N".

Fertiliser guidelines such as the SIX EASY STEPS program aim to improve NUE by ensuring that N fertiliser utilisation is as low as possible, or the fertiliser N recovery is as high as possible. The proviso is that productivity and profitability are not negatively affected. As these 'efficiency' terms are reciprocals of each other, both the rate of N applied and the cane yield influence these calculated values.

The values shown in Table 2.8 (recommended application rates and DYP) were used to determine the target N fertiliser utilisation index (N application rate / DYP) and fertiliser N-use efficiency (district potential yield / N application rate) values that apply to replant / ratoon cane and plant cane in each of the districts (Table 2.9). The target N fertiliser utilisation index value ranges from 1.33 kg N/t cane (for replant / ratoon cane grown on soils with very low soil organic C in districts with a yield potential of 120 t cane/ha) to 0.61 kg N/t cane (for plant cane grown on soils with 1.6% organic C in the higher yield potential (180 t cane/ha) areas of the Burdekin region. Target fertiliser N-use efficiencies therefore range from 0.75 t cane/kg N to 1.64 t cane/kg N respectively. These values reflect the N contribution from soil organic matter and are therefore always higher than normally indicated by the so-called Apparent Agronomic Efficiency of Fertiliser N.

With account taken of other sources of N (legume fallow crops, residual mineral N remaining after horticultural crops that are grown in rotation with sugarcane, and irrigation water), lower N fertiliser utilisation with corresponding higher apparent fertilisation N-use efficiencies (Table2.9). Where sources of N supply enough N to meet the N requirement for sugarcane production, the N fertiliser utilisation index will be zero.

The SIX EASY STEPS program recognises that if a sub-district or farm consistently produces higher yields than the DYP, the baseline application rate should be adjusted upward by 1 kg applied N per tonne of cane above the DYP. For example if the overall yield on a farm in the Bundaberg/Isis district, calculated over a ten year period, is 130 t cane/ha, then the baseline N application should be set at 170 kg N/ha. The N application rates based on soil organic carbon would then be 10 kg N/ha greater than those shown in Table 2.4 and be in line with the values shown for the Mackay / Proserpine district. Conversely, if a sub-district or farm consistently produces lower yields than the DYP, the baseline N application rate should be decreased using the same approach. Obviously if these adjustments are made, the two target N-use efficiency factors will be influenced.

Table 2.8. Target fertiliser N-use efficiency and N fertiliser utilisation index values calculated for the N management guidelines in the SIX EASY STEPS program (Schroeder *et al.*, 2010).

Crop	Soil organic carbon (%)						
	0 – 0.4	0.4 – 0.8	0.8 – 1.2	1.2 – 1.6	1.6 – 2.0	2.0 – 2.4	> 2.4
Wet Tropics, Herbert, Plane Creek, Bundaberg/Isis/Maryborough (DYP* = 120 t cane/ha)							
Replant cane and ratoon after replant	160	150	140	130	120	110	100
Target N fertiliser utilisation index (kg N/t cane)	1.33	1.25	1.17	1.08	1.00	0.92	0.83
Target fertiliser N-use efficiency (t cane/kg N)	0.75	0.80	0.86	0.92	1.00	1.09	1.20
Plant cane after a grass/bare fallow	140	130	120	110	100	90	80
Target N fertiliser utilisation index (kg N/t cane)	1.17	1.08	1.00	0.92	0.83	0.75	0.67
Target fertiliser N-use efficiency (t cane/kg N)	0.86	0.92	1.00	1.09	1.20	1.33	1.50
Proserpine and Mackay (DYP = 130 t cane/ha)							
Replant cane and ratoon after replant	170	160	150	140	130	120	110
Target N fertiliser utilisation index (kg N/t cane)	1.31	1.23	1.15	1.08	1.00	0.92	0.85
Target fertiliser N-use efficiency (t cane/kg N)	0.76	0.81	0.87	0.93	1.00	1.08	1.18
Plant cane after a grass/bare fallow	150	140	130	120	110	100	90
Target N fertiliser utilisation index (kg N / t cane)	1.15	1.08	1.00	0.92	0.85	0.77	0.69
Target fertiliser N-use efficiency (t cane/kg N)	0.87	0.93	1.00	1.08	1.18	1.30	1.44
Burdekin (DYP = 150 t cane/ha)							
Replant cane and ratoon after replant	190	180	170	160	150		
Target N fertiliser utilisation index (kg N/t cane)	1.27	1.20	1.13	1.07	1.00		
Target fertiliser N-use efficiency (t cane/kg N)	0.79	0.83	0.88	0.94	1.00		
Plant cane after a grass/bare fallow	150	140	130	120	110		
Target N fertiliser utilisation index (kg N/t cane)	1.00	0.93	0.87	0.80	0.73		
Target fertiliser N-use efficiency (t cane/kg N)	1.00	1.07	1.15	1.25	1.36		
Burdekin (DYP = 180 t cane/ha)							
Replant cane and ratoon after replant	220	210	200	190	180		
Target N fertiliser utilisation index (kg N/t cane)	1.22	1.17	1.11	1.06	1.00		
Target fertiliser N-use efficiency (t cane/kg N)	0.82	0.86	0.90	0.95	1.00		
Plant cane after a grass/bare fallow	180	170	160	150	140		
Target N fertiliser utilisation index (kg N/t cane)	0.83	0.78	0.72	0.67	0.61		
Target fertiliser N-use efficiency (t cane/kg N)	1.20	1.29	1.38	1.50	1.64		

**DYP = district yield potential*

Table 2.9. Target fertiliser N-use efficiency and N fertiliser utilisation index values for plant cane following legume fallow crops where DYP = 120 t cane/ha) (after Schroeder *et al*., 2010).

Crop	Soil organic carbon (%)						
	0.0 – 0.4	0.4 – 0.8	0.8 – 1.2	1.2 – 1.6	1.6 – 2.0	2.0 – 2.4	> 2.4
Plant (baseline N application rate)	140	130	120	110	100	90	80
Target N fertiliser utilisation index (kg N/t cane)	1.17	1.08	1.00	0.92	0.83	0.75	0.67
Target fertiliser N-use efficiency (t cane/kg N)	0.86	0.92	1.00	1.09	1.20	1.33	1.50
Plant following a poor legume fallow	90	80	70	60	50	40	30
Target N fertiliser utilisation index (kg N/t cane)	0.75	0.67	0.58	0.50	0.42	0.33	0.25
Target fertiliser N-use efficiency (t cane/kg N)	1.33	1.50	1.71	0.92	2.00	3.00	4.0
Plant following a good legume harvested for grain	70	60	50	40	30	20	10
Target N fertiliser utilisation index (kg N/t cane)	0.58	0.50	0.42	0.33	0.25	0.17	0.08
Target fertiliser N-use efficiency (t cane/kg N)	1.71	2.00	2.40	3.00	4.00	6.00	12.0

Details of investigations that underpin the SIX EASY STEPS program

Several replicated small plot experiments provided initial data for the development of the SIX EASY STEPS N program and further validation and/or a sound scientific basis for modifications to the N guidelines (Wood *et al*., 2008). These trials include:

- Herbert H1: Four rates of N (0, 75, 150, 225 kg N/ha) and three varieties (Q158, Q179, NCo310) on a River Bank soil (Macknade series). This trial was terminated after a sugarcane crop cycle.
- Bundaberg BA: Four rates of N [0, 80, 120, 160 kg N/ha (ratoon 1)] and 3 rates of N [(0, 120, 240 kg N/ha (ratoon 2)] on a Redoxic Hydrosol (Clayton series). This trial was terminated after the 2nd ratoon crop.
- Bundaberg BB: Four rates of N (0, 75, 150, 225 kg N/ha) on a Brown Ferrosol (Telegraph series). This trial was terminated after the 2nd ratoon crop.
- Bundaberg BC and BD: Four rates of N (0, 75, 150, 225 kg N/ha) on a Red/Yellow Dermosol (Otoo/Kepnock series).
- Herbert H2 and H3: Trials to compare responses to applied N of sugarcane grown conventionally (1.5 m row spacing) with that grown on pre-formed beds (1.8 m row spacing). These trials are located on a sandy River Bank soil (Macknade series) and a heavier Clay Loam soil (Leach series). Legume break crops are grown between sugarcane crop cycles. These trials are on-going, and are currently in their second crop cycle.
- Bundaberg B1: Four rates of N (0, 75, 150, 225 kg N/ha) and four rates of K (0, 60, 120, 180 kg K/ha) on a Red Clay Loam soil (Otoo series). Legumes are grown as break crops between sugarcane crop cycles. This trial is on-going, and is currently in the last ratoon of the second crop cycle.
- Bundaberg B2: Four rates of N (0, 75, 150, 225 kg N/ha) and four rates of P (0, 15, 30, 45 kg P/ha) on a Humic Gley soil (Fairymead series). The crop was established after a soybean fallow crop. This trial was terminated after a sugarcane crop cycle.

- Mackay M1: Four rates of N (0, 75, 150, 225 kg N/ha) and four 'farming systems' treatments on a non-calcic brown soil (Pioneer series). The 'farming system' treatments include combinations of row spacings (1.5 m and 1.8 m), fallow management (bare and legume fallows), tillage practices (conventional and minimum tillage on pre-formed beds) and previous green cane and burnt systems.
- Tully T1: Four rates of N (Plant crop: 0, 50, 100, 150 kg N/ha; ratoons: 0, 80, 160, 240 kg N/ha) on a Redoxic Hydrosol (Coom series). This trial was located on a previous long-term green cane vs. burnt systems trial. The trial was terminated after a sugarcane crop cycle.
- Tully T2: N trial on a Humic Gley soil (Hewitt series) to validate N requirements on high organic matter soils in the wet tropics. This trial was terminated after a sugarcane crop cycle.
- Tully T3, T4 and T5: Twelve rates of N (0, 30, 60, 75, 90, 105, 120, 135, 150, 180, 210, 240 kg N/ha) on Grey Dermosol (Bulgun series). These trials form part of Danielle Skocaj's PhD project and are on-going, currently under the 4th ratoon crop. Data from these trials will not be presented or discussed here. They are mentioned as a preamble to the later discussion about using climate forecasting to guide N rates in the Wet Tropics.

Results from the initial field trials (Table 2.10) conducted in the Herbert and Bundaberg districts provided data for the development of SIX EASY STEPS N guidelines (Table 2.4 and 2.5). Trials BC and BD were established in the same year and were located on adjacent blocks on the same soil type (Schroeder *et al*., 2005).

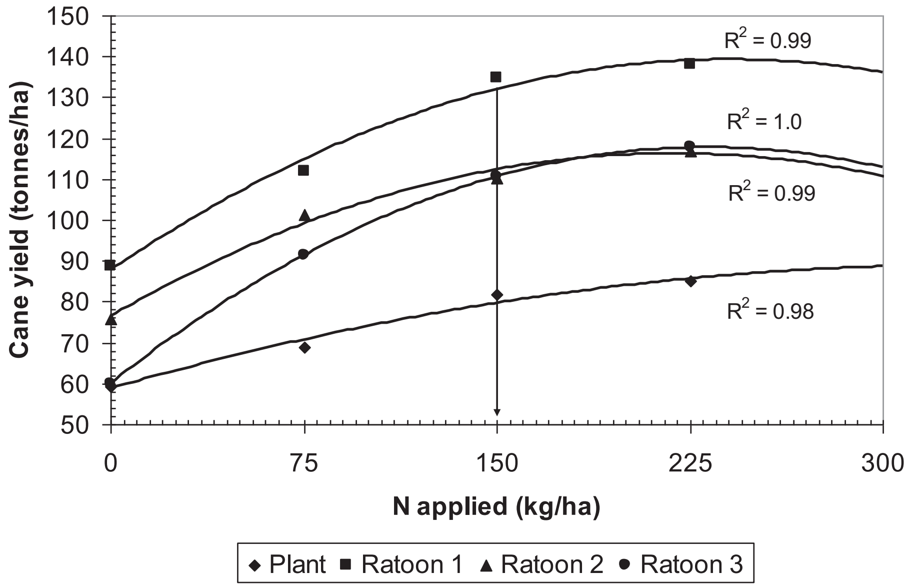
Table 2.10. Summary of recent sugarcane nutrition field trials conducted in the Herbert and Bundaberg districts.

Location and trial number	Soil details		Crops
	Type[1]	Org C (%)[2]	
Herbert (H1)	Chernic Tenosol (River Bank)	0.70	Plant & 3 ratoons
Bundaberg (BA)	Redoxic Hydrosol (Clayton)	1.23	2 ratoons
Bundaberg (BB)	Brown Ferrosol (Telegraph)	1.12	2 ratoons
Bundaberg (BC)	Red/Yellow Dermosol (Otoo/Kepnock)	1.06	1 ratoon
Bundaberg (BD)			2 ratoons

[1]*Australian Soil Classification followed by local soil mapping unit name in brackets.*
[2]*Organic C (%) using the method of Walkley and Black (1934).*

Analysis of variance was used to determine differences in both cane and sugar yield resulting from N treatments. Mean values were separated using least significant differences (LSDs). The quadratic functions fitted to the data allowed appropriate N application rates to be determined for each trial by determining values corresponding to 95% of the predicted maximum yield as indicated by the arrows in Figures 2.11 – 2.14. The initial lack of response to applied N in trial BC (Figure 14) was probably due to residual N in the soil profile and/or N being applied through irrigation water.

Data and results from the other trials identified above (Herbert H2 and H3, Bundaberg B1 and B2, Mackay M1, and Tully T1, T2, T3, T4 and T5) have been, or are being used, to further validate the SIX EASY STEPS guidelines, and provide information for specific circumstances and investigations (as described below in the section entitled "Validation and value of the different approaches to N management".

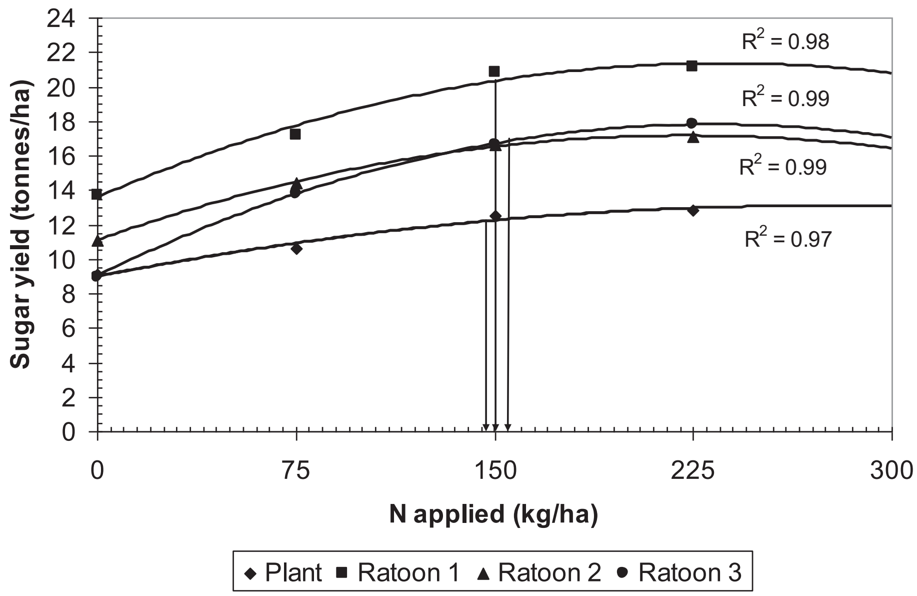


Plant: SE = 3.74; LSD (0.05) = 7.86; LSD (0.01) = 10.78

Ratoon 1: SE = 5.06; LSD (0.05) = 10.62; LSD (0.01) = 14.55

Ratoon 2: SE = 6.21; LSD (0.05) = 13.06; LSD (0.01) = 17.89

Ratoon 3: SE = 5.08; LSD (0.05) = 10.67; LSD (0.01) = 14.62



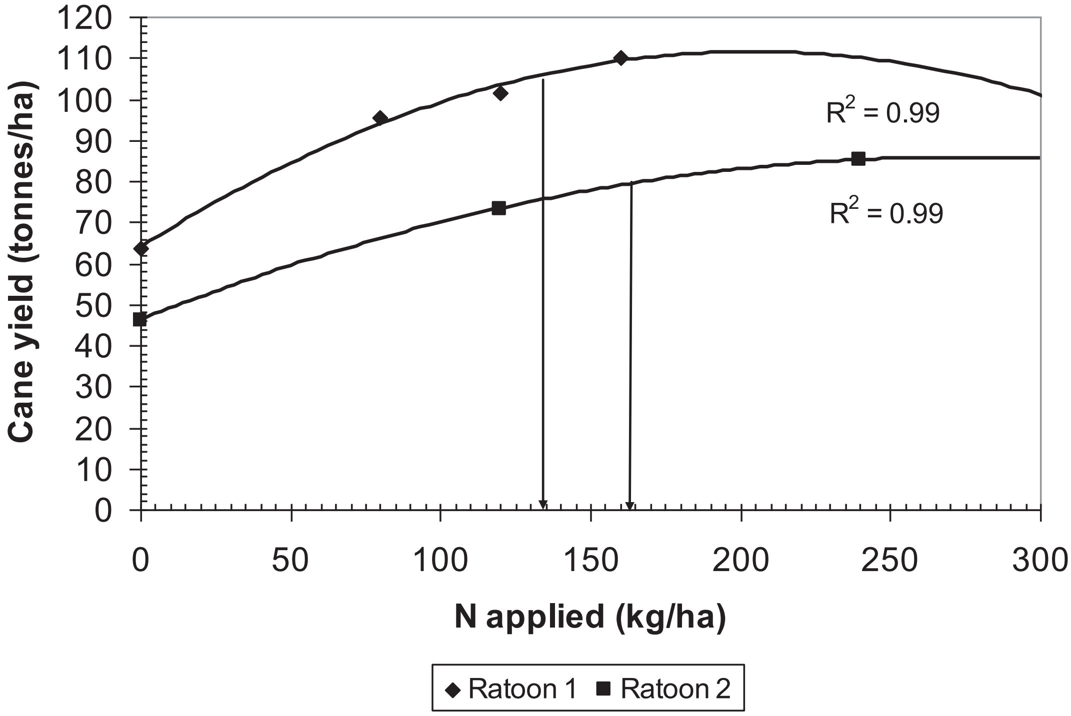
Plant: SE = 0.65; LSD (0.05) = 1.37; LSD (0.01) = 1.88

Ratoon 1: SE = 0.79; LSD (0.05) = 1.66; LSD (0.01) = 2.28

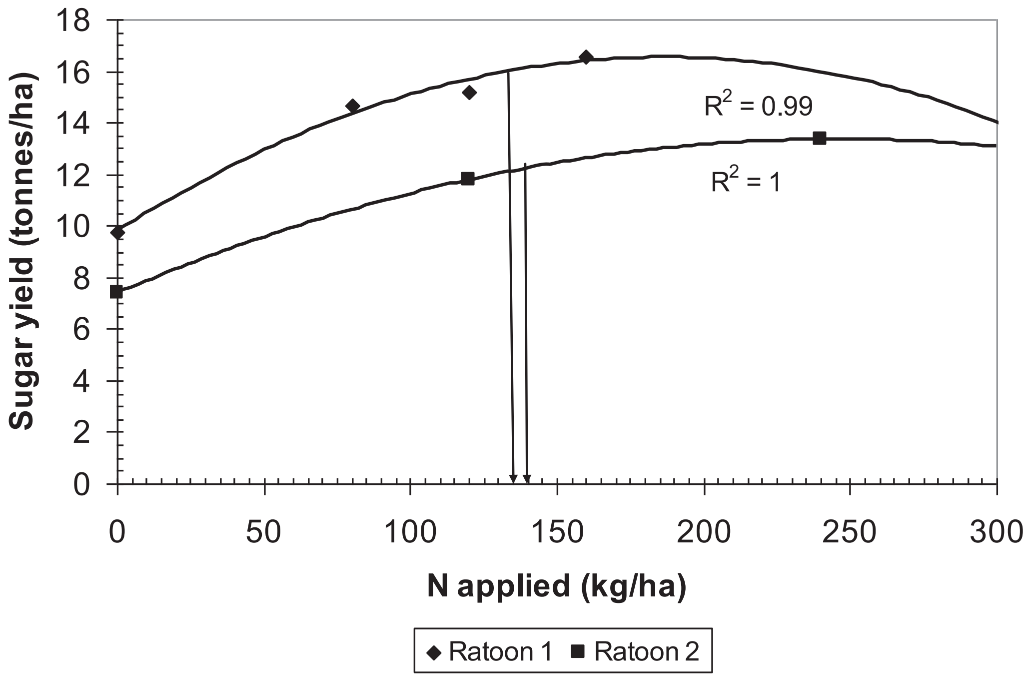
Ratoon 2: SE = 0.97; LSD (0.05) = 2.04; LSD (0.01) = 2.80

Ratoon 3: SE = 0.79; LSD (0.05) = 1.66; LSD (0.01) = 2.28

Figure 2.11. Yield response curves (cane and sugar) resulting from N applied to a Herbert trial (H1). The arrows indicate the application rate corresponding to 95% of the maximum yield predicted by the quadratic functions fitted to the data points (R2 values are shown). In terms of the plant crop the arrows indicate the N rate corresponding to 95% of the yield attained at the highest N application rate (Schroeder et al., 2005).

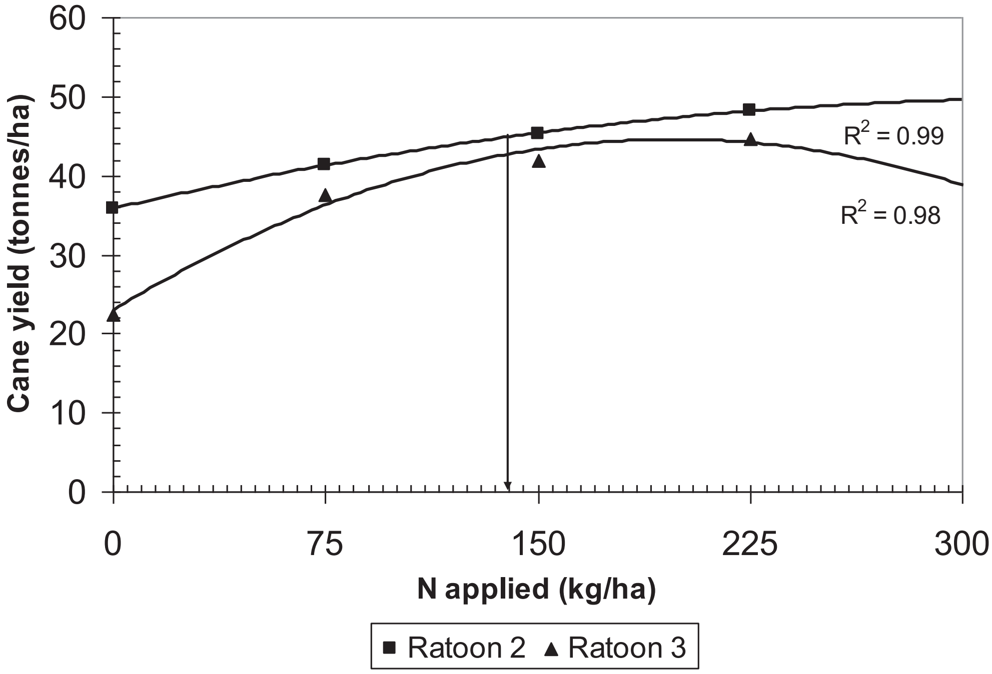


Ratoon 1: SE = 6.64; LSD (0.05) = 14.47; LSD (0.01) = 20.28
Ratoon 2: SE = 2.28; LSD (0.05) = 4.70; LSD (0.01) = 6.37

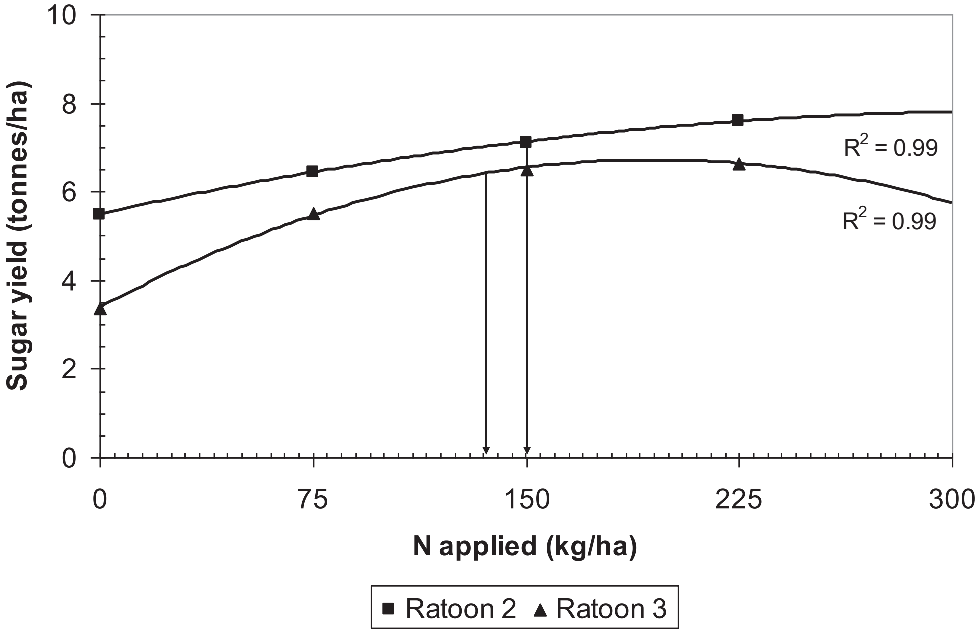


Ratoon 1: SE = 0.92; LSD (0.05) = 1.99; LSD (0.01) = 2.80
Ratoon 2: SE = 0.37; LSD (0.05) = 0.76; LSD (0.01) = 1.03

Figure 2.12. Yield response curves (cane and sugar) resulting from N applied to a Bundaberg trial (Trial BA). The arrows indicate the application rate corresponding to 95% of the maximum yield predicted by the quadratic functions fitted to the data points. R^2 values are shown in each case (Schroeder *et al*., 2005).

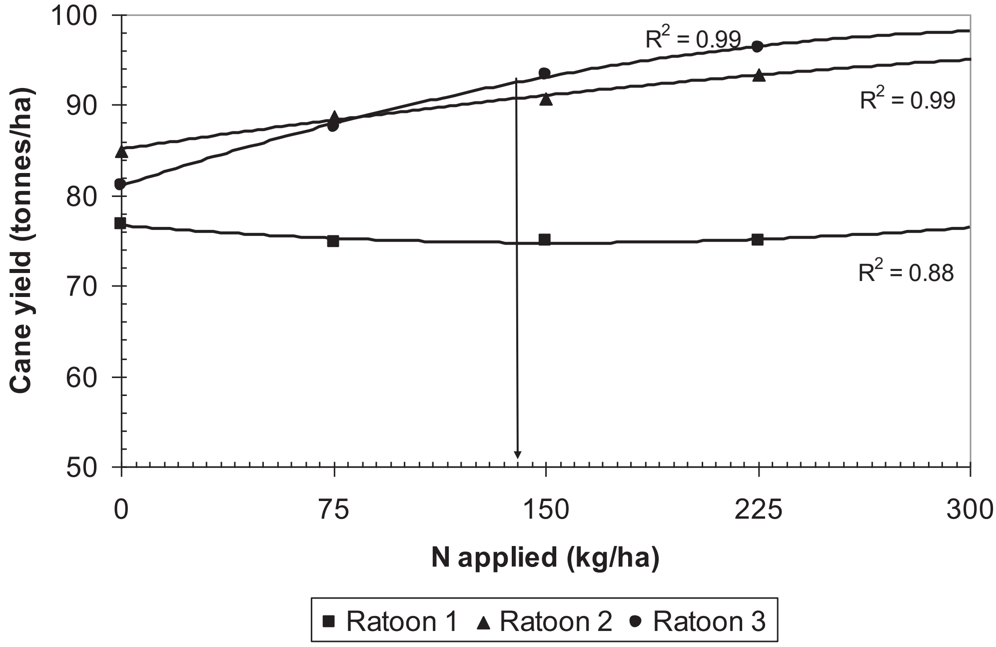


Ratoon 2: SE = 3.14; LSD (0.05) = 6.39; LSD (0.01) = 8.59
Ratoon 3: SE = 3.09; LSD (0.05) = 6.29; LSD (0.01) = 8.45

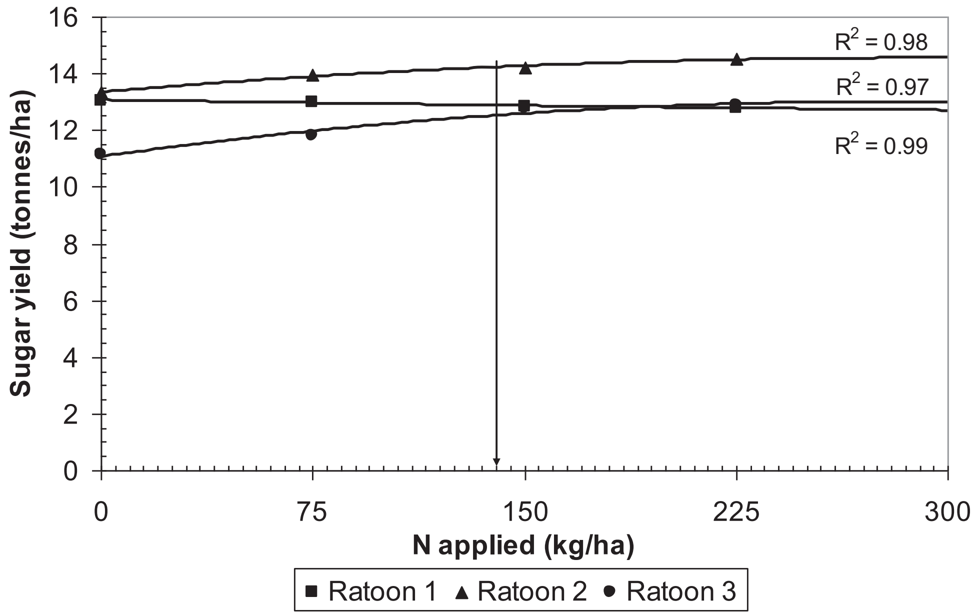


Ratoon 2: SE = 0.49; LSD (0.05) = 1.00; LSD (0.01) = 1.35
Ratoon 3: SE = 0.47; LSD (0.05) = 0.96; LSD (0.01) = 1.28

Figure 2.13. Yield response curves (cane and sugar) resulting from N applied to a Bundaberg trial (Trial BB). The arrows indicate the application rate corresponding to 95% of the maximum yield predicted by the quadratic functions fitted to the data points, R^2 values are shown in each case (Schroeder *et al.*, 2005).



Ratoon 1: SE = 4.12; LSD (0.05) - NS
Ratoon 2:SE = 5.83; LSD (0.05) - NS
Ratoon 3:SE = 3.12; LSD (0.05) = 7.63



Ratoon 1: SE = 0.69; LSD (0.05) – NS
Ratoon 2: SE = 0.92; LSD (0.05) – NS
Ratoon 3: SE = 0.51; LSD (0.05) = 1.24

Figure 2.14. Yield response curves (cane and sugar) resulting from N applied to Bundaberg trials [Trial BC (ratoon 1) and BD (ratoons 2 and 3)]. The arrows indicate the application rate corresponding to 95% of the maximum yield predicted by the quadratic functions fitted to the data points (R^2 values are shown). Due to a significant interaction between N and K applied in ratoon 3, the N response curves for this crop are based on yield data averaged across the K applications of 60 and 120 kg/ha (Schroeder *et al.*, 2005).

2.8 N-Replacement strategy

Genesis of the N-Replacement Strategy

There are various goals that drive philosophies of nutrient management. Soils under native vegetation may be quite fertile, and crops grown on these soils after native vegetation is cleared may need little or no fertiliser (Dalal and Mayer, 1986). However, soil fertility declines as the stores of soil organic matter built up under native vegetation decline under cropping (Wood, 1985) and yields become increasingly limited by the availability of nutrients. At this time increasing attention is usually paid to nutrient management. Initially, nutrient management systems focus on fixed rates of nutrients. However, this approach often results in over-application of nutrients and reduced profitability (Neeteson, 1995). Nutrient management then evolves to systems based on matching the supply of nutrients to crop demand, with demand usually defined by target yields. These systems aim to avoid both the uneconomic over-application of nutrients and the chance of nutrient availability constraining crop yields. As described above, N management in the Australia sugarcane industry has followed this evolutionary pathway.

While matching the supply of N to target yields focuses on achieving productivity and economic goals, target yields may not always be achieved (e.g. Figures 2.4 - 2.9). In this situation N may be applied in excess to the needs of the crop, reducing NUE and grower profitability. Over fertilising crops with N fertilisers may also have detrimental environmental consequences. Thus the next step in the evolution of nutrient management systems is incorporation of environmental goals (Neeteson, 1995) as indicated by both the N-Replacement concept (Thorburn *et al*., 2011) and SIX EASY STEPS program (Schroeder *et al*., 2010b). With the well documented build up and ecological impact of nitrogen in Australia sugarcane growing areas (Thorburn *et al*., 2003b; Brodie *et al*., 2013), the challenge is to better balance economic and environmental goals of N management. The N-Replacement strategy was conceived with this particular challenge in mind (Thorburn *et al*., 2003a; 2007; 2011).

Principles of the N-Replacement strategy

A critical factor in the N-Replacement strategy is the recognition that sugarcane crops get a relatively small amount of N directly from fertiliser, usually about 30-40% of the total N requirement as indicated previously (Chapman, 1994; Vallis *et al*., 1996). The balance is supplied by mineral N in the soil profile and/or that from mineralised organic matter. This situation is not surprising given: (1) the total amount of N in soil organic matter (as much as 3,000 kg/ha to 30 cm depth) dwarfs that in mineral forms (< 100 kg/ha) or applied in fertiliser (Figure 2.3) and (2) measured rates of mineralisation of organic nitrogen (Figure 2.10). Although much of the applied N fertiliser is immobilised by microbes in soil organic matter (Chapman, 1994, Vallis *et al*., 1996; Meier *et al*., 2006), it is subsequently available to crop through the process of mineralisation. In essence, N in soil organic matter provides a substantial buffer between N fertiliser applied to, and the N required by, the crops. Nitrogen fertiliser that is immobilised in soil organic matter will help maintain organic N stores in soils. In this situation, applying N fertiliser to meet average crop yields, may:

- over-fertilise 'small' crops, and either replenish organic N or be lost from the soil (as describe earlier); or
- under-fertilise 'large' crops (which will draw on available mineral N and/or organic N reserves).

The N-Replacement strategy is based on these concepts and provides a framework for aligning N fertiliser applications to the actual amount of sugarcane grown on a field or farm, rather than the potential yields that may be achieved.

A basic aspect of the N-Replacement strategy is that the amount of N removed in a harvested crop needs to be determined. This is done using an estimate of the N concentration of harvested cane [0.6 kg N/t cane (Thorburn *et al*., 2011)], and the actual harvested cane yield within a block. If crops are burnt, the amount of N volatilised through burning trash also needs to be considered. From the N concentration of trash and the amount of trash relative to cane, it is estimated that 0.3 kg N/t cane is lost through burning trash (Thorburn *et al*., 2011). The final attribute that is considered is the proportion of N fertiliser applied that is immobilised in soil organic matter and/or unavoidably lost to the environment relative. This has been estimated to be 0.4 kg N/t cane (Thorburn *et al*., 2011). Thus, to 'replace' the N lost from a field (in harvested cane, to the environment and, where applicable, due to burning), the amount of fertiliser N required by the N Replacement concept is:

- 1 kg N/t cane with green cane trash retention, or
- 1.3 kg N/t cane in burnt systems.

With access to good records, a cane farmer could determine the average yield over a period of time and the N-Replacement concept to determine N fertiliser application rates. Where accurate records are not available, the amount of cane harvested from the previous crop in a block could be used (Thorburn *et al*., 2011).

As well as N from fertiliser, N from fallow legumes and/or mill mud may also be accounted for in the N-Replacement calculations (Park *et al*., 2010; Thorburn *et al*., 2008).

Target fertiliser N-use efficiency

Because N fertiliser applications in the N-Replacement strategy are linked to cane yields, the target N fertiliser utilisation index (kg N/t cane) and N-use efficiency (t cane / kg N) remain constant. The target N fertiliser utilisation index (kg N/t cane) is:

- 1.0 kg N/t cane in green cane, and
- 1.3 kg N/t cane in burnt systems.

The target N-use efficiency (t cane/kg N) is:

- 1.0 kg N/t cane in green cane, and
- 0.8 kg N/t cane in burnt systems.

The degree to which these targets are achieved depend on the accuracy of N applications (i.e., the accuracy of the fertiliser applicator) and trends in yields of successive crops.

2.9 Evaluation of the different approaches to N management

SIX EASY STEPS

Data from the SIX EASY STEPS replicated small plot trials were used to determine response curves in the conventional way (see above) and for other interpretive processes. For example, cumulative response curves for both cane and sugar yields were produced by summing yields from successive crops within the crop cycle and plotting these yields against cumulative N rates (Schroeder *et al*., 2008; 2009b, 2010b). These curves were used to calculate the productivity (cumulative cane and sugar yield), profitability [industry partial net returns (Equation 2 below)] and environmental aspects (fertiliser N-use efficiency) for various N management strategies (Grower-developed, BSES traditional, SIX EASY STEPS and N Replacement approaches)

Industry partial net return = (sugar yield x price of sugar) – (fertiliser cost x application rate (kg/ha) – (cane yield x estimated harvesting costs plus levies) …. Equation 2

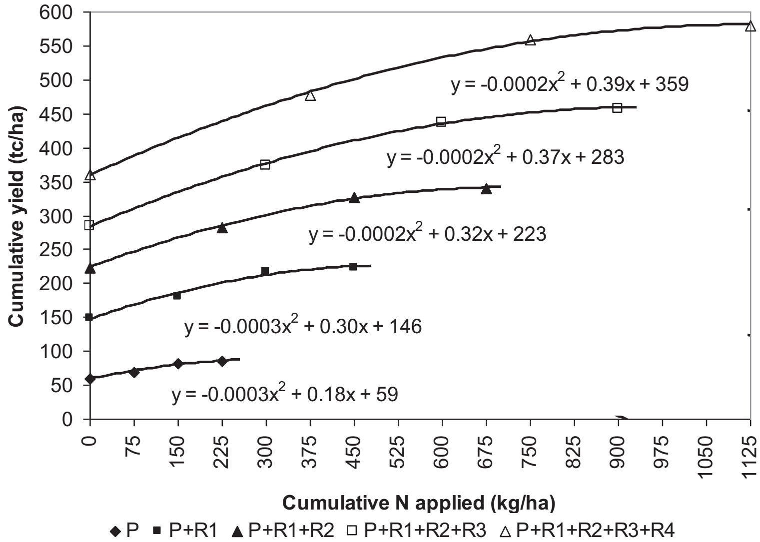
Herbert 1 and Tully 1:

The cumulative cane and sugar response curves for H1 (Schroeder *et al*., 2009b) are shown in Figures 2.15 and 2.16 respectively. The N application rates and corresponding yields obtained from the cumulative response curves for each of the N strategies are shown in Table 2.11. Sugar yields, progressive fertiliser N-use efficiencies (t cane/kg N) and 'industry partial net return' values for the different approaches are shown in Table 2.12. The 'grower-developed' approach (180 kg N/ha/crop) yielded 550 t cane/ha (Table 2.11) and 82.3 t sugar/ha (Table 2.12) over the crop cycle. This resulted in an industry net return of $20,832/ha over 5 years or an average of $4,166/ha/year (Table 2.12). The 'traditional' approach (160 kg N/ha/crop) resulted in a total crop cycle yield of 545 t cane/ha and 81 t sugar/ha, with an average industry net return of $4,173/ha/year. The SIX EASY STEPS N input rate (150 kg N/ha/crop) produced an estimated crop of 541 t cane/ha and 80.9 t sugar/ha for the crop cycle, with a calculated industry net return of $4,165/ha/year. The N Replacement strategy, with N inputs varying according to the yield of the previous crop (Table 2.11), resulted in a total crop cycle yield of 502 t cane/ha and 75.2 t sugar/ha (Table 2.12). The calculated industry net return in this case was $3,993/ha/year.

As with Herbert 1, the data from Tully (T1) were used to determine cumulative cane and sugar yield response curves (Schroeder *et al.*, 2009b). The relationships shown in Figures 2.17 and 2.18). This again enabled yields to be determined for any N input strategy by progressively moving from one response curve to the next as the crop cycle progressed (Table 2.13). The estimated yields (cane and sugar) and calculated industry partial net returns for the different approaches that were tested using Tully data are shown in Table 2.14. The 'grower-developed' approach (150 kg N/ha for the plant crop and 180 kg N/ha/ratoon crop) yielded 304 t cane/ha and 51.2 t sugar/ha over the crop cycle. The industry net return in this case was $3,114/ha/year. The 'traditional' approach (120 kg N/ha for the plant crop, and 160 kg N/ha for each of the ratoons) resulted in a total crop cycle yield of 305 t cane/ha and 51.3 t sugar/ha. The average industry net return was $3,184/ha/year. The SIX EASY STEPS approach (120 kg N/ha for the plant crop and 140 kg N/ha for each ratoons) yielded 303 t cane/ha and 50.9 t sugar/ha for the crop cycle, with an average industry net return of $3,198/ha/year. The N Replacement strategy (N inputs rates as shown in Table 2.14 and calculated

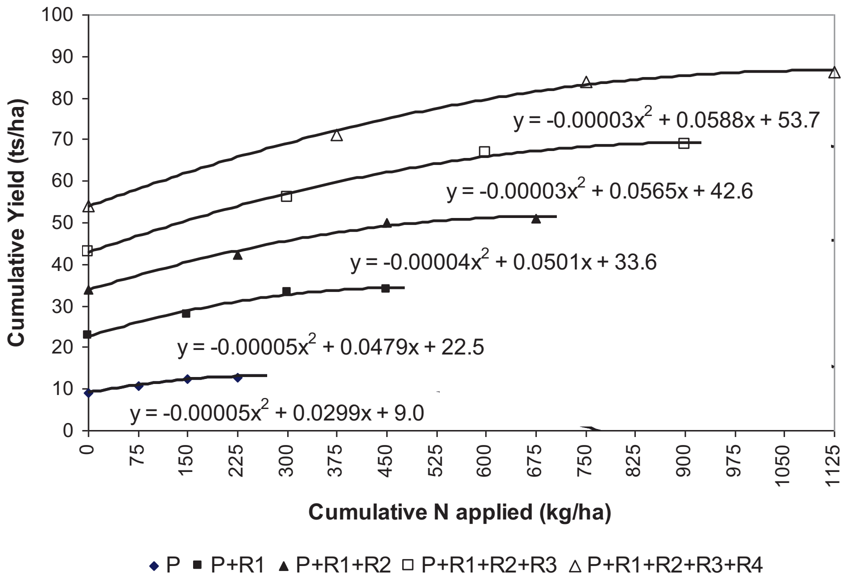
according to the size of the previous crop), resulted in a total crop cycle yield of 277 t cane/ha and 46.3 t sugar/ha. The calculated industry net return was $3,027/ha/year.

The Tully data (Table 2.14) showed that the SIX EASY STEPS approach was the most favourable in terms of the calculated industry net return. The 'grower-developed' approach resulted in a reduced profit of $75/ha/crop compared to the SIX EASY STEPS. The N Replacement strategy, although the most N use efficient (0.66 tc/kg applied N over the crop cycle) resulted in the lowest industry net return ($190/ha/crop lower than that of the SIX EASY STEPS approach). The higher N inputs associated with the 'grower-developed' approach were not warranted because it had the lowest N-use efficiency (0.44 tc/kg applied N over the crop cycle) and did not produce substantially higher yields compared with the SIX EASY STEPS strategy.



P: SE = 2.65; LSD(0.05) = 7.86
P+R1: SE = 4.80; LSD(0.05) = 14.26
P+R1+R2: SE = 7.85; LSD(0.05) = 23.33
P+R1+R2+R3: SE = 9.60; LSD(0.05) = 28.53
P+R1+R2+R3+R4: SE = 11.54; LSD(0.05) = 34.28

Figure 2.15. Herbert trial: cumulative cane yield responses to N applied over a crop cycle [plant crop (P) and four ratoons (R)], with SE and LSD values from the analysis of variance (Schroeder *et al*., 2009b).



P: SE = 0.46; LSD(0.05) = 1.37
P+R1: SE = 0.83; LSD(0.05) = 2.47
P+R1+R2: SE = 1.23; LSD(0.05) = 3.65
P+R1+R2+R3: SE = 1.42; LSD(0.05) = 4.21
P+R1+R2+R3+R4: SE = 1.76; LSD(0.05) = 5.16

Figure 2.16. Herbert trial: cumulative sugar yield responses to N applied over a crop cycle [plant crop (P) and four ratoons (R)], with SE and LSD values from the analysis of variance (Schroeder *et al*., 2009b).

Table 2.11. Herbert trial: N inputs and cumulative cane yields for each of the N management strategies (Schroeder *et al*., 2009b).

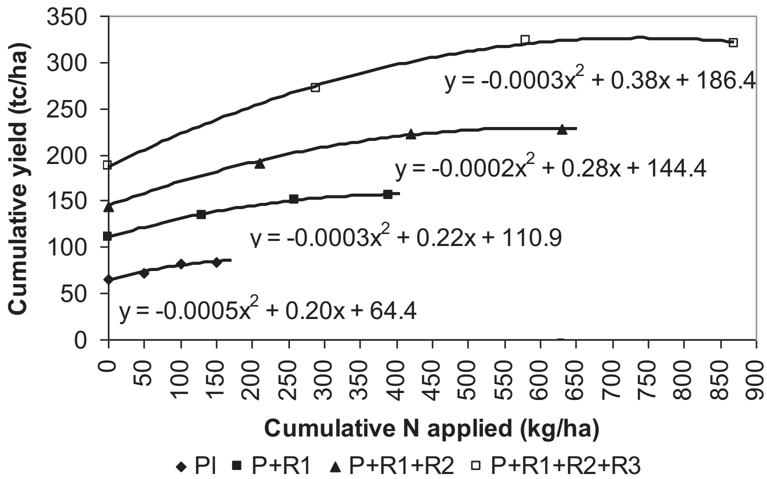
Crop	Grower-developed			Traditional			SIX EASY STEPS			N Replacement		
	N applied per Crop	Cumulative values		N applied per crop	Cumulative values		N applied per crop	Cumulative values		[1]N applied per crop	Cumulative values	
		N applied	Yield		N applied	Yield		N applied	Yield		[2]N applied	Yield
	(kg/ha)		(t cane/ha)	(kg N/ha)		(t cane/ha)	(kg N/ha)		(t cane/ha)	(kg N/ha)		(t cane/ha)
Plant	180	180	81	160	160	80	150	150	79	290	90	72
R1	180	360	217	160	320	213	150	300	211	72	162	188
R2	180	540	340	160	480	333	150	450	328	116	278	298
R3	180	720	444	160	640	436	150	600	432	110	388	395
R4	180	900	550	160	800	545	150	750	541	98	485	502

[1] 1 kg N/t cane in previous crop (Thorburn et al., 2011)
[2] Cane yield of 90 t/ha assumed for the last ratoon of the previous crop cycle. No allowance was made for N removal in the penultimate ratoon.

Table 2.12. Cumulative sugar yields (t sugar/ha), progressive fertiliser N-use efficiencies (t cane/kg N) and calculated industry partial net returns for the Herbert trial (after Schroeder *et al*., 2009b).

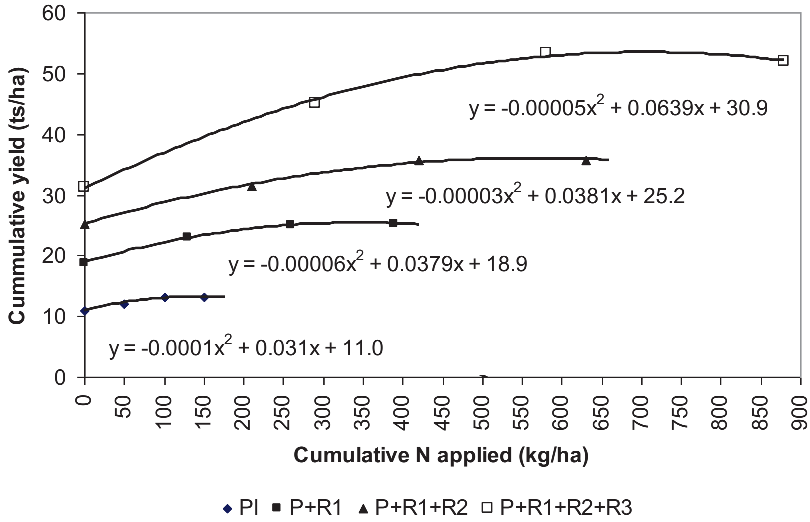
Cumulative crop	Grower-developed		Traditional		SIX EASY STEPS		N Replacement	
	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)
P	12.7	0.45	12.5	0.5	12.3	0.53	11.3	0.8
P+R1	33.3	0.67	32.8	0.67	32.4	0.70	29.0	1.16
P+R1+ R2	49.0	0.63	48.5	0.69	48.1	0.73	44.5	1.07
P+R1+R2+R3	67.8	0.62	66.5	0.68	65.7	0.72	60.0	1.02
P+R1+R2+R3+ R4	82.3	0.61	81.5	0.68	80.9	0.72	75.2	1.04
[1]Industry net return ($/ha)	20832		20864		20825		19916	
Average industry net return ($/ha/year)	4166		4173		4165		3993	
Difference in industry net return from SIX EASY STEPS approach ($/ha/year)	1		8		-		-182	

[1]*Assumptions: Sugar price = $330/tonne, cost of N = $2.60/kg, harvesting costs = $7.25/tonne of cane,*



P: SE = 2.57; LSD(0.05) = 8.90
P+R1: SE = 4.38; LSD(0.05) = 15.17
P+R1+R2: SE = 5.41; LSD(0.05) = 18.73
P+R1+R2+R3: SE = 7.47; LSD(0.05) = 25.83

Figure 2.17. Tully trial: cumulative cane yield responses to N applied over a crop cycle [plant crop (P) and three ratoons (R)], with SE and LSD values from the analysis of variance (Schroeder *et al*., 2009b).



P: SE = 0.50; LSD(0.05): NS,
P+R1: SE = 0.84; LSD(0.05) = 2.89
P+R1+R2: SE = 0.89; LSD(0.05) = 3.10
P+R1+R2+R3: SE = 1.23; LSD(0.05) = 4.27

Figure 2.18. Tully trial: cumulative sugar yield responses to N applied over a crop cycle [plant crop (P) and three ratoons (R)], with SE and LSD values from the analysis of variance (Schroeder *et al*., 2009b).

Table 2.13. Tully trial: N inputs and cumulative cane yields for each of the N management strategies (after Schroeder *et al*., 2009b).

Crop	Grower-developed			Traditional			SIX EASY STEPS			N Replacement		
	N applied per Crop	Cumulative values		N applied per crop	Cumulative values		N applied per crop	Cumulative values		1N applied per crop	Cumulative values	
		N applied	Yield		N applied	Yield		N applied	Yield		N applied	Yield
	(kg/ha)		(t cane/ha)	(kg N/ha)		(t cane/ha)	(kg N/ha)		(t cane/ha)	(kg N/ha)		(t cane/ha)
Plant	150	150	84	120	120	82	120	120	82	2117	117	81
R1	180	330	151	160	280	150	140	260	148	81	198	143
R2	180	510	236	160	440	229	140	400	225	62	260	204
R3	180	690	304	160	600	305	140	540	303	61	321	277

[1]1 kg N/t cane in previous crop (Thorburn et al., 2011); [2]Cane yield of 117 t/ha assumed for the last ratoon of the previous crop cycle. No allowance was made for N removal in the penultimate ratoon.

Table 2.14. Cumulative sugar yields (t sugar/ha), progressive fertiliser N-use efficiencies (t cane/kg N) and calculated industry partial net returns for the Tully trial (after Schroeder *et al*., 2009b).

Cumulative crop	Grower-developed		Traditional		SIX EASY STEPS		N Replacement	
	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)	Cumulative sugar yield (t sugar/ha)	Progressive fertiliser NUE (t cane/kg N)
P	13.4	0.56	13.2	0.68	13.2	0.68	13.2	0.69
P+R1	24.8	0.46	24.8	0.54	24.8	0.57	24.7	0.72
P+R1+ R2	36.4	0.46	36.2	0.52	35.6	0.56	33.1	0.78
P+R1+R2+R3	51.2	0.44	51.3	0.51	50.9	0.56	46.3	0.66
[1]Industry net return ($/ha)	12386		12645		12687		11973	
Average industry net return ($/ha/year)	3114		3184		3198		3027	
Difference in industry net return from SIX EASY STEPS approach ($/ha/year)	-75		-10		-		-190	

[1]*Assumptions: Sugar price = $330/tonne, cost of N = $2.60/kg, harvesting costs = $7.25/t cane,*

2.10 N-Replacement concept - on-farm evaluation strip-trials

The N-Replacement strategy was evaluated in a series of on-farm experiments. Full details of the methods are given by Thorburn et al. (2011) and Park et al. (2010), and only an overview is presented here. Experiments were established in two studies: the first focussed on productivity, profitability, sustainability and environmental impacts at a range of sites. The second study tested the concept of 'discounting' N fertiliser applications in the N-Replacement system for sugarcane with a preceding legume fallow crop at a single site in Mossman.

Experiments with different N fertiliser application treatments were established on 11 commercial farms in mill regions from Mossman to Condong, covering a range of varieties, soil textural categories and Total C values (Table 2.15). Plots were generally large enough (e.g. > 1,500 m2) to allow yield to be determined from commercial harvesting. The exception was MB-2 where the area of each plot was 60 m2 and yield was measured by hand harvesting. All experiments were managed by the farmers using their normal crop management practices.

Table 2.15. Details of the experimental sites (after Thorburn *et al.*,2011).

Site code	Region	Texture (0-0.6 m)	Ratoon number of first crop	Total [1]C (0-0.3 m)	C/[1]N (0-0.3 m)	Variety	Replication
BK-1	Burdekin	sandy clay loam	1R	0.77	14.2	Q96 & Tellus	2
BK-2	Burdekin	sandy clay loam	1R	0.84	15.3	Q117	2
BU-1	Bundaberg	sandy loam to sandy light clay	1R	0.75	14.8	Q138	3
CD-1	Condong	light clay	1R	2.03	13.5	Q151	2
IN-1	Innisfail	sandy clay	2R	1.87	17.9	Q187	3
IN-3	Innisfail	light clay	1R	2.16	16.6	Q186	Unreplicated
MB-1	Maryborough	light clay	1R	1.21	17.8	Q135	Unreplicated
MB-2	Maryborough	sandy clay loam	1R	1.12	18.9	Q138	3
ML-1	Mulgrave	sandy clay	1R	1.17	16.9	Q200	Unreplicated
MS-1	Mossman	sandy clay	2R	1.22	13.4	Q174	3
MS-4	Mossman	light clay	3R	1.24	14.3	Q174	Unreplicated

[1] *Soil C and N concentrations determined by combustion with a LECO CNS analyser.*

Experiments ran for 3 or 4 years at all sites except MS-4 (2 years), and were generally established on first ratoon crops (Table 2.15). Sites BK-1 and BK-2 were fully irrigated, while BU-1 and MB-1 received supplementary irrigation according to the usual practice in Bundaberg and Maryborough. Crops at four sites (BK-1, BK-2, MB-1 and CD-1) were burnt prior to harvest, while crops at the other sites were harvested green with trash retained. The sites in the Burdekin region and one site (MB-1) in Maryborough were burnt prior to harvest.

The N-Replacement strategy (NR) was compared with the farmers' conventional N fertiliser management (NF). The amount of N fertiliser (kg/ha) applied in the NR system was targeted to be 1 kg N/t cane where trash was retained and 1.3 kg N/t cane where trash was burnt, as described above. At some sites a lower N rate treatment (NL) was also included (Table 2.16) to examine the time taken for productivity to decline as a consequence of low N applications. The lower rate was approximately equivalent to that which would occur with the NR scheme following a very poor crop. Fertiliser was applied to the experiments by the collaborating farmers and their applicator was generally calibrated prior to application.

The cane yield (Figure 2.19) and commercial cane sugar (CCS) was measured at each harvest. These yield data were used to calculate industry partial net returns according to Equation 2 for the sites where treatments were replicated and not damaged by cyclones (as was IN-1). The N concentration of the harvested cane was also measured. In addition, soil mineral N was determined at the commencement of the experiments and at each harvest, and these data used with cane yields and N concentrations to calculate the so-called N surplus, an estimate of the amount of nitrogen lost to

the environment (Thorburn et al., 2011). Leaves were sampled to determine N concentration as an indicator of N stress (data not provided here).

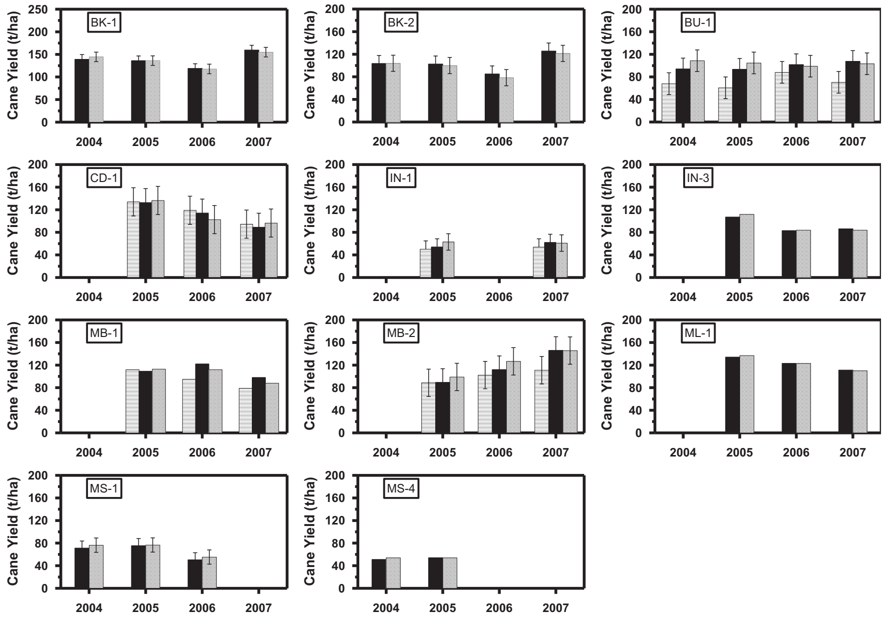


Figure 2.19. Cane yields of sugarcane crops harvested from on-farm experiments comparing the N Replacement system (solid bars) with farmers' conventional N fertiliser management practice (cross hatched bars) and, at some sites, a lower rate of applied N (striped bars), after Thorburn *et al*. (2011). In replicated experiments errors bars indicate the critical difference for comparing between treatments. Note: The BU-1 experiment was established on a site where soil N had been previously rundown; and there are no results for site IN-1 in 2006 due to cyclone damage.

The N applications rates in the NR treatments were lower than the farmers' conventional rates at all sites (Table 2.16). The differences were commonly in the order of 40-100 kg/ha (average 64 kg/ha), but ranged from 6 kg/ha (at site CD-1) to 160 kg/ha (BK-1). Although SIX EASY STEPS N rates were not included as treatments, the N applications rates in the NR treatments were generally lower than those that would result from using the SIX EASY STEPS guidelines. The exception was BK-2 where the NR N rate was 17 kg/ha higher than the SIX EASY STEPS N rate.

Despite the lower N applications for the NR treatment, yields were generally similar to those in the NF treatment (Figure 2.19), with reported differences not significant ($P < 0.05$) at the sites where treatments were replicated (Thorburn et al., 2011). While treatment differences in the unreplicated experiments could not be compared statistically, the relativity in the yields across the different treatments was consistent with the results in the replicated experiments. Yields associated with the NL treatments, at the five sites where they were included, averaged 10-30 t/ha lower than those in the treatments receiving higher N (Figure 2.19), especially in the 2nd and 3rd crops after the treatments were imposed.

Calculated industry partial net returns were higher for the NR treatment than NF at the Burdekin, Mossman and Bundaberg sites, but lower at the Maryborough sites (Table 2.16). The net returns that would have resulted from the SIX EASY STEPS program were estimated assuming the yields under the N rates resulting from SIX EASY STEPS would have been the same as in the NF treatment (assumption: PJ Thorburn, 2014). At BK-1, BK-2, MB-2 and MS1 the SIX EASY STEPS resulted in industry partial net returns higher than the NF. At Bundaberg it was slightly lower by $23/ha (Table 2.16). Although the calculated industry partial net returns were higher for the NR compared to the assumed SIX EASY STEPS rates at the Burdekin and Bundaberg sites, they were lower at Maryborough and Mossman (Table 2.16).

Based on the full set of N-Replacement replicated and unreplicated strip-trials, Thorburn et al. (2011) reported no apparent evidence that cane or leaf nitrogen concentrations were lower in the NR treatments, and that there was no evidence that soil N was being 'mined' to support the yields in the NR treatment at lower N application rates. The similar yields at lower N application rates meant that the amount of N lost to the environment was substantially lower in the NR treatment (Thorburn et al., 2011). The experiments across the regions allowed exploration of the importance of matching N fertiliser applications to 'expected yields' (Thorburn et al., 2011). In the implementation of the NR treatments the amount of N applied was based on the yield of the previous crop; N applications were only precisely matched to the 'needs' of the subsequent crops if yields were constant over time. Where yields increased through time N applications relative to actual yields achieved were lower than the 1 (or 1.3) kg N/t cane proposed in the NR system. This situation happened in the NR treatment at site MB-2. Cane yields of the 2006 and 2007 crops were 25 and 30% higher than the previous crop (Figure 2.19), resulting in actual N applications equivalent to ~0.8 kg/t cane relative to the achieved yield. Yet, applying extra N fertiliser (average of 47 kg/ha) in the NF treatment in these years did not significantly increase yield, particularly in the 2007 crop. These results illustrate the concept that the soil provides an N 'buffer', and it is less important to fertilise for expected yields than commonly thought. It will be important to determine if year-to-year yield variations result in N stress in 'big crops followed by small crops' where variation is greater than experienced in these on-farm experiments.

Table 2.16. Nitrogen application rates and industry partial net returns averaged across all crop harvested at each site (after Thorburn *et al*., 2011). NL indicates the N Low treatment (not implemented at all sites); NF, N Farmer; NR, N Replacement. N application rates results from the SIX EASY STEPS are shown for reference.

Site code	Average N fertiliser rate (kg/ha)				Average industry partial net return ($/ha)[a]			
	NL	NR	NF	SIX EASY STEPS	NL	NR	NF	SIX EASY STEPS
BK-1[b]		159	318	210	-	$4,517	$4,104	$4,385
BK-2[b]		217	326	200	$3,715	$3,150	$2,754	$3,081
BU-1	35	95	140	150	$2,450	$3,329	$3,249	$3,223
CD-1	67	143[c]	149		$3,953	$3,613	$3,604	-
IN-1	68	88	168	120	-	-	-	-
IN-3		117	144	120	-	-	-	-
MB-1	63	128	160	130	-	-	-	-
MB-2	55	111	152	140	$3,446	$3,840	$3,938	$3,969
MS-1		95	177	130	-	$2,085	$2,012	$2,134
MS-4		93	174	130	-	-	-	-

[a]Assumptions: Sugar price = $330/tonne, cost of N = $2.60/kg, harvesting costs = $7.25/tonne of cane. [b]N rates include N in irrigation water at these sites. [c]While this average rate is close to that in the NF treatment, there was substantial year-to-year variability in the rate (i.e., 122, 172 and 136 kg/ha).

Discounting N fertiliser after legume fallow crops within the N Replacement concept

To explore 'discounting' N fertiliser applications for the N contained in a preceding legume break crop, a soybean and sugarcane rotation experiment was established at Mossman within the N-Replacement program (Park *et al*., 2010). A soybean crop was established in a field following a sugarcane crop, grown through the local wet season, and then sprayed out with crop residues ploughed in. One month later sugarcane was planted. The plant crop in all treatments received the same rate of N fertiliser (Table 2.17). Nitrogen fertiliser rates differed in the ratoon crop, with treatments representing the farmer's standard fertilizer rate (NF), the 'standard' N-replacement rate (NR - 1.0 kg/t cane), and the N-replacement rate amended to take account of N provided by the soybean fallow crop to the ratoon sugarcane crop (NRL – 0.7 kg/t cane). The NRL was estimated by assuming 10% the legume nitrogen was likely to be available for uptake by the first ratoon crop (Garside *et al*., 1996). In this experiment, N fertiliser applications ranged from 125 to 73 kg N/ha across the treatments (Table 2.17). There was no difference in yields in the treatment in response to these different nitrogen applications rates.

Table 2.17. Nitrogen application rates and cane yields (after Park *et al*., 2010). NF-N Farm; NR-N Replacement; NL-N Low; NF-N Farmer; NRL-N Replacement adjusted for a preceding legume crop.

Crop	N fertiliser rates (kg/ha)			Yield (t cane/ha)		
	NF	NR	NRL	NF	NR	NRL
Plant	41	41	41	107	111	111
Ratoon 1	125	104	73	83	81	82

2.11 SIX EASY STEPS - demonstration on-farm large-scale replicated strip trials

A substantial number of commercial-scale replicated demonstration strip trial sites (Table 2.18) were established in various regions / districts across the Queensland industry: Bundaberg (B series), Central [Mackay (M series) and Proserpine (P series)], Herbert (H series), Wet Tropics [Johnstone district (J series) and Tully (T series)] and Burdekin (Bkn series). Table 2.18 illustrates the extent of these trials and the wide ranging conditions in which they were conducted. The intent of these trials was to compare traditional grower practice (in terms of nutrient inputs) to the SIX EASY STEPS guidelines (Salter *et al*., 2008). They were co-ordinated locally by the previous BSES and Productivity Services staff to ensure ownership and acceptance of the trials and their results, on-going interaction with collaborating growers, and feedback of results to grower groups. Thirty one of the trials covered two or more consecutive crops. The following process was followed at each site:

- Potential trial sites were identified using a consultative process – grower groups were approached to identify co-operators and appropriate sites.
- These sites were assessed in terms of suitability (size of the block, uniformity of the standing plant crop, uniformity of the block, etc).
- Major soil type(s) in each identified block were identified.
- Separate composite top (0-20 cm) and subsoil (40-60 cm) samples were collected from different parts of the block and dispatched to a commercial laboratory for analysis. Apart from gaining information on the soil fertility status of the block, this sampling also enabled the uniformity of the trial area to be evaluated.
- The analysis results were discussed with the applicable grower.
- SIX EASY STEPS (best-practice) nutrient inputs were determined from soil test values.
- Growers used their own method of identifying their planned nutrient inputs.
- In each case the trial was then established using the identified treatments within randomised and replicated layouts. An example is shown in Figure 2.20.
- Leaf samples were collected during the leaf-sampling season (Feb – April) from the treatment areas in each strip-trial and sent for analysis. On receipt of results, reports were generated and dispatched to the district co-ordinators for distribution and discussion with the co-operating growers.
- Trials were visually assessed for differences in plant growth.
- The trials were harvested within the growers allocated harvest cycle.
- The size of the replicated strips enabled yield (tonnes cane/ha) and CCS data to be collected at the mill after harvest.
- Partial net return per hectare were calculated using a standardised 'cane payment formula' to determine the partial net return per hectare to the grower: Grower partial net return = ((price of sugar x (0.009 x (CCS-4)+0.6)) x cane yield) - (cane yield x estimated harvesting costs plus levies) - (fertiliser cost) (kg/ha) – (cane yield x estimated harvesting costs plus levies).

- Summaries of results were provided to the co-operating grower and grower groups.
- Trials were continued for as many successive seasons as possible.
- Where appropriate, results were reported in papers presented at ASSCT conferences (e.g. a paper entitled “Recognising differences in soil type to guide nutrient inputs on-farm – a case study from Bundaberg” (Schroeder *et al*., 2007c) was presented at the ASSCT Conference in Cairns in 2007.

BSS0268 Strip Trial - Best Practice Nutrient Management

Grower

Farm No. 11586

Block No. 15A

Treatments applied 2 November 2005

Treatments	kg/ha				Product and rate
	N	P	K	S	
Grower					Cal-Am 140(S) @ 884 kg/ha
Best Practise Nutrient Management (BPNM)	134	12	100	22	Cal-Am 140(S) @ 738 kg/ha

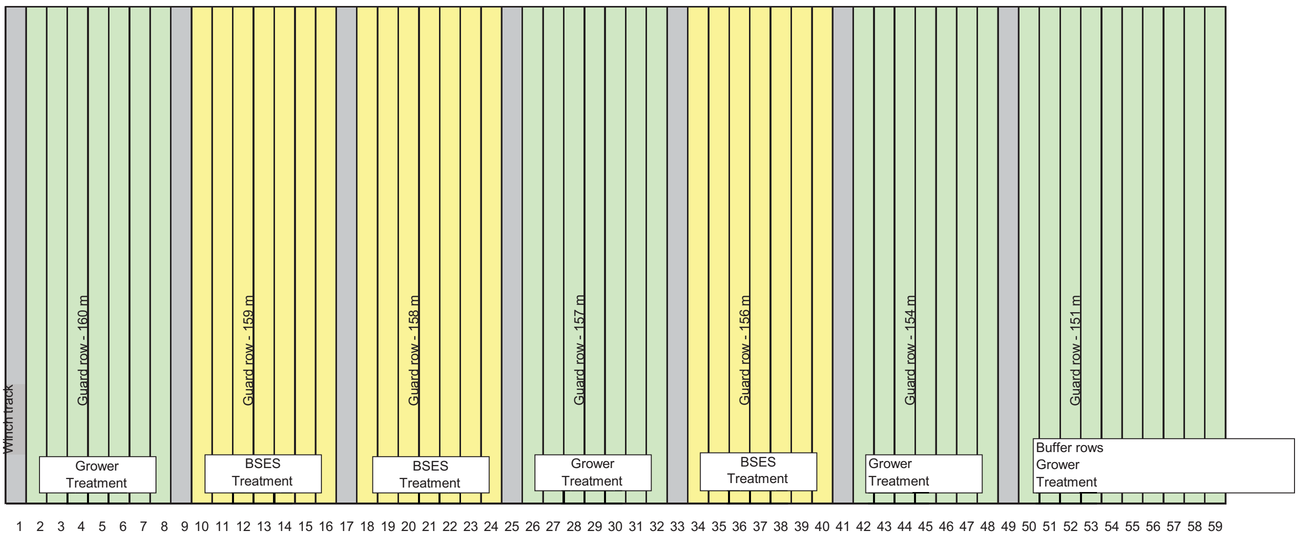


Figure 2.20. Example of the layout of a randomised and replicated strip-trial in which standard grower practice is compared to the best-practice option.

Table 2.18. Replicated demonstration strip-trials conducted in Queensland sugarcane districts.

District	Trial series	2006 Crop	2007 Crop	2008 Crop
Bundaberg	B-ST1	Harvested	Discontinued after 2006	
	B-ST3	Harvested	Harvested	Harvested
	B-ST4	Harvested	Harvested	Harvested
	B-ST5	Harvested	Harvested	Harvested
	B-ST6	Harvested	Harvested	Harvested
	B-ST 8	Established Mar 2006	Harvested cane lost	Harvested
	B-ST9	Harvested	Harvested	Harvested
	B-ST10	Harvested	Harvested	Harvested
	B-ST11		Established in 2007	Harvested
Central	P-ST1	Harvested	Discontinued after 2006	
	P-ST2	Harvested	Harvested in 2007 and then discontinued	
	P-ST4	Harvested	Discontinued after 2006	
	P-ST5	Harvested	Discontinued after 2006	
	P-ST6	Harvested	Discontinued after 2006	
	P-ST7	Harvested	Discontinued after 2006	
	C-ST1	Harvested	Harvested	Harvested
	C-ST2	Harvested	Harvested	Harvested
	C-ST3	Harvested	Harvested	Harvested
	C-ST4	Harvested	Harvested	Harvested
	C-ST5	Harvested	Harvested	Harvested
	C-ST6	Harvested	Harvested	Harvested
	C-ST7	Harvested	Harvested	Harvested
	C-ST8	Established Sep 2006	Harvested	Harvested
	C-ST9	Established Oct 2006	Harvested	Harvested
Herbert	H-ST1	Harvested	Discontinued after 2006	
	H-ST2	Harvested	Harvested in 2007 and then discontinued	
	H-ST3	Harvested	Harvested in 2007 and then discontinued	
	H-ST4	Harvested	Discontinued after 2006	
	H-ST5	Harvested	Harvested in 2007 and then discontinued	
	H-ST6	Harvested without notice and then discontinued		
	H-ST7	Harvested	Discontinued after 2006	
	H-ST8	Harvested	Discontinued after 2006	
	H-ST9	Harvested without notice and then discontinued		
	H-ST10	Harvested	Discontinued after 2006 harvest	
	H-ST11	Harvested	Discontinued after 2006 harvest	
Burdekin	Bkn-ST1	-	Established in 2007	Discontinued
	Bkn-ST2	-	Established in 2007	Harvested
	Bkn-ST3	-	Established in 2007	Harvested
Johnstone catchment	J-ST1	Harvested	Harvested	Harvested
	J-ST2	Harvested	Harvested	Harvested
	J-ST3	Harvested	Harvested	Harvested
	J-ST4	Cyclone damage	Harvested	Harvested
	J-ST5	Cyclone damage	Harvested	Harvested
	J-ST6	Harvested	Harvested	Harvested
	J-ST7	Established Nov 2006	Harvested	Harvested
	J-ST8	Un-replicated (Nov 06)	Harvested in 2007 and 2008, data not used	
	J-ST9	Established Nov 2006	Harvested	Harvested
Tully	T-ST1	-	Established in 2007	Harvested (2008, 09, 10)
	T-ST2	-	Established in 2007	Harvested (2008, 09, 10
	T-ST3	-	Established in 2007	Harvested (2008, 09)
	T-ST4	-	Established in 2007	Harvested (2008, 09, 10)

The data and information from the Central and Johnstone series trials are shown in detail below. Specific examples are used from the Bundaberg, Burdekin and Tully trials for illustrative purposes. In each trial the usual grower practices in terms of N management (but also P, K, S inputs) were compared to those recommended by the SIX EASY STEPS program (as calculated from the specific soil test data for those particular sites). The soil test data used for establishing the SIX EASY STEPS nutrient requirements in the Johnstone district and Central region trials are shown in Tables 2.19 and 2.20, respectively. These tables also indicate the range of soil types and the spread of soil chemical properties. Nutrient application rates for each trial are shown in Tables 2.21 and 2.22 for the Johnstone trials, and in Tables 2.23, 2.24 and 2.25 for the trials conducted in the Central region. In each case the actual, rather than the intended application rates, are shown because of inaccuracy of fertiliser applicator calibrations. In some cases, the SIX EASY STEPS guidelines required other inputs such as Mg, Ca or micro-nutrients.

Average yield [(t cane/ha) and (t sugar/ha)] based on the mean of three replicates together with fertiliser N use efficiencies and partial net returns for the Johnstone district trials: 2007 and 2008 (Tables 2.21 and 2.22 respectively) and Central region trials: 2006, 2007 and 2008 (Tables 23, 24 and 25 respectively) indicate the validity of the SIX EASY STEPS approach over the general grower N management practices.

In comparison to the usual grower practices, the SIX EASY STEPS inputs resulted in generally maintained yields, improved profitability and less risk to the environment (due to lower N and/or P inputs). In particular the calculated average fertiliser N-use efficiencies for the SIX EASY STEPS was 0.66 t cane/kg N in 2007 (Table 2.21) and 0.64 t cane/kg in 2008 (Table 2.22) across all the Johnstone trial sites. This was despite the target SIX EASY STEPS N-use efficiency ranging between 0.8 and 1.3 t cane/kg N for ratoon cane grown in the Johnstone district (Table 2.8). In comparison, the grower practices resulted in fertiliser N-use efficiencies of 0.52 t cane/kg N in 2007 (Table 2.21) and 0.51 t cane/kg N in 2008 (Table 2.22). In progressing from 2007 to 2008 the fertiliser N-use efficiency on average remained more or less constant over the two seasons. However, at some sites (Brosnan, Eubenangee, Maria, Mundoo and Thorpe) the fertiliser N-use efficiencies were more favourable in the 2008 season despite the crop cycle being one ratoon further advanced.

The SIX EASY STEPS guidelines indicate that the target fertiliser N-use efficiencies should range from 0.8 to 1.0 t cane/kg N (Table 2.8) for the sites used for the demonstration strip trials in the Central Region (Tables 2.23, 2.24 and 2,25). However the achieved fertiliser N-use efficiency using the SIX EASY STEPS were on average 0.77, 0.65 and 0.56 t cane/kg N for 2006, 2007 and 2008 respectively. The grower inputs resulted in even lower fertiliser N-use efficiencies (0.59, 0.54 and 0.56 t cane/kg N). This general decline suggests that the fertiliser N-use efficiency appeared to decrease with crop class as the crop cycle progressed.

In relation to nutrient inputs, it was found that in the seasons considered the SIX EASY STEPS N application rates were generally lower than those of the usual grower practice [Johnstone: 126 kg N/ha versus 156 kg N/ha (means of data from Tables 2.21 and 2.22) and Central: 148 kg N/ha versus 185 kg N/ha (means of data from Tables 2.23, 2.24 and 2.25)].

Although the calculated partial net returns were generally in favour of the SIX EASY STEPS, exceptions did occur. For instance, in the Johnstone at the Brosnan and Mundoo sites (Tables 2.21 and 2.22), the SIX EASY STEPS inputs included magnesium oxide, thereby increasing fertiliser costs above those of the grower practice. However, the inclusion of micro-nutrients (Cu and/or Zn) and lime into the SIX EASY STEPS inputs at many of the other sites did not negatively affect the partial net return (despite the added cost). This provides evidence that these nutrients were indeed required. The results also highlight the effect of season on profitability, not only in terms of weather, but also due to the costs of inputs and the price of sugar.

Table 2.19. Selected soil chemical properties for the participative replicated demonstration strip trials conducted in the Johnstone district (Schroeder *et al*., 2009a).

Soil type[1]	Soil pH[2]	Org C3 (%)	PBI[4]	BSES P	Sulphate S	Cu[5]	Zn[5]	ECEC6	Nitric K	Exch. cations		
										K	Ca	Mg
				(mg/kg)				(me%)				
Brosnan	5.8	0.65	55	115	3	0.91	1.03	1.65	0.36	0.08	0.95	<0.2
Bulgun	5.5	2.60	435	125	185	0.25	0.58	4.58	1.75	0.20	1.80	0.85
Eubenangee	5.6	1.60	385	49	52	1.20	0.29	2.70	0.40	0.14	1.60	0.65
Innisfail	4.7	1.25	380	103	49	0.63	0.79	4.83	4.40	0.23	0.78	0.49
Maria	5.4	1.90	200	67	6	0.15	0.15	2.33	0.46	0.06	0.80	<0.2
Mundoo	5.0	1.60	505	31	115	1.65	0.58	1.15	0.15	0.08	0.40	0.20
Pin Gin	4.9	1.95	835	41	275	0.68	0.36	1.98	0.25	0.16	0.98	0.26
Thorpe	5.7	1.02	76	105	2	0.12	0.47	1.77	0.16	0.04	1.10	<0.2
Tully	4.9	0.90	180	24	18	0.45	0.35	3.5	5.10	0.14	1.00	0.31

[1] *Murtha (1986),* [2] *pH$_{(water)}$,* [3] *Walkley-Black organic C (Walkley and Black, 1934)*
[4] *Phosphorus buffer index,* [5] *DTPA extractable Cu and Zn,* [6] *Effective cation exchange capacity*

Table 2.20. Selected soil chemical properties for the participative replicated demonstration strip trials conducted in the Central region.

Soil type[1]	Soil pH[2]	Org C[3] (%)	PBI[4]	BSES P	Sulphate S	Cu[5]	Zn[5]	ECEC[6]	Nitric K	Exch. cations		
										K	Ca	Mg
				(mg/kg)				(me%)				
Mirani	5.8	0.37	22	59	4.5	0.97	0.47	2.60	1.10	0.95	1.75	0.59
Pioneer	5.9	1.25	81	280	5.6	0.87	2.00	6.01	1.10	0.15	4.1	1.7
Tannalo	4.8	0.63	47	52	13	0.29	0.36	2.08	0.90	0.10	0.7	0.33
Kattabul	5.6	0.75	95	39	12	1.3	1.35	7.80	0.48	0.15	4.8	2.5
Marian/Calen	6.0	0.66	42	35	6.9	0.61	0.40	3.90	0.92	0.09	2.5	1.02
Victoria Plains	7.3	1.90	165	47	18	2.4	0.53	42.6	1.35	0.49	24.0	17.0
Mirani	4.9	0.59	76	47	14	0.93	0.66	2.85	0.88	0.13	1.0	0.63

[1] *Holz and Shields (1985),* [2] *pH$_{(water)}$* [3] *Walkley-Black organic C (Walkley and Black, 1934)*
[4] *Phosphorus buffer index,* [5] *DTPA extractable Cu and Zn,* [6] *Effective cation exchange capacity*

Table 2.21. 2007 yield data, fertiliser N-use efficiencies and calculated partial net returns for the different nutrient management strategies used in the participative replicated demonstration strip trials in the Johnstone district (Schroeder *et al*., 2009a).

Soil	Nutrient strategy	Nutrients applied N	P	K	S	Other[2]	Cost	Yield		Fertiliser N-use efficiency	Partial net return[3] (Benefit using the SIX EASY STEPS strategy shown in brackets)	
		(kg/ha)					($/ha)	(t cane/ha)	(t sugar/ ha)	(t cane/kg N applied)	($/ha)	
Brosnan	6ES[1]	150	13	114	29	Mg	417	72.2	9.9	0.48	912	(-16)
	Grower	135	12	141	0	-	382	74.2	10.0	0.49	928	
Bulgun	6ES	101	0	101	0	-	258	64.7	7.6	0.64	589	(128)
	Grower	165	8	90	10	-	380	68.4	7.8	0.41	461	
Eubenangee[4]	6ES	125	8	126	1	Zn	351	71.5	7.2	0.57	277	(66)
	Grower	140	11	137	1	-	356	64.5	6.5	0.46	212	
Innisfail	6ES	127	0	104	0	-	288	99.0	12.8	0.78	1320	(124)
	Grower	177	17	128	13	-	449	106.4	13.4	0.60	1196	
Maria	6ES	115	0	121	5	Zn, Cu	399	77.1	10.3	0.67	930	(9)
	Grower	162	0	95	0		332	77.2	10.0	0.48	921	
Mundoo	6ES	133	13	138	1	Mg	404	59.4	7.0	0.45	385	(-115)
	Grower	148	0	86	0	-	304	58.6	7.0	0.40	500	
Pin Gin	6ES	120	11	124	1	Lime	340	82.3	9.5	0.69	696	(31)
	Grower	135	13	97	10	-	339	78.5	9.1	0.58	665	
Thorpe	6ES	130	0	111	21	Zn	391	101.3	11.3	0.78	800	(189)
	Grower	184	16	111	1	-	400	95.5	10.2	0.52	611	
Tully	6ES	138	24	96	14	Lime	371	109.6	13.5	0.79	1239	(29)
	Grower	162	0	95	0	-	332	105.0	12.9	0.65	1210	
Mean	6ES	127	7	114	9	Various	359	83.2	10.2	0.66	859	(47)
	Grower	159	8	105	4		365	83.0	10.9	0.52	812	

[1] *SIX EASY STEPS.*
[2] *Other nutrients or amendments applied (20% of cost included in calculation of partial net returns).*
[3] *Partial net return = (Sugar price x 0.009(CCS-4)+0.6) x t cane/ha)-(t cane/ha x harvesting costs ($/t cane))-(Fertiliser cost $/ha) Assumptions: sugar price = $285/t, harvesting costs plus levies = $7.20, fertiliser costs according to 2007 prices.*
[4] *Data not included in means because these were un-replicated plots*

Table 2.22. 2008 yield data, fertiliser N-use efficiencies and calculated partial net returns for the different nutrient management strategies used in the participative replicated demonstration strip trials in the Johnstone district (Schroeder *et al*., 2009a).

Soil	Nutrient strategy	Nutrients applied						Yield		Fertiliser N-use efficiency	Partial net return[3] (Benefit using the SIX EASY STEPS strategy shown in brackets)	
		N	P	K	S	Other[2]	Cost					
		(kg/ha)					($/ha)	(t cane/ha)	(t sugar/ha)	(t cane/kg N applied)	($/ha)	
Brosnan	6ES[1]	150	13	114	29	(Table 2.21)	524	77.0	10.0	0.51	968	(-172)
	Grower	126	12	130	0	-	400	79.3	10.3	0.63	1,140	
Bulgun	6ES	97	0	98	0	-	273	47.0	7.4	0.48	1,030	(159)
	Grower	177	11	111	23	-	472	48.6	7.7	0.27	871	
Eubenangee[4]	6ES	125	16	120	1	(Table 2.21)	422	76.0	9.5	0.61	943	(89)
	Grower	110	0	110	0	-	308	66.3	8.1	0.60	854	
Innisfail	6ES	127	0	103	0	-	323	90.6	10.5	0.71	1,071	(98)
	Grower	155	15	112	11	-	414	88.9	11.7	0.57	973	
Maria	6ES	124	0	124	5	(Table 2.21)	420	90.8	12.3	0.73	1,456	(264)
	Grower	155	16	118	2	-	445	88.2	11.1	0.57	1,192	
Mundoo	6ES	124	12	127	1	(Table 2.21)	420	71.2	8.8	0.57	873	(22)
	Grower	142	0	83	0	-	325	67.3	8.4	0.47	851	
Thorpe	6ES	114	0	114	23	(Table 2.21)	394	91.0	11.0	0.80	1,125	(97)
	Grower	149	0	124	36	-	407	88.1	10.5	0.59	1,028	
Tully	6ES	137	24	95	14	(Table 2.21)	423	94.2	12.2	0.69	1,391	(81)
	Grower	160	0	94	0	-	367	86.2	11.2	0.54	1,310	
Mean	6ES	125	7	111	10	(Table 2.21)	397	80.3	10.3	0.64	1,131	(79)
	Grower	152	8	110	10	-	404	78.1	10.1	0.51	1,052	

[1] *SIX EASY STEPS.*
[2] *Other nutrients or amendments applied (20% of cost included in calculation of partial net returns).*
[3] *Partial net return = (Sugar price x 0.009(CCS-4)+0.6) x t cane/ha)-(t cane/ha x harvesting costs ($/tc))-(Fertiliser cost $/ha) Assumptions: sugar price = $320/t, harvesting costs plus levies = $7.50, fertiliser costs according to 2008 prices.*
[4] *Data not included in means because these were un-replicated plots*

Table 2.23. 2006 yield data and calculated partial net returns for the different nutrient management strategies used in the participative replicated demonstration strip trials in the Central region.

Soil	Nutrient strategy	Nutrients applied					Yield		Fertiliser N-use efficiency	Partial net return[3] (Benefit using the SIX EASY STEPS strategy shown in brackets)	
		N	P	K	S	Cost					
		(kg/ha)				($/ha)	(t cane/ha)	(t sugar/ha)	(t cane/kg N applied)	($/ha)	
Mirani	6ES[1]	160	0	97	22	331	103.7	16.0	0.65	2,697	(54)
	Grower	205	0	98	26	397	104.1	16.1	0.51	2,643	
Pioneer	6ES	105	0	0	0	133	136.6	13.0	1.30	1,302	(274)
	Grower	180	0	113	20	391	138.8	13.1	0.77	1,028	
Kuttabul	6ES	153	0	123	10	361	107.6	15.2	0.70	2,331	(71)
	Grower	189	25	90	21	434	107.2	15.2	0.57	2,260	
Marian/Calen	6ES	153	10	102	15	358	106.1	15.5	0.69	2,442	(8)
	Grower	182	0	108	29	400	105.9	15.6	0.58	2,434	
Victoria Plains	6ES	122	11	0	0	187	81.8	10.6	0.67	1,550	(188)
	Grower[2]	180	16	105	20	420	86.9	11.0	0.48	1,362	
Mirani	6ES	142	0	95	9	307	107.3	16.5	0.76	2,789	(-17)
	Grower	166	0	97	23	275	104.4	16.2	0.63	2,806	
Mean	6ES	139	4	70	9	280	107.2	14.5	0.77	2,185	(96)
	Grower	184	7	102	23	386	107.9	14.5	0.59	2,089	

[1] SIX EASY STEPS; [2]Grower treatment: one replicate only
[3] Grower partial net return = (Sugar price x 0.009(PRS-4)+0.6) x t cane/ha)-(t cane/ha x 7.5 $/t cane)-(Fertiliser cost $/ha)
Assumptions: sugar price = $350/t, harvesting costs plus levies = $7.50, fertiliser costs according to 2006 prices.

Table 2.24. 2007 yield data and calculated partial net returns for the different nutrient management strategies used in the participative replicated demonstration strip trials in the Central region.

Soil	Nutrient strategy	Nutrients applied					Yield		Fertiliser N-use efficiency	Partial net return[3] (Benefit using the SIX EASY STEPS strategy shown in brackets)	
		N	P	K	S	Cost					
		(kg/ha)				($/ha)	(t cane/ha)	(t sugar/ha)	(t cane/kg N applied)	($/ha)	
Mirani	6ES[1]	161	0	92	14	298	90.7	12.9	0.56	1,401	(38)
	Grower	205	0	95	14	369	92.3	13.1	0.45	1,363	
Tannalo	6ES	143	10	96	14	319	99.5	13.5	0.70	1,396	(12)
	Grower	193	0	118	21	398	101.1	13.9	0.52	1,384	
Kuttabul	6ES	153	0	123	10	390	104.3	15.2	0.68	1,679	(191)
	Grower	189	25	90	21	486	108.7	15.2	0.58	1,488	
Marian/Calen	6ES	156	0	95	17	366	106.4	17.3	0.68	2,199	(69)
	Grower	173	0	105	19	406	107.4	17.3	0.62	2,130	
Victoria Plains	6ES	135	13	0	0	204	83.0	12.2	0.61	1,460	(102)
	Grower[2]	188	17	110	20	479	95.9	13.8	0.51	1,358	
Mirani	6ES	161	0	92	14	298	112.9	14.0	0.70	1,305	(57)
	Grower	180	0	103	15	333	110.2	13.7	0.61	1,248	
Mean	6ES	152	4	83	12	312	99.5	14.2	0.65	1,573	(78)
	Grower	188	7	104	18	412	102.6	14.5	0.54	1,495	

[1] SIX EASY STEPS; [2] Grower treatment: one replicate only
[3] Partial net return = (Sugar price x 0.009(PRS-4)+0.6) x t cane/ha)-(t cane/ha x 8.5 $/t cane)-(Fertiliser cost $/ha)
Assumptions: sugar price = $280/t, harvesting costs plus levies = $8.50, fertiliser costs according to 2007 prices.

Table 2.25. 2008 yield data and calculated partial net returns for the different nutrient management strategies used in the participative replicated demonstration strip trials in the Central region.

Soil	Nutrient strategy	Nutrients applied N	P	K	S	Cost	Yield		Fertiliser N-use efficiency	Partial net return[3] (Benefit using the SIX EASY STEPS strategy shown in brackets)	
		(kg/ha)				($/ha)	(t cane/ha)	(t sugar/ha)	(t cane/kg N applied)	($/ha)	
Mirani	6ES[1]	160	0	91	15	503	98.3	14.5	0.61	1,770	(57)
	Grower	205	0	97	18	628	99.8	14.9	0.49	1,713	
Tannalo	6ES	161	0	107	14	727	96.2	15.4	0.60	1,851	(83)
	Grower	188	0	125	17	848	97.0	15.6	0.52	1,768	
Kuttabul	6ES	153	0	123	10	734	74.8	11.8	0.49	1,213	(83)
	Grower	189	25	90	21	934	79.3	12.5	0.42	1,130	
Marian/Calen	6ES	153	0	102	14	688	86.9	13.4	0.57	1,493	(43)
	Grower	161	0	107	14	727	86.7	13.4	0.54	1,450	
Victoria Plains	6ES	138	0	0	0	367	64.0	9.2	0.46	1,038	(-74)
	Grower[2]	182	16	110	21	930	88.0	13.0	0.48	1,176	
Mirani	6ES	165	0	93	16	518	69.8	9.5	0.42	863	(-11)
	Grower	184	0	104	18	577	71.7	9.9	0.39	874	
Mean	6ES	153	0	88	12	582	85.5	12.6	0.56	1,369	(30)
	Grower	184	7	107	19	749	88.9	13.0	0.48	1,280	

[1] SIX EASY STEPS; [2] Grower treatment: one replicate only
[3] Grower partial net return = (Sugar price x 0.009(PRS-4)+0.6) x t cane/ha)-(t cane/ha x 8.5 $/t cane)-(Fertiliser cost $/ha) Assumptions: sugar price = $320/t, harvesting costs plus levies = $7.50, fertiliser costs according to 2006 prices.

Two replicated demonstration strip trials established in the Burdekin (Table 2.26) district included the following treatments:

- Usual grower practice
- SIX EASY STEPS approach
- N Replacement strategy

Although the same general methodology was used (as indicated previously), the N contribution from the irrigation water was included in decisions about nutrient inputs. All other major nutrients were applied when requirements were indicated by the soil test results (Table 2.27) indicating that the SIX EASY STEPS approach to nutrient management produced positive results (yields were similar to those achieved with the usual grower practice). Importantly, the average partial net return ($2,813/ha) calculated for the SIX EASY STEPS approach was about $400 better than that achieved from the grower determined inputs.

Table 2.26. Summary: demonstration strip trials in the Burdekin district (2008) – unpublished data (J Dowey, formerly BSES, Limited, Burdekin).

Trial No.	Soil type	Selected soil properties			Ratoon N application rate (kg N/ha)		
		Soil pH(water)	Org C (%)	CEC (me%)	Grower	SIX EASY STEPS	N Repl.
Bkn-ST2	Cracking clay (UGb)	6.6	0.78	15.6	230	108[1]	82
Bkn-ST3	Sandy clay loam (Uma)	6.7	0.58	9.0	232	180	167

[1] *N reduced because of nitrate in the irrigation water*

Table 2.27. Demonstration strip trials conducted in the Burdekin district (2008) – unpublished data (J Dowey, formerly BSES Limited, Burdekin).

Site	Treatment	Nutrients applied (kg/ha)				Yield			Return
		N	P	K	S	(t cane/ha)	CCS	(t sugar/ha)	($/ha)
Bkn – ST2	Grower	248	0	98	8	128	14.3	18.2	2237
	SIX EASY STEPS	119	0	100	10	122	15.0	18.3	2735
	N Replacement	88	0	96	18	114	15.3	17.3	2692
Bkn – ST3	Grower	233	0	0	0	125	15.3	19.1	2583
	SIX EASY STEPS	180	0	0	0	131	15.3	20.0	2891
	N Replacement	167	0	0	0	128	15.3	19.7	2888

Sugar price = $325/t
Return = ((Sugar price x 0.009 (PRS-4)+0.6) x t cane/ha) – (t cane/ha x 8.5 $/t cane) – (Fertiliser cost ($/ha)
2008 Fertiliser prices used

An example from Bundaberg illustrates the use of appropriate management strategies following a fallow legume crop. The particular trial [B-ST3 (Table 2.15)] was established on an alluvial soil (Burnett series) in a block of sugarcane (variety Q205A) after harvest of the plant crop. Two successive crops of peanuts had been grown in the block prior to the plant crop.

In terms of the SIX EASY STEPS approach, the nutrient requirement calculated from a soil test for the 1st ratoon crop was 150 kg N/ha, 0 kg P/ha and 100 kg K/ha. However, the strategy that was actually used took into account the residual N from the fallow peanut crops. As a result the nutrient requirement was decreased to 100 kg N/ha, 0 kg P/ha and 100 kg K/ha. The grower practice in this case, which also recognised the N contribution from the peanut crops, was 130 kg N/ha, 11 kg P/ha and 100 kg K/ha. The grower achieved this by applying his usual ratoon fertiliser blend, but at a lower rate. The harvest results indicated that yields (sugarcane and sugar) were similar in both cases (Figure 2.21).

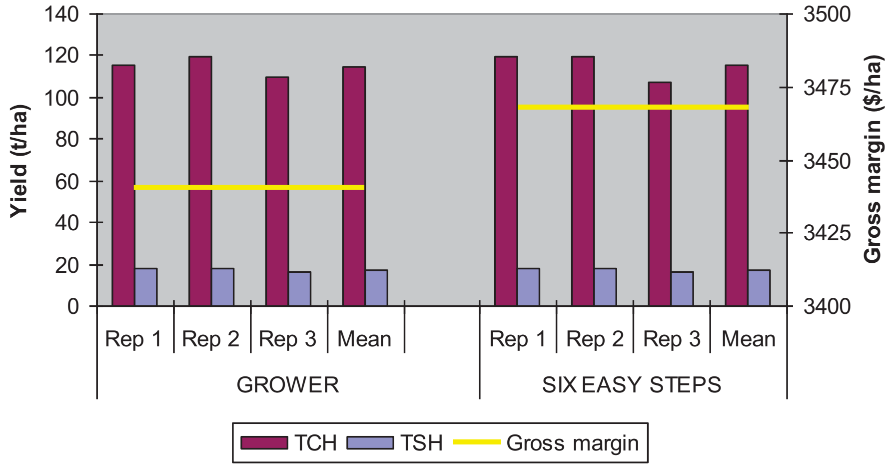


Figure 2.21. Bundaberg trial B-ST3: First ratoon yield data (sugarcane and sugar) and calculated net returns (gross margins) for the grower versus SIX EASY STEPS strategies.

In relation to the second ratoon crop, the SIX EASY STEPS strategy was to test whether any residual N from the peanut crops was still available within the system. As a result the nutrient requirement remained unchanged from the previous crop (100 kg N/ha, 0 kg P/ha and 100 kg K/ha). The grower practice in this case was to revert to his usual fertiliser application rate. This resulted in the following nutrient application: 150 kg N/ha, 13 kg P/ha and 116 kg K/ha. Apart from the P applied, this practice is very close to the unadjusted original SIX EASY STEPS approach. As with the first ratoon, the second ratoon yields were again similar across treatments (Figure 2.22). The net return (gross margins) were in favour of the best practice (SIX EASY STEPS) option by a cumulative $170 /ha.

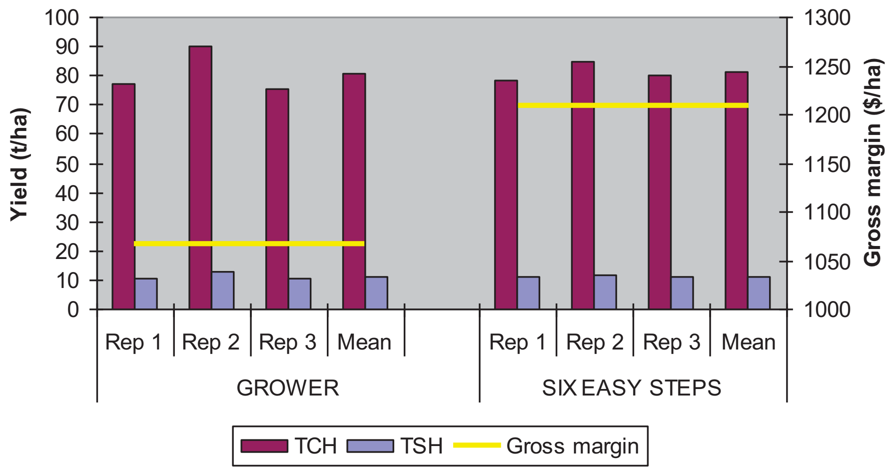


Figure 2.22. Bundaberg trial B-ST3: Second ratoon yield data (sugarcane and sugar) and calculated net returns (gross margins) for the grower versus SIX EASY STEPS strategies.

At trial site B-ST3 (Table 215) the actual efficiency factors obtained from the SIX EASY STEPS inputs (mean N-fertiliser utilisation index value = 1.1 kg N/t cane and mean fertiliser N use efficiency = 0.9 t cane/kg N) were very similar to the target SIX EASY STEPS rates over the three seasons (2006 to 2008) (Figure 2.23). In contrast, the grower strategy resulted in a relatively inefficient system (mean N-fertiliser utilisation index value = 1.5 kg N/t cane) which is indicative of reduced N use efficiency (mean = 0.7 t cane/kg N). The disparity between these two fertiliser N-use efficiencies was related to the fact that a legume had been grown at the site prior to the sugarcane plant crop. This provided further evidence of the need to take account of this source of N in the first ratoon crop after a legume fallow crop.

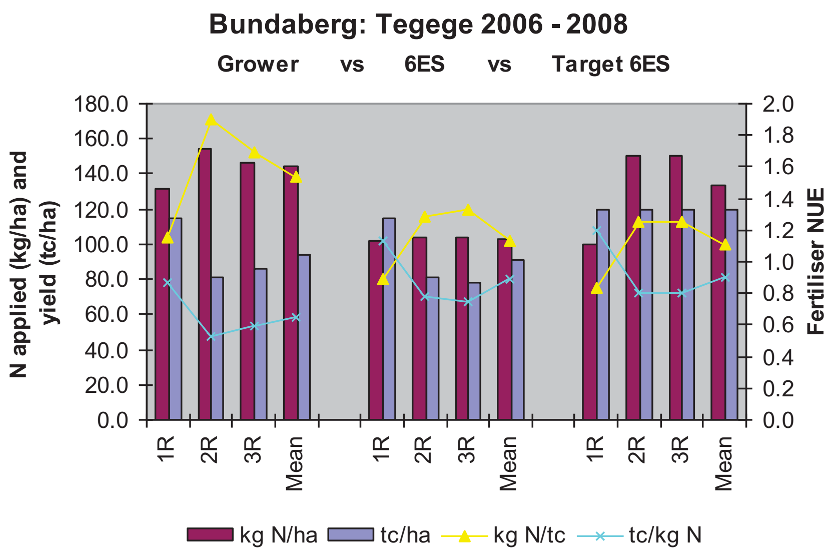


Figure 2.23. N application rates and yield data for a Bundaberg replicated strip trials (conducted at Tegege) together with the calculated N fertiliser utilisation index (kg N/t cane) and fertiliser N-use efficiency (t cane/kg N) values: 2006 – 2008
(Grower strategy vs actual SIX EASY STEPS vs Target SIX EASY STEPS).

Results from the series of replicated demonstration strip trials conducted in the Tully region: sites T-ST1 to T-ST4 (Table 2.15) indicated similar outcomes to the other strip trial results. Despite the SIX EASY STEPS N being on average 17.5 kg N/ha lower than the general grower application rate, both yields and profitability were maintained (Skocaj *et al*., 2012). In contrast, the N Replacement strategy resulted in significantly lower cumulative cane yields, cumulative sugar yields and cumulative industry economic returns over successive seasons compared to the usual grower practices in both well and poorly drained sites (Table 2.28).

Table 2.28. mulative productivity and profitability data for two successive ratoon crops on well drained and poorly drained sites in the Tully district (Skocaj *et al.*, 2012).

Site	Nitrogen treatment	Productivity		Economic return	
		Mean cane yield (TCH)	Mean sugar yield (TSH)	Grower return ($/ha)[2]	Industry return ($/ha)[3]
Well drained	Grower	150a	22.8a	5,411a	8,744a
	6ES[1]	146a	22.2a	5,313ab	8,560a
	NRep	137b	20.8b	5,020b	8,071b
	Lsd (0.05)	5.49	1.07	315	443
Poorly drained	Grower	108a	17.1a	4,085a	6,516a
	6ES	102ab	16.0ab	3,818a	6,101ab
	NRep	91b	14.4b	3,561a	5,613b
	Lsd (0.05)	12.65	2.15	ns	874
a-b Means with the same letter in the same column are not significantly different (P=0.05)					

[1] *SIX EASY STEPS*
[2 and 3] *Assumptions: sugar price = $450/t, harvesting costs plus levies = $7.60/t cane, cane payment formula price adjustment = $0.804, nitrogen fertiliser cost = $720/t inc GST.*

2.12 Delivery of the SIX EASY STEPS N management approach to industry

SIX EASY STEPS program

The SIX EASY STEPS is the 'badged' mechanism for delivering the integrated nutrient management program to industry. It is currently recognised as the basis for best practice nutrient management for sugarcane production in Australia (Calcino *et al.*, 2008; Schroeder *et al.*, 2009d). The overall object is to provide guidelines for sustainable and balanced nutrition across the industry by applying sound scientific principles but also recognising site/soil and regional differences.

The SIX EASY STEPS consists of:

- Knowing and understanding our soils.
- Understanding and managing nutrient process and losses.
- Soil testing regularly.
- Adopting soil-specific nutrient management guidelines.
- Checking on the adequacy of nutrient inputs (e.g. leaf analyses).
- Keeping good records to help interpret trends in production and modify nutrient inputs when and where necessary.

The SIX EASY STEPS program is multi-facetted. It is delivered to industry by means of a grower-orientated short-course program, a series of regional/district specific soil reference booklets and NutriCalc (a user-friendly on-line nutrient requirement calculator and record keeping system). It is underpinned by a continuing nutrient management R&D program.

Grower-orientated short-course program

The overall objective of the SIX EASY STEPS program is to facilitate the use of better nutrient management on-farm. Given the requirement for sustainable sugarcane production, in which optimum productivity and profitability need to be achieved in combination with environmental responsibility, the SIX EASY STEPS aims to accelerate the adoption of best practice nutrient management across the industry. The SIX EASY STEPS approach is based on the premise that nutrient management guidelines should be linked to soil type (Schroeder and Kingston, 2000; Bruce, 2002).

The SIX EASY STEPS approach provides growers with the ability to undertake 'stepwise' improvements in managing nutrients within their farming enterprises. Information has been presented in numerous forums at three levels of complexity. Basic or individual components of the 'SIX EASY STEPS' have been delivered to growers by oral presentations at 'shed meetings' (attended by 10 - 30 growers) or using poster presentations at 'field days'. More detailed information about the "SIX EASY STEPS' has been presented at half-day workshops using a workbook entitled "An integrated approach to sustainable nutrient management for sugarcane". In depth workshops have, and continue to be, presented to growers (involving 12 – 16 attendees at each workshop) with the aim of progressively developing their abilities to use the 'SIX EASY STEPS' to produce nutrient management plans for their farms. These workshops, entitled "Accelerating the adoption of best practice nutrient management", are regionally specific and essentially consist of component parts that correspond to the 'steps' within the SIX EASY STEPS package (Table 2.29). Different workbooks exist for each of the regions. A typical workshop is presented over a 6 - 7 hour period including breaks for lunch and morning and afternoon tea. A fundamental part of the workshop is a Power-Point presentation that comprehensively covers all aspects of the SIX EASY STEPS approach. The workshop is very interactive, with attendees being encouraged to ask questions and to interact with each other, especially during the practical exercises that involve developing nutrient management plans for a hypothetical farm (Calcino *et al*., 2010).

The first course was presented in October 2005 and has been presented on an on-going basis since then. It is estimated that more than 90 workshops have now been presented with the number of attendees exceeding 1000.

As indicated in the SIX EASY STEPS short-course workbook there is no specific need for a nutrient management plan to be compiled in a particular format. However, it should include the process shown below. The plan should be revisited periodically (at least annually) to update the details when and where necessary.

- Step 1: Collate appropriate farm details and past records
- Step 2: Get a soils map for the farm that shows block boundaries
- Step 3: Make sure you are familiar with the soil type(s) within each block
- Step 4: Develop a soil sampling program
- Step 5: Gather any soil and leaf analysis reports / data
- Step 6: Collate previous fertiliser histories of each block
- Step 7: Determine the nutrient and fertiliser requirement for each block
- Step 8: Determine the fertiliser requirement for the farm
- Step 9: Plan the fertiliser application input strategies

Table 2.29. Details of the regional workshops aimed at accelerating the adoption of best practice nutrient management.

Section 1: Knowing our soils, understanding and managing nutrient processes and losses. This part of the workshop is aimed at establishing the need for improved nutrient management and providing a sound basis for soil specific nutrient guidelines. It covers: 1. The concept of best-practice nutrient management. 2. The 'SIX EASY STEPS' approach. 3. STEP 1 – KNOWING OUR SOILS: Soil field properties and what they mean; soil chemical properties. 4. STEP 2 – UNDERSTANDING AND MANAGING NUTRIENT PROCESSES AND LOSSES: Nutrient availability and balanced nutrition.
Section 2: Adopting best practice nutrient management This part of the workshop is aimed at progressing the 'SIX EASY STEPS' approach to ensure that the ingredients for successful nutrient management plans are in place. It covers: 1. STEP 3 – SOIL TESTING REGULARLY. 2. STEP 4 – ADOPTING SOIL SPECIFIC FERTILISER RECOMMENDATIONS: Up-to-date soil- and district-specific nutrient management guidelines. 3. Developing a nutrient management plan for a hypothetical farm.
Section 3: Developing nutrient management plans for your farm. Growers are encouraged to develop nutrient management plans for their own farms. This part of the course covers: 1. Consolidating the value of the 'SIX EASY STEPS' approach. 2. STEP 5 – CHECKING ON THE ADEQUACY OF FERTILISER INPUTS (e.g. leaf analysis, on-farm strip trials). 3. STEP 6 – KEEPING GOOD RECORDS AND MODIFYING NUTRIENT INPUTS 4. Suggesting how growers can initiate the development of nutrient management plans for their farms.

District-specific soil reference booklets

A series of district-specific soil reference booklets that is linked to the SIX EASY STEPS provides information on soil types within a district and on how to manage soils according to principles of sustainability. The SIX EASY STEPS nutrient management guidelines are presented for each district. The first booklet "Soil specific management guidelines for sugarcane production: Soil reference booklet for the Herbert district" was published in 2003 (Wood *et al.*, 2003). Subsequently, similar

booklets have been produced for Proserpine (Schroeder *et al*., 2006c), Bundaberg (Schroeder et al., 2007a), Johnstone (Schroeder *et al*., 2007b), Plane Creek (Wood *et al*., 2011, New South Wales (Panitz *et al*., 2013) and Isis (Panitz *et al.*, 2014) districts/regions. Currently booklets for the Mackay and Wet Tropics region are under production. These booklets are made available free of charge to growers and their advisors due to funding from various sources.

In the introduction to each booklet the intent, objectives and philosophy of the approach is described. The following is an extract from the Isis booklet (Panitz *et al*., 2014):

"These booklets described the basic principles of soil management and present nutrient guidelines for the major cane-growing soils.

"Our philosophy is that knowledge of soils should form the basis for making management decisions on-farm. Not only does soil type influence decisions on which variety to plant and how much fertiliser to apply, but it also has an impact on the choice of tillage practices, planting techniques, drainage and irrigation requirements, and harvest scheduling.

"A major objective of this publication is to help growers integrate their knowledge of different soils. This includes the appearance of soils, their occurrence in the landscape, their properties and how they should be managed. Soil-specific guidelines as presented in this booklet represent a much more precise way of managing fertiliser inputs than the traditional 'one size fits all' approach. It provides a benchmark against which soils and soil analyses can be compared. However, it is not intended as a substitute for on-farm soil and leaf testing. Ideally each block on the farm should be sampled every crop cycle for both soil and leaf analyses. A system of record keeping should also be implemented which records nutrient inputs, changes in soil fertility, and crop productivity and profitability.

"This philosophy is particularly appropriate for the current circumstances in the Australian sugar industry. The escalating costs of fertiliser, the need to reduce production costs and mounting environmental pressures demand responsible soil and nutrient management. The guidelines in this booklet are aimed at providing best-practice soil and nutrient management for Isis cane growers. Use of these will not only maintain or improve crop yields and soil fertility, but will also provide opportunities for cost reductions whilst enhancing sustainability and delivering positive environmental outcomes by minimising possible off-site nutrient movement."

On-line "Nutri-Calc" program

NutriCalc was developed as an online nutrient management support package for growers and their advisors. It is a versatile package with the ability to be integrated with other nutrient and farm management programs. It contains the ability to identify specific farms and blocks, to determine appropriate nutrient management strategies and the cost of fertiliser inputs based on unit prices of nutrients, to select appropriate fertiliser carriers to meet the determined requirements and to record actual nutrient inputs. The useful electronic record-keeping system will enable nutrient/soil fertility trends and economic assessments (as partial net returns) to be calculated at block, farm, catchment and industry scale (especially as more data is entered into the system).

NutriCalc is accessed via the SRA Website and is hosted on the University of Southern Queensland (USQ)/NCEA server. The package received extensive testing and on-going refinement prior to 'going live'. It is accessible to all growers and/or their advisors via a secure login page. NutriCalc enables reports of nutrient management per block to be generated that conform to the requirements of the Queensland Government's Reef Regulations. It was launched at the BSES Field Day in Mackay (May 2011).

2.13 Enhancements to the SIX EASY STEPS

As the SIX EASY STEPS was developed as a decision support system that would evolve and improve with time, the ongoing R&D program provides information that enables the nutrient management guidelines to be modified/improved when appropriate. The following provide some examples of this approach:

Herbert 2 and 3:

Nutrient management guidelines within the SIX EASY STEPS program are based on trial data gathered when the sugarcane was grown mainly in a 'conventional' farming system. Herbert 2 and 3 were aimed at assessing whether the guidelines are still appropriate for sugarcane grown within the 'new farming system' i.e. permanent bed configurations as defined by the Sugar Yield Decline Joint Venture (Garside and Bell, 2006). In these trials, the establishment of the legume crop was good for both conventional and 'new farming system' treatments on the better drained sandy River Bank soil, whereas on the heavier Clay Loam soil, establishment was better on the permanent beds of the new farming system treatment. This variation allowed the opportunity to compare different N inputs to sugarcane following 'good' and 'poor' legume fallows. As expected, no sugarcane yield response occurred in the plant crop following the legume fallow (conventional and permanent beds) for either soil (Figures 2.24 and 2.25).

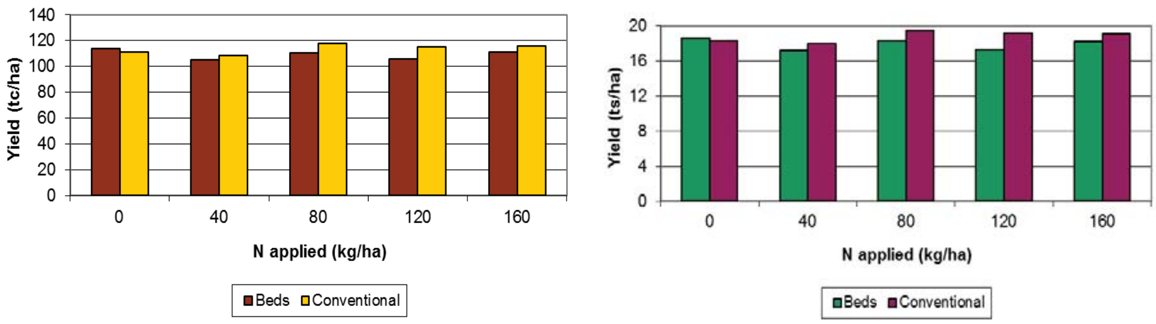


Figure 2.24. Yield (t cane/ha and t sugar/ha) plotted against N applied (kg/ha). The N treatments were applied to a sugarcane plant crop grown on a sandy River Bank soil following a good legume crop on both permanent beds and in a 'conventional' farming system.

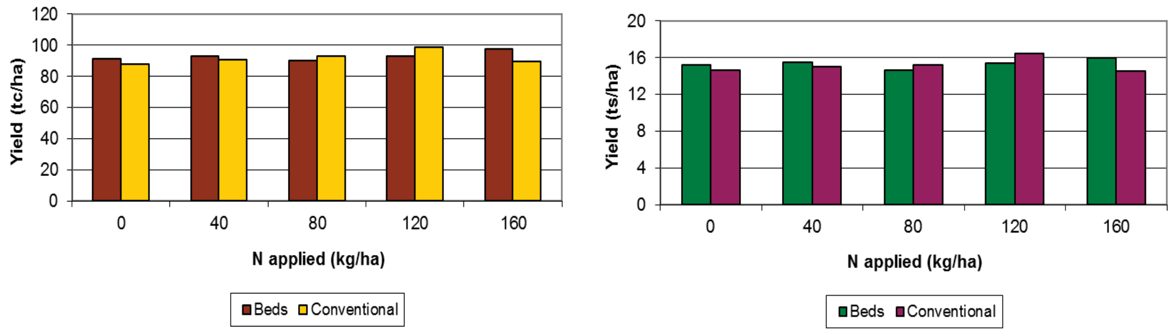


Figure 2.25. Yield (t cane/ha and t sugar/ha) plotted against N applied (kg/ha). The N treatments were applied to a sugarcane plant crop grown on a Clay Loam soil following a good legume on permanent beds and in a 'conventional' farming system.

However, significant (P<0.05) responses to applied N were observed in the first, second and third ratoon crops at both sites. Yield data from the full sugarcane crop cycle (plant cane to 3rd ratoon) following the 'good' and 'poor' legumes on the imperfectly-drained Clay Loam (Herbert 3) are shown here as Figures 2.26 and 2.27 respectively. Soil samples collected from each plot after harvest of the 2nd ratoon indicated that relatively low ammonium and nitrate N remained in the soil profile from the legume fallow (grown three years previously) and from the inorganic N applied prior to the 2nd ratoon crop (Table 2.30). Both forms of mineral N decreased with soil depth.

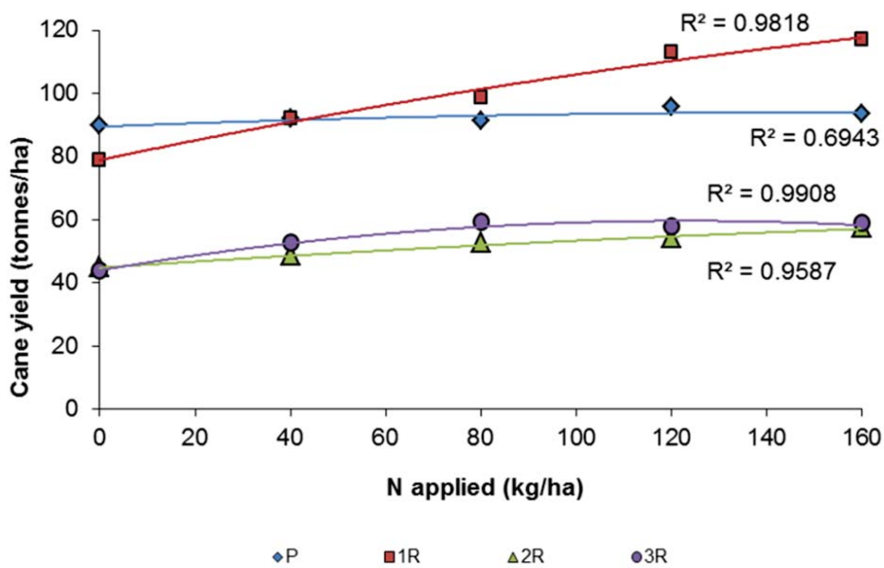


Figure 2.26. Sugarcane yields (tonnes/ha for a crop cycle: Plant crop to 3rd ratoon (2008/09 – 2011/12) following a good soybean break crop (2007/08): 5.9 t dry matter/ha grown on an imperfectly-drained Clay Loam soil in the Herbert district.

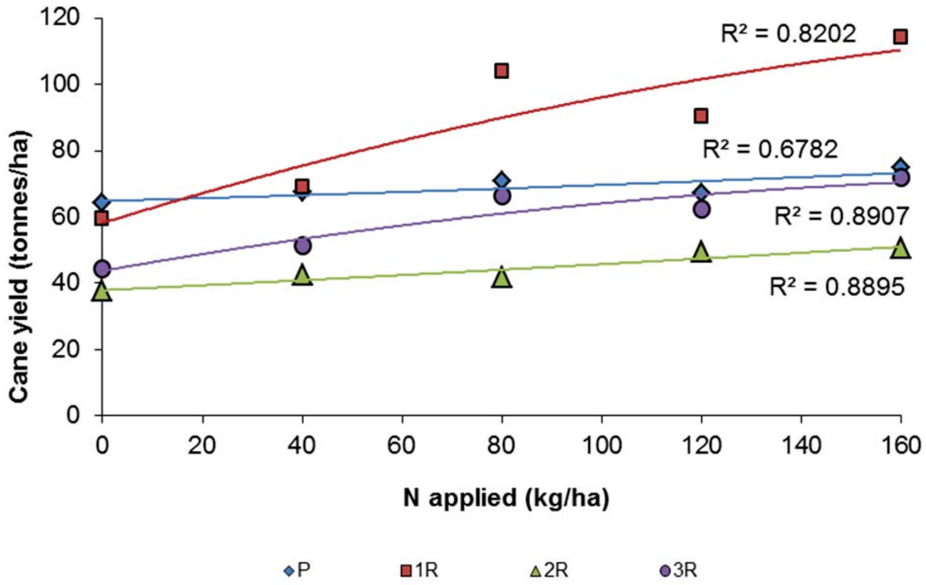


Figure 2.27. Sugarcane yields (tonnes/ha for a crop cycle: Plant crop to 3rd ratoon (2008/09 – 2011/12) following a poor soybean break crop (2007/08): 3.0 t dry matter/ha: grown on an imperfectly-drained Clay Loam soil in the Herbert district.

Table 2.30. Mean soil ammonium, nitrate and mineral N values associated with different rates of applied N and to depth after harvest of the 2nd ratoon of a sugarcane crop cycle following a 'good' legume fallow at the Macknade site in the Herbert District: Clay Loam.

N application rate (kg N/ha)	Ammonium-N (mg N/kg)	Nitrate-N (mg N/kg)	Mineral N mg N/kg)
0	3.9	0.7	4.6
40	4.4	1.0	5.4
80	3.9	0.8	4.7
120	5.9	1.3	7.2
160	3.7	0.6	4.4
SE	0.77	0.25	0.93
LSD	ns (P = 0.05)	ns (P = 0.05)	ns (P = 0.05)
Soil depth (mm)	Ammonium-N (mg N/kg)	Nitrate-N (mg N/kg)	Mineral N mg N/kg)
0 – 200	7.1[a]	2.9[a]	10.0
200 – 400	4.7[b]	0.6[b]	5.3[b]
400 – 600	3.2[b]	0.1[b]	3.2[b]
600 – 800	2.66[b]	<0.1[b]	2.6[b]
SE	0.60	0.21	0.72
LSD	2.33 (P <0.01)	0.81 (P<0.01)	2..80 (P<0.01)

Bundaberg B1:

In the Bundaberg trial (on a Red Clay Loam) responses to applied N occurred in both the plant (2010/2011) and first ratoon (2011/12) crops (Figure2.28). This contrasted markedly to the lack of yield response seen in the plant crop and first ratoon crops (2004/05 and 2005/06 respectively) of the previous crop cycle at the same site following a legume fallow (Figure 2.29). This difference is

probably the result of the marked difference in the rainfall pattern that occurred in the two periods. Whereas average annual rainfall occurred in 2004 to 2006 (Figure 2.30), excessively wet summers were experienced from 2010 to 2012 (Figure 2.31). In excess of 550 mm of rain was measured in late December 2010. The relatively high soil mineral N (ammonium and nitrate) that existed in the soil profile in late November 2004 (Figure 2.32) explains the lack of response to applied N in the trial during the mid-2000s. In comparison, little residual N was found in the soil profile (to a soil depth of 80 cm) after the heavy rains of late December 2010 (Figure 2.33).

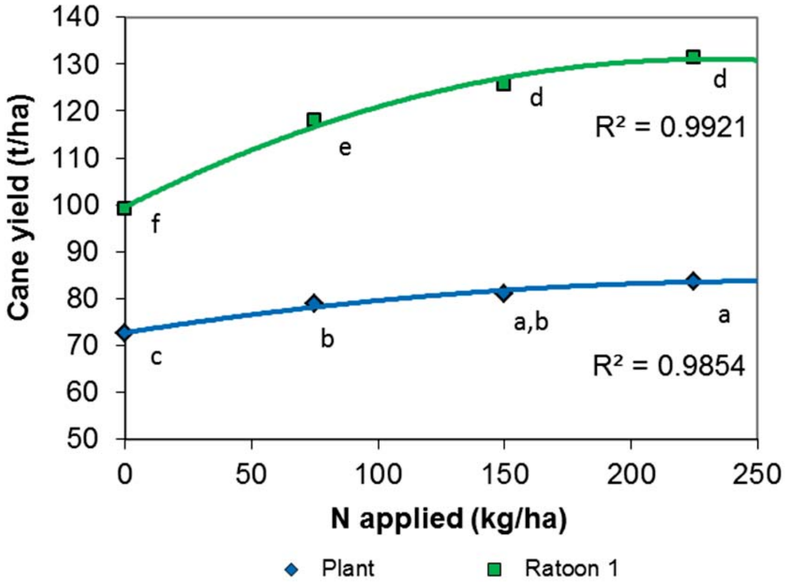


Figure 2.28. Sugarcane yields (tonnes/ha for a plant crop (2010/11) & first ratoon (2011/12) following a fallow crop (7.4 t soybean biomass/ha) grown on a well-drained Red Clay Loam in Bundaberg.

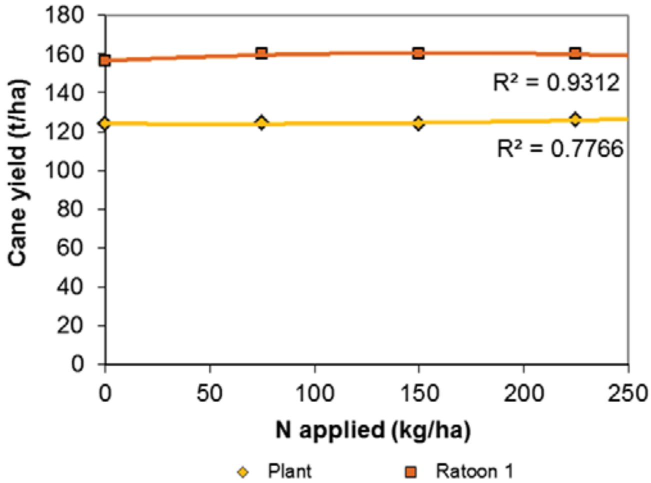


Figure 2.29. Sugarcane yields (tonnes/ha for a plant crop (2004/05) & first ratoon (2005/06) after a fallow crop (3.5 t harvested peanut sugar/ha) grown on a well-drained Red Clay Loam in Bundaberg.

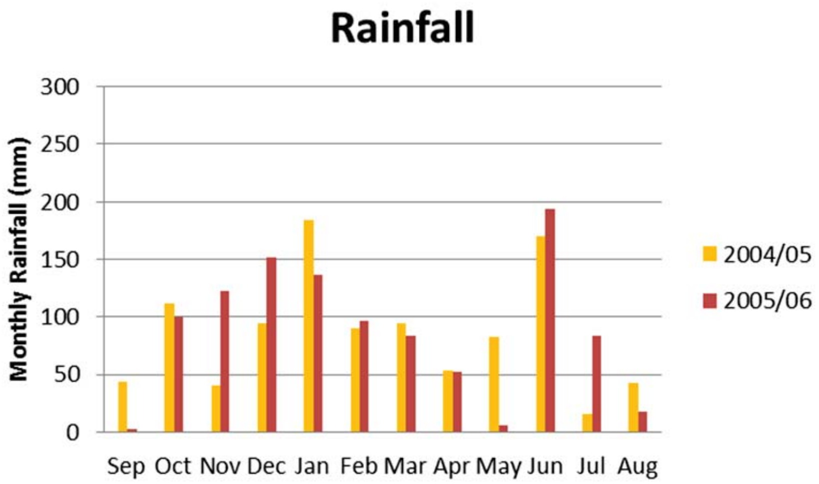


Figure 2.30. Monthly rainfall for the Bundaberg district 2004/05 and 2005/06.

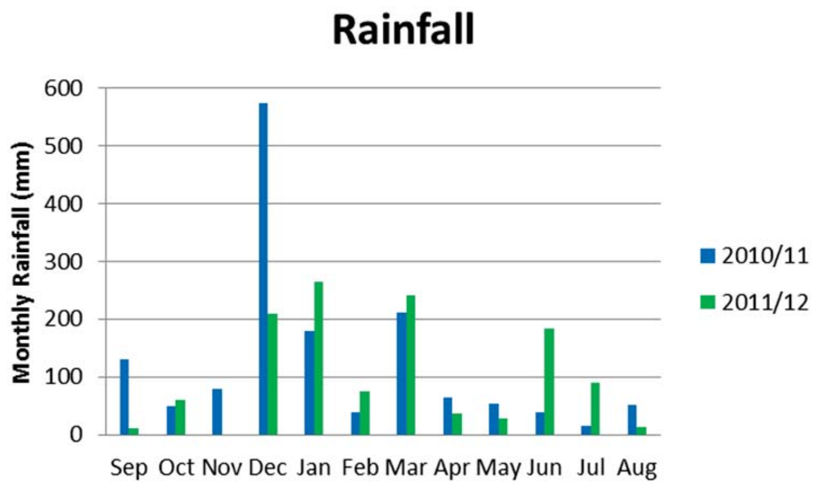


Figure 2.31. Monthly rainfall for the Bundaberg district 2010/11 and 2011/12.

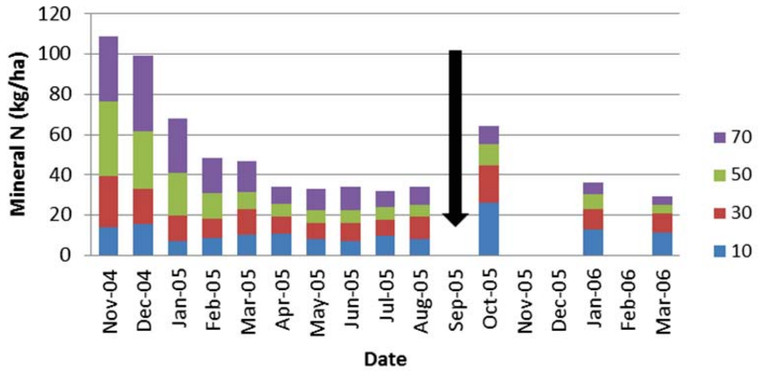


Figure 2.32. Mineral N (ammonium and nitrate) in the soil profile at the Bundaberg trial site (2004/05 and 2005/06) following the legume fallow crop. The arrow indicates the time of harvest of the sugarcane plant crop.

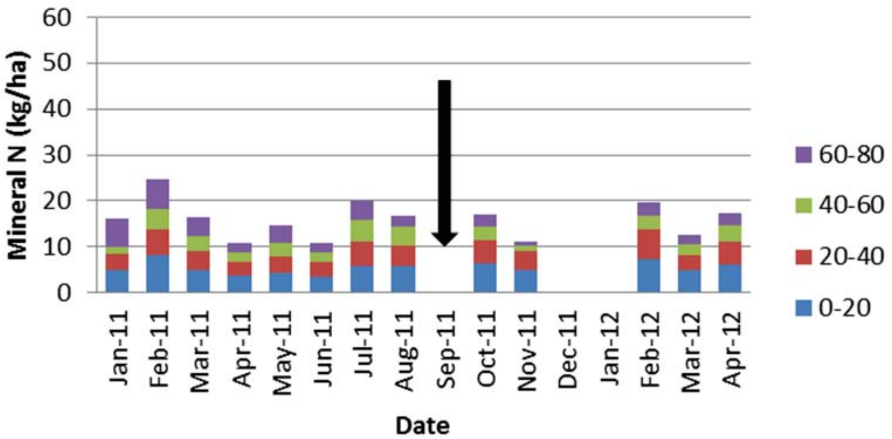


Figure 2.33. Mineral N (ammonium and nitrate) in the soil profile at the Bundaberg trial site (2004/05 and 2005/06) following the legume fallow crop. The arrow indicates the time of harvest of the sugarcane plant crop.

Mackay M1 and Tully T1:

Trials M1 and T1 conducted in very different environments (drier tropics versus wet tropics respectively) indicated that responses to fertiliser N were very similar for cane grown in long-term (15 year periods) burnt and green cane trash blanketed systems (Salter *et al*., 2010; Hurney and Schroeder, 2012). There is therefore, currently, no justification to differentiate the N guidelines within the SIX EASY STEPS program for these types of systems, or to reduce the N application rates for green cane trash blanketed systems that had been in place for at least 3 crop cycles as previously suggested by Robertson and Thorburn (2000).

Tully T2:

This trial was established at the BSES Tully Experiment Station on a Hewitt series soil with an organic carbon of 4.1% C. The objective was to validate the current SIX EASY STEPS guidelines for N requirements for soils with very high organic carbon content or if adjustments were required Unpublished - AP Hurney, DM Skocaj). Six rates of N were applied within a randomised block design.

Yield data (Table 2.31) indicated that there was only a significant response to applied N in terms of sugar yield in the first ratoon. However, the general trends suggest that some N is needed to optimize yield, and that the SIX EASY STEPS guidelines for soils with organic C > 2.4% remain appropriate at present, but further interpretation and possible fine-tuning could occur as more data become available (this and other sites).

Table 2.31. Tully trial: N treatments and yield data: plant and first ratoon crop (2007/08, 2008/09) – unpublished data (AP Hurney, DM Skocaj).

N applied (kg/ha)	Yield					
	Plant crop			First ratoon		
	(t cane/ha)	ccs	(t sugar/ha)	(t cane/ha)	Ccs	(t sugar/ha)
0	109.1	16.4	17.9	57.8	16.4	9.5
50	116.3	16.8	19.5	69.4	16.8	11.6
80	116.7	16.6	19.4	67.2	16.7	11.3
110	109.3	17.2	18.8	71.6	16.8	12.0
140	115.9	16.9	19.6	69.6	16.9	11.8
170	114.5	16.7	19.1	70.5	16.7	11.7
SE	4.7	0.28	0.69	4.0	0.30	0.58
P	0.64	0.38	0.47	0.15	0.86	0.04

Current investigations

Seasonal climate forecasting to guide N rates in the Wet Tropics

It is common practice to align nutrient inputs, including N, with potential or target yields (Thorburn and Wilkinson, 2012). However, the Wet Tropics region experiences extreme inter-annual climate variability and this can have a significant impact on cane yields. For example, the Tully mill area average cane yield was 89, 47, 74 and 89 t cane/ha in 2010, 2011, 2012 and 2013, respectively (Anon, 2014). This makes it difficult to identify the most appropriate yield potential to use when calculating N fertiliser requirements. However, seasonal climate forecasts provide probabilistic information about future climatic conditions and could be used to refine N management strategies, including the yield potential used to calculate N fertiliser requirements.

One of the largest sources of inter-annual climate variability in this region is the El Nino Southern Oscillation, commonly referred to as ENSO (Partridge 1994, Allan *et al*. 1996,). The oceanic component of ENSO has two extreme but closely linked phases: El Nino (Australia experiences drier conditions than normal) and La Nina (Australia experiences increased rainfall and storm activity) (Allan *et al*. 1996). The Southern Oscillation represents the atmospheric component of ENSO. The Southern Oscillation Index (SOI) is used to measure changes in the strength and phase of the Southern Oscillation (McBride and Nicholls, 1983; Kuhnel, 1994; Partridge, 1994). Previous research has demonstrated that the SOI can be used to forecast sugarcane yields for specific mill areas, especially in north QLD (Kuhnel, 1994). The chance of above-average cane yields is higher than climatology for the Tully and Mulgrave mill areas when the October-November SOI remains deeply negative (Everingham *et al*., 2003). This is because deeply negative SOI values during October-November favour lower summer rainfall which generally has a positive impact on cane growth in

these districts owing to increased solar radiation (Everingham *et al*., 2003). For other north Queensland sugarcane regions, a deeply negative (deeply positive) SOI value at the end of the November suggests it is highly likely that cane yields will be above (below) average for the following harvest (Everingham *et al*., 2002). More recently, rainfall around spring-summer has been identified as having the greatest influence on Tully cane yields. Total rainfall from October to February accounts for 30% of the variation in Tully cane yields over a 40 year period (Skocaj and Everingham, 2014).

Trial T1 was re-visited to demonstrate how climatic conditions influence N requirements. The optimum amount of N, considered to be that associated with producing 95% of the maximum yield in each year, was calculated by fitting a polynomial regression to the T1 yield data to generate an annual N response curve (Figure 2.34). The optimal N rate for the first, second, third and fourth ratoon crops was calculated to be 140, 150, 130 and 120 kg N/ha, respectively (Figure 2.34). Overall these rates were fairly close to the SIX EASY STEPS N rate which for this site was 130 kg N/ha/year based on an organic carbon value of 1.30% (Skoacaj *et al*., 2013b). However, it is interesting that the highest optimum N rate was associated with the second ratoon (2R) crop as this corresponded with the second wettest year of the trial (2006/06). Looking at the rainfall distribution for each crop in greater detail shows that rainfall was fairly well distributed between spring and autumn although slightly higher during summer for the 2R crop. The fisrt ratoon (1R) crop also experienced relatively wet conditions but over half of the annual total rainfall occurred in autumn, which is outside the Oct-Feb period identified in the analysis conducted by Skocaj and Everingham (2014). The optimal N rate was lowest for the 4R crop. This is not surprising as it was the wettest year of the trial (2008/09) with the majority of rain falling from Oct to Feb (61.5%) and continuing into autumn (27%). This highlights the impact of climatic conditions on cane yields and N requirements in the Tully region.

Predictions of climatic conditions during the sugarcane-growing season, especially over spring and summer, may help refine N management strategies. As climatic conditions influence crop growth, N demand and N loss processes, it is reasonable to hypothesise that different N management strategies may be required for ‘wet’ vs ‘dry’ years. Unfortunately there is little evidence of seasonal climate forecasts being used to guide N management strategies in sugarcane production. The skill in climate-forecasting capabilities, potential for high N losses and proximity to sensitive ecosystems makes the Wet Tropics region the ideal case study environment to test this hypothesis (Skocaj *et al*., 2013a). Small plot N rate field trials (T3, T4 and T5), crop modelling and statistical methods are being used to generate a time series of N response curves so that the climatic impact on crop responsiveness to applied N can be determined. This will be used to identify the most sustainable N rate for different climatic conditions (i.e. ‘wet’ vs ‘dry’ years) and if changes are required to N fertiliser rates for different climatic conditions. The potential impact on productivity, profitability and NUE resulting from the adoption of a variable N rate strategy in response to a seasonal climate (or yield) forecast as opposed to a fixed N rate, will also be evaluated. In addition to this research, another research project is evaluating the ability to produce earlier and reliable climate or yield forecasts for the Tully mill area in order to adjust N rates annually, before the majority of N fertiliser is applied.

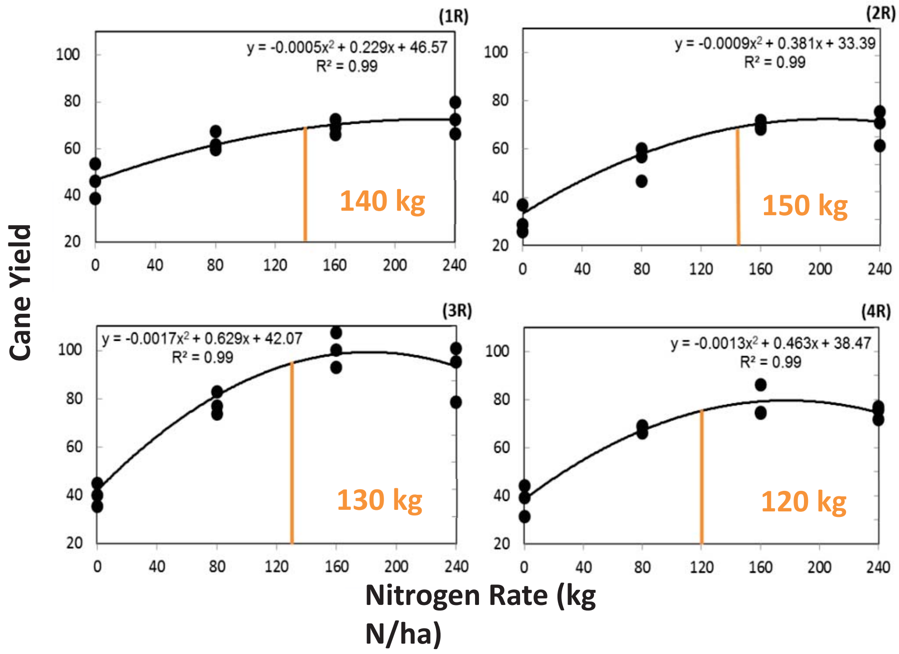


Figure 2.34. Yield response to applied N (0, 80, 160 and 240 kg N/ha) at the T1 trial site (2006 to 2009) for the first, second, third and fourth ratoon crops. The orange vertical line indicates the calculated N rate producing 95% of the maximum yield in each year (Skocaj *et al*., 2013b).

Bioavailability of N from mill by-products

There is wide-ranging acceptance of the yield benefits of using mill by-products as nutrient sources, particularly N (e.g. Moberly and Meyer, 1978; Gilbert *et al*., 2008) within the sugarcane production system. The SIX EASY STEPS program recognises these benefits and allows for discounts to N inputs in particular (Schroeder *et al*., 2005) according to previous estimates of N availability following applications of mill mud, mill ash and mud/ash mixtures (Calcino, 1994; Barry *et al*., 2002). However, the paucity of information on the release rates of N, P and K from these products, and the fact that they are very variable in composition (Barry *et al*., 2002) has prompted evaluation of the bioavailability of nutrients from mill mud/mill ash when applied to soil (Moody *et al*., 2014). Approximately 10% of the total N in the applied mill mud/ash mixture was recovered in the above-ground crop in the first 4 to 5 months after application. This work continues.

2.14 Future evolution and refinements

The following have been identified as topics for future R&D:

- Matching N supply to crop N demand by appropriate legume break crop stubble management, split fertiliser applications and/or appropriate enhanced efficiency fertilisers.
- Proximal sensing using various techniques to assess the adequacy of N inputs.
- Mechanisms / formulations to address temporal and spatial variability in the landscape, soil or crop growth/yields.

- Developing SIX EASY STEPS guidelines for Precision Agriculture (PA) by targeting in-field variability.
- Screening varieties for crop NUE.
- Development of mitigation strategies for denitrification, and a possible decision support component within "SafeGauge for Nutrients" to assess risk of denitrification.
- Development of N management strategies for older ratoons within the crop cycle.
- Development of N management strategies for time-of-harvest (earlier-cut cane versus later-cut ratoons, etc).
- Development of a decision support tool within NutriCalc and SafeGauge for Nutrients to provide advice on the efficacy of enhanced efficiency fertilisers for profitability and environmental outcomes.
- Further assessment of the bioavailability of N (and P) from mill by-products and/or value added products during a cropping cycle.

2.15 Discussion and Conclusions

The Australian sugar industry has continued to recognise the important role of nutrient management in sugarcane production since the inception of the Bureau of Sugar Experiment Stations in 1900. In particular N has been the subject of ongoing RD&E with a large number of trials and investigations conducted by BSES Limited. During the 1990s, the industry recognised the need for nutrient management that aimed at sustainable sugarcane production. Much effort went into better understanding the factors that controlled losses and uptake of N. Due to a concerted effort within the Cooperative Centre for Sustainable Sugarcane Production in the late 1990s and early 2000s, the need was also recognised for nutrient guidelines to be based on soil properties and processes, and the interaction of nutrients with soils. This led to the development of two new approaches to N management - the SIX EASY STEPS nutrient management principles and program, and the N-Replacement concept. The SIX EASY STEPS program was developed using a logically-based 'systems' framework that enables further evolution as further research results emerge. The initial R&D and evaluation phases were extensive. The program has been delivered to industry through various mechanisms, including a widely run short-course program, the ongoing development of district-specific soil/nutrient management booklets, and on on-line nutrient management package. The N-Replacement concept is more environmentally focused. However, with its reduced N-input strategy, maintenance of sugarcane productivity and profitability is less well-tested than SIX EASY STEPS. As such, it cannot be considered as a generally applicable system at this time

Soil and district-specific N guidelines, developed in the SIX EASY STEPS program, are based on DYP, a multiplier of 1.4 kg N per tonne of cane up to a cane yield of 100 tonnes and 1.0 kg N per tonne thereafter, and an N mineralisation index. This system has resulted in target NUE ranging from 0.75 to 1.64 tonnes cane/kg applied N across the industry. The aim of this was, and continues to be, profitable sugarcane production in combination with environmental responsibility.

The on-going developments (since the early 1900s) have ensured continuing improvements in target and actual N-use efficiencies. However, it is important that economic effectiveness of N inputs continues to be considered.

The SIX EASY STEPS N guidelines form the basis of current industry best management practice (BMP). As indicated in the preceding sections of this chapter, these N guidelines have been comprehensively trialled and tested, and continuously updated as new information becomes available. Importantly, the SIX EASY STEPS focuses on all nutritional requirements not just N. It contains a well-developed delivery mechanism and enables further enhancement / refinement. This requires a concerted commitment and ongoing R&D investment to address issues for future evolution and refinements. Any changes to current N BMP should be based on sound scientific evidence with rigorous assessment before being promoted to industry.

Improving NUE should never be seen in isolation to economic effectiveness.

The items listed in the section “Future evolution and refinements” provide the potential for more effective and efficient use of N, and to ensure better uptake by the crop and decreased losses to the environment. In particular, the following are considered as the most important N management R&D topics in the short to medium term:

- Impact of climate variability on cane yield. Improving NUE in this way should be evaluated on a wider range of soil types and sugarcane growing districts
- Any changes to the “district yield potential” used within the SIX EASY STEPS program to calculate N fertiliser requirements should be well-researched and not based on anecdotal evidence. These investigations should not focus on historical yields alone, but also aim at determining yield potential of the upcoming season to ensure crop N demand is not restricted.
- Developing SIX EASY STEPS guidelines for Precision Agriculture (PA) by targeting in-field variability.
- Addressing the temporal N needs of sugarcane by matching N supply to crop N demand.

It is vital that the most appropriate (efficient and economically effective) N inputs are used within the sugarcane production system in Australia. To this end, the combination of the SIX EASY STEPS program and the integrated framework that underpins the program provides a suitable mechanism for future RD&E in nutrient management. Sustainable (profitable and environmentally responsible) N inputs will contribute to the prosperity of sugarcane communities of regional Queensland and the survival of the World Heritage-listed Great Barrier Reef.

2.16 Acknowledgements

The co-authors associated with the SIX EASY STEPS program acknowledge the following:

- The information reported in section 2.13 (Enhancements to the SIX EASY STEPS) that relates to field trials H2, H3, B1 and M1 during the period 2010/11 to 2013/14 was part of Project RRRD020. It was funded partially by the Australian Government's Caring for Our Country Program.
- The replicated demonstration strip-trials B-ST1 – B-ST11, P-ST1 – P-ST6, C-ST1 – C-ST9, H-ST1 – H-ST-11, Bkn-ST1 – Bkn-ST3 and J-ST1 – J-ST9 were conducted on-farm through the efforts of several co-ordinators e.g. Dr Andrew Wood, Glen Park, John Panitz, John Agnew and Jayson Dowie, and the grower co-operators.

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3. Agronomy and physiology of nitrogen use in Australian sugarcane crops

MJ Bell, P Moody, B Salter, J Connellan and AL Garside

3.1 Abstract

While nitrogen (N) inputs are undoubtedly a key contributor to the productivity and profitability of the Australian sugar industry, this review suggests there is considerable opportunity to reduce fertilizer N inputs through improved crop recovery of applied N and improved efficiency of use of that accumulated N to increase biomass production and sucrose accumulation. The current industry approach of calculating N fertilizer requirements based on an aspirational maximum district yield, without reference to site specific management factors or seasonal forecasts, is a significant constraint to making improvements in N use efficiency (NUE). Similarly, adoption of improved terminology and experimental protocols to quantify fertilizer NUE by taking into account background soil N supply and crop recovery of applied N would allow a much clearer focus on fertilizer N management improvement.

A major constraint to achieving improved agronomic efficiency of applied N (t crop yield increase/kg fertilizer N applied) is poor synchronization of N availability with the periods of peak N demand by the crop. In many parts of the industry low fertilizer NUE is driven by seasonal rainfall patterns in the period 3-6 months after planting/beginning of ratooning, combined with the use of fertilizer products in which the N is rapidly converted to nitrate-N that is vulnerable to loss by aqueous or gaseous loss pathways. The development and testing of enhanced efficiency fertilizers (EEF) offer some promise of improvement in this aspect, with management to control losses seemingly an absolute prerequisite to any significant reduction in application rates in the industry.

Once the risk of losses can be reduced, opportunities to fine tune other aspects of fertilizer N management become much more feasible, although current knowledge gaps would need to be addressed. These opportunities include:

- Use of finer scale (farm or block) measures of potential yields to more accurately define crop N demand, with the opportunity to refine these targets using seasonal forecasting tools that can indicate the likelihood of seasonal influences on those yield potentials (e.g. extreme wet weather).
- Improving the prediction of the background contribution from other N sources, viz., *in situ* soil N mineralization, soil amendments such as mill by-products, and legume rotation crops
- Improving the opportunity for in-season N management through the deployment of remote sensing or 'on the go' sensors that can indicate crop N status and link that status to a need for additional fertilizer N inputs – as long as this is possible within the period when fertilizer N application options are still practical.

This review indicates there are clear gaps in knowledge in two other areas that should allow improved NUE. The first lies in the physiology of N use and the opportunities to exploit that through

genetic or management approaches. Current sugarcane varieties do not seem to have an obligate requirement for high crop N contents, being able to yield quite well with low crop N contents. However, they do have the capacity to accumulate luxury amounts of N when it is available, with that N typically accumulating in stalks and being removed from the field at harvest. The ability of genetic approaches to prevent excessive stalk N accumulation and improve N cycling and return in crop residues offers the potential to improve NUE at both a crop and system scale.

Similarly, an improved understanding of N dynamics in the sugarcane cropping system in situations of variable soil types, crop rotations and climatic conditions will allow the industry to develop a more targeted approach to R, D and E investment that will deliver NUE improvements across the industry. This improvement will facilitate the achievement of enhanced environmental performance whilst ensuring the maintenance of a viable and sustainable sugar industry.

3.2 Nitrogen use in the Australian sugar industry

While nitrogen (N) is generally the most substantial fertiliser input in modern cropping systems, there is still considerable uncertainty around management guidelines that aim to optimise application rates. In an ideal world, optimized rates would deliver agronomically and economically effective quantities of N fertiliser so as to minimize environmental losses and provide a profitable return on fertiliser investment. Uncertainty is especially evident in the Australian sugar industry, with major production areas characterized by highly variable soil and climatic conditions. While N fertiliser use has tended to decline in some areas in recent years (e.g. Wood *et al.* 2010 and chapter 1, this review), the sugar industry in Australia is still a significant user of N fertilisers, with annual applications averaging 150-200 kg N/ha in various sugar-producing districts (Fig. 3. 1).

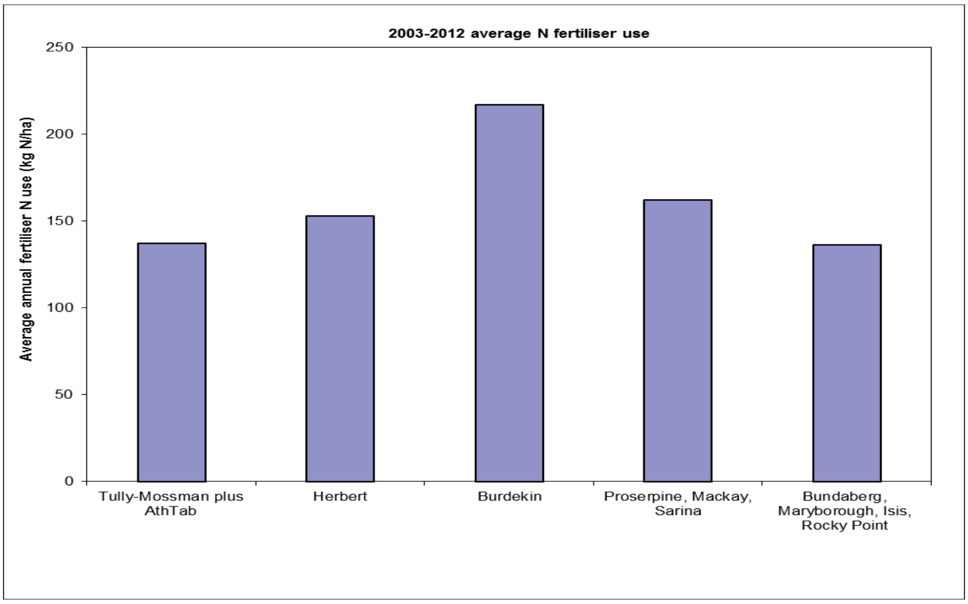

Figure 3.1. Nitrogen fertiliser use across the main growing areas in the Queensland sugar industry (2003-2012). Source - R. Dwyer IPL

Historically, nitrogen fertiliser rates in the Australian sugar industry were originally based on an extensive network of N fertiliser rate trials (e.g. Chapman 1994) that was used to derive response surfaces for plant and ratoon crops grown in the different growing regions of the industry. These recommended rates did not take account of variation in crop yield potentials or soil type variation.

Improvements to these general recommendations were developed to ensure that N rates were better tailored to specific sites, soils and farming systems (e.g., Schroeder *et al.* 2005), with modifications based on management factors (e.g. use of legume crops during fallows between crop cycles) and soil factors that affect N mineralisation. As these guidelines were improved, they were incorporated into various decision support frameworks that attempted to better integrate the many variables involved and progress towards arriving at tailored fertiliser N rate decision for a crop class in an individual block. Simultaneous development of two frameworks occurred during the period post-2000. The first (the 6 Easy Steps package – Schroeder *et al.* 2010) was a package designed to provide a framework upon which a balanced approach to sustainable nutrient management in the sugar industry could be based. The N management approach in 6ES was loosely based around the likely N requirement of a crop with a potential yield based on local soil and climatic factors. An alternate approach to N management (the N replacement approach) proposed by Thorburn *et al.* (2008) varied in that fertiliser N rates were determined on a retrospective basis, aiming to relace the N removed in the preceding harvest as well as that estimated to be lost to the environment.

The assumptions inherent in each of these approaches are covered in the preceding chapter of this review, but are both based on yield targets (expected or informed by the immediate past crop harvest) and a Nitrogen Use Efficiency (NUE) factor calculated as the quantity of applied N required to produce a fresh weight (FW) tonne of cane yield. This NUE was loosely based on previous crop model simulations (Keating *et al.* 1997), and was assumed to be 1.4 kg applied N required per tonne cane up to a yield of 100 tonnes cane/ha with an additional 1 kg applied N required per tonne cane yield thereafter. However, there has been little experimental validation of this NUE parameter in various production regions, and recent reports (Thorburn *et al.* 2011; Bell and Garside 2014) have suggested this NUE factor may be a significant over-estimate of the N required to produce a tonne of cane and the fertiliser N required to meet that crop demand.

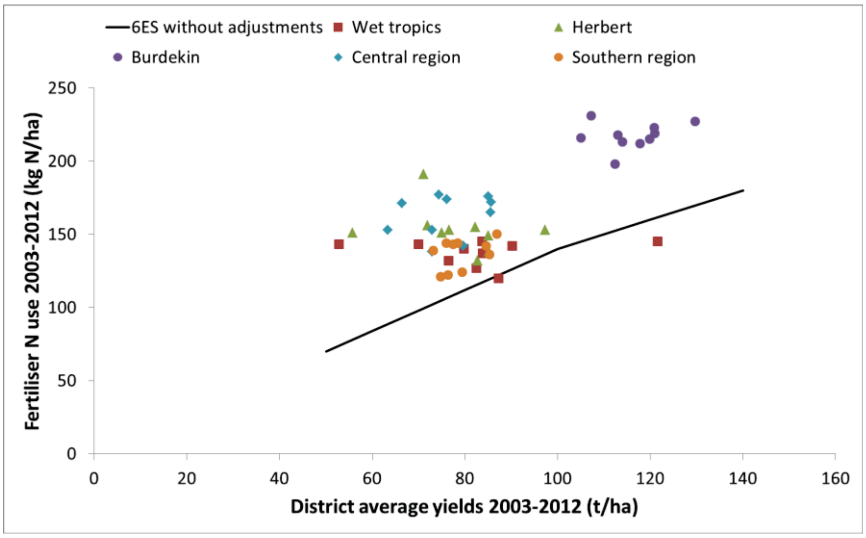

Figure 3.2. Relationship between district average cane yield (t/ha) and district average N fertiliser use (kg N/ha) for the major cane growing regions in Queensland from 2003-2013. The response surface represents the recommended N fertiliser requirement from 6ES for different crop yields without any discount for soil N mineralisation during the growing season.

The inefficiencies inherent in fertiliser N use in the Australian sugar industry are well recognized, despite the advances made in decision support frameworks. This is well illustrated by regional data on both cane yields and fertiliser N use collected over the decade from 2003-2012 and depicted in Fig. 3.2. On average, apparent fertiliser NUE across the industry was 1.9 kg fertiliser N applied/t cane produced. With the exception of one or two seasons in the Wet Tropics (the harvest years of 2004, and to a lesser extent 2010), all cane producing regions applied significantly more fertiliser N than suggested by the 6ES framework for the cane yields produced. This over-application was most pronounced in the Central region (52% greater than warranted for the yield produced), with the Burdekin and Herbert regions (39% greater) intermediate and the Wet Tropics and Southern regions (19% and 23%, respectively) closest to recommended 6ES guidelines. This over-application would have been even greater if the discounts to N fertiliser rate made to account for soil organic matter status and rotation crops had been reflected in the 6ES response surface.

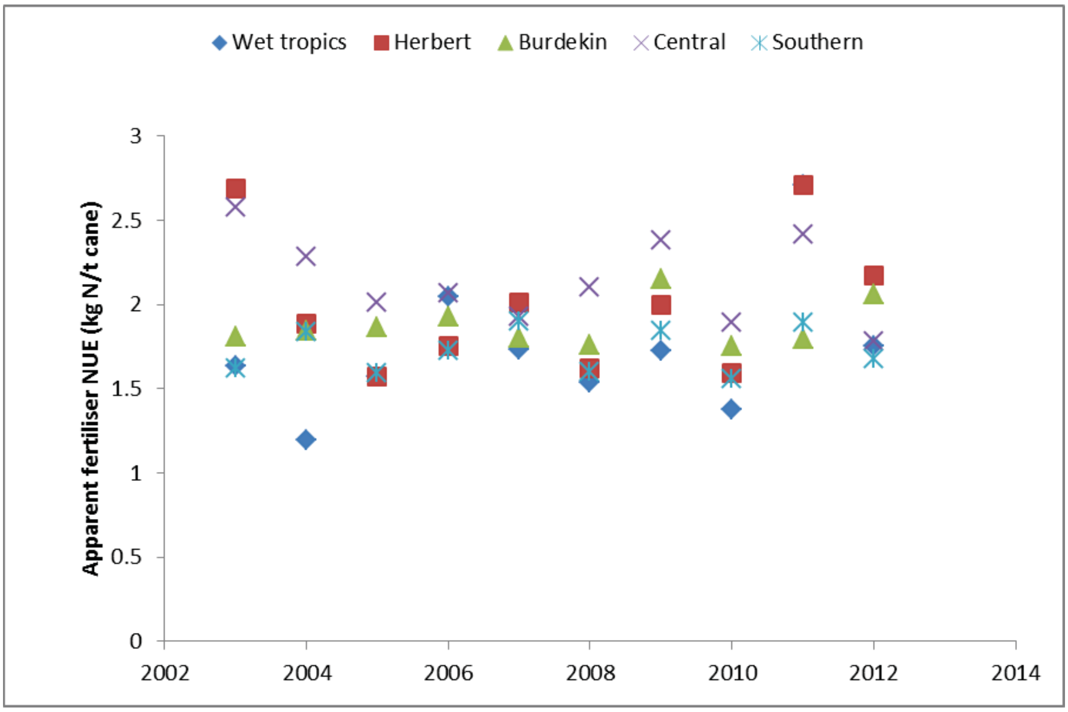

Figure 3.3. Apparent fertiliser N use efficiency (kg N applied/t cane) for the respective cane producing regions of the Queensland sugar industry from 2003-2012.

While regional (Wood *et al*. 2008) and broader industry statistics (Wood 2014, this review) suggest a recent decline in N fertiliser use across the Australian sugar industry, this has not resulted in any noticeable change in apparent N fertiliser use efficiency in any region in the last decade (kg fertiliser N applied/t cane yield – Fig. 3.3). Annual variations in apparent NUE can be $\geq$ 50-100% in some regions (e.g. 1.19 to 2.17 in the Wet Tropics, 1.58 to 2.71 in the Herbert and 1.78 to 2.58 in the Central region), due to seasonal influences on productivity (Canegrowers annual reports). This variability highlights the challenges faced by industry in improving fertiliser NUE in the face of a variable productivity target and an environment where losses can be extreme.

3.3 Apparent N balance derived from a simple budgeting approach

The high N fertiliser rates being used by industry relative to recommended rates from industry decision support tools (Fig. 3.2) suggest fertiliser rates are well in excess of crop demand. This is reinforced when apparent N budgets are calculated based on a range of stalk N concentrations spanning those in published data (i.e. 0.1% to 0.3%N in millable stalk on a dry weight basis – Keating *et a*l. 1999; Thorburn *et al.* 2011). Using district average cane yields and district average fertiliser N application rates, and assuming millable stalk is ~30%DW (Muchow *et al.* 1996), the proportion of applied N removed in harvested cane ranges from 14-18% (0.1%N) to 42-54% (0.3%N), with the N removal rates highest in the Burdekin (Fig. 3.4). However, in any such analysis there are two main caveats – (i) there is an assumption that applied fertiliser N is actually available to be taken up by the crop, and/or (ii) that crop N is predominantly derived from applied N fertiliser.

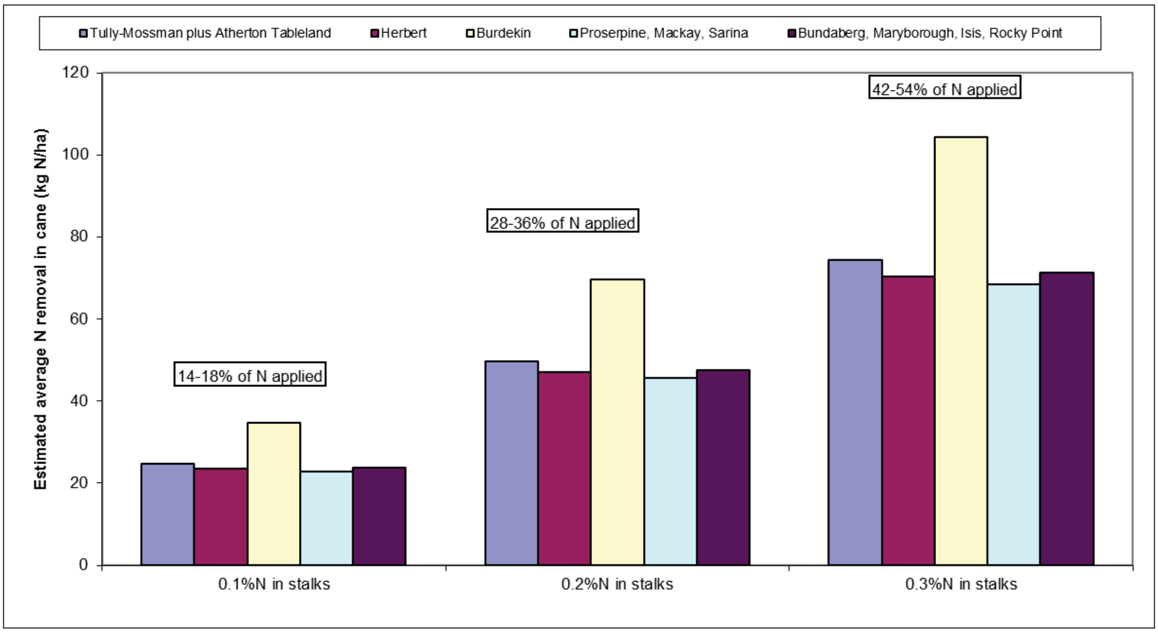

Figure 3.4. Estimated crop N removal (kg N/ha) based on average yields in each production region from 2003-2012 (Canegrowers annual reports) assuming fresh weight cane is ~30% dry matter and a range in stalk N concentrations (0.1 – 0.3%N). Removals are then expressed as a percentage of the district average N fertiliser use over the same period (Figure 3.1).

There is evidence that both these caveats may not be valid in many situations, and data will be reviewed in this document. There are also clear suggestions that the high fertiliser N rates applied in sugarcane cropping systems are as much a practical response to fertiliser use inefficiency resulting (in part) from environmental loss processes as they are to the fundamental N requirements to grow high yielding sugarcane crops. Studies using labelled ^{15}N fertiliser have indicated maximum recoveries in the crop and surrounding soil of just over 60% of N applied, with values more commonly 20-40% (Chapman *et al.* 1991; Vallis and Keating 1994; Vallis *et al.* 1996, Prasertsak *et al.* 2002). Even when the fraction of fertiliser N retained in the soil at crop harvest was considered, losses to the environment (i.e., ^{15}N unaccounted for) were typically 40-50% (Chapman *et al.* 1992; Vallis *et al.* 1996; Prasertsak *et al.* 2002). It is also consistently reported that residual N from applied fertiliser remaining in the soil profile or returned to the field in trash and other crop components does not make a significant contribution to the N uptake in the following ratoon crop (e.g., Chapman *et al.* 1983; Chapman *et al.* 1992; Bell *et al.* 2010).

The fertiliser N not recovered in the soil-plant system is presumed to have been lost by a range of processes which include volatilisation, denitrification, leaching, erosion and runoff. The losses in water (leaching, runoff and erosion) and the implications for water quality in streams and the receiving waters of the Great Barrier Reef Lagoon have recently been reviewed by Brodie *et al.* (2008) and Thorburn *et al.* (2013). While leaching losses can be quite variable, they generally dominate losses from individual fields compared to losses in runoff. Measurements of elevated nitrate-N concentrations in subsoils (e.g., Armour *et al.* 2013), and in groundwater under sugarcane fields (e.g., Rasiah *et al.* 2013) are consistent with the importance of this loss pathway in moderately to well-drained soils.

While leaching appears to be the dominant N loss pathway in water, gaseous losses of N are dominated by denitrification rather than volatilisation where N fertiliser is applied under the trash blanket or subsurface (e.g., Prasertsak *et al.* 2002). However, in that study the reduced volatilisation loss with banding (from 37% of applied N fertiliser to ~5% of applied N) resulted in an effective doubling of losses from leaching and denitrification (from 22% to 40% of applied N) and no improvement in fertiliser N recovery by the crop or retention in the soil N pool. The size of denitrification losses across a cropping year varies considerably with seasonal conditions, soil type and soil N status, with both legume and fertiliser N vulnerable to losses when soils are wet (Allen *et al.* 2008; Wang *et al.* 2012, 2014). The quantitative relationship between total N losses (measured using ^{15}N) and losses from denitrification has yet to be well defined. However, the quantities of N_2O-N lost (Wang *et al*. 2014) and the likely ratios between denitrified N_2O-N and denitrified N_2-N observed in other industries (Grace *et al*. 2009, 2010) suggest this will prove to be a major loss pathway – especially in heavier soils and irrigated or high rainfall environments.

Collectively, this synopsis suggests that the Australian sugarcane industry is an inefficient user of N fertilisers, with increasing environmental and economic pressure on the industry to adopt more efficient fertiliser N practices. These will necessarily need to be built on an improved understanding of the soil N cycle, crop N uptake dynamics and the internal N requirements of the sugarcane crop to produce biomass, cane and sugar yield. Collectively, this understanding will allow the industry to more efficiently capture both soil and fertiliser-derived N for use in crop growth and minimize losses to the environment and any unnecessary export of N in harvested product.

3.4 Terminology used in exploring fertiliser N use efficiency

To provide the framework around which sugarcane N use can be explored, it is necessary to clearly differentiate the various components of crop N acquisition and use. Current industry benchmarks do not clearly differentiate between fertiliser N applied and that recovered by the crop, and also between the fraction of yield derived from background soil fertility and that derived from the application of N fertiliser. We therefore have provided some definitions which can be used to provide clarity to any discussion of different aspects of Nitrogen Use Efficiency in the sugar industry. The concepts behind these definitions have been described in the review by Ladha (2005), with the definitions and acronyms shown in Table 3. 1 used hereafter in this document. A brief discussion of the application of these concepts to the sugarcane crop follows.

Table 3.1. Terminology and acronyms used in the quantification of crop responses to applied N fertiliser.

Description	Acronym
N utilization efficiency - the efficiency with which a crop utilizes accumulated N to produce a unit of crop growth (e.g., t dry matter/kg crop N)	NUtE
Fertiliser N uptake efficiency – the efficiency with which applied N fertiliser is accumulated in crop biomass (kg crop N/kg fertiliser N applied)	$NUpE_{Fert}$
Agronomic Efficiency of Fertiliser N – the efficiency with which fertiliser N is used to produce crop yield (e.g. t cane yield/kg fertiliser N applied)	$AgronEff_{Fert}$

N utilization Efficiency (NUtE)

This efficiency factor describes the relationship between crop N content and the production of dry biomass or fresh weight cane yield, with both parameters typically referring to above ground components. The relationship is typically asymptotic in shape, with an example reproduced from Bell and Garside (2014) in Fig. 3.5. As can be seen from this relationship, the NUtE (in this case, t dry matter produced/kg above ground crop N content) is maximized at low crop N contents, when the relationship is linear. At these low crop N contents the relationship is linear with a zero intercept, as there is no significant above-ground biomass production in the absence of N uptake by the crop. The slope at low crop N can therefore be used to define the maximum growth response that could be expected from increased crop N uptake.

However, this term does not discriminate between N sources (i.e., soil mineral N present at planting or mineralized from organic matter during the growing season, N derived from soil amendments or crop residues during the season, or recovery of applied N fertiliser), and is directly related to physiological processes in the plant – possibly including N partitioning between above and below ground plant parts.

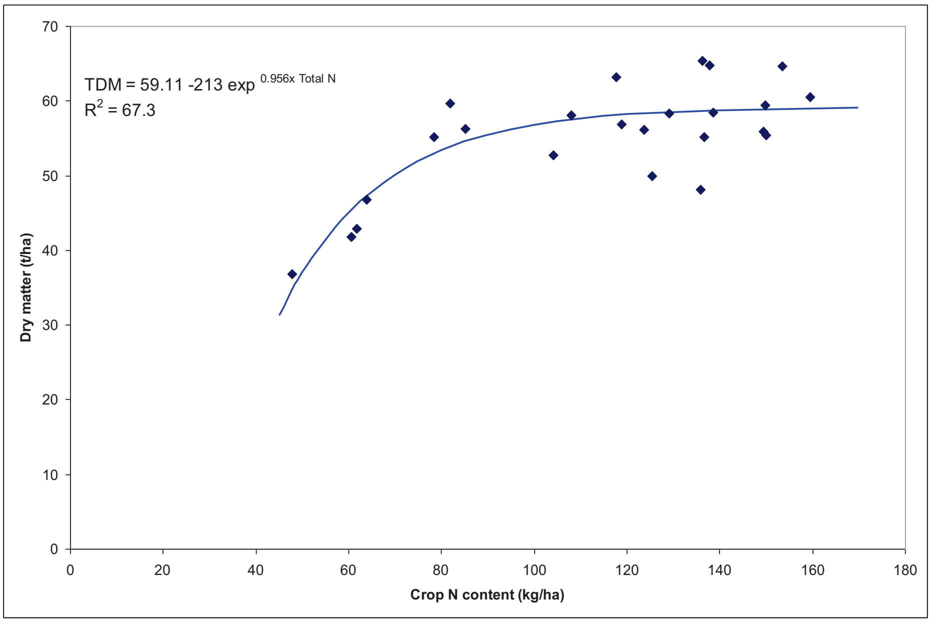

Figure 3.5. Relationship between crop N content (kg N/ha) and dry biomass production for a plant cane crop of Q117 grown in the Burdekin (reproduced from Bell and Garside 2014).

Fertiliser N uptake efficiency ($NUpE_{Fert}$)

This term refers to the efficiency with which N supplied to a field (e.g. from fertiliser, from a soil amendment like mill mud or even from the fraction of a fallow legume crop returned to the soil) is accumulated in crop biomass. Again, due to difficulties in measurement of below ground biomass and N content (i.e., in roots and stools), this measurement is typically restricted to above ground biomass. It is calculated as (kg crop N derived from the applied N source/kg N applied), and is only able to be determined when there are reference treatments/crops to which no N has been applied.

This is necessary to separate the crop N derived from the background soil N pool and the N supplied by the applied N source, and can be used to quantify the fraction of applied N that is lost by various loss processes (e.g., leaching or denitrification) or sequestered in the soil organic N pool.

Agronomic Efficiency of fertiliser N ($AgronEff_{Fert}$)

This term is typically used to describe the increase in crop yield in response to applied N (i.e., kg grain produced/kg N fertiliser applied, or in the case of sugarcane, the tonnes fresh weight cane yield or tonnes of sugar produced/kg applied N). This differs from the current industry benchmark in that the cane yield response is taken relative to the benchmark of the unfertilized yield (i.e., $Y_N - Y_{0N}$), and so this term requires measurement of the yield derived from background soil N sources (that could be achieved with no applied N).

This paper evaluates the available information on the relative contributions to crop N uptake from soil (with contrasting cropping histories) and applied N fertiliser, and documents fertiliser N recoveries in plant and ratoon crops. In so doing, it will indirectly estimate fertiliser N losses and indicate areas for improved N management. Critical to this process will be an assessment of the critical crop N contents for different growth stages/physiological processes and hence the required dynamics of crop N acquisition to meet crop N demand.

3.5 Supply of N to the sugarcane crop from the soil (background N)

This parameter is a key figure in the calculation of both $NUpE_{Fert}$ and $AgronEff_{Fert}$, and as such is critically important in any examination of fertiliser N use in the sugar industry. There are a variety of estimates of background N supply, either measured directly (crop N uptake in the absence of applied N) or indirectly (simply as biomass or cane yield produced with no applied N), in the published literature in Australia and overseas, with a selection of Australian results summarised in Table 3.2.

Perhaps the most extensive set of data from Australian studies was compiled in the paper by Chapman (1994), covering both plant and ratoon cane crops, although unfortunately this was restricted to indirect measures of background N supply (cane or sugar production in the absence of applied N), with no reported measures of crop N content. These results showed yields without N fertiliser that ranged from 80-85% of fertilized crop yields in the plant crop and a lower 40-60% of fertilized ratoon crop yields. Results from other studies before and after that work showed a similar range of relative yields in the plant crops (i.e. 80-100% of Ymax) and a similarly wide but generally higher range in relative yields in the ratoon crops (55-95%) – Table 3.2.

Table 3.2. Cane yields (t fresh weight/ha; Y_{0N}) and crop N uptakes (kg N/ha) for plant and ratoon cane crops grown without applied N fertiliser in the Australian sugar industry. The maximum cane yield with applied N fertiliser ($Y_{maximum}$) in each experiment series is also shown.

Location	Crop cycle	Cane yield (t fw /ha)		Crop N content (Y_{0N})	NUtE for unfertilized treatments	Reference
		Y_{0N}	$Y_{maximum}$	(kg N/ha)	(t fw cane yield/kg N uptake)	
Central region (Mackay)	Ratoons	32-75	80-95	ND	ND	Chapman & Haysom 1991
Central region (Mackay)	Plant Ratoons	60-100 20-70	70-120 50-115	ND	ND	Chapman 1994
Southern region (Bundaberg)	Ratoons	70-86	94-102	93-124	0.75-0.69	Catchpoole & Keating 1995
Southern region (Bundaberg)	Plant Ratoons	115 45-95	130 80-140	155 35-75	0.74 1.28-1.27	Thorburn *et al.* 2003
Southern region (Rocky Point)	Ratoons	53-67	81-98	75-93	0.70-0.72	Kingston *et al.* 2008
Wet tropics (Ingham)	Plant Ratoon	65-67 73-79	82-84 98-99	42-43 42-44	1.54-1.56 1.72-1.79	Bell *et al.* 2010
Southern region (Bundaberg)	Plant Ratoon	77 82-88	77 92-93	161 110-130	0.48 1.34-1.48	Bell *et al.* 2010
Wet tropics (Ingham)	Ratoon	55	80	55	1.00	Wang *et al.* 2014
Burdekin	Plant	112	130	48-60	2.33-1.85	Bell & Garside 2014
Ingham	Plant Ratoon	59 89	85 138	ND ND	ND ND	Schroeder et al. 2003
Ingham	Ratoon	73	167	49	1.50	Muchow et al. 1996
Bundaberg	Ratoon	36-77	48-103	ND	ND	Schroeder et al. 2003

The contribution of soil-derived N to crop N uptake was estimated from the N content of the unfertilized crops in those reports in which it was measured, and this ranged from as low as 35-40 kg N/ha to as high as 130-150 kg N/ha, and was accompanied by a similarly wide range in unfertilized cane yields (45-115 t fw cane yield/ha), as depicted in Fig 6. As a general rule the crop N derived from the soil reserves was greater in the plant than ratoon crops, presumably due to the effects of tillage during the fallow and the decomposition of organic matter and release of N accumulated in roots and stools during the previous crop cycle, although there were some exceptions (e.g. the Ingham site in Bell *et al.* 2010). Similarly, crop N derived from soil reserves tended to be higher in the southern regions (Bundaberg and Rocky Point) than in the Central region, Burdekin or the Wet Tropics (Table 3.2), presumably because the rainfall environment was less conducive to major loss events .

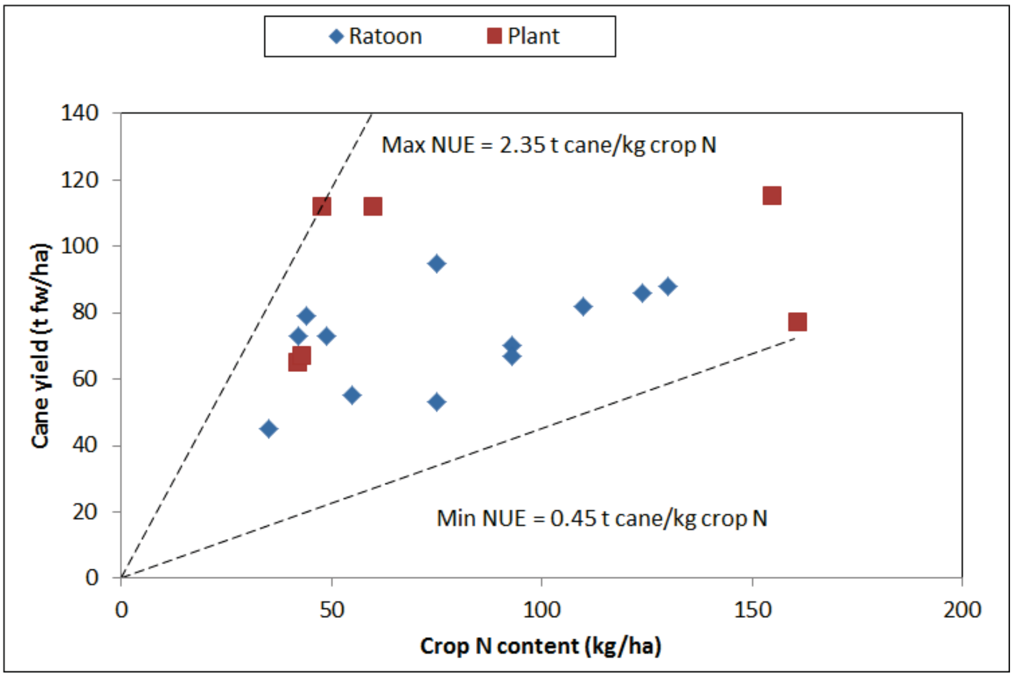

Figure 3.6. Relationship between cane yield (t fw/ha) and crop N content for crops without applied N fertiliser, derived from papers referenced in Table 3.2. The envelope defined by the dashed lines represents the range in NUtE observed in these studies.

As well as providing an estimate of the background soil N supply in these various trials, the relationship between crop N content and cane yield provides an indication of the upper and lower boundaries of NUtE in this data subset. The upper boundary (the left side boundary line indicated in Fig 3.5) represents strongly N-limited cane crops generally operating at near maximum internal NUtE, with 2.35 t cane produced/kg N uptake (or 0.43 kg N required in the crop to produce 1 t cane yield). The right side (lower) boundary in Fig. 3.6 delimits crops where N availability is not a productivity constraint, with as little as 0.45 t cane produced/kg crop N uptake (or 2.2 kg N required in the crop to produce 1 t cane yield). The *ca*. 5-fold range in observed NUtE in these data illustrates the flexibility the sugarcane crop has to yield under contrasting N supply environments. In particular, the apparent capacity of the crop to luxury accumulate N when the N available to the crop exceeds that required for the yield potential in that season is likely to have a major impact on $AgronEff_{Fert}$. Such luxury accumulation may simply be a response to continued high nitrate-N concentrations in the soil water (e.g. from in season fertiliser N applications - Muchow *et al*. 1996), or alternatively a response to unexpected yield constraints such as low solar radiation or restricted water availability at key physiological stages (eg. during tiller shedding, or during stalk filling) that result in crop yields and N demand being much lower than that used to determine fertiliser N requirement.

Rotation history and fallow management can also play a major role in the background N supply, especially in the plant and early ratoon crops in a cane cycle, as reported by Bell *et al.* (2010) and Bell and Garside (2014), and estimated in the simulation study by Park *et al.* (2010). However, while tillage and fallow management can influence the size and lability of soil N pools, the impact on crop N uptake may be variable (Fig. 3.7 below, reproduced from data of Garside *et al.* 1999) or quite small (e.g. Bell *et al.* 2010), depending on the timing of N loss events and the synchrony of N mineralization and crop N demand.

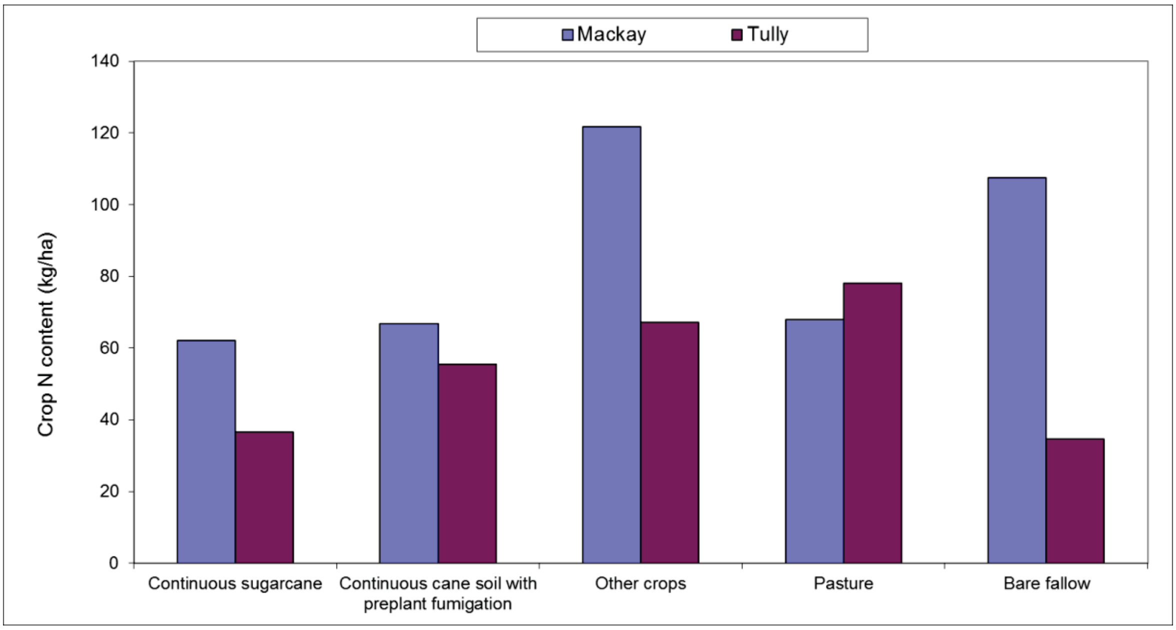

Figure 3.7. The impact of rotation history and soil fumigation on the crop N accumulated in the absence of applied N fertiliser in experiments at Mackay and Tully (data from Garside *et al.* 1999).

The timing of release of soil N reserves for uptake by the cane crop relative to the physiological processes underway in crop development (i.e. tiller addition, stalk retention and subsequent stalk filling) are almost as important as the size of the labile soil N pool in determining the crop N status and potential yields (Schroeder and Wood 2001; Bell *et al.* 2004; Bell and Garside 2005), with this issue addressed in a later section.

3.6 $NUpE_{Fert}$ – the fertiliser N recovered in the above-ground fraction (stalks, leaves, trash)

While there are a large number of N fertiliser rate trials in the sugarcane literature in Australia, many of these focus on agronomic response (i.e. yield responses to varying N application rates and strategies) and do not include an unfertilized control (to assess the soil N contribution) or measure crop N recovery. The trials and publications referred to in Table 3.2, along with ^{15}N recovery studies, are considered in this section, in addition to a series of studies conducted by the Sugar Yield Decline Joint Venture (YDJV) and published in various papers from 1999-2014 (i.e., Garside *et al.* 1999; Bell *et al.* 2003; Garside *et al.* 2006; Bell *et al.* 2010; Bell and Garside 2014). The $NUpE_{Fert}$ values are benchmarked against those derived from a large database of cereal crop studies (primarily rice, wheat and maize) reviewed by Ladha *et al.* (2005). This extensive review of experimental data from across the world suggests median $NUpE_{Fert}$ of 55% across all crops in the year of application, with a further 5-10% recovery in subsequent crop seasons. In the year of application, $NUpE_{Fert}$ of maize (65% $\pm$ 3%) was > wheat (57% $\pm$ 2%) which was > rice (46% $\pm$ 1%).

In plant cane crops the response to applied N fertiliser is typically lower than in ratoons (Table 3.2), but is still generally significant and profitable in terms of cane and sugar yield – with the possible exception of following a fallow legume crop (Garside and Bell 2007). We could find no Australian

studies using isotopic labelling of N fertilisers that quantified fertiliser N recovery during a plant crop and so have instead used the differential N content in above ground biomass between an unfertilized control treatment and the corresponding treatment receiving N fertiliser application as an estimate of fertiliser N recovery by the crop.

Results from a series of published experiments from across the Australian industry are shown in Fig. 3.8. Despite receiving similar fertiliser N rates of 140-180 kg N/ha, there was a wide range in cane yields (50-150 t/ha) and N content in above-ground biomass (40-212 kg N/ha) and almost universally poor $NUpE_{Fert}$. In the unfumigated treatments all except the PORP history in the Burdekin (46%) and the Bare Fallow history at Mackay (36%) recorded low $NUpE_{Fert}$. Values ranged from 1-22%, indicating that the majority of crop N was derived from background soil reserves. The plant crop receiving the standard N treatment (120N) in the Bundaberg study by Thorburn *et al.* (2003) recorded a similarly low $NUpE_{Fert}$ (<10%).

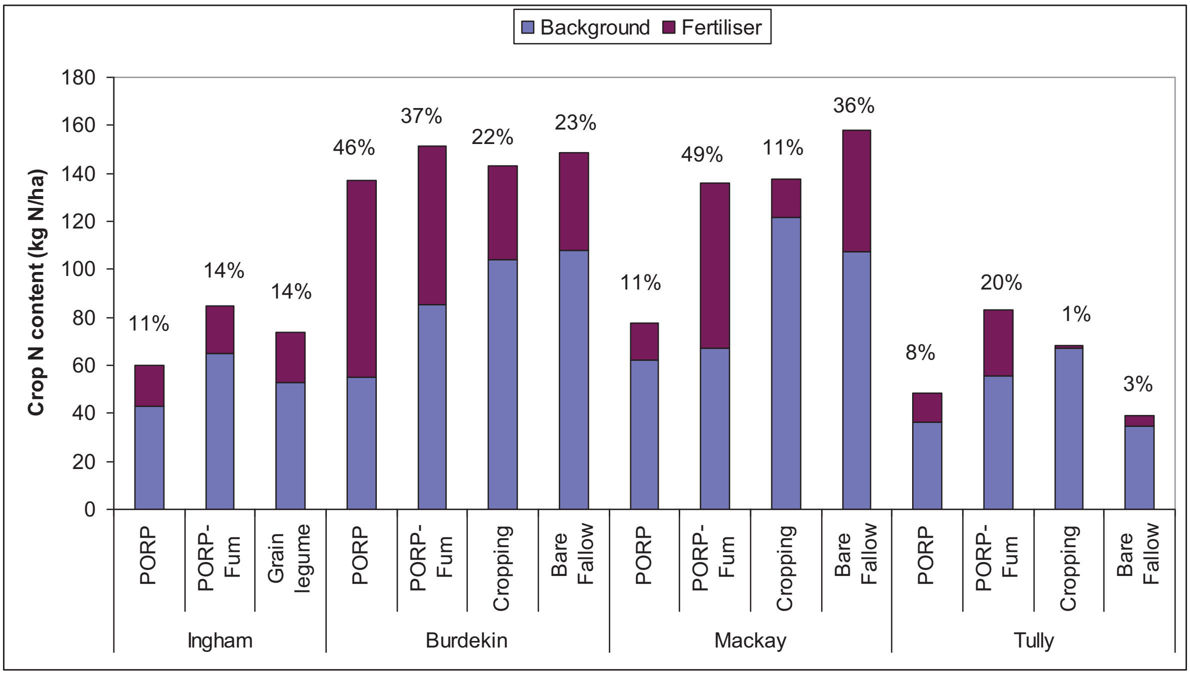

Figure 3.8. Source of above ground crop N content in plant crops grown in rotation experiments conducted in Ingham, Burdekin, Mackay and Tully and reported in Garside *et al*. (1999). Fertiliser N application rates ranged from 140-180 kg N/ha, with the percentage of fertiliser N accumulated by the crop shown for each site-rotation combination.

Interestingly, some of the rotation and soil fumigation studies reported by Garside *et al.* (1999) suggest root health may be a significant factor in the poor $NUpE_{Fert}$ in some instances. This may be illustrated by the apparent improvement in $NUpE_{Fert}$ at Mackay and Tully in the fumigated PORP treatments, where there was a 3-4 fold increase in the amount of fertiliser N recovered in crop biomass compared to the unfumigated treatments (Fig. 3.8). The lack of improvement in $NUpE_{Fert}$ in the fumigated treatment at Ingham was probably related to the extremely wet growing conditions in that season (Garside *et al*. 1999) while that in the Burdekin was more related to the unusually good N recoveries in the PORP treatment.

There have been studies using isotopically-labelled N fertilisers to quantify fertiliser N recovery in ratoon crops. Some of these were specifically focussed on the volatilization losses of N top-dressed onto trash blankets in the early days of adoption of green cane trash blanketing, but those of Vallis *et al.* 1996 (at a variety of southern sites from Childers in Qld south to Broadwater and Harwood in northern NSW), Prasertsak *et al.* 2002 (sites near Innisfail) and Meier *et al.* 2006 (sites near Babinda) either placed N below the trash (Meier *et al.* 2006) or used sub-surface banding typical of current industry practice.

Both banded N studies reported low $NUpE_{Fert}$ in the above-ground components, with averages ranging from 23% -33% in the 1st and 2nd year of 2-year ratoon crops in NSW, respectively; 30-35% in ratoon crops at Childers; but only ~25% in ratoon crops at Innisfail. Both authors reported another 20-25% recovery in soil and roots at the end of the crop year, but the role of that below-ground N in meeting the needs of following ratoons was not determined. The study by Meier *et al.* (2006) recorded much lower recoveries of fertiliser N in above ground plant parts (4-5% of applied N), but conversely much higher recoveries of the applied N from the soil profile – at least at the end of the initial crop season.

The low $NUpE_{Fert}$ from these ^{15}N studies were consistent with results reported for 1R crops by Bell *et al.* 2003, Garside *et al.* 2006 and Bell *et al.* 2010 and presented in Fig. 3.9 below. Despite the lower background soil N supply typical of ratoon crops (compare plant and ratoon crop N in unfertilized crops in Table 3.2, and the contrast between crop N from background sources in Fig. 3.8 and Fig. 3.9), apparent $NUpE_{Fert}$ was again low (11-40%) and within the range reported by the more definitive studies with ^{15}N by Vallis *et al.* (1996) and Prasertsak *et al.* (2002). In other studies conducted in the lower rainfall regions around Bundaberg, successive ratoon crops in the study by Catchpoole and Keating (1995) showed $NUpE_{Fert}$ of 25-50% in successive ratoons as background soil N was depleted, while in the trickle irrigation study of Thorburn *et al.* (2003) $NUpE_{Fert}$ declined from 40-45% in the 1R and 2R crops to ~30% in the 3R crop for the standard (160N) rate.

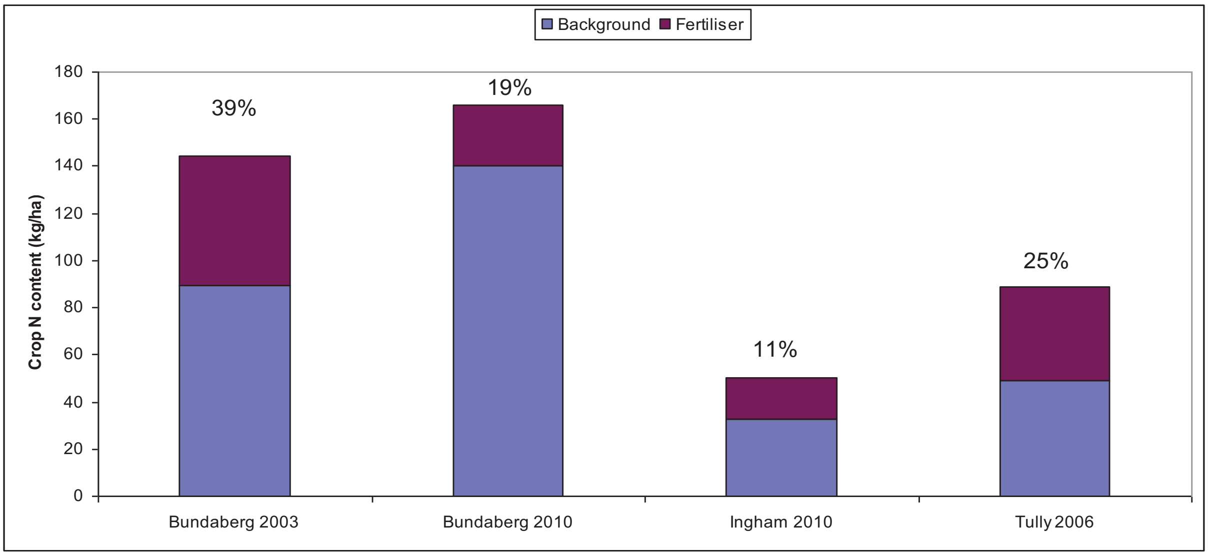

Figure 3.9. Source of above ground crop N content in 1R crops grown in experiments conducted in Bundaberg, Ingham and Tully and reported in papers by Bell *et al.* 2003, Garside *et al.* 2006 and Bell *et al.* 2010. Fertiliser N application rates ranged from 140-150 kg N/ha, with the percentage of fertiliser N accumulated by the crop shown for each location.

Estimates of incremental $NUpE_{Fert}$ were also able to be derived from more recent trials in the Burdekin (without a nil applied N treatment to gauge background N supply) by calculating the change in crop N for an incremental increase in fertiliser N application rate. This analysis was restricted to sites in which a significant (p=0.05) response to applied N was obtained in FW cane yield/ha, with results shown in Table 3. $NUpE_{Fert}$ values ranged from 26% to 48%, with this range similar to that observed in Figs. 3.8 and 3.9 for other trials.

The wide range in observed recoveries illustrates the variation resulting from season/soil/site/management effects, but it is also apparent that under optimal conditions and using best management strategies for maximising crop N uptake, recoveries as high as 50% can be achieved.

Table 3.3. Recovery of fertiliser N (%) from an increment of fertiliser N applied to several crops in the Burdekin District (J Connellan, unpublished).

Year/Crop class/Variety	Applied N rates (kg/ha)	$NUpE_{Fert}$
2012 Plant KQ228	130-210	26%
2012 Plant KQ228	130-210	30%
2013 Plant KQ228	170-250	28%
2013 Ratoon 1 Q183	170-210	48%

3.7 $AgronEff_{Fert}$ – the cane yield response to applied N

We have used the same series of experiments shown in Table 3.2 to assess this parameter, but due to the fact that many of the reported experiments did not set out to generate an N response surface, but instead chose one or a small number of N rates based on local district standards, we have calculated $AgronEff_{Fert}$ from the optimum N rate derived from the response surface where this was available, and also from the recommended standard N rate for that crop class and district (assuming a PORP rotation and without discounting for soil organic matter content – Schroeder et al. 2005).

The data are shown in Table 3.4, with the key points emerging from this being (i) there is a wide range in $AgronEff_{Fert}$ in both plant and ratoon crops; (ii) the range in $AgronEff_{Fert}$ is generally narrower when the optimum N rate is derived from a specific set of response trials (2.0 – 5.0 kg N/t cane in plant crops and 2.0 – 8.9 kg N/t cane in ratoons) than when regional standard N rates are used (7.5 – 15.0 kg N/t cane, with an extreme example at 140 kg N/t cane, in plant crops and 2.7 – 18.9 kg N/t cane in ratoons); and (iii) even when derived from a local rate response trial, the $AgronEff_{Fert}$ is far higher (i.e. more N required to produce an additional tonne of cane) than that implied in the current industry standards for determining fertiliser N rate in the 6ES (Schroeder et al. 2010) i.e. 1.0-1.4 kg fertiliser N/t fresh weight cane yield.

Table 3.4. Cane yields (t fresh weight/ha) with and without applied N fertiliser (Y_{0N} and $Y_{optimum}$ or $Y_{standard}$), applied N rates (kg N/ha) and calculated agronomic efficiency of N use (kg N/t fw cane yield) for plant and ratoon cane crops in the Australian sugar industry. The $Y_{standard}$ refers to an N rate used as district practice, rather than that derived from each N rate trial response function ($Y_{optimum}$).

Location	Crop cycle	Cane yield (N rate)			AgronEff$_{Fert}$ (kg applied N/t cane)		Reference
		Y_{0N}	$Y_{optimum}$	$Y_{standard}$	$Y_{optimum}$	$Y_{standard}$	
Central region (Mackay)	Ratoons	31	80 (160N)	80 (170N)	3.3	3.5	Chapman & Haysom 1991
		43	95 (160N)	95 (170N)	3.1	3.3	
		75	84 (80N)	84 (170N)	8.9	18.9	
Central region (Mackay)	Plant	60	70 (40N)	70 (150N)	4.0	15.0	Chapman 1994
		85	105 (40N)	105 (150N)	2.0	7.5	
		100	120 (100N)	120 (150N)	5.0	7.5	
	Ratoons	25	50 (150N)	55 (170N)	6.0	5.7	
		45	80 (150N)	85 (170N)	4.3	4.3	
		68	110 (150N)	115 (170N)	3.6	3.6	
Southern region (Bundaberg)	Ratoons	70	NA	94 (320N)	NA	13.3	Catchpoole & Keating 1995
		86		102 (160N)		10.0	
Southern region (Bundaberg)	Plant	115	130 (60N)	130 (120N)	4.0	8.0	Thorburn *et al.* 2003
	R1	95	150 (120N)	150 (160N)	2.2	2.9	
	R2	45	105 (120N)	105 (160N)	2.0	2.7	
	R3	40	75 (120N)	75 (160N)	3.4	4.6	
Southern region (Rocky Point)	R3	67	96 (200N)	89 (110N)	6.9	5.0	Kingston *et al.* 2008
	R4	53	79 (100N)	78 (110N)	4.2	4.4	
Wet tropics (Ingham)	Plant	66	NA	83 (150N)	NA	8.8	Bell *et al.* 2010
	R1	76		99 (150N)		6.5	
Southern region (Bundaberg)	Plant	77	NA	78 (140N)	NA	140	Bell *et al.* 2010
	R1	85		93 (140N)		17.5	
Wet tropics (Ingham)	R1	55	NA	80 (140N)	NA	5.6	Wang *et al.* 2014
Burdekin	Plant	112	NA	130 (180N)	NA	10.0	Bell & Garside 2014
Ingham	Plant	59	NA	82 (150)	NA	6.8	Schroeder et al. 2003
	R1	89		135 (150)		3.2	
Bundaberg	R1	51	NA	71 (150)	NA	7.5	Schroeder et al. 2003
	R1	66		96 (150)		5.1	
	R2	36		45 (150)		15.8	
	R2	34		53 (150)		7.8	
	R2	46		73 (120)		4.4	

While $AgronEff_{Fert}$ is generally calculated as the incrementalyield response to applied fertiliser N compared to a nil applied N treatment, many N rate trials in the sugar industry do not include such a nil N treatment. However, there is the opportunity to estimate a surrogate of $AgronEff_{Fert}$ from trials using sequential N rates (i.e. Δ FW cane yield/Δ applied N rate) and assuming that soil N contribution to the crop yield in both treatments is the same. Table 3.5 presents data using this calculation for sites in the Burdekin district where a significant (P=0.05) FW cane yield response was obtained between the specified applied N rates. Interestingly, these incremental $AgronEff_{Fert}$ show a similar range (3.1 – 10.0 kg applied N/t cane) as those recorded in Table 3.4 from trials where the yield response to applied N fertiliser was discounted by the yield of Nil N treatments.

Table 3.5. $AgronEff_{Fert}$ for an increment of fertiliser N applied to several crops in the Burdekin District (J Connellan, unpublished).

Year/Crop class/ Variety	Applied N rates (kg/ha)	Cane yield at lower N rate (t FW cane/ha)	Agron Eff_{Fert} (kg applied N/ FW t cane)
2012 Plant KQ228	130-170	135	7.7
2012 Plant KQ228	130-210	153	8.3
2012 Plant Q208	130-170	126	8.3
	170-210	131	10.0
2012 Plant Q208	130-170	121	5.3
2012 Plant KQ228	130-170	127	4.2
2013 Plant KQ228	170-210	128	3.1
2013 Ratoon 1	170-250	151	10.0
2013 Ratoon 1	170-210	112	4.2

Note that for the third site in Table 3.5 where this $AgronEff_{Fert}$ was calculated for two increments of applied N, $AgronEff_{Fert}$ was lower at the higher N rate increment, indicating diminishing crop responses with higher N inputs - even though a significant yield response was obtained.

Given the typically poor $NUpE_{Fert}$ (often less than half of that recorded for grain crops around the world) and $AgronEff_{Fert}$ (typically 3-10 times higher than that indicated in the 6ES benchmark of 1.4 kg N/t FW cane yield) in both plant and ratoon crops and the significant contribution of background soil N to meeting a significant proportion of crop N demands, the fate of fertiliser N not recovered by the crop would seem to be of critical importance for the continued productivity of the sugarcane farming system. In particular, the relative allocation of fertiliser N into environmental losses and the below ground plant parts and soil organic matter pools that contribute to background N supply is clearly an important factor in the sugarcane N budget.

3.8 Fate of N that is not recovered by the crop

Despite the widespread reporting of large losses of applied N (e.g., Chapman *et al.* 1992; Vallis *et al.* 1996; Prasertsak *et al.* 2002), the significant contribution of background soil N to the N content of both plant and ratoon crops suggests substantial fertiliser N retention in the soil or cane trash, with subsequent mineralization and recovery later in the crop cycle. However, there are few field studies to support this inference – at least within the current crop cycle. For example, studies as far apart in time as those of Chapman *et al.* (1983) in the central districts and Bell *et al.* (2010) in both Ingham and Bundaberg (Fig. 3.10) suggest limited or no carryover of fertiliser N from one crop to the next. Indeed, the results reported in Bell *et al.* (2010) and shown in Fig. 3.10 suggest a lack of significant carryover N in the 1R crop from either a fallow legume crop or N fertiliser applied in the plant crop at both Ingham and Bundaberg – although different loss pathways were postulated between locations. There is considerable conjecture about the residual benefits of N from fallow legumes, with the simulation study reported by Park *et al.* (2010) suggesting carry-over of legume N into ratoon crops could make a significant contribution to reducing fertiliser N requirement in most growing regions.

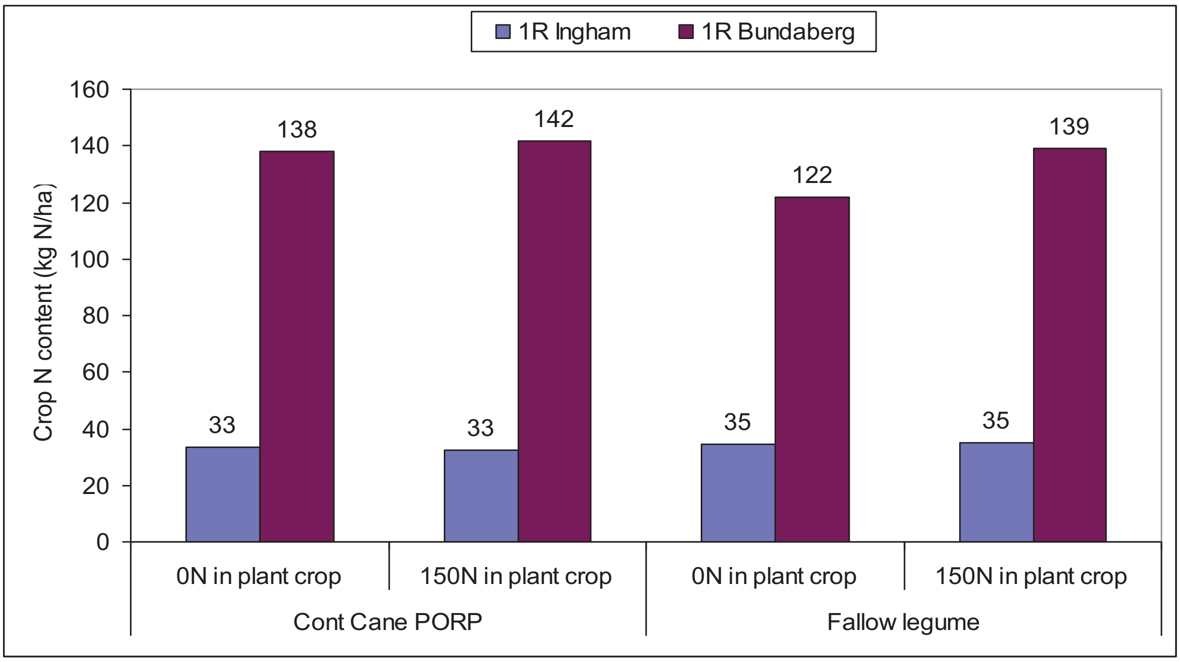

Figure 3.10. Crop N content of 1R cane crops grown at Ingham and Bundaberg after contrasting rotation histories prior to the plant crop (PORP cane or a fallow soybean crop) and with (150N) or without (0N) N fertiliser in the plant crop (after Bell *et al*. 2010).

The lack of demonstrated carryover of fertiliser N applied to the previous crop, despite suggestions that as much or more of the fertiliser N can be found in soil and below-ground plant parts (roots and stool) as in the crop itself (Vallis *et al.* 1996, Prasertsak *et al.* 2002; Meier *et al.* 2006), creates uncertainty as to the source of background N being accessed by the cane crops. While some may be derived from the trash returned in the previous harvest, reports (e.g., Meier *et al.* 2006) suggest this short term release of trash N to the following cane crop is small and relatively insignificant in terms of meeting crop N requirements.

Therefore it appears that in the short term a large proportion of N fertiliser or trash N returned to the soil is immobilised, and may not make a contribution to crop N uptake until it mineralises in the subsequent crop cycle.

While Smith *et al.* (2005) have conducted a detailed review of published information on growth and function of sugarcane root systems, this work focused on functionality and C content/sequestration, and there seems to be little published data on the quantum of N accumulated in root and stool material during a crop cycle, or the rate of release in subsequent cycles. There has been a limited amount of data collected in Australia, primarily from crops at Bundaberg at varying stages in the crop cycle, and this is presented in Table 3.6.

Table 3.6. Stool and root dry matter and N to a depth of 60cm ([A]) or 50 cm ([B]) in a series of rotation experiments at Bundaberg[A] (Bell et al. 2010; Garside and Bell 2012) and at one site in the Burdekin Delta[B] (J Connellan, unpublished).

Crop cycle	History	Stool DM	Stool N	Root DM	Root N	Total DM	Total N
		Kg/ha					
Harvest R1[A]	Contin Cane	5550	39.4	824	5.6	6370	45
	Soybean rotation	5760	49.8	1755	11.8	7520	62
Harvest R3[A]	Peanut rotation	8800	ND	ND	ND		
Harvest R4[A]	Contin Cane	9840	89.6	7790	81	17630	170
9 months Q208 R1 @ 210 kgN/ha[B]	Contin Cane					10140	37

Because there were only measures of stool and total below-ground N after harvest of 1R and 4R crops (Table 3.6), a linear relationship between years under cane and stool or below ground N was used to estimate the rate of below ground N accumulation. This analysis suggests N in the mound (stool and root) accumulates at *ca*. 20 kg N/ha/year while a further 10 kg N/ha/year accumulates in root material down to 60cm. While there are only data from the 1R crop, there are also suggestions that the rate of below ground N accumulation is greater when soil health and N availability is improved by use of break crops. Given the seemingly large contributions from background soil N to crop N supply in early years of a new crop cycle (especially in central and southern production areas) and the reports of similar recoveries of applied N in below ground (soil and roots/stool) parts as in above ground parts, a better understanding of the fate and cycling of below ground N is required.

3.9 Fate of luxury N uptake in the cane crop

An additional factor contributing to the lack of fertiliser N residual effects in situations where luxury uptake has occurred (Table 3.2 and Fig. 3.6) is the accumulation of excess N in stalks, with that N subsequently removed from the field at harvest. This has been reported in a number of studies (e.g., Chapman *et al*. 1983; Muchow *et al.* 1996; Wood *et al.* 1996; Keating *et al*. 1999), although this elevated stalk N concentration is not necessarily related solely to fertiliser N application rate (Keating *et al*. 1999; Thorburn *et al.* 2011). Although Thorburn *et al.* (2011) noted a general lack of correlation between cane N concentrations and N fertiliser treatments in their studies across a range of Australian sites.

Given the uncertain correlation between rates of fertiliser N applied and actual crop N recovery evident in earlier sections of this review, we have calculated the Nitrogen Harvest Index (NHI – the proportion of total above ground crop N that is removed in cane yield at harvest) for a number of trials in published and unpublished reports. These data show a very consistent positive relationship between NHI and crop N content in trials from crops that contain both high N (120-250 kg N/ha) and low (40-100 kg N/ha) N contents in above-ground biomass (e.g. Fig. 3.11a, b), indicating that additional crop N uptake in excess of growth requirements results in that N being stored in stalks and hence removed from the field at harvest.

Interestingly, while the rate of change in NHI was relatively constant in plant and 1R crops at Bundaberg (Fig. 3.11b), both of which contained >120 kg N/ha, the much reduced slope in the 1R crop at Tully (which had crop N contents as low as 30 kg N/ha) suggests this relationship may be relatively insignificant at very low crop N content (i.e. requirements for growth outweigh the tendency to store excess N in stalks). Another example of this situation was a low N ratoon crop at Ingham (reported in Bell *et al.* 2010) where there seems to be little change in NHI until crop N content is >45-50 kg N/ha. As crop N content increased further, NHI again started to increase with increasing crop N content (Fig. 3.12).

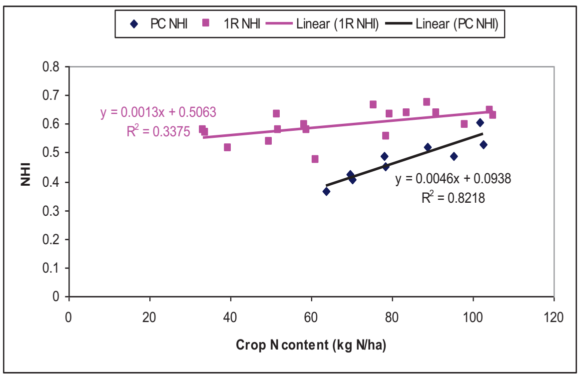

Figure 3.11a. Variation in NHI with increasing crop N content in low N content plant and ratoon crops at Tully (Garside et al. 2006).

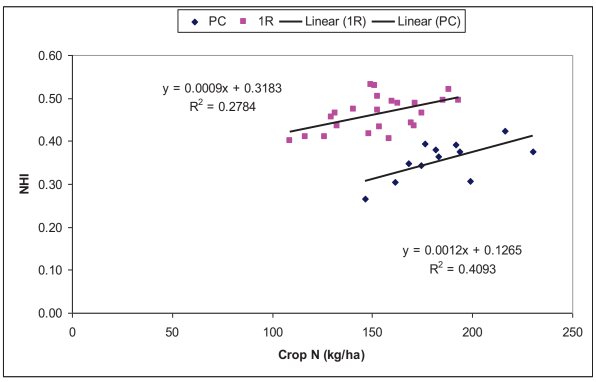

Figure 3.11b. Variation in NHI with increasing crop N content in high N content plant and ratoon crops at Bundaberg (Bell et al. 2010).

Recent studies in the Burdekin (J Connellan, unpublished) have showed variable relationships between crop N content and NHI which may again be related to crop N requirement and relative cane yield responses. Only three of 8 plant crops grown at four rates of applied N over two seasons showed significant ($P<0.05$) increases in NHI with increasing crop N; slopes ranged from 0.0012 to 0.0026 – similar to the plant crop at Bundaberg (Fig. 3.11b) but less responsive than the plant crop at Tully (Fig. 3.11a). Out of 7 first ratoon crops grown in one season in the same district (J Connellan, unpublished), five sites gave significant regression lines and the slope ranged from 0.0007 to 0.0014 which were very similar to the ratoon crops at both Bundaberg and Tully in Fig. 3.11a, b. While we are unable to clearly identify causal factors triggering an increase in NHI, we hypothesize this is related to surplus N availability at sites where additional N produced small or no significant increase in crop growth or yield.

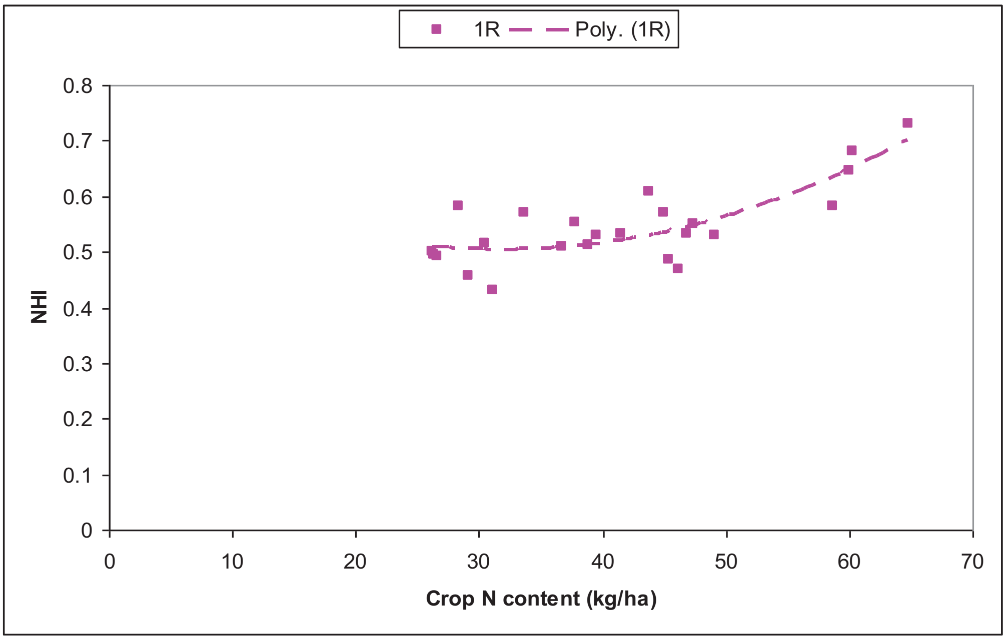

Figure 3.12. Variation in NHI with increasing crop N in a 1R cane crop grown at Ingham and reported in Bell and Garside *et al.* (2010).

3.10 What are the critical growth stages impacted by N supply?

It appears that any attempts to improve NUE in sugarcane will need to be based on a sound understanding of the crop growth stages (depicted in generalized terms in Fig. 3.13 below) that are impacted by N availability and the dynamics of crop N accumulation. This will be essential given the ability of the sugarcane crop to both produce cane yield with relatively high NUtE in situations where N availability is low but luxury accumulate N when availability is high (Fig. 3.6), combined with the susceptibility of applied N fertiliser to losses or immobilisation (at least within a crop cycle) and the resulting low $NUpE_{Fert}$.

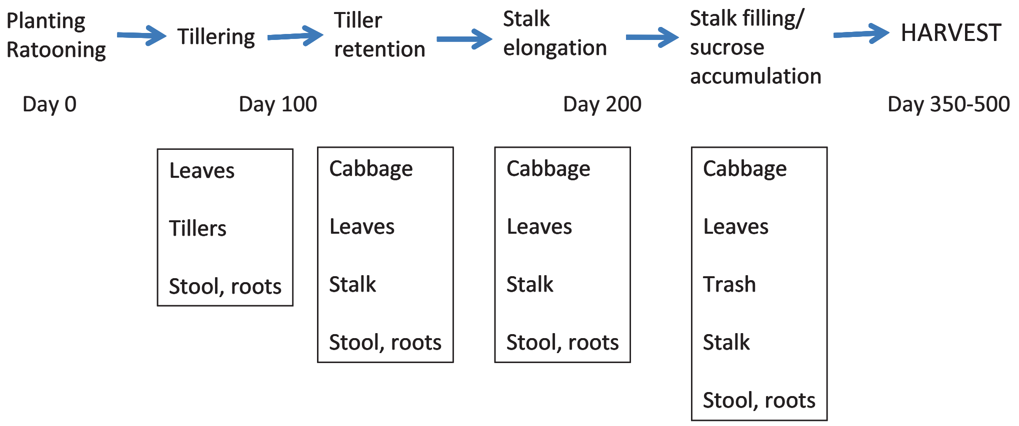

Figure 3.13. Generalized growth stages in a sugarcane crop in relation to a development scale of days after planting or harvest and subsequent ratooning and related to the presence of the various sinks for assimilate and crop N at each stage.

The key physiological processes determining crop yield in sugarcane are based around establishment of primary shoots and subsequent tillers on those primaries, followed by the conversion of a variable proportion of those shoots and tillers into a smaller cohort of stalks, which then gradually increase in weight and sugar content as harvest approaches. An example of shoot/stalk dynamics in response to crop rotation and soil fumigation in a crop of Q141 at Bundaberg, reproduced from Bell and Garside (2005), is shown in Fig. 3.14 and clearly shows the critical growth stages of the crop in that environment. After establishment (planting – 40 DAP), tiller addition occurs on each established primary shoot (*ca*. 40-100 DAP); after maximum tiller numbers are attained, tillers are shed over a period (*ca*. 100 –200 DAP), with the end result being the establishment of a cohort of elongating stalks; finally, these stalks increase in mass and accumulate sucrose during the process of crop maturation (*ca*. day 200/250 – crop harvest), with maintenance of a healthy canopy a key factor in late season biomass accumulation (Bell and Garside 2005). While variations in the timing of each stage occur between planting dates and regions, the pattern is fairly similar except where the plant cane crop is sown in autumn in cooler areas in southern Qld and harvested after a 15-18 month growing season, or where the crop is grown over a 2 year cycle (e.g., in parts of NSW).

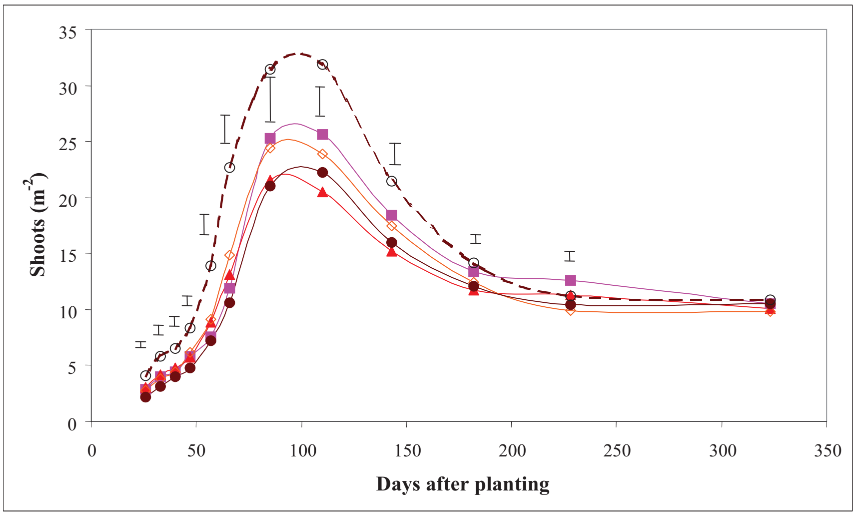

Figure 3.14. Shoot and stalk dynamics of plant crops of Q141 cane at Bundaberg grown after a variety of crop rotations or with soil fumigation prior to planting, after Bell *et al.* 2005.

The generalized growth stages depicted in Fig. 3.13 and the shoot/stalk dynamics in Fig. 3.14 can then be related to patterns of crop N accumulation, which are depicted from trials across various production regions in Fig. 3.15. At the time of maximum tiller numbers at about 100 days after planting or ratooning, crops typically contained <20% of the maximum crop N content. The bulk of crop N uptake occurs during the period from 100 days to around 200 days (6-8 months) after planting, with above ground N then maintained or declining until final harvest. The period of maximum N demand is clearly in this 3-5 month period, when tiller shedding and final stalk number is determined, with suggestions that this period of N accumulation may be shorter in ratoon than plant crops (e.g., Wood *et al.* 1996 showed peak N accumulation at 150 days in a ratoon crop compared to *ca*. 200 days in a plant crop grown in the Burdekin). This is probably related to the more rapid and synchronised establishment of a cohort of shoots and stalks from an existing stool in ratoon crops, compared to the more gradual phenological development of a plant crop and its root system.

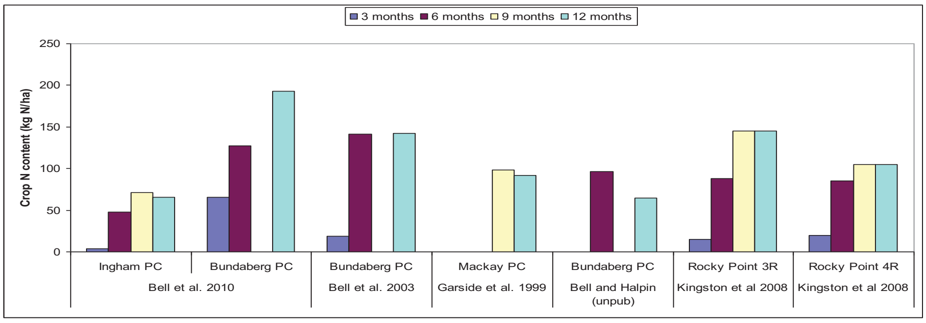

Figure 3.15. Accumulation of above ground N at different crop ages in plant and ratoon crops grown at Ingham, Mackay, Bundaberg and Rocky Point. Data are derived from published (Garside *et al.* 1999; Bell *et al.* 2003; Kingston *et al.* 2008; Bell et al. 2010) and unpublished (Bell and Halpin 2014) data.

The role of N availability in determining maximum tiller number at *ca*. 3 months after planting/ratooning is illustrated in the continuous cane systems (trash retained), and to a lesser extent the continuous cane (trash removed) and the pasture histories in the paper by Bell and Garside (2005), with Fig. 3.3 from that paper reproduced as Fig. 3.16 here. Application of N fertiliser at planting in this experiment in the Burdekin showed that in rotation backgrounds in which soil mineral N was low, basal N applications could increase tillering on primary shoots although effects were small relative to other soil health-related factors. However, given the general lack of correlation between peak shoot number and final stalk number at harvest (Bell and Garside 2005, 2014), it is suggested that the importance of optimizing early season crop N status is low, and probably only limited to situations where primary shoots are suboptimal – either due to poor establishment in the plant crop or low stool numbers resulting from harvester damage later in the crop cycle. Given the small crop N content at this early growth stage (typically 15-30 kg N/ha, Fig. 3.15) any fertiliser N requirement is likely to be small, although there is little published research on the benefits of optimization of early N application strategies.

The most critical period in which N availability and crop N uptake influence crop yield potential is therefore the period between peak tillering and the determination of the cohort of stalks that will contribute to final crop yield, with this period coinciding with the rapid accumulation of crop N shown in Fig. 3.15 (i.e., tiller retention and the beginning of stalk elongation, from *ca.* 100-200 days after planting/harvest). As illustrated by Bell and Garside (2014) and reproduced in Fig. 3.17 below, even in situations where soil N availability is high (Crop or Bare Fallow histories) or where a combination of soil health and nutrient availability benefits have produced very high peak tiller numbers (i.e. after soil fumigation), fertiliser N applications and increased crop N content can result in the retention of a greater proportion of tillers until final crop harvest.

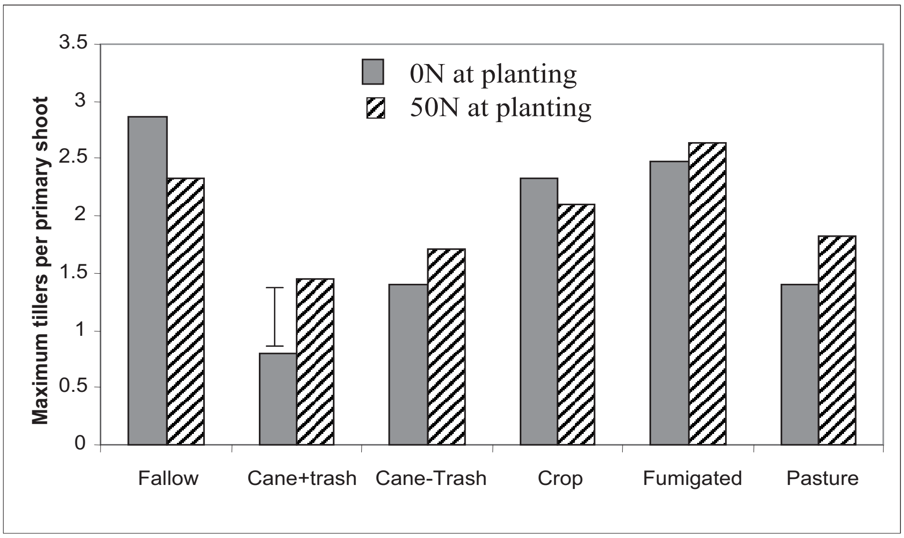

Figure 3.16. Effect of rotation break and N fertiliser applied prior to planting on the maximum number of tillers initiated on each primary shoot of a Q117 plant crop in the Burdekin. Vertical bars indicate significant differences at P<0.05.

The significance of any increased tiller retention resulting from improved crop N status will be variable, given that late season stalk death can occur (i.e. due to factors such as lodging, rat damage, loss of trash etc. outlined in Wood *et al.* 1996), and that there is demonstrated compensation between stalk number and individual stalk weight that can moderate any yield response to differences in stalk density at harvest (Bell *et al.* 2004; Bell and Garside 2005). However, the extent of compensation for low stalk numbers with increased stalk weight can be limited by poor growing conditions during the stalk-filling period (Garside *et al.* 2004), and also seems to be a product of both genotype and environment (Bell and Garside 2005, Bell *et al.* 2007), with interactions for the current suite of genotypes poorly defined.

Regardless of whether N is available for uptake during the stalk-filling phase late in the growing season, there is little published evidence of continued N uptake by the crop. Differences in crop N content usually result from differences in N accumulation during the prior period of rapid uptake during the tiller shedding/stalk elongation period, with an example (Fig. 3.18) shown from Bell *et al.* (2003). In this case, greater N availability due to a soybean fallow or N fertiliser application produced most impact on crop N accumulation between 3 and 6 months after planting (the rapid uptake period), rather than during the subsequent 6 months through to harvest (Fig. 3.18) – despite evidence of significant amounts of soil mineral N in the profile of those treatments at crop harvest.

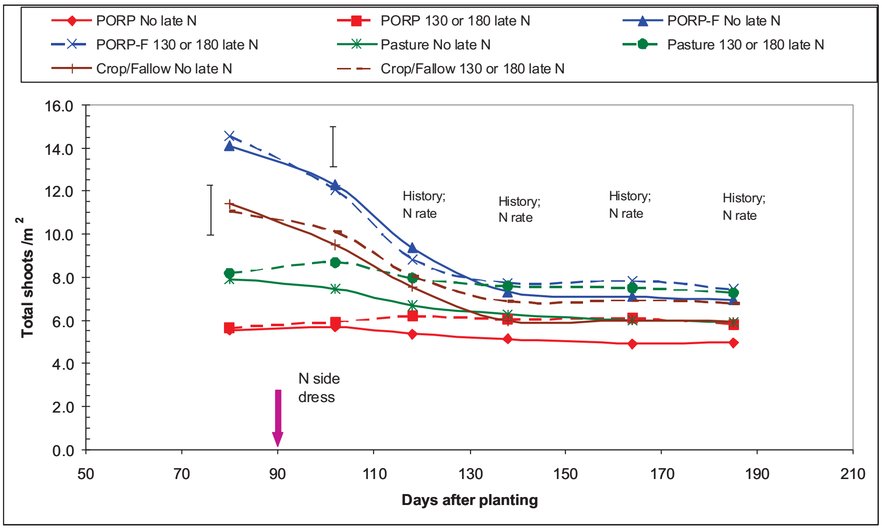

Figure 3.17. Impacts of rotation/fumigation history and N fertiliser application rate/strategy on tiller loss and establishment of the final stalk cohort (from maximum tiller number at 80 DAP until 185 DAP). Vertical bars indicate the History * N rate interaction LSD if significant, while main effects of History or N rate/management are indicated at each measurement date (after Bell and Garside 2014).

While later season N accumulation has been shown to make only a minimal contribution to total crop N uptake, crop N status (specifically N content in the green leaf material) during this period has been shown to be important for overall biomass accumulation (i.e., increasing individual stalk weight), as well as for changing the partitioning of new biomass into sucrose in maturing stalks. There are many reports of high N availability impacting negatively on the sucrose concentration of cane delivered to the mill (i.e. depressing ccs), but few of these reports separate the impact on ccs of the bulk cane

harvested (i.e. varying proportions of whole/live stalks, suckers and trash – e.g. Crook *et al*. 1999) from any physiological impact on ccs of sucrose accumulation in stalks. One of the few that did (Muchow *et al*. 1996) concluded that the phenomenon of lower ccs with high N supply could largely be explained by negative impacts of N on stalk dry matter content, with the small decreases in sucrose concentration in dry millable stalks at high N relatively insignificant compared to the large positive effect of N supply on stalk biomass. High N availability therefore has a greater effect on commercial measures expressed on a fresh weight basis (cane yield and ccs) than on any physiological measures of crop performance (i.e. stalk biomass and sucrose concentration on a dry weight basis).

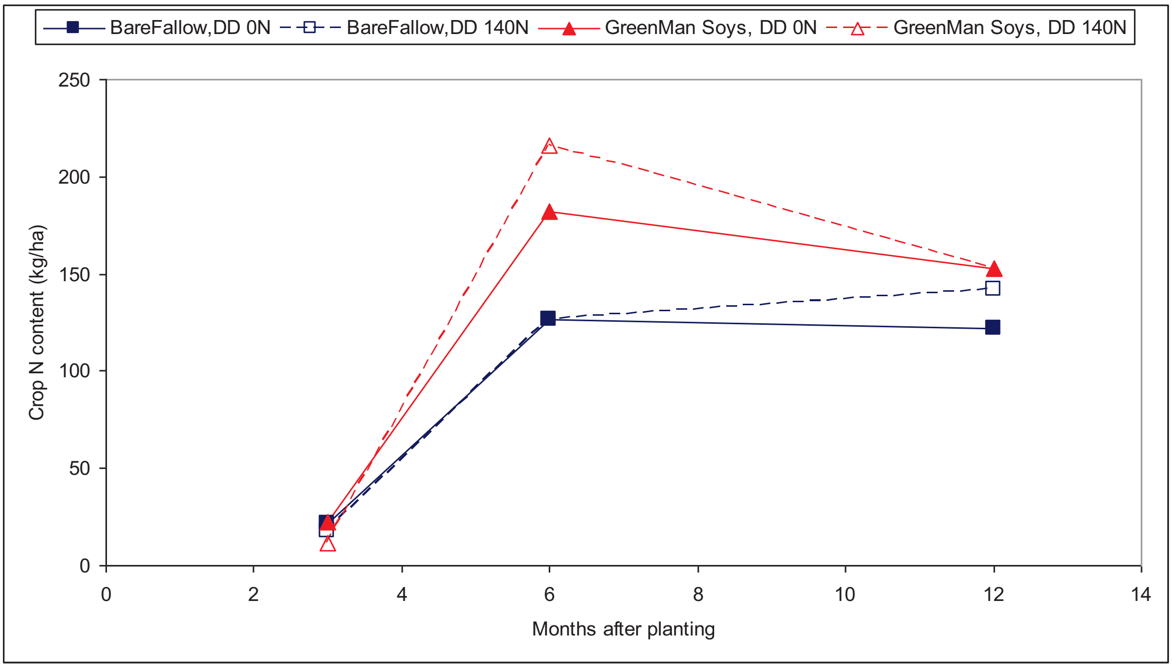

Figure 3.18. Accumulation of N in above ground biomass in a plant crop of Q188 grown at Bundaberg after contrasting fallow histories (bare fallow or a green manure soybean crop) and with different rates of N fertiliser application (0 or 140N) – after Bell *et al.* 2003.

Perhaps of greater concern is the impact of late season N availability on the quality of the harvested material. Elevated late season soil N has been shown to contribute to suckering (Salter and Bonnett 2000; Bonnett *et al*. 2004), particularly when combined with late season moisture availability, with the lower ccs content of suckers resulting in dilution of ccs in the harvested sample compared to whole stalks. Similarly, lodging has been shown to reduce ccs in whole stalks, especially immediately after the lodging event, as well as resulting in greater proportions of low ccs extraneous material in the harvested sample (Singh *et al*. 2000). While a causal relationship between excessive N use and lodging was not determined, the general association between high N rates and rapid early biomass production and propensity to lodging was noted.

Given the lack of clear evidence of a relationship between crop N content and the total accumulation of sucrose in whole stalks, we have therefore restricted our coverage to the effect of N on development of crop yield and total biomass.

3.11 What are the minimum internal crop N requirements to retain stalks, accumulate biomass and produce cane yield?

The analysis of crop performance in unfertilized cane crops shown in Fig. 3.6 suggested a fairly broad envelope of crop N contents that could produce a specified cane yield. This ranged from a low of 0.45 to a high of 2.35 t fw cane/kg crop N uptake, illustrating the range of possible outcomes that can result from the ability of the cane crop to luxury-accumulate N in biomass.

As illustrated from the data in Fig.3. 5 the relationship between dry matter production, and indeed fresh weight cane yield and shoot/stalk number/m^2, is typically asymptotic in shape given a wide enough range in crop N contents within a given trial. However, depending on the N available during the season and the treatment mix, there are often a subset of those treatments which are N-limited, and where the growth parameter is linearly related to crop N content. If that N limitation is severe, then the linear relationship would be expected to pass through the origin (i.e., no above ground biomass production should occur without above ground N accumulation). Bell and Garside (2014) demonstrated that response pattern for a Q117 plant crop in the Burdekin for both total dry biomass and cane yield, suggesting a minimum NUtE of 1.42 kg N/t dry biomass and 0.57 kg N/t fw cane yield. In the case of dry biomass, a linear relationship with a zero intercept was fitted to the data shown in Fig. 3.5 for crop N contents <90 kg N/ha to derive the minimum NUtE of 1.42 kg N/t dry biomass.

We have undertaken similar analyses for various published and unpublished experiments from across the Australian cane industry, with assessments made at both 6-8 months (where available) and at crop harvest, with data shown in Table 3.7. We have initially fitted a full linear model ($y = ax + b$) to the data, and where the intercept was not significantly different to zero and there was not a significant drop in the % variation accounted for in the statistical model, we have fitted the linear model $y = ax$ to the data and reported the slope parameter ($\pm$ standard error) in the table.

We have also undertaken similar analyses for shoot/stalk number, reasoning that the impact of crop N content on tiller retention and final stalk number should also be related to crop N content in trials where there was a sufficiently wide range in crop N. However, given that the shedding of tillers illustrated in Fig. 3.17 is unlikely to extend to death of primary shoots unless at exceptionally low crop N, these relationships were expected to have a positive intercept (approximating the number of primary shoots established) rather than passing through the origin. In this instance we fitted the full linear model and quoted the slope parameter ($\pm$ standard error) in the table as the amount of crop N required to retain an additional tiller/m^2 to contribute to final cane yield.

The available data represent a range of climatic zones (although uniformly high crop N contents in trials from Bundaberg south excluded all those studies) as well as genetic differences associated with locally adapted varieties in the different regions. We are therefore unable to determine whether the differences in minimum NUtE recorded in the various studies are related to environmental influences, genetic effects or some combination of both.

Table 3.7. Minimum crop N uptake (kg N/ha) necessary to accumulate dry matter (t dw/ha), produce cane yield (t fresh weight/ha) or retain additional stalks (stalks/m^2) in N trials from across the Australian sugar industry. Figures in brackets are the standard errors of the slope coefficients, *NR* indicates sample not collected and *HiN* indicates minimum NUtE relationships could not be determined due to high crop N status.

Location	Crop cycle	Minimum crop N requirement (6-9 months) to produce...		Minimum crop N requirement at harvest to produce...			Reference
		1 t tdm/ha	1 stalk/m^2 slope	1 t tdm/ha	1 t fw cane/ha	1 stalk/m^2 slope	
Wet tropics	**Plant**						
	Q187 (Tully)	*NA*	*NA*	*HiN*	*HiN*	*HiN*	Garside *et al.* (2006)
	Q117 (Tully)	3.78 (0.11)	12.68 (0.29)	2.26 (0.17)	0.73 (0.05)	44.4 (22.3)	Garside et al. (1999)
	Q117 (Ingham)	2.47 (0.06)	29.8 (5.2)	2.29 (0.05)	0.89 (0.02)	40.8 (5.1)	Garside et al. (1999)
	Q200 (Ingham)	2.54 (0.06)	32.2 (7.06)	1.57 (0.03)	0.63 (0.01)	19.5 (2.2)	Bell et al. (2010)
	Ratoons						
	Q187 (Tully)	*NA*	*NA*	2.56 (0.06)	0.80 (0.02)	16.7 (1.6)	Garside et al. (2006)
	Q200 (Ingham)	1.79 (0.04)	8.3 (1.4)	1.10 (0.03)	0.44 (0.01)	21.0 (6.0)	Garside et al. (2006)
Burdekin	**Plant**						
	Q117	*NA*	*NA*	1.42 (0.02)	0.57 (0.01)	28.7 (6.9)	Bell & Garside (2014)
	Q208 (Delta)	3.19 (0.80)	14.77 (6.81)	*NA*	*NA*	*NA*	Connellan 2014 (unpub.)
	KQ228 (BRIA)	6.69 (0.70)	5.29 (5.58)	*NA*	*NA*	*NA*	
	Q200 (BRIA)	6.89 (0.60)	10.17 (3.06)	2.59 (0.36)	1.15 (0.20)	10.6 (2.6)	
	Q200 (BRIA)	6.93 (0.59)	15.33 (2.25)	*NA*	*NA*	*NA*	
	Q208 (Delta)	4.24 (1.07)	22.23 (4.55)	*NA*	*NA*	*NA*	
	Q208 (Delta)	3.91 (0.70)	26.31 (6.27)	*NA*	*NA*	*NA*	
	KQ228 (BRIA)	*NA*	*NA*	2.36 (0.62)	0.86 (0.27)	14.3 (7.4)	
	Q183 (Delta)	*NA*	*NA*	3.16 (0.58)	1.15 (0.19)	29.5 (9.3)	
	Ratoons						
	KQ228 (BRIA)	4.51 (0.54)	30.80 (3.38)	*NA*	*NA*	*NA*	Connellan 2014 (unpub.)
	KQ228 (Delta)	*NA*	*NA*	2.00 (0.29)	1.49 (0.31)	*ns*	
	Q183 (BRIA)	*NA*	*NA*	2.80 (0.24)	1.49 (0.34)	37.5 (18.3)	
	Q208 (Delta)	*NA*	*NA*	1.67 (0.53)	*HiN*	*HiN*	
	Q208 (BRIA)	3.26 (0.24)	9.59 (1.03)	2.71 (0.24)	0.95 (0.09)	10.9 (1.7)	
Central region	**Plant**						
	Q117 (Mackay)	3.6 (0.2)	16.1 (3.3)	2.2 (0.2)	0.84 (0.05)	12.8 (0.6)	Garside *et al.* (1999)
Average		4.1	18.0	2.2	0.9	23.9	

While the number of trials and reports with sufficiently low crop N to meet the requirements of severe N limitations were limited, those that were found suggest a reasonable degree of consistency in NUtE for both dry matter and cane yields, although there is considerably greater variability in the relationship between crop N content and stalk density. The latter is probably not unexpected, given that stalk density is a combination of stalks arising from primary shoots as well as from retained secondary tillers. While tillering and tiller retention has been shown to be influenced by crop N status

(Figs. 3.16 and 3.17), the proportion of final stalk number arising from retained tillers is also directly influenced by the number of primary shoots (i.e. crop establishment - Bell and Garside 2005). As a result, the variation in crop N required to retain an additional stalk/m^2 in Table 3.7 is derived from regressions in which the intercept (i.e. stalk number when crop N is 0) may reflect the number of established primary shoots as much as the crop N status.

The maximum NUtE for dry matter in a mid-season sampling (6-9 months age, or at the end of the majority of crop N uptake – Fig. 3.15) was always greater (average of 4.1 kg N/t dry matter) than that determined from samples at crop harvest (2.2 kg N/t dry matter), presumably due to the dilution of crop N content during the sucrose accumulation phase of stalk-filling and the general lack of crop N accumulation in these late stages of crop growth (Fig. 3.15). The relationship between the mid-season and harvest NUtE values were remarkably consistent (60-70% higher in the mid-season sampling), with the exception being the Q117 crop at Ingham. In this study extensive water-logging and crop damage in the latter growth stages resulted in a decline in stalk numbers and no net dry matter accumulation in the last 4 months of the growing season (Garside *et al.* 1999).

There was a three-fold range in NUtE for above ground dry matter produced at final harvest (1.10 – 3.16 kg N/t dry matter), with the previously reported data from the Burdekin (Bell and Garside 2014) fitting in the lower end of that range. There was no obvious separation between plant and ratoon crops, while the suggestion of a higher NUtE in Q200 in the Bell and Garside (2010) study was not supported by results from the Burdekin trial of Connellan (unpublished data). Given that the range in dry matter production across the various trials in this assessment was from ~15-70 t/ha, with no relationship between crop size and NUtE, the relationship would suggest crop N contents would range from ~20-80 kg N/ha (lower boundary) to 50-200 kg N/ha (upper boundary).

A similar analysis of cane yield data produced an approx. 3-fold range in maximum NUtE, with values ranging from 0.44-1.49 kg N/t fresh weight cane yield. In a similar response pattern to that for dry matter production, there were no apparent distinctions between high and low yielding cane crops (i.e., Burdekin vs other areas) and no consistent improvement in NUtE with any particular variety. This suggests the minimum crop N content required to produce 100 and 150 t cane crops as between 45-65 kg N/ha (lower boundary) and 150-220 kg N/ha (upper boundary). Interestingly, the higher NUtE boundary for the unfertilized cane crops derived in Fig. 3.6 (2.35 t fresh weight cane yield/ kg N) was almost identical to the lower boundary of NUtE in Table 3.7 (i.e., 0.44 kg N/t fresh weight cane which is equivalent to 2.27 t fresh weight cane yield/ kg N) derived from this independent set of experiments.

3.12 Implications for N management

- Whilst the sugarcane crop can accumulate large quantities of N, there is no evidence that the crop is incapable of using N efficiently to produce both biomass and cane yield. Indeed, there are many examples of crops from Mackay north in which acceptable cane yields have been achieved with relatively low crop N contents, while the majority of applied N fertiliser is either lost to the environment or sequestered in the soil organic matter pool or in the below ground crop components (roots and stool).

- The current fertiliser N benchmarking method (dividing the fresh weight cane yield by the kg fertiliser N applied) is clearly inappropriate for assessing fertiliser N use efficiency. This is due both to the large (and unaccounted for) contributions to crop N uptake and yield from background soil N mineralization and also the consistently poor recoveries of applied N fertiliser in above ground crop biomass.
- The Australian sugar industry needs to re-examine approaches to fertiliser N management in terms of accepted NUE principles –agronomic efficiency of applied N (t cane or sugar yield/kg applied N, after allowing for the background soil N contribution) and the recovery of applied N by the crop. Our analysis suggests greater quantities of background N mineralization are captured by crops in southern production regions (Bundaberg and south), probably due to lower environmental losses in less extreme rainfall environments, and this is currently not reflected in fertiliser management guidelines.
- If NUE principles used in other cropping systems can be employed in the sugar industry, a more realistic assessment of fertiliser N use efficiency can be undertaken. This is likely to show current $AgronEff_{Fert}$ values that are much lower (i.e., more efficient) than the 5-10 kg fertiliser N required/t additional cane yield above background derived from current experimental trials, and certainly a long way from the $AgronEff_{Fert}$ required to achieve a maximum NUtE of 0.5-1.0 kg crop N uptake/t fw cane yield.
- While the fertiliser efficiency benchmarking methods can be enhanced with a concerted research effort using established NUE principles and approaches, current N fertiliser use by Industry is approximately 50% higher than the 1.0-1.4 kg N fertiliser/t fw cane yield advocated in 6ES. Part of the reason for over-fertilization is the desire to compensate for large environmental losses, with the risks more pronounced in this industry than most because of environmental conditions during the growing season. However, data show that higher fertiliser rates do not always lead to greater crop N uptake, and even if they do, the additional N uptake often leads to greater rates of N removal/t cane at harvest and limited carryover benefits.
- There are currently no financial or enforced regulatory incentives for cane growers to re-evaluate fertiliser N management strategies, although narrowing profit margins and fluctuations in fertiliser price have resulted in a closer examination of all crop inputs. However, given the environmental conditions under which sugarcane is grown it is clear that N fertiliser rates are unlikely to be reduced substantially unless it can be demonstrated that productivity is maintained while losses can be minimized.

3.13 Conclusions and knowledge gaps

There are some key knowledge gaps that need to be addressed to improve N use efficiency in the sugar industry, thereby improving profitability and reducing environmental impacts. These include –

- Developing a more realistic approach to assessing crop N demands by considering productivity data for individual blocks or 'productivity zones' on a farm, rather than district yield potentials. The latter are too easy to dismiss as not being relevant to an individual farm. This approach will be an essential first step to rationalizing N fertiliser decisions.
- Utilizing the improvements in seasonal forecasting to develop predictive tools to modify annual block or productivity zone yield targets to better reflect likely crop N demand, and to provide guidance on fertiliser N application strategies and product choices.
- Developing an improved understanding of the potential contribution to crop N demands that can be met from mineralization of N from background soil organic matter and crop residues, and making (conservative) allowances for this in N fertiliser decisions. This will involve more than the simple discounting based on soil organic matter content in the current 6ES steps guidelines.
- Improving the understanding of N cycling in the trash-soil continuum, and in particular both the rates and quantum of below ground N accumulation in roots and stools during a crop cycle and the importance of this N pool to the background soil N supply for subsequent crop cycles. This will ultimately lead to an assessment of total crop N requirement (above and below ground) that can be factored into fertiliser N decisions.
- Improving industry understanding of the risks associated with N management in high rainfall and irrigated environments and developing N management strategies that are more responsive to N loss pathways and potential loss events.
- Increase the intensity of work with enhanced efficiency N fertilisers that can potentially better match supply to demand and/or maintain N in a form less vulnerable to loss (e.g., ammonium-N). This will involve development of partnerships with the fertiliser industry so that manufacturers clearly understand the product characteristics that the industry requires. A fundamental requirement for this understanding is the development of a decision support framework that matches crop N requirements in a particular district/soil/season with the appropriate enhanced efficiency fertiliser product.
- Improve rapid in-crop diagnostics for crop N status that can be conducted prior to critical crop growth stages so that management interventions can be considered. Given that these critical growth stages often occur during the summer wet season, the diagnostics are more likely to involve proximal, rather than remote, sensing. The latter is likely to be limited by cloud cover during this critical time period.

3.14 References

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4. Genetic improvement of nitrogen use efficiency in sugarcane

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4.1 Abstract

Nitrogen use efficiency (NUE) is a complex trait that encompasses the uptake of nitrogen (N) by plants and its use for growth and productivity. There is agreement that solving the environmental and economic concerns of N inefficiencies for all cropping systems warrants the two-tiered approach of agronomic innovation in conjunction with genetic crop improvement. Breeding programmes for most crops have centred on high mineral fertilisation inputs, failing to exploit genetic differences under lower N input. Genetic variation for NUE and interactions with N supply have been demonstrated in several species, including sugarcane, and screening crop performance with varied N supply allows identification of promising genotypes and traits. Genetic studies showed that the selection strategy for improving NUE will vary with crop, germplasm and target production environment. Despite the advancement of our knowledgebase and the existence of genetic variation NUE as a target trait has not been harnessed in most crops.

The complexity of NUE requires understanding of the underlying biology as the impacts of particular traits differ across growth environments and genetic background. There has been a substantial body of work dissecting NUE-related attributes in maize and wheat, but very limited in sugarcane and similar biomass crops. Nitrogen metabolism enzymes are a major focus of NUE research. Advancements in this area of research led to transgenic manipulation of N metabolism with promising results in maize, canola, rice and sugarbeet, and is being explored in sugarcane by the South African sugar industry. Molecular markers for NUE traits have been identified in several crops and are under much investigation in grain crops. Attracted by these tools and technologies, breeding programs for grain, feed and biofuel crops are making significant investments to improve NUE. Promising traits for sugarcane include N responsiveness, N uptake and accumulation (stalk filling stage, early crop season), shoot and root vigour, improved nitrate use, remobilisation into stools, and maintenance of leaf N status to ensure maximum photosynthetic competency and radiation use efficiency throughout the crop season.

To advance genetic improvement of NUE in sugarcane greater understanding of sugarcane N response is required and this is a long-term undertaking. There are no dedicated sugarcane breeding programs for NUE globally, but there is growing in interest in developing NUE crops in Brazil, China, South Africa and India. A better understanding of the extent of genetic variation for NUE in the local germplasm and crop-specific N physiology is fundamental for developing successful strategies for genetic improvement of NUE. Screening of Australian sugarcane breeding lines and current varieties, and a detailed physiological investigation, including below-ground attributes, especially N uptake, storage and use in the context of sugarcane commercial production is a priority. From a practical crop improvement perspective, the overarching strategy should be to select clones for high responsiveness to applied N. The experience in grain crops suggest that more gain (improved varieties for reduced N conditions) can be realised by selecting for yield under low N input, or alternating high and low N conditions. This information is not available for sugarcane. Evaluating

various selection strategies relevant to sugarcane should be undertaken at least in those regions where N leakage is a pressing issue.

4.2 Introduction

Much of the innovation in agricultural production has been to ensure that crops are not resource limited and maximum yields are achieved. Consequently, synthetic nitrogen (N) fertiliser has become a staple of crop agronomy, and variety development for high-yielding crops has been carried out with high resource inputs, including in the Australian sugarcane industry. More recently, the environmental and economic penalties of N fertiliser use have re-directed R&D globally to address the difficult task of ensuring yield security with reduced fertiliser inputs to avoid off-site losses and inefficiencies. To improve N use efficiency (NUE) in broad acre crops, multifaceted approaches combine agronomic improvement in combination with genetic advances.

An example of recent investment into NUE is the European Union project "*NUE crops Improving nutrient use efficiency in major European food, feed and biofuel crops (maize, wheat, canola, potato) to reduce the negative environmental impact of crop production*" initiated in 2009. Over 5 years (€ 6 million), 10 academic centres and 3 breeding companies in 6 EU states, China and the USA, are advancing knowledge for breeding N efficient crops to integrate into innovative management. Initial project outcomes reflect the dual emphasis on crop genetics and agronomy with (i) improvement of germplasm (ii) identification of molecular markers for NUE to reduce costs of field-based phenotyping, (iii) understanding genotype-by-environment-by-management interaction and, (iv) emerging nutrient management including variety selection for organic farming systems (see special issue Euphytica 2014 volume 199).

There is consensus that a two-tiered approach of crop breeding and management will maximise advances in NUE in the context of crop and cropping system idiosyncrasies. This is most relevant to cropping systems vulnerable to climate extremes, soil and management constraints, which includes sugarcane cropping in Australia. Compared to maize, wheat and rice, the characterisation of Australian sugarcane germplasm is in its infancy and there is very limited knowledge on regulatory processes impacting N acquisition and metabolism in sugarcane.

The preceding chapters have outlined the limitations of N management in Australian sugarcane production. Of significance is the consideration that projections for improved management is estimated to only reduce N losses by up to 60% while the frequency of years with high N losses is estimated to increase by 10–15% (Biggs et al. 2013, Thorburn & Wilkinson 2013). Minimising N losses by optimising rates and timing of N application remains a difficult task due to the limited capacity to predict weather and accompanying soil processes and crop growth. Together, these considerations highlight the need to maximise crop N uptake and utilisation through management and variety improvement. Here we evaluate the progress made in improving crop NUE more generally in crops that have been targeted and a view of the genetics and trait physiology of sugarcane. We will outline knowledge gaps and opportunities for the genetic improvement of sugarcane.

4.3 Genetic improvement for nitrogen use efficiency

Improving NUE is a challenging goal for plant breeding due to its complexity; genetically and physiologically. In contrast to breeding for disease resistance (assessed with comparatively straightforward susceptibility-resistance ranking), NUE is composed of multiple efficiencies that are the result of integrated N pathways ranging from soil uptake, metabolism, internal use, storage, remobilisation through to loss. As N is an essential building block of structural and functional molecules and quantitatively the most important nutrient that plants acquire from soil, acquisition and use of the element are regulated across all levels of organisation, from molecule, cell, organ, plant to whole crop. The greatest efforts to understanding and improving NUE have targeted grain crops (maize, wheat, rice) due to their global significance as food crops and the need to maximise grain N (protein) content. Strategies for genetic improvement of NUE include

(i) selecting for yield in the target low N environment (Bänziger et al. 1997);

(ii) indirect selection at high input for yield potential (Foulkes et al. 2009);

(iii) trait or genomic selection methods (Hirel et al. 2007; Masclaux-Daubresse et al. 2010);

(iv) transgenics (Xu et al. 2012).

There has been less emphasis on biomass crops for NUE although maximising production with lower N input is now being pursued in bioenergy crops and forage grasses (Brégard et al. 2000, Yang et al. 2009, Yu et al. 2013). Investigation of the plant model *Arabidopsis thaliana* has allowed unravelling the regulatory mechanisms underpinning NUE in context of developmental plasticity in diverse genetic backgrounds (Chardon et al. 2010, 2012). Studies on genetically distinct Arabidopsis collections have dissected fundamental processes of N uptake and regulation of N use at cellular and whole plant levels.

This research has demonstrated in Arabidopsis that 'harvest index' (yield relative to total biomass) remains stable irrespective of N nutrition, genetic background or the various relationships between N and carbon, and has outlined quantitative genetics of NUE (Masclaux-Daubresse et al. 2010). Translating the knowledge gained from Arabidopsis to crops is the subject of current research globally. A comparative summary of research on genetic improvement in major grain crops; maize, wheat, rice and sugarcane is presented in **Table 4.1** and outlined in more detail in the sections below.

Table 4.1. Comparative summary of research focused on genetic improvement in NUE including germplasm development and traits linked to NUE in major grain crops; maize, wheat, rice and sugarcane.

	Crop			
	Maize	Wheat	Rice	Sugarcane
Germplasm screened	Broad[2,4,68]	Broad[44, 87]	Broad[41, 119]	Narrow-Moderate[58]
NUE component identified at low N supply	N utilisation[59] N uptake[20, 68]	N uptake[44]	N uptake[6]	
Selection strategy for enhanced NUE/N stress	High and low N input[2,20]	Alternate intermediate/high N input[64]		No dedicated programme Recommended high N input
Target traits				
Morphology	Root architecture[101]			
Physiological	Green leaf area-stay green[71]	Early vigour[47] Early root vigour[48] Stay green[95]	Stay green[39]	Photosynthetic NUE[75]
N metabolism	Glutamine synthetase (GS) molecular markers[31]	GS molecular markers[70]	GS molecular Markers[63] Nitrate storage[14]	
Transgenic targets[*]	GS activity[54]	Alanine aminotransferase activity (AlaT)[a] GS activity[28]	Root N transporters[72] GS activity[114] AlaT activity[93] Dof1[114]	AlaT activity[b]

[*]Reported in literature; [a]ACPFG and CSIRO join forces with Vilmorin & Cie to commercialise Nitrogen Use Efficiency wheat in Australia 2012- www.csiro.au; [b] www.arcadiabio.com

Genetic variation for NUE in crops

Field screening of genetically diverse populations has demonstrated that large genotypic variation for NUE (yield produced per unit of available N in the soil, including fertiliser) exists in breeding germplasm and varieties of several crops (tropical maize, Bänziger et al. 1997; European maize, Bertin and Gallais 2000, Presterl et al. 2003; wheat, Le Gouis et al. 2000; timothy, Brégard et al. 2000; barley, Sinebo et al. 2004; rice, Samonte et al. 2006). Despite the inherent genetic variability in all germplasm that has been studied in this respect, NUE as a target trait has not been harnessed to improve most crops. Recent efforts have identified elite germplasm for improvement programs of bioenergy crops with NUE as a key trait (Yang et al. 2009). The potential for NUE improvement from unselected germplasm is illustrated in *Miscanthus*, a bioenergy crop and close relative of sugarcane. Twenty-three accessions (genotypes) of *Miscanthus*, collected from a wide range of geographic regions, grown without fertiliser additions displayed 50- and 3.5-fold variation in biomass and N concentrations, respectively indicating that large gains for NUE are possible (Yu et al. 2013).

Impact of N supply and NUE

The response of genotypic variance to reduced N supply depends on germplasm and severity of N stress, and no consistent response has been observed across species (Gallais & Coque 2005). There is indication that breeding programs have resulted in loss of adaptive capacity for low N environments. This is evident in maize where lines derived from landraces, but not varieties, displayed higher variability at low N than high N supply (Prestel et al. 2003).

Screening crop germplasm with two or more contrasting N supply regimes has established a significant genotype-by-N interaction that (i) reflects genotypic differences in responsiveness to N, and (ii) different processes controlling NUE at limiting and high N supply. To effectively improve NUE it is necessary to dissect the processes controlling NUE. The first process "*N-uptake efficiency*" denotes the amount of N acquired by the crop from fertiliser and/or soil (kg N in the crop per available in soil). The second process *"N utilisation efficiency"* denotes the capacity of the crop to use the acquired N for biomass (yield) production (tonnes crop biomass per kg N in the crop). Note that most field studies consider only above-ground biomass for NUE components although below-ground structures are an integral component of NUE.

Genetic variation occurs for both components of NUE. Early research in maize showed that N uptake and utilisation efficiencies are influenced differently by N supply (Moll et al. 1982). In maize hybrids grown under high N supply the differences in NUE were largely influenced by N uptake efficiency, whereas with low N supply, NUE was driven by N utilisation efficiency (Moll et al. 1982). In contrast to maize, evaluation of 20 wheat genotypes at two N supply rates (0, 170 kg N ha^{-1}) demonstrated that N uptake efficiency contributes more to NUE at low N than high N supply (Le Gouis et al. 2000).

Similarly, comparison of three rice varieties at five N supply rates produced parallel N response curves and demonstrated that genetic traits that drive maximum N uptake lead to greater biomass (Borrell et al. 1998). Understanding the genetic basis of NUE will aid genetic improvement as the regulatory mechanisms controlling the two components of NUE are species-specific (Hirel et al. 2007); this is further complicated by interactions with climate, changing soil water and nutrient availabilities and plant developmental stages (Hirel et al. 2011).

Knowledge on the 'optimum' yield reduction is required for gauging genetic variability at low N supply. The reason is that if N limitations in the growth environment are too severe, the genetic variability is supressed and variance in response to environmental factors increased (Gallais & Coque 2005). Which 'low N strategy' will be favoured depends on the goals of the genetic variance to be investigated as breeding programs *versus* fundamental research often differ in their aims, and NUE traits that are expressed in particular situations may differ across N supply regimes. Pursuing NUE traits that compromise economic yield will have little value in commercial variety improvement programs.

Selection Strategies

To maintain high crop productivity under reduced N input requires a decision on whether genotype selection in breeding programmes be conducted under low or high N input (Hirel et al. 2007). This a crop-specific issue and requires a good understanding of crop growth dynamics in response to N and water, genetic diversity for NUE in the germplasm, plant available N in a cropping system and the

economic threshold of farm-level yield to make cropping an economically and environmentally sustainable enterprise. Technically the efficiency of selection at high N supply for varieties subsequently grown in low N input environments is influenced by the correlation of yield at low and high N supply, and heritability at high *versus* low N supply (Gallais & Coque 2005). Heritabilities are dependent on genetic and environmental variances. A reduction in heritability due to decreased genetic variance and increased environmental (or error) variance is often observed under stressful growth conditions (DoVale et al. 2012, Gallais et al. 2008). However, there are exceptions. Analysis of maize yield from 21 trials (49-144 genotypes per trial) grown with low (no N-fertiliser) or high N supply (200 kg N ha^{-1}) showed reduction in grain yield with low N ranging from 15 to 56 % (Presterl et al. 2003). While environmental variance was greater at low N input, genetic variance was higher and heritability estimates ranged from 36 to 94% (high N) and 41 to 88% (low N). It was concluded that selection in the low N system was more effective than under high N supply (Presterl et al. 2003). Similarly, selection for tropical maize under high N for performance under low N was considerably less efficient than selection under low N when relative yield reduction due to N stress exceeded 43% (Bänziger et al. 1997). Overall, these insights have prompted the notion that low N selection environments can maximise selection gains for NUE.

For many years, the CIMMYT (*International Maize and Wheat Improvement Center*) wheat breeding program selected lines under intermediate N supply and improved NUE (Ortiz-Monasterio et al. 1997). Comparing five selection strategies in wheat, the selection alternating between high and low N inputs, resulted in the highest yields at intermediate and high N levels (Van Ginkel et al. 2001). This indicates that indirect selection at high N supply may be alternated with direct selection at low or intermediate N supply in breeding programmes for varieties adapted to low N input.

In maize, interactions of genotypes with environments are generally higher than the genotype-by-N supply interaction (Bertin & Gallais 2000, Gallais & Coque 2005) and this is also likely to occur in other crops. It is therefore necessary to evaluate multiple sites and years for a robust measure of NUE. From the data available in the public domain, a generic genetic improvement approach by breeding is not emerging for NUE.

Historically, variety improvement through breeding has relied on direct selection for yield and often clone selections are conducted under growing conditions that maximises yield potential. Direct selection for yield has been successful irrespective of the crop, breeding strategy or cropping system. This long-term trajectory underpins the notion that selection for yield under favourable conditions would be effective in improving yield across diverse production conditions, even under stressful environments. However, the relationship between potential yield and actual yield generated by primary producers breaks down under growth-limiting environmental conditions and the impact can be severe with certain genotype-environment combinations. This situation is particularly evident when crops experience moderate to severe abiotic stresses, especially water, N and temperature stresses. Hence, to maximise productivity, the actual association between yield potential and actual yield under growth-limiting conditions should be determined for each genotype-environment combinations, which is often impractical for cost and operational reasons.

4.4 Trait Physiology and NUE improvement

Yield has a relatively low heritability across crops and a selection approach based on yield may not be the most efficient as there is a high genotype-by-environment interaction (Jackson et al. 1996, Foulkes et al. 2009). Understanding traits at the crop physiological level may help to identify indirect selection criteria that could be applied to accelerate breeding for trait improvement. The dominant contributing components of physiological traits in general are species- and context-dependent. Characterising physiological and biochemical responses to N supply in crops has two aims: (1) to understand the effect of N supply, both form and quantity, on crop developmental processes to optimise fertiliser source and application, and (2) to identify traits that could be developed into screening or selection traits in breeding programmes.

Experience in grain and other crops suggests that characterisation of genotype responses arising from selection for yield under target environments such as low N input provide valuable information for traits contributing to yield (Sylvester-Bradley & Kindred 2009, Sadras & Richards 2014). Traits that are major contributors of yield under low N input can be used as an added selection parameter in combination with yield to accelerate the genetic improvement of target trait and yield. Use of secondary traits as indirect selection for yield is applicable to both high-yielding (e.g. N non-limiting) and yield-limiting (e.g. low N) conditions as it complements direct selection for yield in target environments (Sadras & Richards 2014). Examples from other resource use efficiency focussed breeding include canopy temperature (Rebetzke et al. 2002), seedling vigour (Richards & Lucas 2002), and carbon isotope discrimination (Farquhar & Richards 1984) for improving wheat yield under well-watered and water-limited production conditions. For NUE of maize, glutamine synthetase activity and grain yield are robust traits under low N (Hirel et al. 2007). A recent finding in sugarcane showed high genetic correlation and heritability between canopy conductance and cane yield under varying levels of water supply at multiple production regions.

This insight strengthens the prospect of trait-based selection for improved sugarcane varieties for different target environments (Basnayake *et al.* 2014; unpublished results). However, NUE is even more complex and further knowledge on the physiology of traits that could be used in NUE is necessary.

Morphology, physiology or biochemical characteristics conferring or associated with traits such as NUE are rarely implemented as selection traits for breeding improved varieties due to the need to fulfil a number of criteria including: (i) strong genetic correlation with yield; (ii) higher heritability than yield; (iii) stable across different populations, production conditions and generations; (iv) no association with yield penalty under non-stress conditions; and (v) easy/inexpensive to measure a large number of genotypes.

A number of traits associated with, or considered to be contributing to, NUE in previous crop research are briefly discussed below. Their significance in improving NUE in sugarcane will be considered in the context of sugarcane cropping and N dynamics (section 4.5).

Canopy attributes

Breeding for high crop biomass results in increased NUE, as N uptake and utilisation efficiency increase due to N dilution and feedback control of N uptake by the plant's growth rate (Lemaire et al. 2007). Biomass production is dependent on N supply through leaf development as leaf area index and specific leaf N content (amount of N per unit leaf area) (Gastal & Lemaire 2002). Genetic variability of the processes that drive leaf growth and senescence is an avenue for enhanced NUE and performance at low N. Leaf longevity was the main physiological factor explaining genetic gain in maize yield, associated with improved N uptake during grain filling (Rajcan & Tollenaar 1999). In sorghum, the capacity of a genotype to retain green leaf area for longer ('stay-green' trait) is associated with improved performance (Borrell et al. 2000). In contrast, two maize hybrids that differed in the rate of chlorophyll loss displayed no direct relationship between the progression of leaf senescence and N uptake during grain fill (Martin et al. 2005). Whether the stay-green trait is beneficial for NUE and yield across crop species requires evaluation in field conditions under varying N supply (Hirel et al. 2007).

Photosynthetic NUE

Photosynthetic proteins (RuBisCo, light harvesting complexes) and chlorophyll, contain a large proportion of leaf N. In plants with C3 and C4 modes of photosynthesis, RuBisCo alone comprises up to 30% (C3) and 10% of leaf N (C4) (Sage et al. 2014). There are consistent and strong relationships between maximal photosynthetic rates and leaf N concentration, which is described as 'photosynthetic NUE' (Evans 1989). C4 plants like maize and sugarcane have a comparatively high photosynthetic NUE ranging from 0.2 to 0.8 mmol (mol^{-1} N s^{-1}) compared to C3 plants (Ghannoum et al. 2011). In addition to maintaining high leaf N status in low N environments, adapting leaf anatomy and maximising N allocation to RuBisCo and light-harvesting complexes can to improve photosynthetic NUE (Ranjith & Meinzer 1997).

Nitrogen metabolising enzymes

An example of the progress made by integrating whole-plant physiology and quantitative genetics was demonstrated by finding that glutamine synthetase can strongly influence NUE (Hirel et al. 2001, Hirel et al. 2007). Quantitative trait locus (QTL) analysis based on high density molecular linkage maps determined the genetic basis of NUE in maize. Field screening maize populations combining measures of physiological traits (N assimilating enzymes activities, nitrate concentration in tissues) and agronomic indices revealed co-localisations of QTLs for glutamine synthetase activity, grain N content and yield. This suggests that glutamine synthetase activity is a main contributor for high NUE in maize (Hirel et al. 2001). Using transgenic technologies and mutagenesis (forward and reverse genetics), fundamental roles of were demonstrated for two cytosolic glutamine synthetase isoforms in determining kernel grain number and kernel size (Martin et al. 2006). Association genetics can link gene nucleotide polymorphism of glutamine synthetase gene, *Gln1.3,* to an increased yield in a diverse maize population to identify the best performing *Gln1.3* allele (Hirel et al. 2011). Following functional validation of candidate genes using approaches detailed above indicates that potential exists for marker-assisted selection for crop breeding (Hirel et al. 2011). However, use of marker-assisted selection for NUE remains at proof-of-concept stage. Confirming the link between grain yield and glutamine synthetase, co-locations between QTLs of cytosolic glutamine synthetase locus and

yield have been identified in rice (Obara et al. 2001). In contrast, the role of glutamine synthetase is not as clear in wheat. QTLs for glutamine synthetase activity collocating with grain N content did not map at any glutamine synthetase gene locus, revealing unknown factors involved in the trans-regulation of glutamine synthetase (Chardon et al. 2012). Recently, a role for glutamate synthase in controlling NUE has been established in wheat using consensus markers across the four genomes (wheat, maize, rice, sorghum) increasing the accuracy of QTL detection (Quraishi et al. 2011). Further work will clarify the roles of these N-metabolising enzymes in NUE across and within species diversity. A key central role of cytosolic glutamine synthetase in N assimilation concurs with improved NUE in vegetative growth of rice when grown with ammonium as N source (Kusano et al. 2011).

Root traits

Roots are central to resource acquisition from soil. The complexity of roots includes temporal and spatial development and diverse functions, and the practical difficulties inherent to quantifying root traits in soils are reason that little is known about the contribution of root traits to N acquisition and crop productivity. Attempts to synchronise the timing of fertiliser application with plant demand is often hindered by insufficient knowledge of soil-root-microbe interactions, mobilisation of N in soil, and the time required by roots to proliferate in response to N availability (Palta & Watt 2009). The role of environmental conditions, in addition to plant traits, is illustrated in wheat. Genotypes with early shoot and root vigour and higher root length density had greater uptake of nitrate and yield in soils with high N leaching potential (Liao et al. 2004, 2006). Similarly, a dense root system may facilitate greater N uptake when a large component of the crops' N budget originates from soil organic matter (rather than dissolved N fertiliser), due to competitive advantage over soil microbes.

To avoid the difficulties inherent to characterising root traits in field-grown crops, screening for genetic variability in root traits is often performed in controlled conditions with young plants. Genomic approaches, including QTL identification, have been undertaken to dissect the variability in root architecture and investigate the effects of this variability on yield (Tuberosa et al. 2003, 2011). QTLs that associate with root traits in controlled conditions have been studied in maize under low and high N supply (Liu et al. 2008). A major QTL for the average axial root length explained 44% of the phenotypic variation and co-localised with previously described QTLs for grain yield under low N (Bertin & Gallais 2000). Similarly, coincidences between QTL for root length and N uptake are reported in wheat (Lapreche et al. 2006). Those studies demonstrate that artificial growth conditions characterise root traits relevant to NUE sufficiently well. Avenues investigating field screening root traits throughout crop development and QTL analysis are currently being explored (Cai et al. 2012). However, incorporating root traits into breeding programmes remains a challenge, the only morphological root trait correlated to increased yield that is currently incorporated into breeding selection is 'shallow branch root angle' in beans due to a role in phosphorus efficiency (Palta & Watt 2009, Lynch 2007). That selection programme operating in East African systems was facilitated by early engagement of breeders in the research program and training in phenotyping (Lynch 2007).

In another example, comparison of the N-efficient maize inbred line 478 and N-inefficient line Wu312 assessed if the amount of N acquired by plants with different N acquisition ability was determined by the shoot growth potential or by root size (Peng et al. 2010). Root growth and N uptake were coordinated with shoot growth and demand for nutrients. Although a large root system and high root

length were beneficial for efficient N acquisition from soil, in the presence of sufficient N, the amount of N taken up by the contrasting maize genotypes supply was determined by shoot growth potential rather than root size (Peng et al. 2010). A knowledge gap remains in understanding the interaction of genotype-by-environment-by-management on root N uptake, partitioning and utilisation.

Storage and remobilisation

N uptake is subject to strong negative feedback regulation, therefore the capacity to store N in vacuoles or as proteins (such as RuBisCo) can circumvent down-regulation of N uptake and allow 'luxury' storage. In Arabidopsis, the capacity to store nitrate was a significant determinant for growth at limiting N supply (Richard-Molard et al. 2008, North et al. 2009). Greater NUE during vegetative growth was also associated with increased ability to store nitrate in stem tissues in a comparison of two rice varieties (Fan et al. 2007). Understanding of the physiological processes that enable crops to withstand periods of N shortage and limit the negative consequences for subsequent vegetative growth would assist the selection of varieties able to tolerate temporary N deficiency.

Key processes involving N storage and remobilisation through glutamine synthetase and their genetic variation are critical for determining grain productivity and yield (Hirel et al. 2007). Nitrogen storage and remobilisation drives N relations in perennial crops over numerous harvesting cycles. In the biomass crop *Miscanthus*, senescence (associated with frost events) triggers remobilisation of N to below ground rhizomes for storage (Heaton et al. 2010). Therefore harvesting *Miscanthus* biomass after senescence rather than at maturity can reduce N removal (Yu et al. 2013). Genotypic differences in shoot N concentrations of *Miscanthus* at maturity and during senescence demonstrate that selection can target genotypes with high N remobilisation potential to minimise removal of N with harvested biomass. Similarly, genetic differences were evident across 31 accessions of switchgrass (*Panicum virgatum*) with between 19 to 61% of plant N remobilised to rhizomes (Yang et al. 2009). That demonstrated variation in N remobilisation efficiency appears relevant to the management of harvests and the performance of ratoon crops, and highlights that knowledge of belowground N dynamics is likely to be relevant for NUE traits of sugarcane.

4.5 Transgenic approaches to NUE improvement

Processes involving N uptake and primary metabolism, regulatory pathways, and the interactions between C and N metabolism interactions, are targets for genetic engineering of NUE. Recent reviews discuss target genes in context of plant species tested in this respect (Xu et al. 2012, Rothstein et al. 2014). Most studies reported in the published literature in crops and Arabidopsis have been directed at (i) increasing N uptake by modifying membrane transporter activities located in roots (i.e. increasing the capacity for N import into roots and transport from root to shoot) and (ii) manipulating steps of N metabolism *via* nitrate reductase or glutamine synthetase (see section 4.3). There is agreement that the sole up-regulation of nitrate and ammonium membrane transporters and nitrate reductase expression does not improve NUE. An exception was the overexpression of an ammonium transporter in rice with transgenic lines producing more grain per plant when grown in controlled conditions in pots with low ammonium supply (Ranathunge et al. 2014). However, whether this result can be successfully scaled up to cropping systems remains unknown as transgenic lines were unable to down-regulate ammonium uptake with moderate-to-high supply. Such inability

may hinder growth in soils with fluctuating ammonium concentrations. Improved understanding of membrane transporters will advance transgenic and non-transgenic approaches targeting NUE.

Several successful NUE transgenic strategies have manipulated the balance between N and C metabolism through altered N-metabolising enzyme activities. Growth at low N supply and NUE was improved with over-expression of cytoplasmic and plastidic glutamine synthetase genes (Masclaux-Daubresse et al. 2010, Fuentes et al. 2001). In wheat, overexpressing cytosolic glutamine synthetase increased biomass, root growth and grain N content. The effect was attributed to altered glutamate:glutamine signalling that changes the balance of N assimilation between ammonium assimilation from photorespiration and remobilisation (Habash et al. 2001). Similarly, increased growth with overexpression of cytosolic glutamine synthetase occurs in poplars (Gallardo et al. 1999), lotus (Vincent et al. 1997) and tobacco (Fuentes et al. 2001), suggesting its generic impact across plant taxa. Grain yield increased by as much as 30% in maize with its own cytosolic glutamine synthetase gene up-regulated [patent AU2007306040(A1)]. These examples demonstrate that knowledge of function of the two glutamine synthetase isoforms (in cytosol and plastids) allowed identification of appropriate engineering targets for more rapid advances in NUE.

While numerous studies have created transgenic plants with altered glutamine synthetase, few have targeted glutamate synthase which catalyses glutamate synthesis and affects glutamine:glutamate signalling. In transgenic rice lines over-expressing glutamate synthase, grain yield improved by as much as 80% (Yamaya et al. 2002) while other studies did not confirm this effect (Masclaux-Daubresse et al. 2010).

Transgenic manipulation of downstream N metabolism with alanine aminotransferase has produced promising results for increasing yield in N-limited environments. In rice and canola grown in the field under N-limiting supply, tissue-specific up-regulation of alanine aminotransferase with root-specific promoters improved growth, tissue N content and yield (Good et al. 2007, Shrawat et al. 2008). Transgenic canola grown with 40% less N fertiliser produced the same yields as non-transgenic plants. This dramatic increase in NUE was attributed to a higher uptake of nitrate from soils and associated with a notable decrease in glutamine and glutamate in stems. Similarly, overexpression of alanine aminotransferase in rice lead to increased biomass and N content in stems but was associated with an increase of glutamine and asparagine in tissues (Shrawat et al. 2008). Transgenic plants also had a finer, denser and more branched root system. Although the biochemical mechanisms for the NUE-enhancing effect of alanine aminotransferase remain unresolved, its action *via* synthesis and degradation of alanine, and a role of alanine as an intercellular N and C shuttle highlight that downstream manipulation of N metabolism can improve NUE (Shrawat et al. 2008).

Advancing NUE through manipulation of the transcription factor Dof1, which regulates several C-metabolism enzymes, has been explored to increase the generation of carbon compounds in maize. Up-regulated by Dof1 are N-responsive genes that improve NUE through a coordinated regulation of N and C metabolism. Up-regulation of Dof1 in Arabidopsis resulted in ~30% increase in tissue N content, higher concentrations of soluble amino acids, and enhanced growth under N limitation (Yanagisawa et al. 2004). Furthering these discoveries and combining overexpression of transcription factor and N-metabolising enzymes, transgenic tobacco lines overexpressing Dof1 (Dof1.7), cytosolic glutamine synthetase (GLN1;4) and plastidic glutamine synthetase (Wang et al. 2013) displayed changes in the levels of intermediate metabolites including nitrate, glucose, sucrose, malic acid, citric

acid and amino acids. The transgenic plants had higher activities of C and N metabolism enzymes (glutamine synthetase, nitrate reductase, phosphoenol-pyruvate carboxylase, pyruvate kinase). Exogenous Dof1 and glutamine synthetase genes influence the physiological and metabolic processes involved in plant growth which resulted in 29 to 47% increases in dry weight in 90-day-old tobacco plants with low N supply (Wang et al. 2013).

Current limitations of transgenic approaches for improving NUE include the complexity of the NUE within each crop species and the need to identify the best targets for manipulation. A consideration is also the time from discovery to commercial release (Rothstein et al. 2014). For example, 20 years have elapsed since research on genes encoding alanine aminotransferase and discovery of a NUE phenotype in canola. No commercial varieties have been released as yet (Rothstein et al. 2014), and while successful field trials are being reported, no peer-reviewed data is available to confirm these claims.

4.6 Genetic improvement of sugarcane NUE

Status of genetic improvement research in sugarcane

In sugarcane, characterisation of genotypic N response and N physiological traits has been limited and fragmented across global sugar industries with little effort directed to variety improvement through breeding. The majority of studies are reported from Brazil, South Africa, US and Australia, and most are limited to a small number of genotypes.

Historically, Brazilian sugarcane varieties have been selected for high yield with low inputs of synthetic N fertiliser (Nogueira et al. 2005) as a large proportion of plant N demand was supplied by soil N reserves (and possibly biologically fixed N). Expansion of the Brazilian sugar industry into more marginal land over the past two decades has resulted in increased use of N fertiliser (Martinelli et al. 2008) and an increased focus on refining N fertiliser management (Franco et al. 2011). Characterisation of N responses of varieties in Brazil has centred a round dissecting the relationship between sugarcane varieties and endogenous N-fixing microorganisms (Urquiaga et al. 1992, 2012). In South Africa the thrust was on variety responsiveness to applied N in commercial production conditions. Over several decades the South African sugar industry has evaluated and implemented the potential for variety-specific N rate recommendation (Meyer et al. 2007). In Australia, the focus has been on N agronomy (Wood et al. 2010) with recent efforts evaluating the potential of sugarcane germplasm for genetic improvement (Robinson et al. unpublished, and see section 4.5). In the USA, germplasm evaluation for NUE has been driven by the displacement of sugarcane cropping from organic-matter rich soils to sandy soils in Florida (Todd et al. 2014). Comparisons of two Hawaiian varieties with contrasting drought and salinity tolerance have provided mechanistic understanding of processes influenced by N and salinity stress (Meinzer et al. 1994, Ranjith and Meinzer 1997, Meinzer & Zhu 1998).

Genetic variation in sugarcane NUE

Brazilian germplasm

Information on the extent of genetic variation for NUE in the Brazilian germplasm is limited. Over a 15-year field experiment (2 cycles, 13 cuts) on acrisol soils without fertiliser addition, seven Brazilian varieties did not differ in biomass and N accumulation (Urquiaga et al. 2012). However, *Saccharum spontaneum* cv. Krakatau, also included in the study, had higher N accumulation, which was correlated with greater shoot N concentration and relative contribution of leaf N biomass to total N in the plant (Urquiaga et al. 2012). While the authors propose biological nitrification inputs, this finding also suggests that unselected species cane may possess useful NUE traits that have been selected against in varieties.

South African germplasm

Historically, the South African sugar industry is a forerunner in sugarcane N research, establishing many agronomic practices applied to commercial sugarcane cropping. Genotype-specific responses to N supply were reported in South Africa nearly 70 years ago, with Co281 out-yielding Co301 at low N supply, and Co301 out-yielding Co281 at high N supply (Meyer et al. 2007). To provide variety fertiliser recommendations, genotypes have been screened with differing N supply. For example, evaluation of biomass production and sucrose yield of seven varieties (NCo376, N12, N14, N16, N19, N24, N25) over 12 months in outdoor sand cultures with three N rates (low N 2.1 mM to high N 6.4 mM N, Schumann et al. 1998) showed N12 and N19 being the most N use-efficient at medium N supply (40-50 g sugar g^{-1} N), and average at high N supply (18 g sugar g^{-1} N). In contrast, inefficient variety N14 increased biomass >2-fold from medium to high N supply but had lower NUE (15 and 16 g sugar g^{-1} N at medium and high N supply, respectively) (Schumann et al. 1998). Based on subsequent field trials, fertiliser recommendations for N14 were increased by 30 kg N ha^{-1} while a reduction of 20 kg N ha^{-1} was recommended for the most efficient variety N19 (Meyer et al. 2007, Weigel et al. 2010). This outlines how knowledge of variety-specific responses can lead to improved fertiliser use in commercial cropping.

USA germplasm

As with Brazil, USA sugarcane germplasm has not been extensively characterised for NUE. Comparison of four sugarcane varieties grown on sandy soils in Florida showed that a variety (CP65-357) selected on sandy, N-deficient soils produced 1.5-2.6-fold greater yields across a wide range of N supply rates (0 to 896 kg N ha^{-1}) than varieties (CP63-588, CP56-59, CP68-1026) that had been selected on N-rich soils (Gascho et al. 1986). The field trial detected no significant variety-by-N supply interaction, but inferences are limited as the single row plots may have been impacted by competition. However, CP65-357 had the highest N utilisation efficiency in hydroponic culture and produced more biomass than the other varieties (Gascho et al. 1986).

Breeding selection strategies for varieties adapted to sandy soils were evaluated by testing genotype response to mill mud application in sandy soils to remove variance caused by geographic separation of sand and organic soils (Todd et al. 2014). Thirty-one sugarcane genotypes, including promising breeding lines, varieties and an *Erianthus* accession were grown over two cropping cycles on sand with and without mill mud. Despite high N application (225 kg N ha^{-1} split between 3 applications)

across the trial, with/without mill mud treatments provided contrasting N and water supply environments. Application of mill mud increased average yield across all genotypes from 80 to 150 tonnes cane per hectare but differing genotype response demonstrated a significant genotype-by-soil treatment interaction. Three genotypes CPCL01-0877, CP01-2930 and *Erianthus* were well-adapted to sand as evidenced by the relatively high yield on sand compared to other genotypes and no significant increase in yield with application of mill mud. Adaptations that confer an advantage to CP 01-2390 on sandy soil were further assessed by comparing this genotype with two commercial varieties grown in pot culture supplied with four N rates (0-225 kg N ha^{-1}). Genotype and N rate significantly affected plant NUE, but no significant interaction was detected between genotype and N rate for yield and fertiliser NUE (Zhao et al. 2014). It is likely that while root traits have a strong impact on nutrient capture in the sandy soil of the field trial, this is not expressed in pot culture. This illustrates that caution required in extrapolating genotype performance or efficiency rankings across test systems and the necessity to dissect the traits underlying NUE.

Australian germplasm

The largest evaluation of sugarcane germplasm for NUE under controlled conditions (Robinson *et al.* 2007) and in the field (Robinson *et al.* unpublished results) was conducted in Australia. However, prior to this study very little effort was directed to understand the genetic variation of NUE in the Australian germplasm. Wood *et al.* (1996) investigated growth and N accumulation dynamics of two leading varieties (Q117, Q138) receiving high N fertiliser supply over a plant and ratoon crop. Both varieties produced similar biomass, Q117 accumulated more N while Q138 had a greater ability to dilute N throughout the crop cycle (Robertson et al. 1996, Wood et al. 1996). The study did not determine if cessation of crop N accumulation was caused by depletion of soil N sources, reduced N uptake activity of roots, reduced crop N requirement, or a combination of these factors.

Evaluation of genetic variation in NUE at limiting and sufficient N supply has long been limited by the small number and range of genotypes tested and the difficulties of controlling N supply in the field. Addressing this, genetic variation for NUE was assessed in a bi-parental mapping population at limiting (0.4 mM N) and replete (10 mM N) N supply in the glasshouse (Robinson et al. 2007). The male parent was Australian variety Q165 bred for high sugar yield with high N fertiliser rates while the female parent was *S. officinarum* accession (IJ76–514) not selected for yield or performance in high N environments. Screening 61 progeny over three months showed that biomass production of genotypes varied nine-fold with low N supply and four-fold with high N supply (Robinson et al. 2007). Nitrogen utilisation efficiency (g dry weight biomass g^{-1} plant N) was on average two-fold greater at low than high N supply. Within N treatments, genotypes differed up to two-fold at low N (143 to 303 g DW g^{-1} N) and high N (53 to 110 g DW g^{-1} N) supply. Quantitative trait loci analysis of N utilisation efficiency in this mapping population under similar experimental conditions identified significant marker-trait associations (MTAs) that accounted for 3-12% of phenotypic variation in the male parent and 3-19% of phenotypic variation in the female parent (Whan et al. 2010). MTAs were detected for biomass, shoot N content and internal NUE, leaf protein content, and glutamine synthetase activity (Whan et al. 2010).

The significant MTAs identified for N utilisation efficiency may reflect different selection pressures on the parental lines (male parent Q165: variety selected under high N; female parent *S. officinarum* IJ76-514: accession evolved under low N). In support of this notion, no positive MTAs were detected

under high N supply for N utilisation efficiency among markers from Q165, whereas six of ten MTAs detected in IJ76-514 were positive. At low N supply, 13 MTAs, five of which were positive for N utilisation efficiency, were detected in IJ76-514 compared with four of seven markers that were positive in Q165 (Whan et al. 2010). Markers with the greatest effect were inherited from *S. officinarum* accession IJ76-514. Therefore, variation for internal NUE under high N may be lower in varieties than unimproved genotypes, indicating that greatest gains for improving N utilisation efficiency may occur by introgressing unselected germplasm. These findings further highlight the importance of screening genotypes at lower N supply to characterise variation in NUE (Whan et al. 2010).

Follow-on research screened 64 sugarcane genotypes in the field, motivated by the genetic variation in NUE observed in young, glasshouse-grown plants (Whan et al. 2010) and successful field screening for genetic variation in water stress response (Basnayake et al. 2012). Plants were grown over three crop cycles at two sites (Mackay, Burdekin) with low (20-40 kg N ha^{-1} yr^{-1}) and industry recommended (160-200 kg N $ha^{-1}yr^{-1}$) fertiliser rates (Robinson et al. unpublished). Fifty-three genotypes were common across both sites and comprised of Australian commercial varieties (30%), foreign varieties (23%), parental lines from the Australian breeding program (36%), introgression clones including backcrosses of species cane *S. spontaneum* and *Erianthus* spp. with commercial varieties (11%).

At Mackay and Burdekin, yield reduction with low N supply averaged 22% and 45% respectively over three year crop cycle (plant to 2nd ratoon), highlighting that environmental effects are considerable drivers for performance at low N fertiliser supply. Significant genotypic variation in NUE was observed with N accumulation and allocation. Genotypes demonstrated a range of N accumulation in the Mackay plant crop ranging from 57 to 138 kg N ha^{-1} (low N supply) and 92 to 193 kg N ha^{-1} (recommended N supply, Fig**.** 4.1).

The wide range of responses in varieties was also illustrated with allocation of N to leaves in the low N crop ranging from 25 to 58 % of N allocated to leaves (Fig. 4.2).

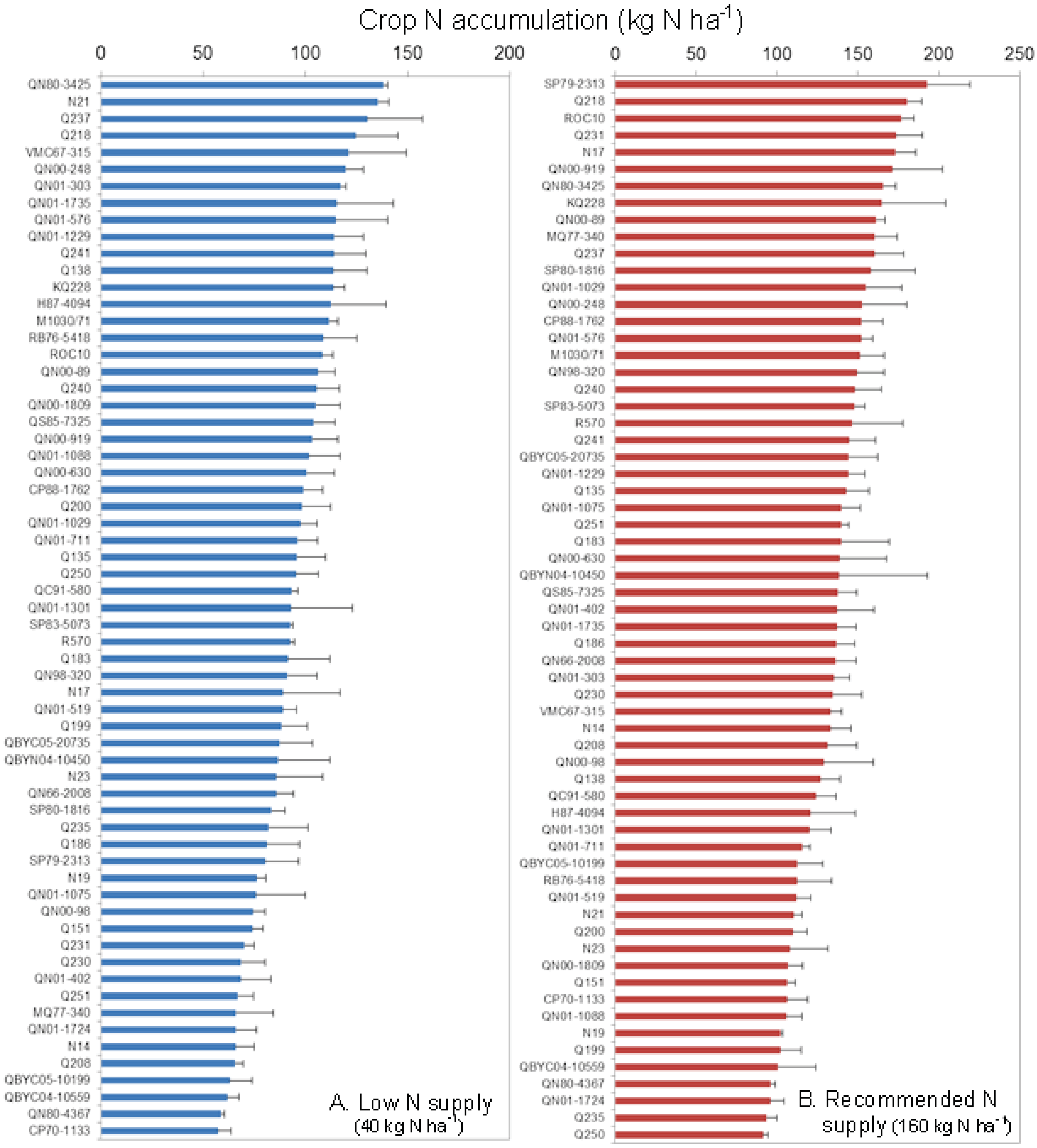

Figure 4.1. Nitrogen accumulation (kg N ha^{-1}) at harvest of genotypes supplied with (A) 40 and (B) 160 kg N ha^{-1} in the plant crop at the Mackay site (Robinson *et al.* unpublished).

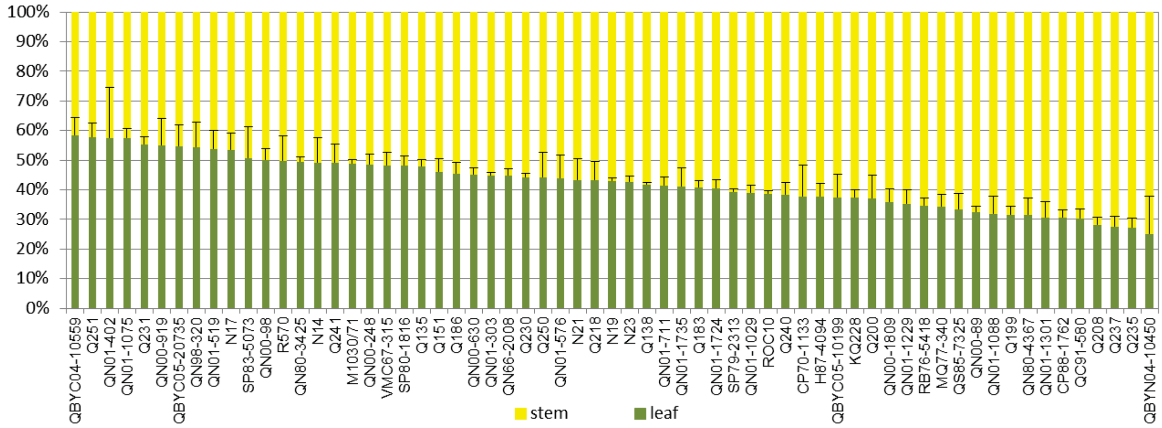

Figure 4.2. Proportional N allocation to leaves and stem of genotypes at harvest (12-months growth) supplied with 40 kg N ha^{-1} in the Mackay plant crop (yellow stem-N, green leaf-N).

At the Burdekin site, broad sense heritabilities for yield (TCH, tonnes cane per hectare) were moderate to high (>0.6, Table 4.2) in plant and 1st ratoon crops indicating that the observed genetic variability at both N supply rates was high relative to experimental error. The low heritability observed in the 2nd ratoon at the Burdekin site is likely attributable to declining soil N availability, the severity of the N stress decreasing observable genetic variance and increasing environmental variance. Low N plots received only 100 kg N in total over three years with annual rates of 20-40 kg N fertiliser. Overall there was no impact of N supply on estimates of heritability for yield.

The results from the Mackay trial were different to those observed in the Burdekin trial. The estimated yield reduction in Mackay for the plant, 1st ratoon and 2nd ratoon crops were and 11, 22 and 35%, respectively. At the Mackay site the variance of genotype-by-N supply interaction compared to the variance of genotype was relatively low in the plant crop but it showed an upward trend in the ratoon crops, suggesting the increasing intensity of genotype- by-N interaction with increasing N deficit (Table 4.3). Moderate broad sense heritabilities were observed for both plant and ratoon crops and heritability did not decrease with increasing N limitation across crop classes (Table 4.3). This highlights the impact of the level of N stress on segregating genetic variability of NUE as was outlined above.

Table 4.2. Mean, genetic variance and heritability (H^2) for yield TCH for genotypes grown with low (20-40 kg N ha^{-1} yr^{-1}) and recommended N supply (160-200 kg N ha^{-1} yr^{-1}) for plant (P), 1st ratoon (1R) and 2nd ratoon (2R) crops in Burdekin and Mackay (extracted from SRA milestone report 12, project number UQ044).

Site	N supply	Crop	#	Mean	Variance	Genetic variance	Heritability	Coefficient of variation
Burdekin	Low	P	192	54	201	179	0.73	0.38
	Low	1R	192	53	115	55	0.6	0.24
	Low	2R	192	35	126	16	0.27	0.35
	Rec	P	192	87	221	171	0.7	0.22
	Rec	1R	192	99	253	143	0.63	0.20
	Rec	2R	192	69	344	126	0.52	0.32
Mackay	Low	P	192	109	284	204	0.68	0.21
	Low	1R	192	89	235	85	0.52	0.20
	Low	2R	192	50	90	50	0.62	0.26
	Rec	P	192	123	344	108	0.49	0.18
	Rec	1R	192	114	183	130	0.68	0.16
	Rec	2R	192	78	109	92	0.72	0.2

Table 4.3. Variance components for genotype and N supply main effects and genotype-by-N supply interaction for each crop class at Burdekin and Mackay for cane yield TCH. N supply rates were: Burdekin low supply (20, 40, 40 kg N ha^{-1}) and recommended N supply (180, 200, 200 kg N ha^{-1}) Mackay low supply (40, 40, 40 kg N ha^{-1}) and recommended N supply (160, 160, 160 kg N ha^{-1}).

	Burdekin			Mackay		
Source	Plant	1R	2R	Plant	1R	2R
N supply	553	1064	566	95	328	367
Genotype	139	70	40	139	106	60
G*N	29	34	32	20	0	13
Error	236	178	234	310	215	99

Traits and clone selection strategies for sugarcane NUE improvement

Considerations for sugarcane plant and crop development, crop N dynamics and potential NUE traits

Sugarcane is mostly cultivated as an annual crop in climates characterised by hot summers, moderate winters and unpredictable periods of high precipitation. Unlike seasonal crops such as cereals, sugarcane experiences large fluctuations of growth influenced by weather and resource availability. In Australia, sugarcane is planted in autumn and spring. Planting time and weather conditions strongly impact growth and N dynamics over the crop season. For instance, autumn-planted crops have limited growth during winter and have low N demand until spring. Spring planted crops,

especially those planted late, experience a rapid decline in available N following wet season when it enters the high N demand stalk development phase. (Bell et al. 2014, this volume). Much of crop N demand during the main stalk growth stage is met by N becoming available from soil. Generally, dissolved fertiliser-N (mostly applied as urea in spring) has been absorbed by the crop and soil microbes, incorporated into soil pools, or has been lost from soil. Sugarcane experiences different forms and highly variable availability of N, driven by soil, weather and crop management. Successfully meeting crop N demand over phenological stages that range from low to very high N over the 9-12 month (up to 24 months) growth cycle, is likely to require region-specific approaches that consider variety specifics. For example, a vigorous strongly tillering variety may have more N acquired early in the season than a low tillering variety although little is known about the remobilisation of N from tillers to support stem development later. Similarly, little information is available on N storage in stools and roots despite its likely relevance in N relations. Thus, constraints on availability, uptake and use of N have to be considered in context of crop growth and development for selecting traits and selection strategies aimed at genetic improvement of NUE.

Response of sugarcane to N availability manifests across plant structure and function. Nitrogen availability influences root growth, tillering, canopy development, leaf pigment characteristics, stalk development, water relations, N uptake and use, photosynthesis and radiation use efficiency among others. These and related attributes determine crop performance and yield. Hence, maximising the impact of the most N responsive and yield-determining traits is critical for NUE improvement.

N uptake as a target for sugarcane NUE improvement

Increased capacity for N uptake and storage can improve NUE in grain crops (Hirel et al. 2007). This knowledge, along with the fact that sugarcane crops may rely on N derived from soil reserves during the peak N demand suggests increased N uptake as an avenue to improve NUE. However, unlike grain crops, little is known about the extent of genetic variation for N uptake in sugarcane germplasm (Ranjith 2007, Robinson et al. 2011). For example, when analysing N source preferences, commercial varieties, accessions of *S. spontaneum*, and *S. officinarum* supplied with replete and equimolar concentrations of nitrate and ammonium, discriminated against nitrate (40 to 50% of ammonium uptake) (Robinson et al. 2011). In contrast, sorghum and maize acquired similar amounts of nitrate and ammonium and *Erianthus* took up to 80% nitrate relative to ammonium (Robinson et al. 2011).

Similarly, field-grown *Erianthus* and sorghum had up to 30-fold higher nitrate concentrations in stems than sugarcane (Ishikawa et al. 2009). Higher ammonium relative to nitrate uptake has also been demonstrated in several South African varieties using an in vitro experimental system (Hajari et al. 2014). Thus, sugarcane varieties and progenitor species appear to have a lower capacity to acquire, transport and store nitrate than related grain and grass species, which suggests improved nitrate acquisition and storage as worthwhile NUE target.

An additional (and perhaps complimentary) approach is selecting sugarcane genotypes able to exude nitrification inhibiting compounds. There is much research in this area because nitrate is the N form most easily lost from soils, and agricultural soils often have a high nitrate status due to an active population of nitrifying microbes. Similar to sugarcane, related giant grass, *Andropogon gayanus* acquired ammonium preferentially and reduces nitrification; interestingly a stronger ability to reduce nitrification was associated with greater biomass production in native African savannah where nitrate

is prone to leaching (Rossiter-Rachor et al. 2009 and references therein). Nitrification inhibitor compounds (approximately 300 are currently known) prevent the enzymatic conversion from ammonium to nitrate by nitrifying microbes, and causality was established in varieties of *Brachiaria*. Varieties with enhanced exudation of brachialactone lowered soil nitrification rates and N_2O emissions from soil (Subbarao et al. 2009). Initial screening of crops for such nitrification inhibition potential have revealed capacity in sorghum but not in maize, rice, wheat or barley (Subbarao et al. 2013), indicating that species within the Poaceae family, including the sugarcane-relevant Andropogonodae *supertribe,* differ in their response to nitrate. Sugarcane as a 'low nitrate user' has a mismatch with a 'high nitrate environment' early in the growing season when urea fertiliser is converted to ammonium and rapidly nitrified.

Strong N rate-dependent variation in nitrate uptake has been reported in sugarcane with N-limited plants having a 2-fold greater maximal nitrate uptake rates (Vmax) than plants well-supplied with nitrate. In this context it is important to note that sugarcane takes up and metabolises organic N in the form of amino acids (Vinall et al. 2012), a finding with bearing on maximising NUE via improved uptake and use of soil-derived organic N.

From the perspective of clone selection it is important to consider the declining leaf N content from the early stage of crop development, the impact on carbon fixation and possible linkage to N uptake capacity. In a field study employing ^{15}N fertiliser Franco *et al.* (2011) estimated a 40 and 70% fertiliser N contribution during the early stages of growth which was reduced to 10 and 30% near crop maturity in plant and ratoon crops, respectively. This combined with the strong dilution of leaf N content 6 months after planting or harvest (Wood et al 1996, Allison et al 1997) demonstrates the inherent biological constraints in accessing and using N in the later part of the crop cycle and the need to reduce this biological barrier to increase NUE.

Overall, increasing N uptake could be a key contribution to improved NUE of sugarcane. However, to the best of our knowledge no known easily tractable surrogate trait to select high N uptake genotypes in large populations exist in any crop.

Canopy development as a selection trait for NUE improvement

An understanding of the dynamics of crop growth and N accumulation is required to improve NUE, irrespective of the approach. Ultimately, growth drives demand for resources including N. The first 3-4 months of early growth present challenges and opportunities for improving NUE as plants represent a smaller N sink than later in the season when growth accelerates. Low sink strength in the early season is compounded by growth-limiting temperatures over winter (autumn-planted crops) or moisture deficit (spring-planted crops). Limited capacity for N uptake is consistent with observations that the N content of young crops can be less than 20% of the maximum crop N content (Bell et al. 2014, this volume).

The large variation in tillering and rate of canopy development during early growth presents a good opportunity for identifying vigorous genotypes in a genetically diverse population such as the early stage clonal selection trials in breeding. Canopy size could be a potentially useful selection trait for vigour as it positively correlated with both shoot and root production in sugarcane. In a pot study

shoot growth was associated with root biomass and length (Magarey and Grace 1997). However, the generality of this observation needs validation.

Larger canopy allows greater light capture and increased radiation use efficiency, and drives crop productivity (Inman-Bamber 2014). During early growth sugarcane has the highest rate of photosynthesis which declines with age and has been linked to dilution of leaf N (Allison et al. 1997, van Heerden et al. 2010). Variation in canopy N relations due to genotypic differences in uptake and partitioning of N among different genotypes has been assessed in other species (Masclaux-Daubresse et al. 2010, Sadras & Lawson 2013). Sugarcane varieties differed in N accumulation in the leaves (Wood et al. 1996), with potential for this to be quantified by proximal and remote-sensing technologies (Robson et al. 2014, this volume). Collectively, canopy size could be a useful trait for selecting vigorous and N use-efficient genotypes in sugarcane.

Increased photosynthesis and radiation use efficiency as avenues for improving NUE

Sugarcane cultivated with recommended commercial N fertiliser rate displayed a decline in specific leaf nitrogen (SLN, amount of N per unit leaf area) from upper to lower canopy leaves and throughout the crop season (Ludlow et al. 1991, Allison et al. 1997). In maize and sorghum, maximum net assimilation rates (45-50 µmol CO_2 m^{-2} s^{-1}) were achieved at SLN of ~1.0-1.5 g N m^{-2} and declined when SLN was below this threshold level (Muchow & Sinclair 1994). In sugarcane, the SLN threshold is considered to be higher at 1.7-2.0 g N m^{-2} (Ludlow et al. 1991). In over 50% of crops with high N fertiliser rate (>160 kg N ha^{-1}) evaluated in Australia, SLN was <1.2 g N m^{-2} at the 4000 g m^{-2} biomass growth stage (≈40% of the final yield, Park et al. 2005). This finding indicates that photosynthesis was limited by low SLN during much of the crop cycle, which could not be reversed by external N supply. It is suggested that SLN decline can be attributed in part to a physiological constraint rather than N availability alone as all crops showing declining SLN received >200 kg N ha^{-1} (Park et al. 2005), though crop N status measured by stalk N or nitrogen nutrition index (Lemaire & Gastal 1997) was not determined. Supporting this side-dressing of 100 kg N ha^{-1} showed only small moderation in SLN and photosynthesis decline (Allison et al. 1997), attributed to the preferential storage of N in stalks (Stevenson et al. 1992).

This physiological constraint has implications for improving NUE and yield as canopy photosynthesis declines at the time when rapid stalk growth and development commences. With the causes of declining SLN unknown there is agreement that crop N demand is highest at the rapid stalk development stage and that a large portion of the required N is sourced from soil N reserves (Bell et al. 2014, this volume).

Further insight into physiological traits that affect NUE came from comparative analysis of CO_2 fixation in two Hawaiian varieties (H65-8235, H65-7052) (Ranjith & Meinzer 1997). Photosynthetic NUE differed between varieties at all N supply rates compared to dry weight accumulation which was significantly higher in H65-8235 only at high N supply. Nitrogen-efficient H65-8235 had higher leaf N, chlorophyll content, RuBisCo activity and photosynthetic rate than inefficient H65-7052 at all levels of N supply explored. Higher photosynthetic NUE was associated with greater relative partitioning of leaf N to chlorophyll and RuBisCo. Importantly, RuBisCo production was more sensitive to N deficit than PEP carboxylase. The variation in leaf N investment in RuBisCo and chlorophyll (Ranjith & Meinzer 1997) and the substantial variation for N supply-dependent RuBisCo activity and NUE in a

large genetically diverse collection of C_4 grasses (Ghannoum et al. 2005) suggest the prospect of further improvement of NUE in sugarcane by screening breeding population for traits related to photosynthesis.

Exploring variation in N metabolism to improve NUE

Glutamine synthetase is considered the key regulator of NUE in a range of species examined (Section 4.3, 4.4). Yield increases of approximately 10% were achieved in maize genotypes with increased glutamine synthetase activity (B. Hirel, INRA, *pers comm*). In contrast, this enzyme was not found to be a determinant of internal NUE in young sugarcane plants (Robinson et al. 2007). Characterisation of glutamine synthetase activity, N uptake rates and feedback mechanism will clarify the relationship between ammonium assimilation, NUE, and yield. It is important to note that the high glutamine synthetase, high yielding and high NUE maize genotypes did not show increased vegetative growth compared to their low yielding and low NUE counterparts. (B Hirel INRA, *pers comm*).

Root systems

Genotypic differences in root growth have been identified in controlled soil and hydroponic cultures (Schumann et al. 1998). In hydroponic cultures, all varieties increased shoot growth 4- to 6-fold in response to a 3-fold increase in N supply. In contrast, root growth remained unaltered in one variety, but increased 2- and 3-fold in two other varieties (Schumann et al. 1998), demonstrating that root and shoot responses can differ. A pilot field study in Australia demonstrated that Q117 had more vigorous root and shoot growth than two unselected genotypes in contrasting N supply regimes (0 or 100 kg N ha^{-1}) (Robinson et al. 2009). Without N fertiliser, relative root growth was reduced by ≈50% in Q117 and the more N-sensitive genotypes compared with a 30% reduction in the less sensitive genotype which preferentially partitioned root production to the deeper profile. In both N treatments, the N-sensitive genotype had over 90% of root mass in the top 40 cm of soil, while the less sensitive genotype and Q117 produced 60 and 83% of roots in the top 40 cm (Robinson et al. 2014).

Glasshouse experiments in Hawaii showed that drought tolerant variety H69-8235 invested more biomass to roots at low N supply than drought-susceptible variety H65-7052 (Ranjith 2006). The partitioning of biomass resulted in root:shoot ratios of 0.48 and 0.38 for drought- resistant and drought-susceptible varieties, respectively (Ranjith 2006). Overall these findings highlight that improvement for NUE may be achieved with beneficial root-shoot allocation and exploration of the soil profile. It remains to be established if varieties selected for root vigour will have enhanced N uptake.

The interdependence of NUE and water use efficiency

Recurring water deficit is a common occurrence in the rain-fed cropping areas that account for ≈70% of sugarcane production worldwide. In Australia nearly 60% of sugarcane crops experience water deficit to varying degrees (Inman-Bamber 2007). Responses to water deficit include rapid reduction in stomatal conductance, photosynthesis and growth as well as reduced nutrient uptake, including N (Lakshmanan & Robinson 2014).

Ranjith and Meinzer (1997) investigated WUE and NUE in two Hawaiian varieties with short and long-term N limitation. Consistent with reports in grain crops, rate of photosynthesis declined with decreased N availability and leaf N. Intrinsic WUE (ratio of photosynthetic rate and stomatal conductance) increased with decreasing leaf N content in both varieties as stomatal conductance showed a larger decline than photosynthesis. Midday water potential also declined as adjustments in stomatal conductance were not sufficient to balance transpiration with reductions in root hydraulic conductance occurring with low N availability. These observations suggest that in sugarcane, as in other crops, N is involved in co-ordinating stomatal and plant hydraulic conductance to balance water loss and maintenance of tissue turgor for sustained growth. The relationship between photosynthetic NUE and WUE are dependent on the prevailing N and water stresses as with declining water availability a trade-off is likely as stomatal restriction will increase WUE but limit efficiency of leaf N and photosynthesis (Meinzer & Zhu 1998). In this context, selection for yield under water and N deficit consistently improved wheat yield (Sadras & Lawson 2013). A similar approach may produce yield benefits for sugarcane as most crops are grown in rain-fed areas that experience some level of water stress in most years.

Transgenic approaches

Breeding programs usually take about 12 years to develop, test and launch a new sugarcane variety. The transgenic approach using candidate genes is proposed as an alternative to introduce or improve commercially-important traits. Development of transgenic sugarcane is aggressively pursued in many major sugar industries and the first transgenic sugarcane crop, engineered to improve drought tolerance, is now in cultivation in Indonesia (ISAAA 2013). Despite a large investment in commercial transgenic sugarcane development worldwide, to the best of our knowledge, the collaborative program by the South African Sugarcane Research Institute and the agricultural biotechnology company Arcadia Biosciences (www.arcadiabio.com) remains the only one aimed at improving NUE in sugarcane. This work employs manipulation of alanine aminotransferase activity, an Arcadia Biosciences (www.arcadiabio.com) proprietary technology, to improve crop NUE and yield.

In a related development, SES VanderHave, an international sugarbeet breeding and marketing company and Arcadia Biosciences have conducted three years of field trials of NUE sugarbeet varieties with the results showing consistently higher yields produced by transgenic lines than non-transgenic controls under various N application rates (ISAAA 2013).

4.7 Conclusions

This review of the published literature and our own research outlines the complexity of NUE as a trait *per se* and for plant breeding. It highlights that NUE has only comparatively recently become a target in high-production crops due to concern about the economics and environmental consequences of high N input cropping with a considerable N pollution footprint. Since the mid-20th century, crop breeding has favoured high resource inputs and this may have inadvertently selected against NUE (and other resource use efficiencies). Main findings are:

- Large genetic variability for NUE exists in all tested crops, including sugarcane;
- Nitrogen use efficiency is a genetically and physiological complex trait and there is so far no indirect selection trait available for variety development in any crop;
- Understanding of components of NUE and their regulation from molecular to whole crop level has advanced greatly in the past decade in grain crops;
- NUE research is most advanced in maize and wheat. In maize a central nitrogen metabolism enzyme, glutamine synthase, and several QTLs and DNA markers are emerging as potential selection tools for improving NUE;
- Genetic studies showed that the selection strategy for improving NUE will vary with crop, germplasm and target production environment;
- Transgenic manipulation of N metabolism is showing promising results in maize, canola, rice and sugarbeet and is being explored in sugarcane by the South African sugar industry;
- There are no dedicated sugarcane breeding programs for NUE globally, but there is growing in interest in developing NUE crops in Brazil, China, South Africa and India.

4.8 Recommendations

A better understanding of the extent of genetic variation for NUE in the local germplasm and crop-specific N physiology is fundamental for developing successful strategies for genetic improvement of NUE. Screening of Australian sugarcane breeding lines and current varieties, and a detailed physiological investigation, including belowground attributes, focusing on N responsiveness and the regulation of N uptake, use, storage and remobilisation in the context of sugarcane commercial production is a priority.

Initiate multidisciplinary research to identify large effect NUE traits to be used as a selection trait for NUE improvement in breeding program.

Based on the developmental features of sugarcane and commercial sugarcane cropping systems the key targets for NUE improvement are responsiveness to applied N, increased N uptake and radiation use efficiency. More specifically, any improvement to increase N uptake and N responsiveness at the most N demanding phase of crop development- the stalk-filling phase, and retaining more N in leaf would improve radiation use efficiency, yield and N relations of the whole cropping system.

The experience in grain crops suggest that more gain (improved varieties for reduced N conditions) can be realised by selecting for yield under low N input, or alternating high and low N conditions. This information is not available for sugarcane. Evaluating various selection strategies relevant to sugarcane should be undertaken at least in those regions where N leakage is a pressing issue.

A well-defined, co-ordinated, long-term targeted research program involving a multi-disciplinary team of breeders, physiologists, soil scientists, agronomists and modellers will be a more productive approach for improving NUE in sugarcane.
Opportunity for transgenic and molecular marker-assisted improvement of N-efficient variety development should be explored through collaborative research with multi-nationals or other relevant institutions.

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5. Investigating remote sensing technologies and their potential for improving nitrogen management in Sugarcane

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5.1 Abstract

This paper investigates remote sensing as a technology for accurately determining leaf nitrogen content in agricultural crops, thus determining its potential for supporting improved nitrogen management in the Australian sugar industry. A review of commercially available active and passive, proximal and airborne, multispectral and hyperspectral sensors as well as relevant research on various cropping systems identified a number of benefits and limitations to the varying technologies. On the basis of these out comes four strategies for the possible application of remote sensing to measuring foliar Nitrogen concentration in sugar are proposed. These include:

1. Identifying specific spectral wavelengths measured from a growing sugar plant canopy that directly correlates to leaf Nitrogen concentration. These wavelengths could form the basis of specific vegetation indices to be derived from imagery collected from airborne sensors i.e. Worldview 3 satellite or alternatively used to develop specific active sensors to be mounted on ground based vehicles or manually deployed;
2. Implementing a ‘fertiliser response index’ approach where limited and non- limited nitrogen reference strips are used to calibrate vegetation indices such as NDVI, measured by a range of commercially available sensors (active and passive); These calibrations when applied across the remaining crop can indicate the spatial variability of leaf N concentration, thus supporting targeted applications of N.
3. Integrating imagery derived crop vigour maps with additional spatial layers such as harvester yield maps, soil surveys, topography etc. to identify inherent crop ‘productivity’ zones that exist both temporally and spatially. This information can direct strategic plant sampling to establish if a relationship exists between the productivity zones and leaf nitrogen content. If such a relationship exists then again an opportunity exists for the strategic application of N.
4. Identifying if the nitrogen content of harvested material measured by NIR at the mills can be used to calibrate the extracted spectral information from imagery captured over the corresponding crops. If such a correlation can be identified then the opportunity exists to extrapolate that relationship across all crops within the growing region, therefore deriving crop, farm and regional N maps.

Additionally, Remote sensing offers a number of indirect benefits for improving the monitoring and management of foliar N such as ‘value adding’ crop modelling by offering a within season measure of crop performance; as a non-destructive screening tool for assessing the nitrogen use efficiency (NUE) of cultivars in breeding trials; identifying sub regional locations better suited to high NUE cane varieties; as a non- invasive tool for measuring the response and effectiveness of various nitrogen application strategies i.e. mill mud, six easy steps etc.

5.2 Introduction

Nitrogen is as an essential element for sugar cane production. It is a main constituent of chlorophyll i.e. 75% (Lawlor 1993), assists with regulating plant growth processes, contributes to the production of chemical compounds that improve pest and disease resistance, and supports development of biomass and yield (Munoz- Huerta *et al.* 2013). Optimal cane growth requires that water and nutrition, including nitrogen is non-limiting. Australian sugar growers generally apply excess nitrogen as insurance against unknown levels of soil fertility (Thorburn *et al*. 2003). However, excess plant nitrogen can reduce sucrose levels and sugar quality (Muchow *et al*. 1996), result in harmful runoff and leaching into water ways resulting in algal blooms, starfish outbreaks and eutrophication. As well as be a needless waste of money for growers.

Identifying the optimal amount of nitrogen to apply is extremely difficult as its use efficiency is influenced by a range of factors including N- NH3 volatilization, leaching, lack of synchrony between crop demand and N availability, seasonal and varietal influences on crop response, variability in soil organic matter and N mineralisation potential (Bragagnolo *et al*. 2013). Judicious fertiliser management requires growers understand the spatial and temporal fertiliser requirements of their crop, while at the industry level; some understanding of nitrogen usage would be beneficial for reporting against environmental regulations.

Currently, there are few options for obtaining this information. Soil sampling and tissue testing can provide an accurate measure of plant available nutrition during a given crop cycle, but it is time consuming and expensive. Historically few Australian sugar cane growers have actually based their fertiliser applications on regular soil or leaf tissue sampling (Johnson, 1995; Wood *et al*. 2003; Keating *et al*. 1997). However, this number has increased in recent times with the induction of mandatory soil N testing under The Environmental Protection Act 1994- Great Barrier Reef Amendment Act 2009 - Section 80 (http://www5.austlii.edu.au/au/legis/qld/consol_act/epa1994295/s80.html). The Australian rice industry has implemented a laboratory based near infrared (NIR) system for measuring the nitrogen content of rice at the panicle initiation (PI) growth stage. This information along with a recommendation of an optimal top dressing application rate is then supplied back to growers. Industry-wide, up to 35% of growers are collecting, drying and supplying tissue samples for this purpose; some 2598 samples from 897 crops in the 2011/ 2012 season (Dunn 2012). This example demonstrates how an industry can embrace what was considered blue-sky research and technology only 15 years ago for the purpose of improved broad scale N management. Additionally the collection of point source measures of N at this scale, particularly if sampling locations are spatially referenced, offers and extensive data set for the calibration of remotely sensed imagery.

The two commonly-used destructive methods for measuring plant tissue Nitrogen is the Kjeldahl digestion and Dumas combustion. The Kjeldahl- digestion method involves three main processes; wet digestion, distillation and ammonium estimation, and provides a measure of nitrogen bound to organic compounds and ammonium. The disadvantages of the Kjeldahl method is that it is destructive, requires toxic reagents, is labour intensive due to sample pre-processing (30 minutes per sample) and most importantly does not provide a measure of nitrate and nitrites, unless a salicylic acid then sodium thiosulfate digestion is undertaken (Munoz- Huerta *et al*. 2013). The Dumas-combustion method is considered an improvement to the Kjeldahl method as it is not limited to organic forms of Nitrogen and does not require the toxic reagents. However, it is similarly

destructive, time consuming and incomplete combustion of the sample can result in Nitrogen loss (Unkovich *et al*. 2008).

As an alternative to the destructive sampling methods, optical reflectance measurements of leaves and plant canopies by proximal and remote sensing techniques have been examined as a 'non-invasive' means of measuring leaf nitrogen uptake. Remote sensing is defined as 'the acquisition of information about an object without being in physical contact with it' (Elachi and Van Zyl 2006) and predominantly includes sensors that generate their own light emission (active) and those that rely on external or ambient illumination, typically solar irradiance (passive). Both sensing methods have been well documented as tools for measuring a range of plant characteristics via the reflectance, transmittance, absorbance or fluorescence properties of a leaf. The following section evaluates the pros and cons of proximal/remote sensing technologies.

5.3 Spectral properties of leaves and foliar nitrogen

In order to assess whether remote sensing may be able to measure foliar nitrogen concentration, an understanding of the optical properties of a growing plant is required. The spectral response curve of healthy green leaves is characterised by strong absorption within the visible part of the electromagnetic spectrum (400 – 690 nm) followed by a transition region from low to high reflectance, termed the red- edge (RE) (680- 780 nm); strong leaf reflectance within the near infrared (NIR) region (700-1300 nm); and a gradual decline through the mid near infrared region (MNIR) (1300-2500 nm) (Figure 1).

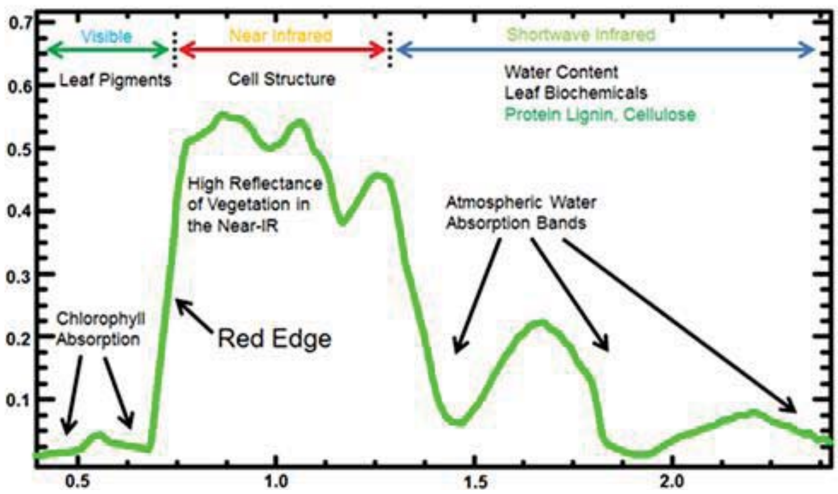

Figure 5.1. Spectral reflectance response curve of a healthy green leaf. The Y-axis is the value relative to the target irradiance level, and the X-axis is the wavelength in micrometres (µm). Source: http://www.markelowitz.com/Hyperspectral.html.

The relatively low reflectance in the visible region of the electromagnetic spectrum is the result of light absorbing compounds, namely pigments with chlorophyll absorption 'troughs' at 450 nm (blue) and 650 nm (red) being the predominant features (Rao *et al*. 1998, Curran *et al*. 2001). The small reflectance peak at (510 – 580 nm) corresponds to the visible green wavelength and is attributed to chlorophyll pigment and is the reason leaves appear green to the human eye (human eyes are more or less insensitive to wavelengths exceeding ~670 nm). This region (400 – 700 nm) is termed the

photosynthetically active region (PAR) and corresponds to the spectral range where approximately half the solar flux penetrates through the earth's atmosphere and constitutes solar irradiance at plant level. The actively-growing constituents of plants, owing to their photosynthetic activity, and the subsequent biomass ascribed to these constituents is often referred to as photosynthetically-active biomass (PAB). The spectral properties measured within the PAR region area are also strongly influenced by leaf area index (LAI). LAI is defined as the area of leaf presented per unit area of ground viewed and is a measure of the number of leaf layers in a canopy, although leaf orientation also plays an important role in LAI. LAI generally ranges between 0 (i.e. bare soil) to approximately 3-5. At LAI greater than 3-5, leaf transmissions are reduced preventing backscattered radiation reaching an overhead sensor, effectively limiting a sensors response to the top layer of leaves only.
The red edge region (RE) indicates a transition between the strongly absorbing red wavelength region of the leaf through to the highly scattering near infrared region. The near infrared spectral region often provides a strong insight to the 'health' or 'vigour' of a plant. Up to 60% of incident solar radiation in this wavelength region is back-scattered (reflected) and transmitted (downwards) through interaction with the spongy mesophyll tissue, palisade tissue, the interfaces of cell walls with air, protoplasm and chloroplasts within the leaves (Campbell, 1996). Any desiccation or loss of plant turgor will affect these plant structures and influence the amount of perceived backscatter (or transmission).

When exposed to radiation within the NIR spectral region, the atomic bonds of certain molecules display harmonic vibrations at specific wavelengths within the MNIR. These molecular bonds vibrate in either a stretching, a continuous change in the interatomic bond axial distance between two atoms, or bending manner where there is a change in bond angle (Shenk *et al.* 2001). This bond vibration is considered anharmonic at higher vibration states, resulting in overtone bands. These overtone and combination bands typically correspond to the presence of the lightest atom hydrogen, and combinations of this atom with carbon, oxygen, nitrogen or sulphur, all of which are the basic building blocks of organic materials. Other poorly bonded carbon molecules commonly identified include those with stretching vibrations such as C=O, C-C and C-Cl (Shenk *et al*. 2001, Osborne *et al.* 1993, Nilsson 1995, Curran *et al*. 2001).

In terms of nitrogen uptake, prior research has identified that a varied concentration of nitrogen within plant leaves will influence its reflectance/ absorbance characteristics across most spectral regions (Abdel- Rahman *et al*. 2010). Increased nitrogen concentration has been shown to lower reflectance within the visible spectral region, increase reflectance in the near infrared region, and a shift in the transitional red edge slope (Rodriguez *et al*. 2006, Hansen and Schjoerring 2003). The integration of these discrete spectral regions, through the derivation of vegetation indices, has also been shown to be strongly correlated to changes in vegetation condition. Vegetation indices (VIs) are simple mathematic operations performed on the multiple-waveband reflectance data that have been used effectively across multiple cropping systems for identifying, quantifying or discriminating water stress, disease, pests and nutritional status. A number of these are considered relevant to nitrogen (N) nutrition in plants by offering a measure of pigment composition, for example carotenoids, chlorophylls and xanthophylls (summarized in Table5.1). The most widely-used mathematical combination of Red and NIR wavelengths is the normalised difference vegetation index (NDVI) (Rouse *et al*. 1974).

Table 5.1. Hyperspectral indices used in this study for the assessment of plant pigments and vegetation condition.

Index Name	Formula	Association with relevant plant pigment	Reference example
Leaf and Canopy Chlorophyll Index	$\mathrm{LCCI} = \left(\frac{R_{750} - R_{705}}{R_{750} + R_{705}}\right)$	Indicator of chlorophyll content and hence early stages of leaf senescence as R_{705} is maximally and R_{750} is minimally sensitive to chlorophyll	(Gitelson and Merzlyak 1994a, b)
Normalised Difference Vegetation Index	$\mathrm{NDVI} = \left(\frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}\right)$	NIR and Red are broad reflectance bands 775-825 nm (NIR) and 650-700 nm (R) that include most key pigments. NDVI increases with leaf area index (LAI) and photosynthetically active radiation (PAR) or biomass (PAB).	(Campbell 1996; Tucker 1979; Tucker et al. 1981)
New Vegetation Index	$\mathrm{NVI} = \left(\frac{R_{777} - R_{747}}{R_{673}}\right)$	Sensitive to chlorophyll *a* and *b*	(Gupta et al. 2001)
The Physiological Reflectance Index	$\mathrm{PhRI} = \left(\frac{R_{550} - R_{531}}{R_{550} + R_{531}}\right)$	Follows diurnal changes in the xanthophyll pigments and photosynthetic rates.	(Gamon et al. 1992; Penuelas et al. 1994)
Nitrogen Reflectance Index	$\mathrm{NRI} = \left(\frac{R_{570} - R_{670}}{R_{570} + R_{670}}\right)$	Similar to NDVI above- but strictly relevant to nitrogen and hence chlorophyll-*a*.	(Aparicio et al. 2000; Diker and Bausch 2003; Filella 1995; Hansen and Schjoerring 2003; Tarpley et al. 2000; Zhao et al. 2005a; Zhao et al. 2005b)
Normalised Pigment Chlorophyll Ratio Index	$\mathrm{NPCI} = \left(\frac{R_{680} - R_{430}}{R_{680} + R_{430}}\right)$	Ratio of carotenoids relative to chlorophyll due to nitrogen stress and NPCI varies with the ratio of total pigments to chlorophyll. Used to evaluate the proportion of total photosynthetic pigments to chlorophyll.	(Young and Britton 1990; Penuelas et al. 1994)
Anthocyanin Reflectance Index	$\mathrm{ARI} = \left(\frac{1}{R_{550}}\right) - \left(\frac{1}{R_{700}}\right)$	Anthocyanin accumulation is induced by strong light, UV-B irradiation, low temperature, drought, wounding, bacterial and fungal infections, nitrogen and phosphorus deficiencies.	(Gitelson et al. 2001)

		ARI proposed for the estimation for accumulation of anthocyanin in intact senescing and stressed leaves	
Photochemical reflectance index	$PRI = \left(\frac{R_{570} - R_{531}}{R_{570} + R_{531}}\right)$	R_{531} associated with state of the xanthophyll cycle and as xanthophyll pigments fulfill a photoprotective role, and key to light use efficiency (LUE). High levels of xanthophyll activity are thus associated with high stress (low LUE).	(Trotter et al. 2002; Penuelas et al. 1994; Penuelas et al. 1995b)
The Structure-Insensitive Pigment Index	$SIPI = \left(\frac{R_{800} - R_{445}}{R_{800} + R_{680}}\right)$	Used to estimate the ratio of carotenoids to chlorophyll-*a*.	(Penuelas et al. 1995a; Blackburn 1998)
Plant Scenescence Reflectance Index	$PSRI = \left(\frac{R_{678} - R_{500}}{R_{750}}\right)$	Similar to SIPI in that it targets carotenoids: chlorophyll ratio. Used to quantify leaf senescence and 'ripening' processes.	(Merzlyak et al. 1999)
The transformed chlorophyll Absorption and Reflectance Index	$TCARI = 3\left[(R_{700} - R_{600}) - 0.2(R_{700} - R_{550})\left(\frac{R_{700}}{R_{670}}\right)\right]$	Highly sensitive to chlorophyll pigments	(Haboudane et al. 2002)

5.4 Passive remote sensing systems

Passive remote sensing systems are those that require external illumination of the target typically by solar illumination (sunlight). Of course, the most commonly used passive sensor is the human eye which provides a spectral sensitivity between 390 to 750 nm. This region corresponds with the PAR range of plants (400 to 700 nm) and it is therefore sensitive to changes in a plants greenness i.e. yellowing when a plant is under stress, to dark green when non-limited. Leaf colour charts (LCC) have been developed for some crops to take advantage of this sensitivity by providing some calibration between the visual greenness of a leaf and its nitrogen concentration, particularly where nitrogen is the only limiting factor.

Figure 5.2. Leaf colour chart (LCC) used for nitrogen uptake assessment in Maize. Source (Witt *et al.* 2007).

These charts have been used predominantly in rice to establish nitrogen uptake at panicle initiation (Ali *et al*. 2012, Singh *et al*. 2012 and Gaddanakeri *et al*. 2007), maize (Witt *et al*. 2007) and sugar cane (Gaddanakeri *et al*. 2007 and Auearunyawat *et al*. 2012). However, accuracies were influenced by variations in ambient light, human perception and cultivar (Ali *et al*. 2012). Colour digital cameras (i.e. RGB) coupled with automated digital image analysis have also been investigated across a number of industries to remove the human error (Mirik *et al*. 2006, Graeff *et al*. 2008, Mercado-Luna *et al*. 2010 and Auearunyawat *et al*. 2012). However, image processing is still time consuming, and as with the LCC assessment ambient light (for target illumination during photography), varietal (cultivar), seasonal and locational differences still complicated the analysis.

In addition to the use of handheld digital cameras, many optical sensing systems are deployed on ground, in aircraft or on satellite platforms. These sensors can be multispectral or hyperspectral in nature. Multispectral generally includes those sensors with low spectral resolution, with non-continuous spectral data provided over a limited number of wavebands centred about discrete wavelengths. Passive multispectral sensors include the majority of airborne and satellite based sensors. In the last two decades, there has been a dramatic increase in the development and deployment of commercial satellite platforms. Spatial resolutions have increased from coarse (e.g. MODIS), to medium resolution (e.g. Landsat, SPOT5 and ALOS) to very high resolution (e.g. Quickbird, IKONOS, GeoEYE, Worldview2 and 3, SPOT6, Pleiades etc.). The spectral resolution has also increased

with Worldview3 (launched August 2014) for example, offering 16 spectral band widths, with 8 located within the mid infrared region. Capture times, minimum capture area and cost have also greatly improved, making the satellite-based applications more adoptable for agricultural industries. A comparison table of commercial available satellites is provided by Geoimage (http://www.geoimage.com.au/PDFs/Satellite%20Table%20_LR_SEP2014.pdf).

An additional sensing platform that has seen a dramatic increase in development and deployment in recent years is the Unmanned Airborne Systems (UAS). These systems offer rapid on-site deployment, extremely high spatial resolution (e.g. 2cm), can be retro-fitted to carry a wide range of optical and thermal sensors, can provide rapid turnaround of data and been shown to be effective for mapping production and nutrition properties across a range of cropping systems (Berni *et al*. 2009, Hunt *et al*. 2010). These platforms may provide as useful platforms for the sugar industry following further research and development. However, current regulations and flight time (battery power) may have limitations for the larger broad acre crops.

Hyperspectral sensors provide high spectral resolution data with many wavelengths and small band widths (1 nm). Ground based sensors include integrating field-of-view (fov) sensors such as field spectrometers i.e. ASD FieldSpec® (Boulder, Colorado, USA: Analytical Spectral Devices. Inc.) and CropScan MSR (CropScan, Rochester, MN, USA). These sensors are non-imaging and collect radiance over a full sensor 'footprint' defined by the geometry of the fore optic assembly. Other sensors are imaging; for example airborne sensors including Hyvista (http://www.hyvista.com), Fugro (http://www.fugro.com), Airborne Research Australia (ARA) (http://www.airborneresearch.org.au) and satellite based platforms such as EO-1 Hyperion.

A major limitation to passive remote sensing is that the detected signal will always be influenced by the illumination conditions including those that arise from solar illumination and sensor view angles (elevation and azimuth) as well as those that influence path radiance (from the source to the canopy then back to the sensor) i.e. cloud cover and aerosols (Goel 1988; Kaufman 1989; Goel and Qi 1994; Hill and Sturm 1991; Edirisinghe *et al*. 2001). Satellite images can be expensive; image capture may be delayed from continued cloud cover and competition for imagery; imagery turnaround time can be slow; and spectral resolution is generally limited. However this is improving with the recent launch of WorldView3. Airborne hyperspectral imagery does offer greater spectral resolution but it is expensive to obtain. Field spectrometers offer excellent spectral resolution, but are expensive to purchase, influenced by cloud cover, require some in field calibration, and difficult to use over tall crops, such as sugar cane.

5.5 Active optical remote sensing systems

To overcome the limitations faced by passive sensing technologies (in terms of their reliance on sunlight) several active remote sensing systems, including ground and airborne sensors, have been developed. Active optical sensors (AOS) rely on the synchronous detection of backscattered radiation from the target, illuminated by an integral light source, as a means of removing the effects of changing ambient light conditions (Lamb *et al.* 2002; Devadas *et al.* 2009; Künnemeyer *et al*. 2001; Holland *et al*. 2004; Inman *et al*. 2005). However, due to limitations in the intensity of the light sources used (halogen globes or light-emitting diodes, LEDs); AOS's have generally been limited to proximal sensing configurations such as those ground- based hand-operated or boom-mounted. The main AOS used for

biomass and nutrition assessment within a range of cropping systems are the GreenSeeker (NTech Industries, Ukiah, CA, USA), Crop circle™ (Holland Scientific, Lincoln NE USA) and the Yara® N sensor ALS (Yara International ASA).

Figure 5.3. Two examples of AOS systems: (a) Crop Circle™ and (b) GreenSeeker. Source: Trotter and Lamb, (2013).

The GreenSeeker sensing system emits NIR and Red through 3 LEDs, with reflected light received through three photo-detectors (PD) placed behind a Fresnel lens. The configuration of these sensors is 660 nm (red) and 770 nm (NIR) with an approximate bandwidth of 25 nm (FWHM) for each peak. The Crop Circle™ sensor is another example, although variants contain red/NIR and amber/NIR wavelength combinations, and a version containing three polychromatic (white) LED's. The latter, rather than relying on 'filtering' by virtue of the wavelength specified in the LED sources, relies on filtering of the detectors by interchangeable narrow-bandwidth filters. The spectral sensitivity of the sensors can be customised with interchangeable filters ranging from 532 nm (green) to 760 nm (RE) (Holland *et al.* 2004).

Recent research by Lamb *et al*. (2009) investigated the mounting of the hand held active optical sensor (Crop Circle ACS-210, Holland Scientific, Lincoln NE USA) on a low-level airborne platform (flying 4 m above ground level- AGL). A further evaluation of a more powerful Raptor™ ACS-225LR (Holland Scientific, Lincoln NE USA) flown at 45 m above crop canopy produced NDVI values that strongly correlated with those collected on-ground (Lamb *et al*. 2011(b)). For sugar cane, classified NDVI maps derived from the Raptor sensor showed comparable zonal segregation to those derived from an IKONOS satellite image, with minimal impact from various flying heights or direction (Robson *et al*. 2013). The benefits of an airborne active system is that imagery can be acquired under cloudy conditions and over large established crops where on-ground surveys may otherwise be time-consuming, or result in crop damage from sensors mounted on ground based vehicles. Lastly, these sensors are relatively inexpensive (~$5-10k), can be easily retrofitted to UAS or existing aircraft and can be deployed on low-level aircraft already undertaking other operations such as top-dressing (Lamb *et al.* 2009).

An obvious addition to the active sensors is the leaf chlorophyll transmission sensors that include SPAD meters and fluorescence sensors. The SPAD (SPAD 502 Chlorophyll meter, Konica-Minolta Co. Japan) is a proximal sensor where the leaf is placed within a small chamber and exposed to red (640 nm) and infrared light (940 nm) (Netto *et al*. 2002). The difference in transmission between these two wavelengths is strongly correlated to chlorophyll content per unit leaf area (Scharf *et al*. 2006).

Fluorescence sensors measure the small amount of light emitted from a chlorophyll molecule at a higher wavelength to that in which it was absorbed (Tremblay *et al*. 2012). The influence of nitrogen concentration on a chlorophyll molecule can be determined via fluorescence a number of ways including: variable chlorophyll fluorescence, leaf chlorophyll content-related fluorescence emission ratio, blue-green fluorescence, and epidermal screening of chlorophyll fluorescence (Tremblay *et al*. 2012). The limitations of these methods are they are time consuming to collect, can be influenced by temperature and diffuse sunlight and require site- specific measurements i.e. not suitable for airborne of vehicle based platforms, as such are difficult to obtain in large crops such as sugar cane. Common fluorescence sensors include Dualex and Multiplex® (FORCE-A, Orsay, France). The Dualex measures the concentration of chlorophyll and polyphenols, a secondary metabolite produced under nitrogen stress, using a UV (375 nm) and red light source (650 nm). It also measures the fluorescence response of polyphenols, which directly absorb UV light, to that emitted by the chlorophyll molecules (695 nm) (Munoz-Huerta *et al*. 2013). The Multiplex measures emitted fluorescence at yellow (590 nm), red (685 nm) and far red (735 nm) following excitation of molecules using UV (373 nm), blue (470 nm), green (516 nm) and red-orange (635 nm) light (Gholzen *et al.* 2010).

Active optical sensors have been widely used in cropping (Holland *et al.* 2004; Inman *et al.* 2005; Sui *et al.* 2008; Lamb *et al.* 2009; Tremblay *et al.* 2009; Solari *et al*. 2008). However, the limited number of wave bands they provide i.e. Red/NIR-combination providing either NDVI or simple ratios (Holland *et al*. 2004; Sui *et al*. 2008; Inman *et al*. 2005; Stowell, 2008; Tremblay *et al*. 2009; Lamb *et al.* 2009) reduces their effectiveness over large biomass crops such as sugar cane due to sensor saturation either from high absorption (red) or reflectance (NIR). Lamb *et al*. (2002) demonstrated NDVI and, in particular the NIR band plateaued with increasing number of leaf layers owing to the inability of the NIR to 'penetrate' beyond the top 3-5 leaves. Also as they infer nitrogen content from chlorophyll concentration, they are subject to error as chlorophyll is also influenced by a range of biotic and abiotic stresses, crop age and cultivar differences. Conversely, fluorescence sensors do not rely on chlorophyll or biomass for the estimation of nitrogen concentration, but rather changes in the biophysical attributes of the leaf well before that of the photosynthetic structures. As such they may provide as a useful site- specific management tool for the Australian sugar cane industry to value add the airborne multi/ hyperspectral imagery (McMurtrey *et al.* 2003). Munoz-Huerta *et al*. (2013) provides a good summary of the advantages and disadvantages of the sensing technologies discussed.

5.6 Remote sensing for plant foliar nitrogen concentration estimation

General cropping systems

There has been much research evaluating remote sensing and the measurement of foliar Nitrogen concentration across many cropping systems including corn (Bagheri *et al*. 2013; Tahir *et al*. 2013; Barker and Sawyer 2012; Bragagnolo et al. 2013); Wheat (Rodriguez *et al*. 2006; Johnson and Raun *et*

al. 2003; Raun *et al*. 2002; Zillmann *et al*. 2006; Yao *et al*. 2013; Erdle *et al*. 2011; Tilling *et al*. 2007); Cotton (Rao *et al*. 2008; Raper *et al*. 2013): Potatoes (Goffart et al. 2004; Nigon *et al*. 2014), and Rice (Rao *et al*. 2008; Dunn 2012).

For corn, Bagheri *et al*. (2013) identified strong correlations between a range of vegetation images derived from Aster (advanced space borne thermal emission and reflection radiometer) imagery and total N% at the V13 growth stage. Indices that produced the best correlations included: normalised difference vegetation index (NDVI; R^2= 0.72), soil-adjusted vegetation index (SAVI; R^2= 0.74), optimised soil- adjusted vegetation index (OSAVI; R^2=0.73), modified chlorophyll absorption ratio index 2 (MCARI2; R^2= 0.79) and modified triangle vegetation index 2 (MTVI2; R^2=0.87).

Rodriguez *et al*. (2006) used a passive spectrometer (FieldSpec, Pro JR ASD, Co, USA) to measure the canopy reflectance of wheat at a number of growth stages. They found that most of pigment based indices positively correlated to N concentration, including the canopy chlorophyll content (CCCI) that offered some separation from canopy cover and water content. Johnson and Raun *et al*. (2003) developed a nitrogen response index (RI) for winter wheat, where unlimited N and N-deficient strips were used to derive a relative NDVI to N% calibration. Using this methodology a passive or active sensor can be deployed to determine and immediately respond (on-the-go) with site-specific N applications. Raun *et al*. (2002) identified a 15% increase (i.e. from 30% to 45%) in fertiliser efficiency using this approach. Yao *et al*. (2013) compared reflectance data measured by an ASD field spectrometer, CropScan and GreenSeeker to determine which sensor produced the highest accuracy in determining nitrogen uptake in wheat. An NDVI (807 and 736 nm) derived from the ASD provided the highest accuracy (R^2= 0.89; RMSE of 1.440 g N m^{-2}). Calibration models were also developed between the three sensors indicating the spectral prediction models developed for one sensor may be adapted to suit another.

Rao *et al*. (2008) identified a strong correlation between the reflectance properties of mature cotton and late-growth rice using hyperspectral (400 to 2500nm) EO-1 Hyperon data and leaf nitrogen content (LNC) (R^2 = 0.87 to 0.90). A plant biochemical index (PBI) derived from a simple ratio of 810 and 560 nm wavelengths proved to be highly accurate in predicting LNC, whilst NDVI provided poor correlations for leaf nitrogen content (R^2 = 0.35). Dunn (2012) reported high accuracies (R^2 =97.6, RMSEP of 0.115%) predicting the nitrogen content of dried and ground rice leaf samples using a laboratory based Bruker Fourier- Transform NIR instrument (Figure 4). The validation set used for the prediction included 500 collected over 10 growing seasons.

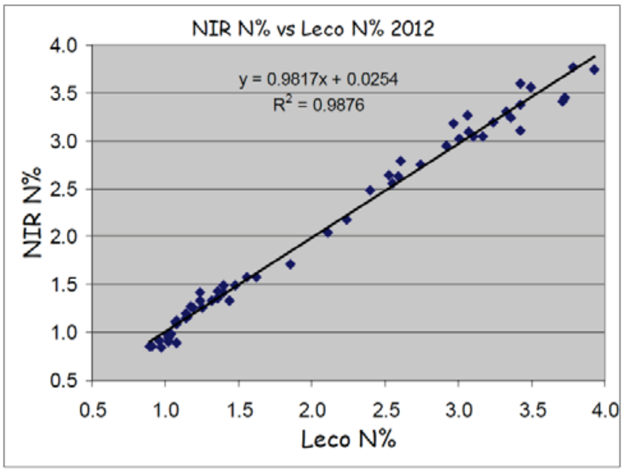

Figure 5.4. Relationship between actual Leco nitrogen concentrations measured to that predicted with the NIR calibration. Source Dunn (2012).

Although laboratory based NIR analysis does involve destructive sampling, it does indicate that nitrogen content can be measured accurately, with calibrations that are insensitive to seasonal conditions and cultivar differences. As suggested by Dunn (2012) there is a great opportunity to extrapolate this technology to within crop environments, therefore negating the need for destructive sampling.

Sugar cane systems

Published research relating to the spectral measurement of Nitrogen uptake in sugar cane is relatively limited compared to cereal crops. The level of complexity and scientific rigour involved in the studies ranges significantly from high spatial and temporal analysis through to single crop studies. Similarly the technologies used range from simple band ratio instruments through to hyperspectral sensors.

Jackson *et al.* (1980) found varying N treatments (112 kg/ ha and 0 kg/ ha) applied on a Hawaiian cane trial could be spectrally separated using a band ratio (R_{760}- R_{900})/ (R_{630}- R_{690}). Canopy reflectance was measured with a radiometer mounted on 4 m aluminium pole. Patil and Nadagouda (2008) observed a corresponding increase in NIR reflectance and NDVI (R_{620} -R_{680} nm and R_{770} – R_{860} nm) measured with a hand held spectroradiometer (Optomech Engineers Pty. Ltd. Model 041) with higher fertigated nitrogen rates.

Abdel-Rahman *et al*. (2008) measured the spectral reflectance characteristics of the lamina (i.e. midrib removed) of sugar cane leaves using a FieldSpec® spectroradiometer (350–2500 nm) under laboratory conditions. This study found a simple ratio of R_{744}/R_{2142} correlated best for estimating leaf nitrogen concentration (N %) in sugar leaves 4 to 5 month of age (R^2 = 0.74) and (R_{2200}-R_{2025})/ (R_{2200}+R_{2025}) for 6 to 7 month old cane (R^2 = 0.87). The first order derivative of a number of additional specific wavelengths 1680 -1693 nm, 2334, 2395 and 2396 nm were also identified to be correlated to leaf nitrogen, supporting related published results (Borolo *et al*. 2003, White *et al*. 2000, Muting *et al*. 2004). Under field conditions the simple ratios R_{743}/R_{1316}, R_{743}/R_{1317}, and R_{741}/R_{1323} from first-order derivatives of leaf reflectance gave the best correlations with leaf N% (R^2 = 0.76, 0.75 and 0.74

respectively), producing root mean square errors of prediction (RMSEP) of 0.089% 0.092% and 0.084% (Abdel-Rahman *et al*. 2010).

Portz *et al*. (2012) used a N-Sensor[s] ALS (Yara international ASA) to derived 10 m interpolated vegetation index (VI) maps (VI = In R_{760} – In R_{730}) * 100) of 8 Brazilian sugar cane crops (15 to 25 ha). This was repeated at 0.2 m, 0.4 m and 0.6 m stalk heights. The VI layers were classified into 5 classes with 2 samples (4 rows * 5m) collected for each class. High coefficients of determination were identified between the interpolated VI value corresponding to each sample site and N uptake determined by the kjeldahl method (R^2= 0.79 to R^2= 0.94). Measurements at the 0.2 m growth stage proved too early, whilst some saturation occurred at the 0.6 m stage. Separate calibration functions were suggested for each growth period. However, the combination of all data sets into a 'generic' calibration still produced an R^2 = 0.84 with an RMSE of 9.14 g kg^{-1}.

Rather than trying to directly correlate N % to a spectral measure, Lofton *et al*. (2012) investigated the fertiliser response index approach (RI_{NDVI}) developed by Raun *et al*. (2002) and Johnson and Raun (2003). Measures of NDVI were obtained with a handheld GreenSeeker AOS (R_{670} and R_{780}) at weekly intervals for three weeks, three weeks after spring fertiliser application (May, northern hemisphere). Harvest occurred from late October to early December. Nitrogen was applied as urea-ammonium nitrate (UAN 32-0-0) at rates ranging from 0 to 201 kg/ha across eight cultivars of cane. The response index (RI_{NDVI}) was calculated from the high N-rate treatments, considered non-limited (90 to 201 kg N/ha), and divided by the control (check) plots where no N fertiliser was applied.

$$RI_{NDVI} = (NDVI_{\text{unlimited N}}/NDVI_{\text{no-applied Nfert}}).$$

$$RI_{HARVEST} = (Yield_{\text{unlimited N}}/Yield_{\text{no-applied N fert}}).$$

Strong correlations were identified between RI_{NDVI} and $RI_{HARVEST}$ as cane yield (TCH) (R^2 = 0.92) and sugar yield (TSH) (R^2 = 0.81). This result suggests that site-specific N management of a sugar cane crop could be achieved with NDVI as long as some calibration is obtained over non limited and limited applied nitrogen sites. As Australian sugar cane crops generally receive excessive N, the inclusion of N limited calibration strips would be essential for the fertiliser response index approach to be evaluated and subsequently adopted.

Recent research undertaken in Australia has identified the vegetation index N2RENDVI (a normalised difference vegetation index based on the mid near infrared and red-edge wavebands) derived from Worldview2 (WV2) satellite imagery to be strongly correlated to leaf % nitrogen (N) measured across replicated trials in the Mackay and Burdekin growing regions (Robson unpublished data). A strong correlation (R=0.74; n= 167) was observed between the pixel N2RENDVI values from imagery collected over both sites (Burdekin 24 May 2013 and Mackay 19 April 2013) and co-located leaf % N samples collected earlier in the season (February and March 2013) (Figure 5.5). The strong correlation achieved across both growing regions, including 16 cultivars suggests N2RENDVI may be less susceptible to the influences of cultivar and growing location than other spectral reflectance vegetation indices.

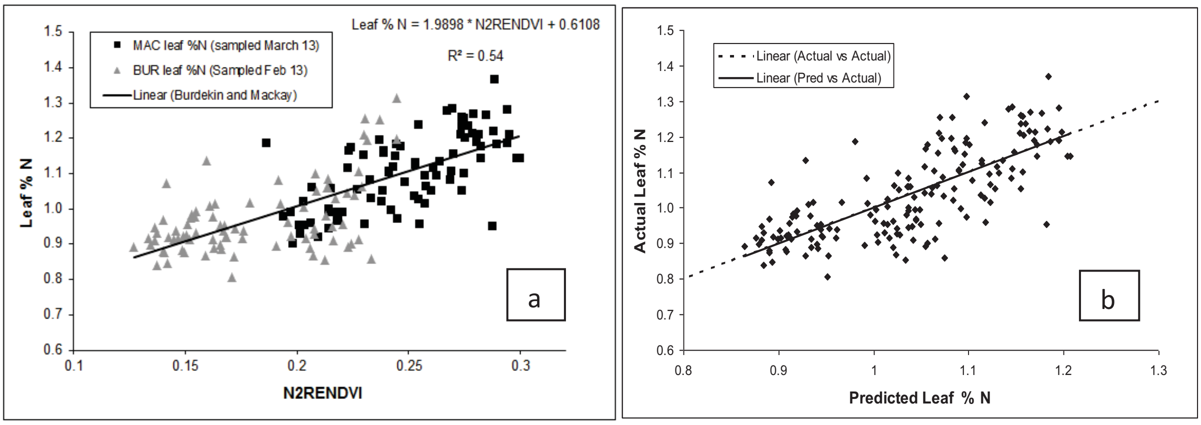

Figure 5.5a. Correlation between leaf % N sampled from the Burdekin (Feb 2013) and Mackay (March 2013) and co-located pixel N2RENDVI values derived from WorldView2 images (Burdekin 24 May 2013 and Mackay 19 April 2013). b. Actual versus predicted leaf % N from both trial sites using the algorithm in Figure 5a. Sourced from Robson *et al*. unpublished data.

The derivation of a leaf % N – N2RENDVI regression algorithm (Figure 5a), allowed the extrapolation of the point source measurements into a regional map (Figure 5.6). An earlier methodology employed by Robson *et al*. (2013) to convert satellite image pixel reflectance values into potential yield (TCH) can be similarly applied here, namely pixel reflectance values converted into N2RENDVI values and then into % leaf N using the regression algorithm (Leaf % N = 0.19898 * N2RENDVI + 0.6108).

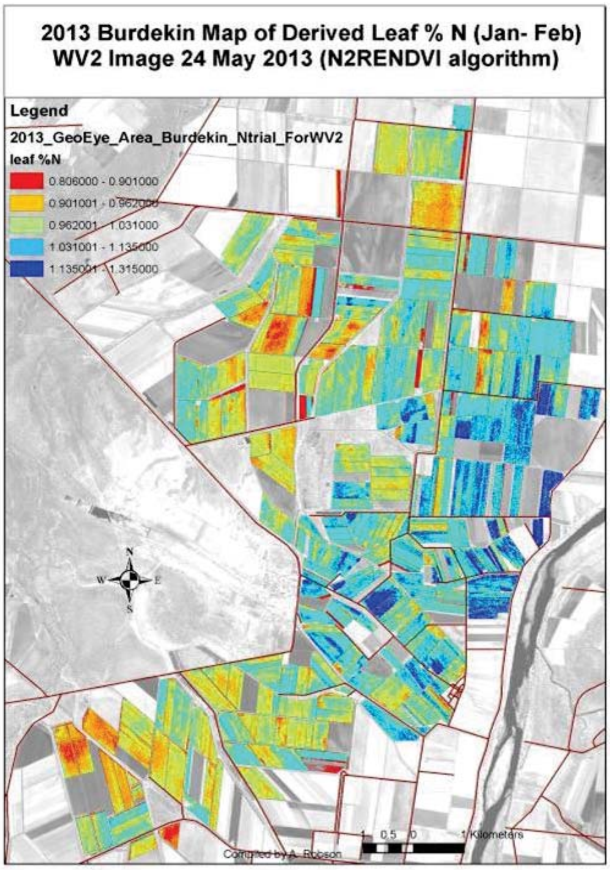

Figure 5.6. Classified map of leaf % N derived from the regression algorithm between measured leaf N % and N2RENDVI value derived from a Worldview2 satellite image captured 24 May 2013. The classified map encompasses sugar cane crops grown within a 100km^2 region of the Queensland Burdekin intensive sugar cane growing area.

Notwithstanding that the region mapped in Figure 6 may contain cultivars and growing conditions that are outside of the original calibration dataset in Figure 5a, it does provide a useful relative indicator of crop N status at the crop and farm scale. The classified map also provides some indication on how one farming system may be performing in comparison to surrounding crops. In this example, a decline in leaf % N from high (1.1- 1.3 %) to low (0.8 – 0.9 %) can be seen extending from the Burdekin river westwards (Figure 5.6). Whether this transition is the result of soil type, topography or other environmental factors, this information prompts further investigation and certainly significant ground truthing for both calibration and validation processes. With access to information such as this, growers are more likely to adopt some form of precision agricultural technologies to manage the spatial variability identified at the sub-field scale. The limitations of this approach includes the need for ground truthing, i.e. with-in crop sampling to calibrate the imagery; cost of high spectral and spatial resolution imagery to cover entire growing regions and an inability to capture imagery due to continual cloud cover. The latter is particularly relevant to most Australian sugar cane growing regions where continual cloud cover generally extends from January until March.

Additionally, the timing in which variability maps are made available to growers greatly influences their useability. In the example presented here, imagery was collected in April and May with the leaf % N maps derived soon after. This information obtained close to harvest would have been received too late to assist with any remedial action within that growing season due to stalk damage from any mechanical application of N. However, the information would be extremely beneficial for guiding the management of subsequent ratoons if the spatial patterns were identified to be temporally consistent. The more obvious solution is to provide these maps at a growth stage where mechanical applications are less destructive i.e. sugar cane less than 3 months old.

In order to evaluate the opportunities and challenges of providing image-base data earlier in a cropping cycle, a repeat experiment was conducted over the Mackay trial during the 2013/14 growing season (WV2 captured 5 Jan 2014; sampled 3 December 2013). The vegetation index N2RENDVI was again identified to produce the highest correlation coefficient to leaf % N when evaluated against other vegetation indices tested (Robson unpublished data). Hyperspectral measurements (ASD FieldSpec®) also conducted over the same Mackay trial (48 plots comprising of 3 nitrogen rates and 16 cultivars) on the 3 December 2014 identified the same wavelengths as those within the broader satellite image wavebands as influential in explaining leaf % N (Figure 5.7). The RE waveband in particular demonstrated the shorter wavelengths to have a large negative correlation with leaf % N, whilst the longer wavelengths exhibited a strong positive correlation. This is typical of the 'tug of war' between the chlorophyll absorption associated with red end of the RE and the intercellular scattering (i.e. strong reflectance) characteristics of the near infrared (NIR) end and is why the RE is strongly influenced by chlorophyll/ N concentration. The wavelengths corresponding with the WV2 NIR 2 (N2) band produced the highest positive regression coefficients in explaining % Leaf N.

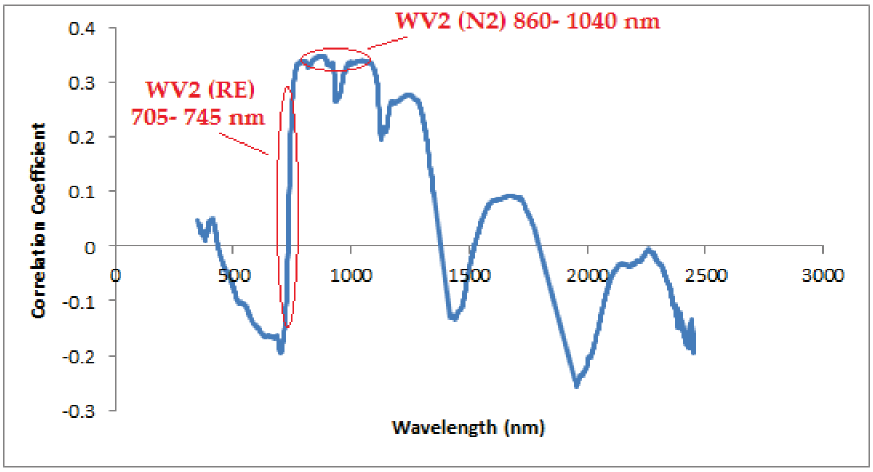

Figure 5.7. Correlation coefficients derived between individual wavelength reflectance data measured with a field spectrometer on the 3 Dec 2014 and corresponding % leaf N.

These initial results indicate that satellite remote sensing, particularly with sensors that provide a red edge (RE) and mid infrared (MIR) band, may be effective in delineating spatial variability in leaf % N. Certainly, these images would require on- ground calibration either through tissue sampling such as that undertaken by the rice industry, or potentially through the use of calibrated non- destructive proximal sensors i.e. active and fluorescence sensors.

5.7 Report summary

The various papers presented in this review indicate that nitrogen concentration within a sugar cane canopy can be determined using spectral reflectance, particularly within the spectral ranges 400- 700 nm (visible region), 700 - 780 nm (Red edge region) and 1300- 2500 nm (mid infrared). However, external parameters such as abiotic and biotic constraints, cultivar variation, stage of plant growth etc. can influence the spectral responses and ultimately nitrogen calibrations (Rodriguez *et al*. 2006, Hansen and Schjoerring (2003).The addition of in-field calibration of sensors with limited and non-limited nitrogen applications did reduce this error. Additionally, Abdel-Rahman *et al*. (2008) indicated that specific wavelengths directly correlated to nitrogen compounds is achievable, in particular 2025 nm a wavelength associated to a C=O stretch 2nd overtone- Urea response. This suggests that a nitrogen specific algorithm may be developed that is less like to be affected by cultivar, locational and seasonal variability.

As well as the influence of additional factors on nitrogen prediction, sensor saturation issues resulting from sugar cane at later growth stages were also identified (Portz *et al.* 2012). This was due to a high leaf area index and leaf/canopy chlorophyll content; largely manifested in high PAB canopies (Sims and Gamon 2002, Simoes *et al*. 2005), and was particularly relevant for simple ratios developed from near infrared and red wavebands. A focus on spectral wavelengths less susceptible to the saturation effect, such as the red- edge and mid infrared region, may provide a solution to the saturation issue. The red edge region was identified to be significantly correlated to nitrogen concentration in a number of the studies (Portz *et al*. 2012, Abdel-Rahman *et al.* 2008, Jackson *et al*. 1980, Rodriguez *et al*. 2006 and Yao *et al*. 2013), whilst the mid infrared was identified by Patil and Nadagouda, (2008), Abdel-Rahman *et al*. (2008). Robson (unpublished data) identified a vegetation index derived from RE and MNIR reflectance to be less influenced by growing location, cultivar and growing season than 13 other pigment and structural based vegetation indices examined.

5.8 Recommendations

The research presented in this review demonstrates that remote sensing technologies could conceivably provide a measure of leaf nitrogen in sugar cane. There a number of methodologies (strategies) available for evaluation/consideration by the Australian sugar cane industry.

The first strategy is to identify specific spectral wavelengths measured from a growing sugar plant canopy that directly correlate to leaf Nitrogen concentration. Research by Abdel-Rahman *et al*. (2008) has indicated that there are indeed specific wavelengths that appear directly correlated to nitrogen concentration in the plants, outside of the typical Red and NIR indices. Subsequent vegetation indices derived from these specific wavelengths are potentially less likely to be influenced by cultivar, growing location, season etc. and may be used to derive accurate foliar nitrogen specific maps from the individual crops level to that of whole growing regions. Previously, the ability to extrapolate wavelengths beyond 1000 nm to airborne sensors has been limited and expensive requiring systems capable of 'sensing' beyond the range of traditional silica detectors. The recent launch of the Worldview3 satellite (August 2014) may be suitable with the addition of 8 MNIR bands between 1195 – 2365 nm. Alternatively, the specific wavelengths could potentially develop a simple, active, 'point and click' nitrogen sensor, similar to the Felix F- 750 (http://www.felixinstruments.com/product-brochures/f750-brochure.pdf) developed for measuring brix and dry matter in Mangoes. It is worth

noting, that many of the cost- effective developments in detection technologies involving LEDs have resulted from the communications industry, focussing on laser and light-emitting diodes between 1100 – 1600 nm. If wavelengths above 2000 nm are required, as suggested by Abdel-Rahman et al. (2008), then further sensor technology development may be required.

The second proposed strategy involves a relative measure of crop response to available nitrogen (Rodriguez et al. 2006). Following the methods presented by Johnson and Raun *et al*. (2003) and Lofton *et al*. (2012), limited and non- limited nitrogen reference strips could be used to calibrate commercially available active or passive sensors, as long as they do not experience saturation (Portz *et al*. 2012). For sugar cane, sensors such as the Crop Circle or possibly the Yara N- Sensor may be better suited as they offer flexibility in selecting spectral bands such as red- edge, green or higher wavelength segments of the NIR region less likely to saturate at high LAI. If validated, this approach would enable growers with on-ground sensors to develop a rapid calibration using the reference strips and deliver variable rate 'on-the-go' nitrogen rates to an entire crop based on canopy reflectance. This approach is currently adopted within cereal, wheat and corn crops (Reiter *et al*. 2014; Raun *et al*. 2010). A major limitation of this approach to sugar cane is crop height after 3 months of growth, depending on growing location and class, where any mechanical application of remedial N based recommendations from remote sensing technologies will result in stalk damage. Unfortunately research has indicated that most nitrogen accumulation in cane plants occurs within the 3- 6 month growing period (Wood *et al.* 1996). So an early measure may not truly reflect a crop's nitrogen uptake.

A third strategy looks at implementing remote sensing into precision farming system to compliment additional spatial layers including harvester yield mapping, soil surveys, and strategic plant sampling (Bramley 2009; Taylor *et al.* 2007). When combined these technologies can define the spatial and temporal orientation of productivity zones, that when ground truthed can be used to direct targeted applications of crop inputs, particularly nitrogen. This ensures each production zone receives an optimal rate relative to its capacity to respond (Bramley 2009). Currently, the majority of the Australian sugar cane industry receives crop vigour maps derived from SPOT5 satellite imagery for determining yield variability (Robson *et al.* 2012; Robson *et al.* 2013). These maps could also be used to identify the spatial and temporal consistency of low and high performing cane at the within crop to regional level. Implementing a framework such as that adopted in the Rice industry (Dunn 2012), growers or productivity services could be encouraged to collect representative leaf samples within these various productive zones and have them measured for nitrogen content, possibly by the affiliated mill. Although this method would not allow for a within season response to nitrogen uptake, it can guide management strategies i.e. six easy steps (Schroeder *et al*. 2010) for subsequent crops. Additionally, the use of imagery can identify sub regional trends in production that if ground truthed could be correlated to nitrogen content. This information can assist with identifying large nitrogen deficient areas, thus supporting possible aerial top dressing in the case of a post flood event or the planting of higher nitrogen use efficiency (NUE) cane varieties if the constraint is identified to be a continual occurrence, such as soil type.

As a forth strategy, Thorburn *et al*. (2003) raises the possibility of monitoring N concentration in harvested material brought to mills. This information measured with an NIR system can indicate nitrogen removal at the crop level. This data could either be extrapolated across the entire growing region using the mill geographical information system (GIS) crop boundary layers, or potentially used to calibrate remote sensing data collected over each corresponding crop during that growing season.

Maps derived from either method can indicate both the spatial and temporal trends in nitrogen removal, and therefore provide useful information regarding industry nitrogen use. For this to be achieved NIR systems and appropriate calibrations for measuring N concentration would have to be installed at each mill.

Irrespective of the methodology or technology deployed to validate the accuracy of any specific wavelength approach, extensive ground truth sampling and hyperspectral data collection would be required, including Kjeldahl or Dumas analysis of samples. This would have to be undertaken over multiple locations, cultivars, nitrogen rates and growing seasons to ensure robustness.

Finally, the research presented in this review indicates that with an improved understanding of the spatial and temporal variation of crop performance relative to N fertiliser, such as that provided by remote sensing technologies, growers have the ability to refine fertiliser practices to ensure they are more financially and environmentally sustainable.

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6. Increasing nitrogen use efficiency in Australian sugarcane crops: Insights from simulation modelling

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6.1 Abstract

Simulation modelling has been a valuable tool in helping farmers manage N in a range of farming systems. In the APSIM model, the Australian sugarcane industry has access to a very well developed and tested capability for simulating many features of sugarcane production systems. One of the earliest applications of this capability was identification of the "rule of thumb" for sugarcane N requirements that is a critical part of the SIX EASY STEPS system. However, there have been many applications and developments of N simulation capability since then. Applications include testing concepts on new ways to manage N fertiliser and N inputs from organic sources, supporting industry policy positions in greenhouse gas mitigation, and facilitating evaluation of government policy to improve water quality.

The latter work was conducted on a sufficient scale to give an approximate representation of the diversity of the block- or farm-level variability in behaviour of sugarcane production across the industry. We re-analysed outputs from these simulations to investigate: (1) The range of sugarcane NUE likely across the various environments and management practices in Australia, (2) which management practices result in high NUE, and (3) whether there regional differences in sugarcane nitrogen requirement. We found that:

1. There is a wide range of simulated NUE, from ~0.3 t cane/kg N where yields were low (i.e. < 50 t/ha) to >5 t cane/kg N where yields were high and nitrogen fertiliser inputs low (mainly in plant crops). Climate has a large effect on sugarcane growth and hence NUE.

2. Of the wide range of management practices simulated the **only** practice significantly influencing NUE in ratoon crops was N fertiliser application rate. N rate also contributed to NUE in plant crops, although the management of the preceding fallow was also important.

3. Average sugarcane N requirement varied between districts (from 1.3 to 1.8 kg N/t cane), but there was no evidence for N requirement differing between low and high (i.e. >100 t/ha) yielding crops.

These simulation results have a number of implications for increasing NUE in the Australian sugarcane industry. In particular, they support:

- Industry initiatives to reduce current industry-average N fertiliser application rates to rates given by the SIX EASY STEPS guidelines. They also show the potential to refine the single "rule of thumb" value for N requirements in SIX EASY STEPS to a district or even smaller scale.

- Investigation of management technologies (e.g. use of enhanced efficiency fertilisers and/or application of precision agriculture) to facilitate reductions in nitrogen rates below those currently recommended in the SIX EASY STEPS guidelines.
- Efforts on integrating seasonal climate forecasting into nitrogen fertiliser management systems.

They also suggest that a decision support system based on the predictive capacity of APSIM may be valuable in assisting cane farmers accessing and incorporating climate variability and seasonal climate forecasting into their N management.

6.2 Introduction

Nitrogen (N) fertiliser additions are an important contributor to productivity in sugarcane (and other) farming systems, so it is important to ensure N supply is sufficient for crops to achieve optimum yields. However, applying N fertiliser also increases losses of N to the environment, with clear evidence of N from Australian sugarcane affecting nearby groundwaters (Thorburn et al., 2003a) and marine and other aquatic ecosystems (Brodie et al., 2013; Thorburn et al., 2013b), as well as emitting substantial amounts of the potent greenhouse gas nitrous oxide (Thorburn et al., 2010). Thus, the Australian sugarcane industry faces the challenge of maintaining productivity while minimising environmental impacts of N fertiliser use. Meeting this challenge will require an increase in N use efficiency (NUE, tonne of cane grown per kg of N fertiliser applied) in Australian sugarcane production systems.

Understanding key processes of crop physiology, soil nutrient and water cycling, and how these interact with each other and the climate is the foundation for any decisions on managing crops. There are mechanistic, process-based models that incorporate a representation of these processes that are increasingly being used across a wide range of cropping industries to explore complex issues (Holzworth et al., 2015). Modelling has an established track record of use in research and on-farm decisions making in the Australia grains industry, to the point where it is now widely accepted as a "standard analytical tool" in agronomic research (Robertson et al., 2014). An important application of models in this industry has been, and continues to be the analysis by farmers of economic optimum N fertiliser management (Hochman et al., 2009). Even though this example from Australia grains industry is relatively recent, the application of models to N-related problems in agriculture has a long history with the development of coupled soil-crop N models dating to the 1980's (Kersebaum et al., 2007). Thus models, whether as research tools or aids for farmers' decision making, are likely to have an important place in meeting the challenge of increasing NUE.

The history of modelling sugarcane crops and cropping systems is not as long as that for grains crops. However, over the past 20 years there has been a concerted effort in some sugarcane producing countries to develop and apply sugarcane models (as described below). To date these models have mainly been applied to examine the capture and use of water by these crops. However, there is capability in some models for examining N cycling in sugarcane crops and cropping systems. This capability has largely come about through the development of sugarcane crop models within modular crop-modelling frameworks (Jones et al., 2001; Holzworth et al., 2014) that include the modules necessary to represent N cycling in cropping systems.

In this paper we examine insights on NUE in Australian sugarcane production systems that can be gained from simulation modelling. We commence by describing the processes need to be included in a model to simulate NUE, and then review existing sugarcane models to determine which have this functionality. We then look at the past application of models for better understanding N cycling in Australian sugarcane production systems and provide examples of the benefits of these studies to the Australian sugarcane industry. Finally, we re-analysed previously run industry-scale simulations to answer three questions:

1. What are the ranges of NUE are likely to occur in Australian sugarcane production under the range of climates, soils and common management practices found?
2. Which of these management practices result in high NUE?
3. Are there regional differences in sugarcane nitrogen requirement, and therefore the potential to regionally customise nitrogen management guidelines?

Importantly, as well as contributing to our understanding of NUE in sugarcane in a way not previously done, these analyses provide an example of how modelling can be applied to provide insights into NUE. Further analyses could help improve N management guidelines and increase NUE and, of course, insights gained from application of simulation model need to be evaluated in the field. We conclude this paper by suggesting some other applications (which have been found valuable in the Australian grains industry) that could help farmers and the sugarcane industry optimise NUE and identify some areas where better understanding of biophysical processes in Australian sugarcane producing areas would improve models.

6.3 Sugarcane N modelling capability

What crop and soil processes should be represented?

To comprehensively simulate N dynamics in cropping systems, models need to include a range of crop growth and soil processes. The main processes are outlined in this section to provide a framework for describing the N modelling capability in existing sugarcane models. The purpose here is neither to describe all possible processes, nor the mechanistic detail of the process.

Relevant process in the crop-soil system

Like many crop models, sugarcane models commonly use intercepted radiation to produce assimilates, (through photosynthesis) which are partitioned into different part of the plant (e.g. structural stalk, sucrose, leaves, roots, etc). Growth is affected by temperature, water stress and N stress. It can also be affected by lodging and water logging (which reduce the efficiency of radiation capture). As carbon (C) is assimilated, water is lost from the crop as transpiration. The rate of loss is affected by atmospheric conditions. As well as growth, senescence is also modelled. Leaves (and cabbage) senesce in response to factors such as ageing, light competition and water stress. Lodging can cause stalk death. Senesced leaves and other plant parts are ‘transferred’ to the soil surface to be crop residues. These can also be removed from the crop model if the crop is burnt.

In many models, these processes are represented by a step of sequential steps (O'Leary, 2000; Singels, 2011). The climate on a given day sets the potential amount of C that be assimilated through photosynthesis. C can only be assimilated if there is sufficient soil water available to meet transpiration demands, and assimilation will be constrained if there is insufficient soil water to meet the potential assimilation. N is also needed for the allocation of biomass to different parts of the plant, and it is this process that drives the demand for uptake of N from the soil. N concentrations in the different parts of the plant will decrease if inadequate N is available from the soil to meet the demand. N concentrations in leaves affect assimilation of C, so low leaf N concentrations will limit growth. In structural parts of the plant (e.g. stalk) low N concentrations do not affect growth.

To represent the effect of water and N stresses on crop growth, soil water, C and N processes need to be modelled. Soil water models need to partition rainfall (and irrigation) between runoff and infiltration, allow water to evaporate from the soil and move downwards and upwards in the profile in response to water potential gradients, allow solutes to move with water (and in response to concentration gradients) and roots to extract water. There are two common approaches to soil water modelling: treating the soils as a series of layers with water stored in each layer and moving between layers (the 'tipping bucket' approach) or representing the flow of water between specified depths in the soil in response to soil water potential gradients and the hydraulic conductivity of the soil (i.e. Richards' equation models).

Soil N dynamics are mediated by soil organic matter (usually represented as organic C, and often referred to simply as soil C), so modelling soil N dynamics implies modelling soil C processes. Addition of organic C compounds (e.g. senesced root, crop residues) increases soil C, and decomposition of C compounds decreases soil C. There are a wide range of organic C compounds in soils with differing decomposition rates. This range is commonly represented as a number of discrete 'pools' of C, each characterised by their potential decomposition rate and N (and in some cases P) concentrations (usually specified as C/N ratios). During decomposition, N in the decomposing pool is mineralised to ammonium (NH_4) through the process of ammonification. NH_4 can then transformed to nitrate (NO_3) through the process of nitrification. N is immobilised when organic C compounds with high C/N ratios (i.e. low N concentrations) are added to the soil and start to decompose. As a general rule, residues with C/N ratio > 25 will result in immobilisation. Given that sugarcane residues (trash) have C/N ratios of 80-200 (Robertson and Thorburn, 2007), the process of immobilisation exerts a large influence on soil N dynamics in sugarcane production systems.

All the above processes can occur throughout the soil profile, and models commonly treat C as occurring as layers in the soil (analogous to the 'tipping bucket' soil water models). They are most active at shallow depths (e.g. to 0.3 m) and consequently some models only consider soil C and N processes to this depth (e.g. DayCent; Parton et al., 1998), possibly as a single layer. However, there are circumstances where N processes deep in the soil profile can be important for crop growth (e.g., crops receiving little or no N fertiliser). As well, all the above processes are microbial processes that are sensitive to the soil environment, e.g. temperature, water content, and acidity. Thus to simulate them the dynamics of soil temperature, water content, etc, need to be simulated.

It should be noted here that there are models which only represent soil C dynamics without coupling that to N such as RothC (Skjemstad et al., 2004). So, whereas (mechanistically) modelling soil N implies modelling soil C, the reverse is not true.

The mineral forms of N, NO_3, and NH_4, can undergo a number of fates in the environment. NO_3 is taken up by plants, moved through (and potentially leached from) the soil with water flow (some models also represent diffusion driven by concentration gradients), move into runoff and be lost from the profile/field by that pathway or be denitrified and lost from the profile in gasses (N_2 and N_2O). NH_4 is preferentially consumed by decomposer organisms, and so is converted from mineral to organic form through immobilisation. Plants, including sugarcane (Robinson et al., 2011), can also take up NH_4. A number of these processes are mediated by soil microbes, so are affected by the soil environment.

Crop residues and other organic compounds (e.g. mill mud) that lie on the soil surface also need to be represented. Residues decompose and 'transfer' C (and N) to soil organic matter. Residues also reduce evaporation and runoff from soil and so impact soil water. The mass of residues at any time is the result of additions and removals of residues from the soil. Additions include the 'transfer' of sugarcane trash (and potentially cane lost during harvesting) from the crop model to the residue model at harvest (or any other time specified by the modeller). Removals include decomposition (which depends on residue C/N, moisture, temperature, etc), burning or incorporation during tillage.

Issues with model application

Simulating the effect of N management on crop growth and development implies the simulation of a large number of soil (as well as crop) processes. These processes depend on a range of parameters (some constant, some variable) that need to be estimated or determined. These parameters fall into three categories: (1) 'universal' constants, (2) species/variety parameters, and (3) site-specific parameters. The allocation of a parameter into one of these categories can differ between different models (and the culture of different modelling groups). However, many soil parameters (e.g. soil C decomposition rates) can be considered universal constants, and so their values do not need to be determined at every site. Crop phenology parameters are often taken as constant for a particular crop variety: That is, once determined they can be applied unaltered in subsequent applications of the model. Site-specific parameters include many soil capacity (e.g., soil water holding capacity, soil C concentration, bulk density) and flow rate (e.g., hydraulic conductivity, runoff) parameters, or crop rooting depth (as limited by sub-soil constraints to root growth). Ideally values for these site-specific parameters can be estimated by direct measurement. However, that may not be possible for various reasons (e.g., spatial variability in the parameter, not measured) in which case the values can be estimated by calibration against data on an associated process (e.g., calibrating soil hydraulic properties against measurements of soil water content dynamics). The uncertainty about which category a parameter belongs to can often arise from lack of knowledge about the process or differences in model structure. An example of the former is the development of nitrification rate parameters for sugarcane soils (Meier et al., 2006a) which are now used routinely in sugarcane applications with the APSIM model (e.g., Thorburn et al., 2011). An example of the latter is radiation use efficiency in sugarcane, which is treated as a species constant in APSIM (Keating et al., 1999) but has been treated as a (calibrated) site-specific variable in an application of the DSSAT-CaneGro model (Marin et al., 2011).

As well as issues over model parameter estimation, application of a systems model at a site requires a great deal of detailed information in addition to that required for determining values for all the site specific parameters. Information is needed on climate, management and initial conditions to a level of

detail not commonly collect in field experiments. Conversely, simulating crop growth at a site provides insights into a wide range of factors at the site that would otherwise be unknown (or perhaps guessed at). It can also highlight errors in measured data, for example when two measured values are mechanistically not possible. Thus a particularly valuable use of models is as a 'scaffold' for providing more complete analysis of data from experiments, addressing issues like erroneous or missing data, predicting values for processes not measured (e.g., providing a complete water, N and C balance) and placing the experiment into a broader context of environments.

Review of available models

Many models can be configured to represent sugarcane, so a list of potential sugarcane models is large. However, there are approximately six models that could be considered 'dedicated' sugarcane models, and at least another four where a sugarcane-specific application of more general crop models has been published (Table 6.1). Of the dedicated models, APSIM-Sugar and CANEGRO (whether in the DSSAT framework or the derivative version, Canesim) are clearly the two most widely used. For the dedicated models, there have been a number papers describing the evolution of the models and comparing and/or contrasting the approaches taken describing growth and development of the sugarcane crop (Lisson et al., 2005; O'Leary, 2000; Singels, 2011), so those details will not be discussed here. There is also an international collaboration to inter-compare and improve these models (*AgMIP Sugarcane*, Thorburn, Singels and Marin; http://www.agmip.org/sugarcane/) that, for many models, is providing a mechanism for their first application to environments outside the region of their development. An exception here is APSIM-Sugar, which drew on data from 19 experiments in four countries in its development (Keating et al., 1999). This comprehensive development of APSIM-Sugar has been highlighted within the broad crop modelling community as an example of robust model testing (Bellocchi et al., 2010; Sinclair and Seligman, 2000).

All these sugarcane models represent the interactions between sugarcane growth and development, climate and soil water availability. Of more relevance here is the capacity of these models to simulate crop N dynamics and, by implications, soil C, N and water dynamics. DayCent/Century and EPIC have strong reputations for applications to natural resource management issues, which include crop N, soil C/N and soil water dynamics. Sugarcane production systems have been simulated in Australia with Century (Vallis et al., 1996) and in Brazil with Century (Galdos et al., 2009) and DayCent (Vargas et al., 2013). A sugarcane model (AUSCANE) was developed within the EPIC framework in Australia in the late 1980's (Wegener et al., 1992), but there has been little published on it subsequently. OntoSim-Sugarcane is a model developed within OntoSim, an ontology-based simulation data modelling environment (Beck et al., 2010). An N modelling capability could be developed within that environment, although applications to date have focussed on growth, water relations and phosphorus movement (Kwon et al., 2010a, 2010b). The focus of the AquaCrop model is crop growth and water relations (Steduto et al., 2009), and it does not have an N modelling capability at this time.

Of the dedicated sugarcane models, Canesim (a simplified version of Canegro), CASUPRO and QCANE do not represent N cycling. DSSAT-Canegro is an implementation of the Canegro model (Inman-Bamber, 1991) with the DSSAT framework (Jones et al., 2003). This framework includes a reasonably comprehensive representation of soil N cycling (Porter et al., 2010). To access this functionality, crop N uptake and responses were added to the Canegro model (van der Laan et al., 2011). However, there has been little further testing and/or application reported of this model.

APSIM-Sugar exists within the APSIM framework (Holzworth et al., 2014) which has included soil N modelling since its inception (Probert et al., 1998). Thus crop N dynamics were included in APSIM-Sugar during its creation. The model has been applied to many issues relating to understanding and managing N in sugarcane production systems (reviewed by Thorburn et al., 2005). These and subsequent applications have led to developments in modelling soil-related processes in these production systems, notably: trash decomposition (Thorburn et al., 2001b); nitrification (Meier et al., 2006a); N leaching (Stewart et al., 2006; Thorburn et al., 2011); N losses through runoff (Biggs et al., 2013; Thorburn et al., 2011) and denitrification (Thorburn et al., 2010); and contribution of N from fallow legumes to subsequent sugarcane crops (Park et al., 2010). The model has also been coupled into larger modelling frameworks to study sugarcane value chain diversification (Archer et al., 2008) and water quality improvement (Carroll et al., 2012). While most N-related applications of the model have been in Australia, the model has been proven in South Africa (Thorburn et al., 2002; Van Antwerpen et al., 2002) and, more recently, Brazil (Marin et al., 2014, 2015; Pessim De Oliveira et al., 2014).

Table 6.1. List of models with a 'track record' of application to sugarcane. Models are arbitrarily differentiated on whether they represent a dedicated effort to detail the physiology of sugarcane crops, or are sugarcane-specific applications of more general crop models.

Dedicated models	Models with published applications
1. APSIM-Sugar (Keating et al., 1999) 2. Canesim (Singels and Donaldson, 2000) 3. CASUPRO (Villegas et al., 2005) 4. DSSAT-Canegro (Singels et al., 2008) 5. MOSICAS (Martiné and Todoroff, 2004; Martine et al., 1999) 6. QCANE (Liu and Bull, 2001; Liu and Kingston, 1995)	7. AquaCrop (Steduto et al., 2009) 8. DayCent/Century (Parton et al., 1998) 9. EPIC (Williams, 1990) / AUSCANE (Wegener et al., 1992) 10. OntoSim-Sugarcane (Kwon et al., 2010a, 2010b).

6.4 What has modelling capability told us about NUE in the past?

Previous simulation studies have mainly focuses on identifying the optimal application rate of N fertiliser, how this is influenced by climate and management, and the environmental consequences of sub-optimal (usually supra-optimal) N applications. These issues obviously have direct application to understanding NUE; the optimal N rate can be taken as one at which the NUE-profitability trade-off is maximised (Keating et al., 1997). In this section we will highlight modelling studies on some specific issues relevant to NUE.

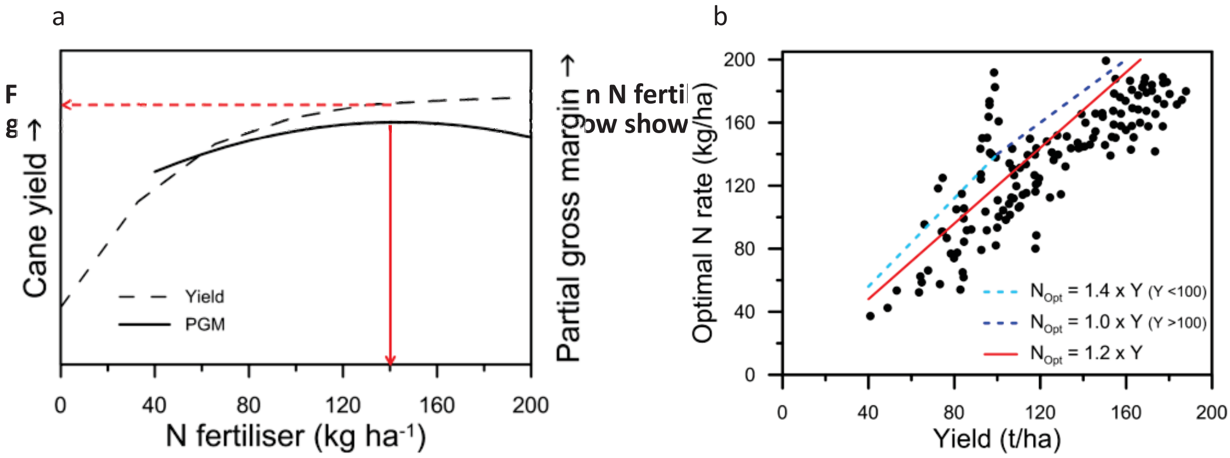
Optimal N fertiliser application rates

Sugarcane N requirements

In perhaps the first major application of simulation modelling to the problem of better understanding optimal N fertiliser management in sugarcane, Keating et al., (1997) simulated sugarcane yields under a wide range of N fertiliser applications (0-300 kg/ha) on three soils of different N fertility (i.e. soil C concentration) over ~100 years under the climate of Ingham (18.65°S, 146.17°E). They determined the optimum rate of N for each crop, defined as the rate at which economic returns became negative; i.e.

the additional revenue gained by applying more N was less than the cost of fertiliser and harvesting (Figure 6.1a). They showed that, **on average**, optimal N rate was higher in soils with poorer N fertility; however, the yield of **individual** crops had the largest impact on optimal N rate, with there being a wide range of optimum N rates over the 100 years simulated. The yields were primarily determined by climate, with soil N fertility having a secondary effect.

From these simulations they investigated the relationship between the N fertiliser requirement (i.e. the amount of N required to grow a tonne of sugarcane) and yield and developed a "rule of thumb" that sugarcane required 1.4 kg N/t cane for yields < 100 t/ha, and 1.0 kg N/t cane for yields higher than that (Figure 6.1b). This "rule of thumb" was incorporated into Six Easy Steps (Schroeder et al., 2010a) as the basis of sugarcane N requirements.



N rate) giving maximum partial gross margin and the dashed arrow shows the yield at this N rate. (b) The optimal N rate (N_{Opt}) and yield (Y) for sugarcane crops simulated over 100 years at Ingham (redrawn from Keating et al., 1997). The dashed lines show the "rule of thumb" for sugarcane N fertiliser requirement developed by Keating et al., (1997) for crops yielding < 100 and >100 t/ha. The solid line is the N fertiliser requirement derived by quantile regression analysis (described below).

Another conclusion drawn from these results by Keating et al., (1997) was that the profit-N rate response curve was quite 'flat' around optimum N rates (Figure 6.1a), an economic phenomenon observed in many aspects of agriculture (Pannell, 2006). The conclusion Keating et al., (1997) drew was that it made sense to apply N fertiliser at higher than optimal rates in terms of farm economics. However, N management has a broader context because of the environmental (i.e. water quality and greenhouse gas) consequences of N fertiliser management in agriculture, and Keating et al. (1997, P 234) stated "*...that more precise N fertiliser management, that better reflects soil supply and crop demand, is a goal worth striving for in the sugarcane industry*." This goal is still highly relevant today.

Two approaches to target yields in N recommendations

Given that crop size is the biggest determinant of crop N requirements and hence N fertiliser applications (Keating et al., 1997), and crop size varies strongly from year-to-year due to many factors outside farmers' control (e.g. climate and time of harvest; Lawes et al., 2002), how can these factors be incorporated into N fertiliser management strategies? The common approach to formulating N fertiliser recommendations is to couple some expectation of the yield of a crop (commonly an aspirational 'target') to information of the amount of N needed to achieve that yield. Determining the latter factor is relatively straight forward (Keating et al., 1997; Thorburn et al., 2011a). Thus the main problem is setting expectations about crop yields. It makes sense for target yields to be 'optimistic' minimising the risk of crop N stress. However, such optimistic targets are seldom met (Schroeder et al., 2010b), meaning that vast majority of crops are over-fertilised. How might yield targets be refined? This question was addressed in two separate simulation studies.

Abolish the target

Having a target yield is an attractive component of an N management system because of the fear that, under ideal climatic conditions that will occur from time-to-time, crops will have access to inadequate N. This fear is magnified by the perception that N is readily lost from soil (through leaching and/or denitrification) in the wet conditions experienced by much of the Australian sugar industry (Weier, 1994). However, 60 to >95% of N taken up by sugarcane crops comes from mineralised soil organic matter (Meier et al., 2006b; Vallis and Keating, 1994) so yield of a particular crop is relatively insensitive to the amount of fertiliser N applied. In this situation, a target crop yield could be replaced by an average yield. Such a system, where N fertiliser application rates are determined by estimates of N removed in harvested cane and lost to the environment, was hypothesised and tested through simulation (Thorburn et al., 2003b) prior to being tested in the field (Thorburn et al., 2011a).

There were two conclusions drawn from the simulations. First, the original development of the concept was to use the actual amount of N removed in harvested cane rather than an estimate. A problem was identified with that approach: N concentrations in sugarcane stalks are quite variable because of luxury uptake of N by sugarcane, with smaller crops generally having higher N concentrations than bigger crops regardless of the amount of N fertiliser applied (within agronomically sensible limits). Using the actual amount of N removed in harvested cane resulted in "feed-forwards" in simulations that resulted in ever-increasing or ever-decreasing N application rates. These feed-forwards were eliminated by the use of a constant (average) N concentration. The second conclusion from the simulations was that cane yields in such a system would be little different from those resulting from farmers' conventional N management practice at the time. This conclusion was validated in field testing in a wide range of environments in the Australia sugar industry (Thorburn et al., 2011a), with the exception of the super-humid tropics (Skocaj et al., 2012). This environment was not tested in the original simulations. However, the results of the field trials in that environment, that show maximum cane yields are achieved at N application rates greater than those of past or current recommendations (Skocaj et al., 2012), are consistent with simulation conducted in that region (Thorburn et al., 2011b).

Better predict the target (from climate forecasting)

An industry group in Tully was interested to see if seasonal climate forecasting could be used to identify if 'splitting' fertiliser applications would increase yield and profitability, while reducing environmental N losses in the region. A simulation study (Thorburn et al., 2011b) was undertaken in participation with the group to evaluate different strategies for splitting N fertiliser applications based on seasonal climate forecasts taken from the Southern Oscillation Index (SOI) Phase system (Stone and Auliciems, 1992): That is, if a 'wet season' was forecast, either less N fertiliser could be applied; or the conventional amount of N could be 'split'; or a lesser amount initially applied followed by more later in the season should the actual rainfall be less than forecast (and crop yield potentially be higher). 'Control treatments' included in the simulations were N fertiliser consistently applied either at one time or split. Thus there were five different management systems simulated. Two soils with contrasting texture, the fine textured Coom soil and the coarse textured Thorpe soil, were included in the study.

In the 'control' simulations, the yield response to added N fertiliser differed between years and soil types. Yields were relatively unresponsive to increased N at rates above 150-180 kg/ha in the Coom soil, although there were some years (2001 and 2003) when yields kept responding to N above these rates (Figure 6.2). Patterns were different in the coarse textured Thorpe soil, where yield kept responding to N, more so in 'wet' years than 'dry' years (2002-2004). These simulation results are consistent with local experience, where farmers' conventional N rates (~150 kg/ha) give higher yields than lower rates (Skocaj et al., 2012).

Splitting N fertiliser resulted in higher yields at lower N rates in approximately half of the years simulated, although the effect was much stronger but confined to 'wet years' in the coarse textured Thorpe soil than the Coom soil (Figure 6.2). The N management rules conditional on seasonal forecasts did not give a better outcome than applying N fertiliser in two 'splits' every year (data not shown), because of the inaccuracy of seasonal forecasts (e.g., a forecast 'dry' year turning out to be 'wet').

This study shows the difficulty in predicting future crops yields. The seasonal forecasting system used did not provide the magnitude of benefits from improved N fertiliser management that the industry group was hoping for (Thorburn et al., 2011b). Future improvement in climate forecasting may change this situation.

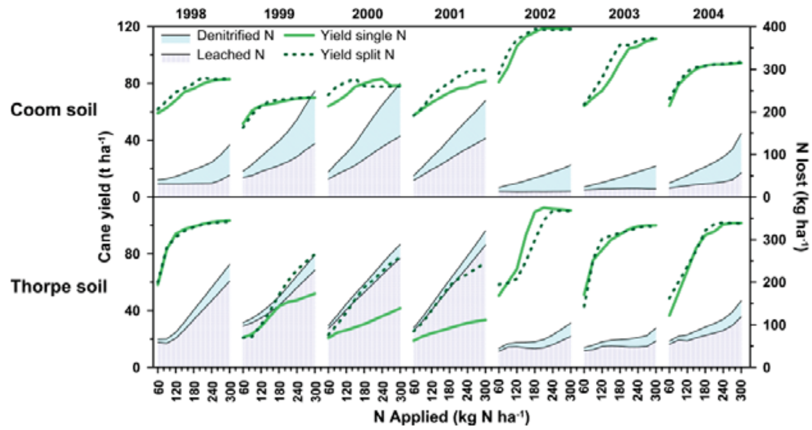


Figure 6.2. The simulated response of sugarcane yield and average environmental N losses (through denitrification and leaching) to different rates of N fertiliser in two soils, the fine textured Coom soil and the coarse textured Thorp soil, over seven years (after Thorburn et al., 2011c). N fertiliser was applied either in a single application or split over two applications.

How does trash blanketing affect crop N fertiliser needs

The rapid adoption of green cane harvesting-trash blanketing (GCTB) in Australia during the 1980's and 1990's (Kingston and Norris, 2001) raised the question of whether N fertiliser recommendations, which had largely been developed in burnt cane systems (Chapman, 1994; Keating et al., 1997) should be modified to account for the effect of the N (20 to >50 kg/ha; Robertson and Thorburn, 2007) contained in trash blankets. This is a complex question for two reasons. First, almost all (e.g. >95%; Meier et al., 2006b) of the N in trash is immobilised in soil organic matter as trash decomposes – it is not directly taken up by the plant – a phenomenon that is not altered by incorporating trash into the soil (Meier et al., 2006b). Thus the effect of retaining trash on crop N supply is determined by the effect of trash on N mineralised from soil organic matter. Second, retaining trash on the soil increases soil C (Thorburn et al., 2012) and substantial amounts of N (i.e., 100's of kg; Robertson and Thorburn, 2007) will be immobilised in soil organic matter through this C accumulation phase. Short-term (i.e. < 10 year) experiments risk reflecting this transition phase rather than the subsequent equilibrium. A series of trash (+/-) by N fertiliser rate factorial simulations were conducted across a wide range of soil types and environments to understand this issue (Thorburn et al., 2004; Vallis et al., 1996). These predicted that, at equilibrium, yields would be higher in GCTB systems in water-limited environments as a result of lower evaporation from soil covered with trash blankets. Similar results are predicted for South Africa (Van Antwerpen et al., 2002) and Brazil (Pessim De Oliveira et al., 2014). In water-limited environments, the higher yield potential with GCTB could require high applications of N. More broadly however, there was little evidence that retention of trash substantially changed optimum N rates despite the increased N mineralisation potential (~40 kg/ha/yr; Robertson and Thorburn, 2007) of trash blanketed soils after they had reached equilibrium.

This work also showed the potential limits caused to sugarcane yields through N stress if fertiliser applications were inadequate to meet the 'immobilisation demand' of the C sequestered in the soil following the retention of trash (Figure 6.3). At low rates of N, yields of trash blanketed crops are less than those of burnt crops for a time (indicated by the red arrow in Figure 6.3) until the soil C and N

cycling comes into equilibrium with the C inputs from trash. The lower the N rate, the longer this time period and the greater the yield reduction. Once the soil has reached this equilibrium (indicated by the blue arrow in Figure 6.3), yields of trash blanketed crops will be greater than burnt crops (in a water-limited production environment). Understanding the crop yield dynamics in this disequilibrium phase leads to two important conclusions (Thorburn et al., 2004). First, it helps explain the contrasting results of some experiments comparing yields of GCTB and burnt sugarcane: The yield advantage or disadvantage of the trash blanketed treatment may depend on the amount of N applied relative to crop needs. Second, the major 'wave' of adoption of GCTB happened at a time when N applications on cane farms were clearly in excess of crop needs and recommendations (both old and new), so farmers were inadvertently ensuring there was adequate N to supply the immobilisation demand of trash C sequestered in soil.

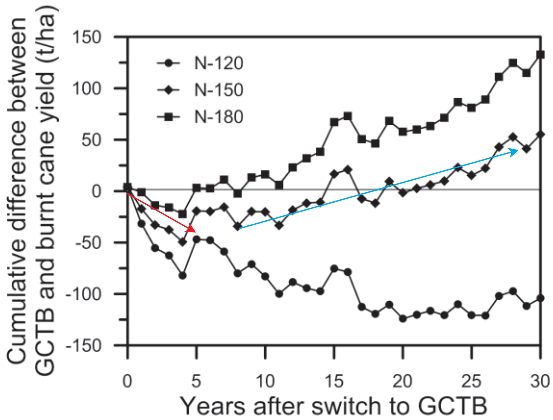


Figure 6.3. The simulated effect of N fertiliser application rates on the cumulative difference in yield of trash blanketed and trash burnt sugarcane crops (after Thorburn et al., 2004). The red arrow depicts the period in which yields of trash blanketed crops are lower than burnt crops because of N stress induced by the immobilisation demand of C sequestered in the soil. The blue arrow depicts the time when soil C has come into equilibrium with the addition of trash, the N immobilisation demand is met by the increased mineralisation capacity of the soil, and so the greater yield potential of the trash blanketed crops in this environment (Mackay) is be realized.

The fact that the N in trash blankets does not substantially 'replace' N from fertiliser (Thorburn et al., 2004) begs the question; what is the fate of this N? This question was addressed in a detailed simulation analysis of the effect of trash retention on N cycling in the wet tropics (Meier and Thorburn, 2014) which predicted that the additional N available in trash blanketed soils was either lost to the environment or taken up by the crop through the process of 'luxury uptake'. [Luxury uptake is a phenomenon whereby plants take up N in excess of the amount needed to maintain growth (Römheld, 2012)]. At low rates of N there was no luxury uptake and yields were higher in the trash blanketed system. At these low N rates however, yields were less than those at optimum N, so the N in trash only served to reduce the loss of yield at sub-optimal N rates. This is a situation that cane farmers would clearly try to avoid.

Projected climate change

Concerns over the health of the Great Barrier Reef (GBR) are driving improvements to the management of sugarcane farms (Reef Water Quality Protection Plan Secretatiat, 2014). The question arises whether these improvements will be equally effective in projected future climates. Simulation studies have been undertaken to investigate the impact of projected climate change on yields and N losses from sugarcane production in the wet tropics (Webster et al., 2009) and Mackay regions (Biggs et al., 2013). In the more detailed of these studies, Biggs et al., (2013) investigated the complex interactions between a factorial of proposed sugarcane management systems (including changed N fertiliser management), soil types, sub-regional climatic variation and four climate change projections (developed from general circulation models and greenhouse gas emission scenarios). Management practices, such as tillage, fallow management and N inputs, were grouped into five systems according to the perceived benefits to water quality. The study predicted that the improvement in farm management needed to meet water quality improvement goals will not be greatly affected by climate change. The frequency of years with very high N losses (and hence extreme ecological risk) was predicted to increase by up to 10-15%. Compared with traditional practices, improved management systems were predicted to reduce N losses by up to 66% during these years. The results of this study, as did that of Webster et al., (2009), supported continued improvement of sugarcane management systems in both the current and a range of potential future climates. However, there are important uncertainties about the effects of elevated atmospheric CO_2 concentration on plant assimilation rates and the characterisation of extreme climate events that deserve further study.

Supply of N from organic sources to sugarcane crops

Fertiliser is not the only source of N inputs into sugarcane production systems. Legumes grown in fallows can contain substantial amounts of N. So too can mill mud. The N in legumes and mill mud is in organic forms, which need to decompose and be mineralised before it is available to crops. Simulation studies have provided valuable insights into the temporal patterns of the mineralisation process and the contribution of N from these sources to subsequent sugarcane crops.

Mill mud

As discussed above in the context of trash blanketing, organic compounds of high C/N ratio initially immobilise N as they decompose prior to the time when soil mineral N increases. A study of soil N dynamics following mill mud applications (Bloesch and Barry, 2003) was able to be reproduced accurately with APSIM (Figure 6.4) by parameterising mill mud in the APSIM Surface Organic Matter module.

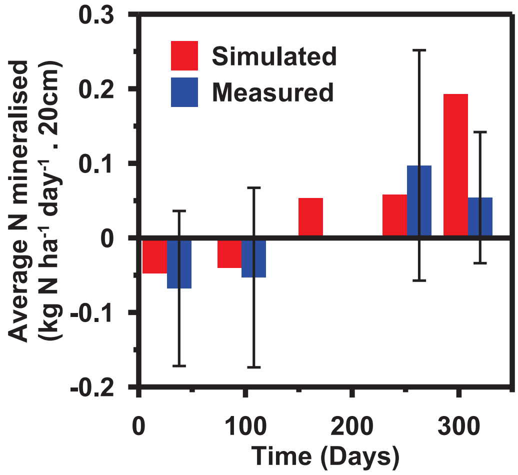


Figure 6.4. Simulation of N mineralised in soil following application of mill mud in comparison to measured values from Bloesch and Barry, (2003).

Simulations of how sugarcane N responses are affected by different rates of mill mud applied to the crop show that sugarcane is less responsive to N fertiliser when mill mud is added (e.g. Figure 6.5). Sugarcane yields become increasingly less responsive to N fertiliser as mill mud application rates increase, and the effect is generally consistent whether mill mud is added during the plant crop or the second ratoon crop. The patterns of results were also consistent across a wide range of production environments (i.e., southern, Burdekin and wet tropics). The reduced responsiveness of sugarcane to N fertiliser was caused by the applied mill mud increasing soil C and N (both total and microbial) and mineral N (e.g. Figure 6.6). Soil C and N increases were generally proportional to the application rate of mill mud, and were of similar magnitude across the cropping cycle (i.e. they did not diminish through time after the mill mud application).

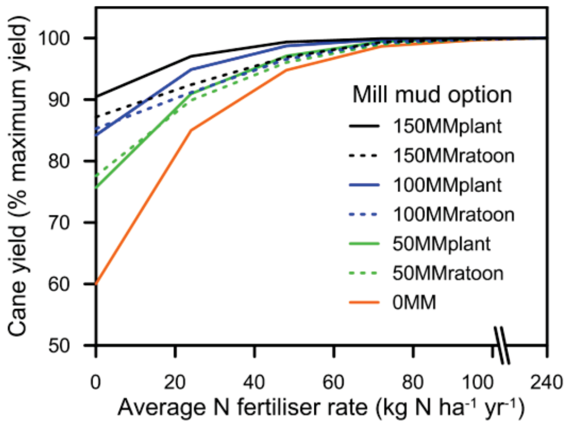


Figure 6.5. Simulated response of sugarcane yields (relative to maximum yields) to N fertiliser and mill mud applications at Mossman. Mill mud was applied at two times, during the plant crop or the second ratoon crop (in a crop cycle of plant crop plus four ratoons).

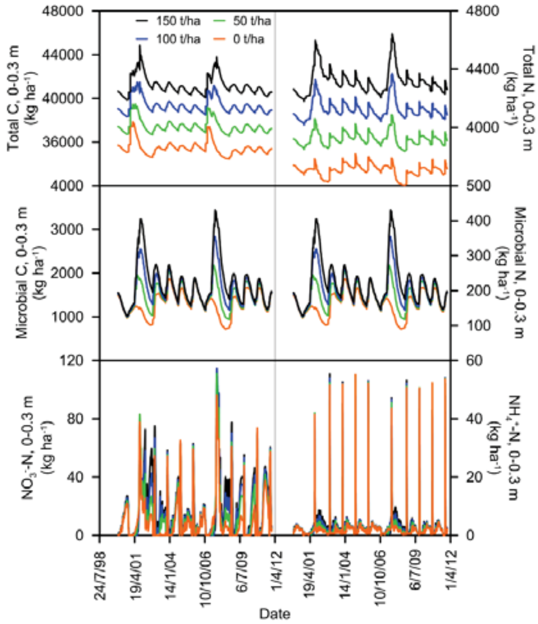


Figure 6.6. Simulated response of sugarcane yields (relative to maximum yields) to N fertiliser and mill mud applications at Mossman. Mill mud was applied at two times, during the plant crop or the second ratoon crop (in a crop cycle of plant crop plus four ratoons).

Not surprisingly, the application of mill mud not only increased soil C and N, it also increased losses of N to the environment. Even at optimal N fertiliser application rates, N lost to the environment was greater when mill mud was applied, especially at high rates (data not shown).

Legumes

A fallow legume crop has the same general effect on sugarcane N fertiliser requirements as mill mud applications (Park et al., 2010). A difference in the effect of legumes compared with mill mud is that the effect of fallow legumes on crop N fertiliser response (Figure 6.7) and soil C and N (data not shown) diminishes over successive crops to be small by the third ratoon crop. The reason for the smaller duration of impact may be the lower C/N ratios of legume biomass compared with mill mud, which causes N to mineralise faster and either be taken up by the crop or lost from the profile mainly in the plant and first ratoon crops.

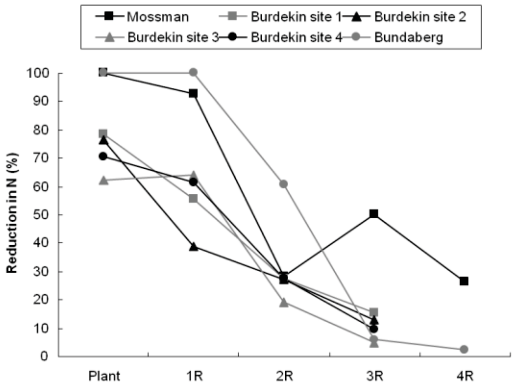


Figure 6.7. Simulated dynamics of soil (0-0.3 m) C and N in response to mill mud at planting applied at different rates at Mossman.

Environmental consequences of sub-optimal N management (and low NUE)

The application of models to examine the environmental consequences of sub-optimal N management has been an active area of work for many years. There have been two main foci for the work; water quality and greenhouse emissions. As well as investigating the causes and management of these problems, an important facet of this work has been the use of model results in economic and policy analyses.

Water quality

Initial simulation studies on water quality focussed on leaching of N below the root-zone (Keating et al., 1997; Stewart et al., 2006; Thorburn et al., 2001a; Verburg et al., 1998) driven by concerns over high NO_3 concentrations in groundwaters in sugarcane producing districts (Thorburn et al., 2003a). Results consistently found that N leaching was proportional to N fertiliser applications because of the lower NUE and higher N surplus (the difference between N inputs to a crop and N removed in harvest products and burnt residues) at the high application rates (Figure 6.8).

More recent applications have included N lost through runoff, because of concerns for the health of the GBR and the combination of impact of N, particularly dissolved N, on the declining health of GBR ecosystems (Brodie et al., 2013) and the clear link between N fertiliser applications and N losses in catchments draining into the GBR lagoon (Thorburn et al., 2013b). With runoff, as with leaching, N losses increase as N fertiliser applications and N surpluses increase and NUE decreases (Figure 6.8).

An important new role for modelling N has emerged within this GBR context. A modelling framework has been established to evaluate the effect of farm management changes on losses of N and other pollutants (Carroll et al., 2012). N losses simulated under different management practices (i.e., N application rates, splitting N applications, tillage, fallow management, in-field traffic, and irrigation) and soils and climates in the different coastal catchments (Shaw et al., 2013) are input to a catchment model (Waters et al., 2013) to be aggregated to N loads discharged from rivers. These predictions are regularly released to the public in a ‘report card’ format (e.g., Reef Water Quality Protection Plan Secretatiat, (2014).

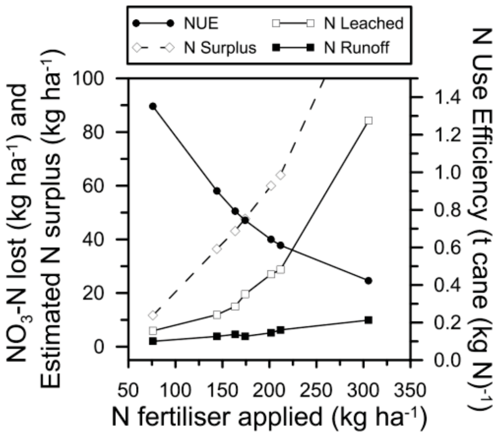


Figure 6.8. Predicted reductions in optimal N fertiliser requirements for successive sugarcane crops grown following fallow legumes in different regions (after Park et al., 2010).

The combination of management practices, soils and climates results in numerous (i.e., 10^6) field scale simulations, providing a platform for an unprecedented analysis of Australian sugarcane production systems. This platform has underpinned two types of analyses to date. Government policy has been providing incentives for farmers to adopt improved management practices to reduce N losses from sugarcane farms (Brodie et al., 2013), but what practices have the greatest influence on N losses? Biggs and Thorburn, (2013) applied 'data mining' techniques to identify relationships between the different management practices and N lost from field through different pathways (runoff, leaching and denitrification). Each of the GBR basins was analysed separately because of climatic and management differences. The amount of N fertiliser applied determined the total loss of N from fields (i.e. the sum of runoff, leaching and denitrification), with the partitioning of this loss between the different possible loss pathways determined by climate, soil type and other management practices. More specifically, the 'other' management practices were tillage, controlled traffic and, where relevant, irrigation, and these mainly affected N lost via runoff. Reduced N application rates, with reduced/zero tillage and controlled traffic were predicted to be the most effective management practice that farmers could adopt to reduce N losses to the GBR.

The type of analyses to which this simulation output database has contributed is economic analyses of different management practices. Recent results of these analyses have included; defining the cost effectiveness of targeting management change to areas of high N loss and low cost of change (Roebeling et al., 2009; van Grieken et al., 2013a); defining the regional socio-economic costs and benefits, including the high regional costs if sugarcane production is reduced to levels and make sugar milling financially unviable (van Grieken et al., 2013b); and that, even where adoption of improved practice potentially result in economic gains to the farmer, these gains vary considerably between farming enterprises and the management changes can be associated with 'transition costs' that will reduce the magnitude of the gain (van Grieken et al., 2014).

Greenhouse gas emissions

A more recent environmental concern has been greenhouse gas emissions during sugarcane growth, as these emissions reduce the attractiveness of sugarcane as a feedstock for bioenergy production (Galdos et al., 2010; Macedo et al., 2008; Renouf et al., 2008). N fertiliser applications and low NUE stimulate emissions of nitrous oxide (N_2O) from soils (Figure 6.9a) and N_2O is a very potent greenhouse gas with a global warming potential approximately 300 times that of carbon dioxide (IPCC, 2001). Consequently N_2O emission from soils are the largest source of global warming potential in the production of sugarcane (Renouf et al., 2010, 2008). A capacity to simulate N_2O emissions has been developed in the APSIM model (Thorburn et al., 2010). Simulations have been used to understand the processes causing N_2O emissions from Australian sugarcane production systems (Thorburn et al., 2013a), as well as identify management strategies for reducing these emissions and evaluate the consequences for sugarcane production of government policies designed to limit emissions. A possible policy option maybe to increase the price of N fertiliser. As N fertiliser prices increase, the economic optimum N application rate decreases, which in turn reduces N_2O emissions (Figure 6.9b). However, the higher price of N fertiliser also reduces the profitability of sugarcane production.

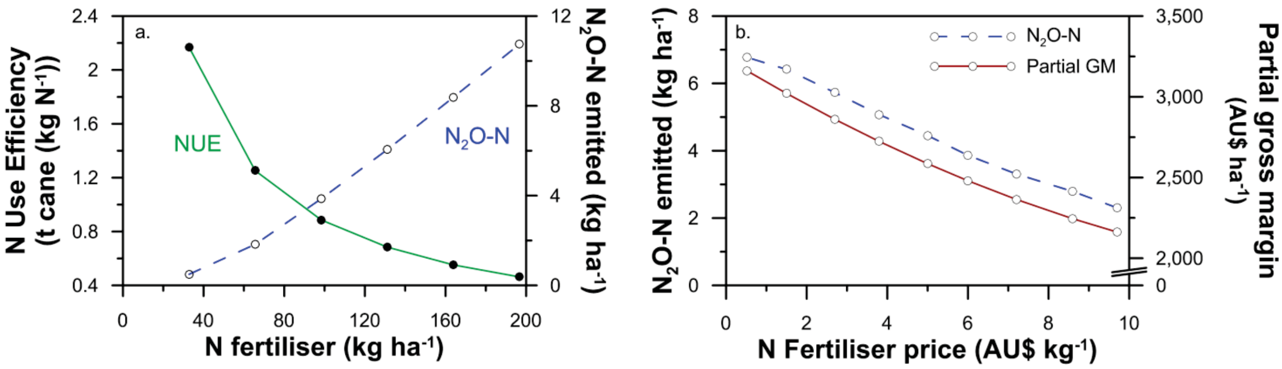


Figure 6.9. Simulated (a) response of N use efficiency and nitrous oxide emissions to increasing N fertiliser applications, and (b) response of nitrous oxide emissions and profitability (partial gross margins at optimal N application rates) to increasing N fertiliser price for a site in the Mackay area. From Thorburn et al., (2013)

6.5 What does the (current) modelling capability tell us about NUE?

Clearly past simulation studies have had an important impact on N fertiliser recommendations and hence the NUE that could be/has been achieved by Australian sugarcane farmers. However, there have been advances made since these early studies were undertaken based on better understanding, and representation in models of processes such as trash decomposition (Thorburn et al., 2001b), sugarcane rooting activity (Smith et al., 2005), nitrification (Meier et al., 2006a) and denitrification (Thorburn et al., 2010), and impacts of water logging (Skocaj et al., 2013; Meier and Thorburn, 2014) and lodging (Singh et al., 2002). As well, capacity has been built for undertaking large numbers of simulations as part of the program evaluating the effect of improved farm management on GBR water quality (Carroll et al., 2012), so simulation analyses no longer need to be confined to a small number of 'fields' as has been normal in the past (e.g. Keating et al., 1997; Thorburn et al., 2011a, 2004; Vallis et al., 1996).

Thus it is timely to revisit the questions of defining current, and identifying ways to improve NUE in Australian sugarcane production.

This issue was addressed through a simulation study, in four parts: (1) Undertaking simulations of simplified management systems to gain insights into the effect of climate on cane yield, NUE, agronomic efficiency and N losses. (2) Expanding this analysis to explore the NUE that might be achieved in a range of sugarcane management practices, climates and soils that approach the scale of the entire sugarcane production area within GBR catchments. (3) Then, analysing the management practices within this simulation output that were associated with greatest NUE. (4) Finally, we predict the N fertiliser requirement (which is the inverse of NUE) in a sub-set of these simulated management systems to put the previously developed “rule of thumb” (Keating et al., 1997) into a broader context.

Impacts of climate on factors determining NUE

In the example given above on investigating the benefits of climate forecasting in the Tully region, there were substantial differences in yields and N losses between years and soils (Figure 6.2). We can explore these types of simulation outputs to better understand the processes driving the responses and annual variation. Understanding these responses will be helped by comparing predictions for Tully, a high rainfall environment (average rainfall ~4,000 mm), with those from a contrasting environment such as Mackay (average rainfall ~1,700 mm). So we undertook simulations in these two regions.

Overview of the simulations

Simulations were based on the approach taken in the Tully climate forecasting study (Thorburn et al., 2011b) described above. Yields and N losses were predicted for crops harvested each year from 1998 to 2004. These years included contrasting climates: For example, rainfall in Mackay ranged from approximately 900 to >2,000 mm and at Tully from approximately 2,300 to 5,700 mm (Figure 6.10). A simplified production system was represented in the simulations to remove the confounding effects of factors such as harvesting time, crop class and crop management (except for N fertiliser rate) on the predicted parameters. All crops in the simulations were ratoon crops, harvested green in mid-September with no tillage performed. N fertiliser was applied as urea, buried in the soil (to minimise losses through volatilisation) at a wide range of rates (up to 210 kg/ha). The simulated crops at Mackay received no irrigation, to enhance the effect of annual rainfall variability (as opposed to trying to reflect common practice in that region). In the simulations, the first ratoon crop (i.e. harvested in 1998) was preceded by a plant crop that received 135 kg/ha of N fertiliser and harvested at 14 months age (in 1997). Prior to the plant crop, 79 years of sugarcane production (a plant crop followed by four ratoon crops) was simulated to allow soil organic matter pools in the model to reach their dynamic equilibrium. To remove the confounding effects of the interactions between N fertiliser rate and soil organic matter build up or decline in the ratoon crop simulations, soil organic matter pool sizes were reset after ratoon crop harvests to the values simulated at harvest of the plant crop.

At both locations, two soils of contrasting texture and soil carbon content were included in the simulations. In Mackay, there was a fine textured Vertosol (mk-02, Table 6.2) and a coarser textured loam (mk-01) described in previous simulation studies in the region (Biggs et al., 2013). The average carbon concentrations (0-0.3 m) were 1.3 and 0.9 %, respectively.

In Tully, we used the same soils as in the previous study (Thorburn et al., 2011b), a gleyed Brown Dermosol (tu-02) and a coarser textured Yellow Dermosol (tu-03). The average carbon concentrations were 1.0 and 0.7 %, respectively.

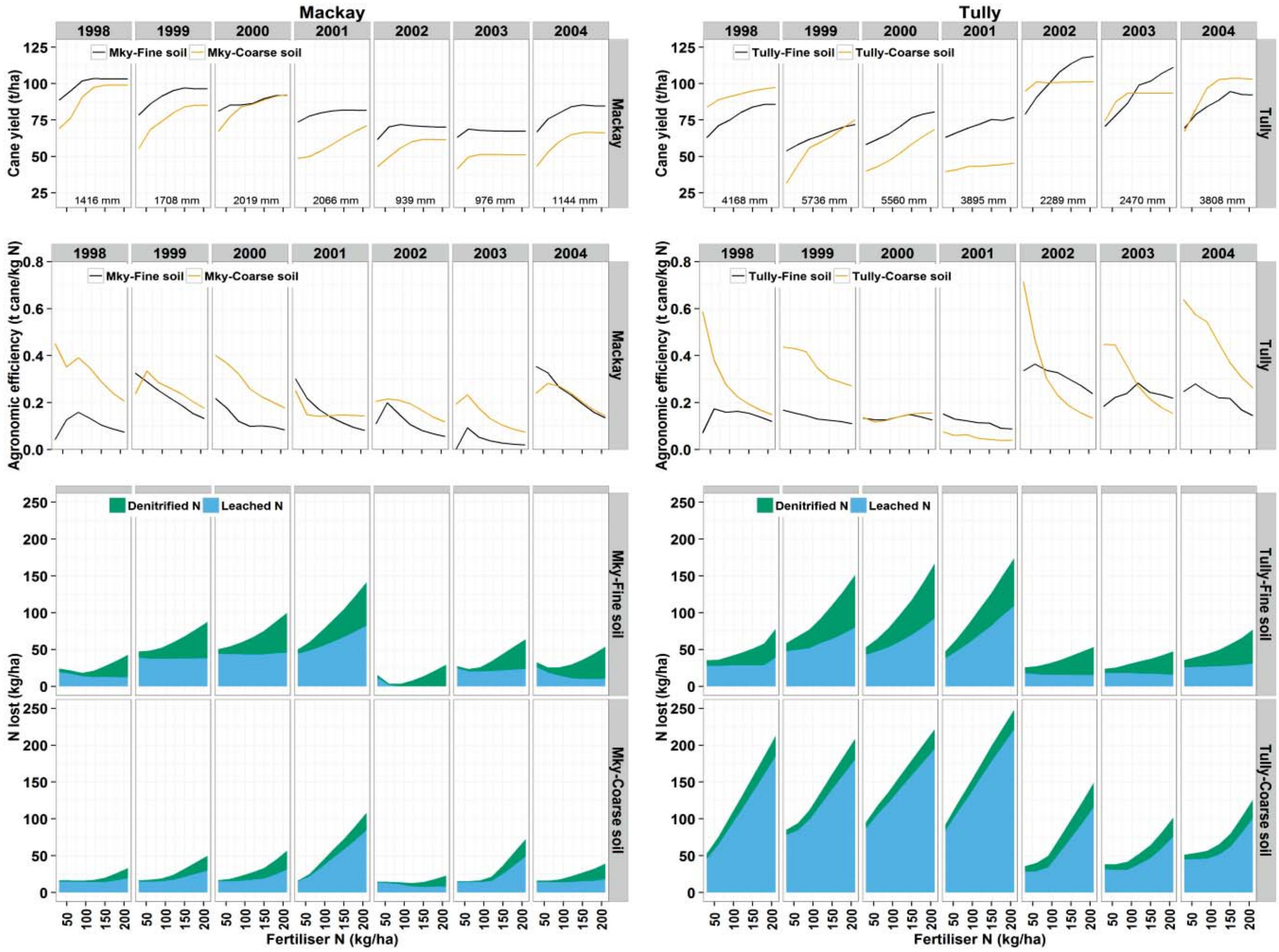


Figure 6.10. The response in cane yields, nitrogen use efficiency (NUE), agronomic efficiency and N lost through denitrification or leaching for ratoon crops (harvested at 12 month age) simulated under a wide range of N fertiliser application rates with climate data from two locations for two soils of contrasting textures in each location. The total rainfall falling during each crop is listed under the yields, and details of the simulations are given in the text.

Table 6.2. Details of the soil types collected from detailed experimental work and soil reports in each region.

Region	Soil code	Soil type
Bundaberg	bu-02	Red Dermosol
	bu-11	Red Kandosol
	bu-13	Redoxic Hydrosol
Burdekin BRIA	bh-01	Medium Clay
	bh-02	Medium clay
Burdekin DELTA	bk-03	Silty clay loam / light clay
	bk-04	Silty clay / coarse sand
Mackay	mk-01	Loam
	mk-02	Vertosol
	mk-03	Heavy clay loam
Tully	ba-01	Ferrosol
	ba-02	Hydrosol
	tu-02	Brown Dermosol
	tu-03	Yellow Dermosol

Annual variations in yields and N parameters

In the Mackay simulations, simulated yields with the fine textured soil were higher than with the coarse textured soil in six of the seven years (Figure 6.10). The higher yields were generally due to the higher water holding capacity of the fine textured soil. The 2000 crop, when the yields were similar in both soil types (except at low N rates), not only received relatively high rainfall (the second highest rainfall in the simulations) but temporally well distributed rainfall such that soil water holding capacity was less important in determining the yield. The effect of soil texture was not as consistent in the Tully simulations.

At both locations, yields were simulated to increase with increasing N fertiliser applied (Figure 6.10). The magnitude of the increase however, was variable between locations, soils and years. In many years, yields reached a 'plateau' and did not increase with additional N. However, the N rate at which the plateau was reached was variable. In Tully, yields did not plateau in 1999 and 2000, the two wettest years, although the increase in yields with increasing N above 150 kg/ha was small in the fine textured soil in 2000.

At high N rates (e.g., > 150 kg/ha) there was some impact of rainfall on simulated yields. For Mackay, the lowest yields occurred in the two driest years (2002 and 2003). However, yields could be high (e.g. > 80 t/ha) when the rainfall was ~1,400 mm (1998) or ~2,200 mm (2000). For Tully the impact of rainfall was clearer, with crops experiencing high rainfall more likely to have low yield due to lower radiation in wet years.

Agronomic efficiency (AE) was calculated for the yields simulated at each N rate from:

$$AE = (Y_N - Y_{N0}) / N, \qquad (1)$$

where Y_N is the predicted yield at a particular N rate (N, kg/ha) and Y_{N0} is the predicted yield with no N fertiliser applied. Agronomic efficiency generally declined when yields approached or reached a 'plateau' and the numerator of Eqn 1 ($Y_N - Y_{N0}$) changed little with increasing N rate (Figure 6.10). Maximum AE values varied between years and locations, from close to 0.4 t cane/kg N at Mackay in

1998, 2000 and 2004, to >0.6 t cane/kg N at Tully in 1998, 2002 and 2004. These high values occurred at low N rates, as expected, and generally in the coarse soils (Mackay in 2004 being the exception). Further, maximum AE values were higher in the coarse textured soils in five of the seven years at both sites. The coarse textured soils had lower soil C content than the fine textured soil (as described above), and so the contribution of mineralised N to crop N requirements would potentially be lower in these soil explaining the greater relative response to N fertiliser. At high N rates, AE values in the different textured soils were more similar (and also lower than at low N rates), as expected because the supply of N from fertiliser over shadows different amounts of N from mineralised soil carbon in the different soils. In fact, in Tully in 2002 and 2003, AE values at high N rates were higher in the fine textured soil as yield were still responding to additional N applications in this soil, but not the coarse textured soil. In Tully, 2002 and 2003 were the two driest years of those simulated and we hypothesise the lower soil water holding capacity of the coarse textured soil was the primary limit to yields and adding high amounts of N fertiliser in these years was agronomically 'inefficient'. The patterns in AE seen in these simulations suggest that that AE is a complex parameter and it is difficult to attribute a particular AE value, or difference in AE values between different situations to a single causal factor.

Like yields, simulated N losses generally increased with increasing N fertiliser applied (Figure 6.10). Losses were also variable between locations, soils and years. Losses were generally higher in the fine than coarse textured soil for Mackay, but higher in the coarse textured soil for Tully. A greater proportion of N was lost by denitrification than leaching with the fine textured soils at both locations, with this proportion increasing as N fertiliser applications increased. Losses were also generally related to rainfall, for example being highest (at the highest N rates) in 2001. However, while 2001 was a 'wet' year, it wasn't the year with highest rainfall at either Mackay or Tully.

Are yields more N-limited in 'wet' years?

As described above, both yield and N losses are affected by rainfall (although there patterns are complex). This raises the question of the degree which N losses might be limiting yields, especially in years of high rainfall. To explore this question we looked further at relationships between rainfall, yields and N losses, but only at a single, relatively high N rate (180 kg/ha). This rate was chosen as it is both a rate at which many farmers in these two districts might apply N, and one at which simulated yields are (or almost) not N-limited.

Simulated yields tended to increase with rainfall at Mackay, but decrease at Tully (Figure 11a). As yields changed NUE also changed (given that the same amount of N fertiliser was applied in all simulations). Thus NUE tends to increase with increasing rainfall at Mackay, but decrease at Tully, indicating the strong climatic impact on NUE.

While yields (and NUE) were affected by rainfall, the relationship between rainfall and yields is complex, as noted above. This complexity results in relationship between yield and total rainfall only being significant ($P < 0.05$) in the simulations of the fine textured soil with the Tully climate In contrast, N losses increased with increasing rainfall at both locations (Figure 6.11b). The relationships were significant for both soil in the Tully simulations ($P < 0.10$) and the fine textured soil with the Mackay climate ($P < 0.05$).

At ‘face value’ the trends for both yields (Figure 6.11a) and N losses (Figure 6.11b) to increase with increasing rainfall in the Mackay simulations suggests that rainfall limited cane yields more than N. If so, applying more N fertiliser would not have notably increased yields. This was this case in 13 of the 14 crops simulated: there was only one situation where applying 30 kg/ha more N fertiliser (i.e. the 210 kg/ha N rate) was simulated to notably (i.e. by more than 2%) increase yields; the coarse soil in the wettest year simulated, 2001 (Figure 6.11a).

The relationship between rainfall and yield was different in the Tully simulations, with high rainfall giving lower yields (Figure 6.11a) and higher N losses (Figure 6.11b). For both soils, cane yields were negatively correlated ($P < 0.05$) with rainfall (data not shown). It is tempting to assign ‘cause and effect’ to this correlation. However there are climate factors, importantly radiation (Figure 6.12), that are related to rainfall and affect sugarcane growth independent of N dynamics. The limitation of N on crop growth in the simulations is indicated by the increase in yield from the application of more N fertiliser. In the 14 crops simulated, six had yields increase by more than 2% with the application of 30 kg/ha more N fertiliser (Figure 6.11a) indicating that these crops were N-limited at 180 kg N/ha. Of these six N-limited crops, three occurred in the two highest rainfall yields (1999 and 2000), although another crop in these years (the fine textured soil in 2000) was not N-limited. Of the other three N-limited crops, two occurred in a year (2001) with close to average rainfall and one in a relative dry year (2003). Thus, while crops simulated at Tully tended to be N-limited in the wettest years, that was not an inevitable situation; N limitations could occur in any year. Presumably rainfall distribution is an important factor as well as amount.

The simulation results discussed in this section show the complex interrelationships that exist between climates, crop growth, N fertiliser rates and N losses to the environment, even with a highly simplified representation of sugarcane crop management. If in these simulations a particular outcome was unlikely to be caused by a single factor, that conclusion will be even more applicable in sugarcane crops exposed to the full range of management practices that occur in commercial sugarcane production.

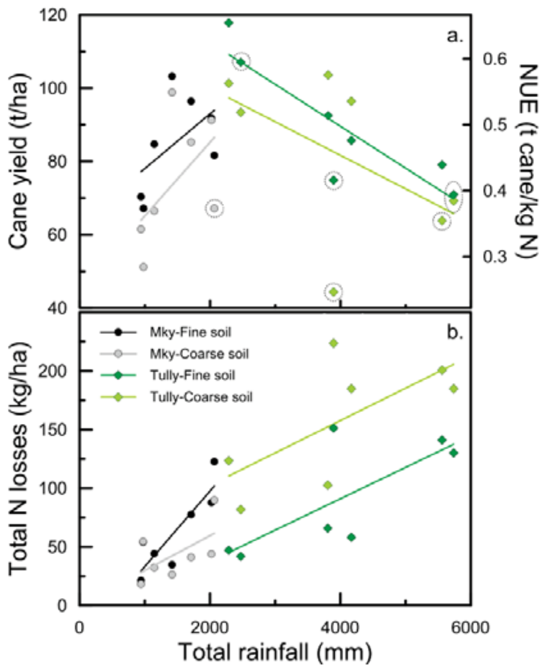


Figure 6.11. The simulated relationship between total rainfall falling during each crop and (a) cane yield and NUE, and (b) total N losses (i.e. denitrification plus leaching) for crops simulated in Figure 10 with 180 kg/ha of N fertiliser applied. The lines indicate the trends in the data. The points circled indicate crops where yields simulated with 210 kg/ha of N fertiliser were more than 2% greater than yields at lower N rates. [NB: In (a), NUE is derived from cane yield divided by 180.]

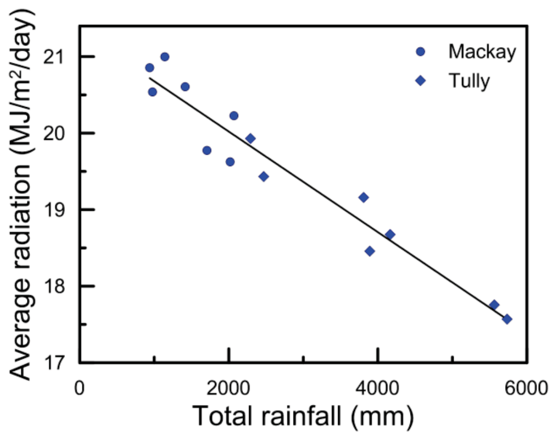


Figure 6.12. The variation in average daily radiation with rainfall for the crops simulated in Figure 6.10.

The range and drivers of NUE in sugarcane production

Overview of the simulations

Sugarcane yields were simulated under a wide range of soils and climates in five contrasting regions. Simulations were undertaken with APSIM-Sugar and associated soil modules described above (APSIM version 7.3). Soils, meteorological stations ("met-stations") and management practices were simulated in factorial combinations within the five regions, Bundaberg, Burdekin River Irrigation Area (BRIA), Burdekin Delta (DELTA), Mackay-Whitsunday, and Tully. The whole Burdekin region was considered as two regions because of the difference in soils and management (especially irrigation) practices

between the BRIA and the DELTA (Thorburn et al., 2011). Model parameters were collated from previous studies to represent important soil types in each region. There were two soils types in each of the BRIA and DELTA regions, three in the Bundaberg and Mackay regions and four in the Tully region (Table 6.2). Long-term historical climate data was obtained for representative meteorological stations in each region.

A general sugarcane cropping cycle was defined for the simulations. Sugarcane was planted in autumn (April - June) and harvested 14 to 15 months later. Ratoon crops were harvested after approximately 13 months. There were three ratoons simulated for the Burdekin regions and four in other regions. The field was then fallowed for six months. In the Burdekin regions, if a legume grain crop was grown in the fallow (fallow management options are outlined below), sugarcane planting was delayed by one month and the plant crop was harvested after 13 months. All crop residues were retained on the surface after harvest except in the Burdekin where they were 'burnt'. All fertiliser N was applied as urea at a depth of 50 mm, so ammonia volatilisation was considered negligible.

Crops were irrigated in the Bundaberg, Mackay and Burdekin simulations. Irrigation was limited to an annual maximum of 375 mm for Bundaberg and 100 mm for Mackay-Whitsunday. In the two Burdekin regions, four different irrigation strategies were simulated that gave a wide range in the amount of irrigation applied per crop (averaging 809, 1537, 2114 and 3780mm), achieved through spanning the typical differences in the amount of water applied in each irrigation (50, 80, 110 and 150 mm) and the frequency (approximately each 7-14 days) of irrigations (Thorburn et al., 2011a; Biggs and Thorburn, 2014). The amount of water per irrigation was 37.5 mm for Bundaberg and 42.5 mm for Mackay-Whitsunday limited to a maximum of 375 mm/crop for Bundaberg and 100 mm/crop for Mackay-Whitsunday. Runoff from each irrigation was explicitly simulated based on soil hydrology parameters and antecedent soil conditions (Empson et al., 2012; Thorburn et al., 2011), rather than estimated from generic irrigation efficiency assumptions (as is commonly done). The effects of water logging and lodging were included in the simulations, with the 'rules' governing these processes coming from experience gained in simulating field experiments (e.g. Thorburn *et al.*, 2011a; Skocaj et al., 2013; Biggs and Thorburn, 2014; Meier and Thorburn, 2014).

Management practices explored in the simulation were rates of N fertiliser, timing of N fertiliser application date (relative to planting or harvesting), splitting N applications in plant crops, fallow management (bare, a ley legume or a grain legume), tillage (four levels, increasing in number and severity of operations) and in-field traffic management (controlled traffic or conventional). N fertiliser amounts applied came from either two recommendation 'systems' or fixed amounts per crop. The two systems were Six Easy Steps (Schroeder et al., 2010a), where the amount of N varies according to district and soil type, and N Replacement (Thorburn et al., 2011a), where the amount of N applied depends on the actual yields grown. The fixed amounts simulated in Bundaberg, Mackay and Tully varied from 80 to 240 kg/ha/crop in ratoon crops, with 25% less N applied to plant crops. In the two Burdekin regions, higher fixed amounts (110-320 kg/ha/crop) were simulated to account for the higher yield potential in these regions.

To avoid having patterns in climate coinciding with the patterns in the cropping cycle, simulations were started in each of six years; 1902 – 1907. Simulations run until 2011, and outputs amalgamated over the six 'start years'. Simulation outputs prior to 1927 were discarded to minimise the effect of non-equilibrium effects in the modelled system on simulation results.

The combination of regions, soils, management practices and years resulted in 6.9M simulated crops, compromised of 1.5M plant crops and 5.4M ratoon crops.

Range in simulated NUE

NUE (t cane/kg fertiliser N) was calculated for all simulations. There was a wide range of NUE within the 6.9M simulated sugarcane crops, with values of ~0.3 t cane/kg N in some simulations where yields were small (i.e. < 50 t/ha), and > 5 t cane/kg N where yields were high and N fertiliser inputs low (Figure 6.13). This high variation results from the numerous interactions between climate (as illustrated above, Figure 6.11a), soils and management to produce a wide range of yields that, in many cases, were independent of the amount of N applied. For example, the linear patterns apparent in Figure 6.13 are the result of different yields (coming from climate, soils and management interactions) in different years when a constant N rate (e.g. 140 kg/ha) was applied to crops in the simulations.

High NUE values (i.e. > 2 t cane/kg N) dominantly occurred in plant crops (Figure 6.13), representing the low N fertiliser inputs to plant crops that occurs with some of the N management systems simulated (e.g. reducing N fertiliser applied following a legume fallow). However, most plant crops had NUE values of 0.7 to 1.8 t cane/kg N occurring at yields of 70 to 150 t cane/ha. In comparison, the most common NUE values in ratoon crops were 0.4 to 1.2 t cane/kg N occurring at yields of 70 to 110 t cane/ha.

There was a trend for NUE to increase with increasing yield in plant crops. In ratoon crops however, the highest yields (e.g. > 120 t/ha) were generally associated with a NUE value of 0.8 to 1.2 t cane/kg N, whereas the highest NUE values (i.e. > 2 t cane/kg N) were mainly associated with yields < 100 t/ha.

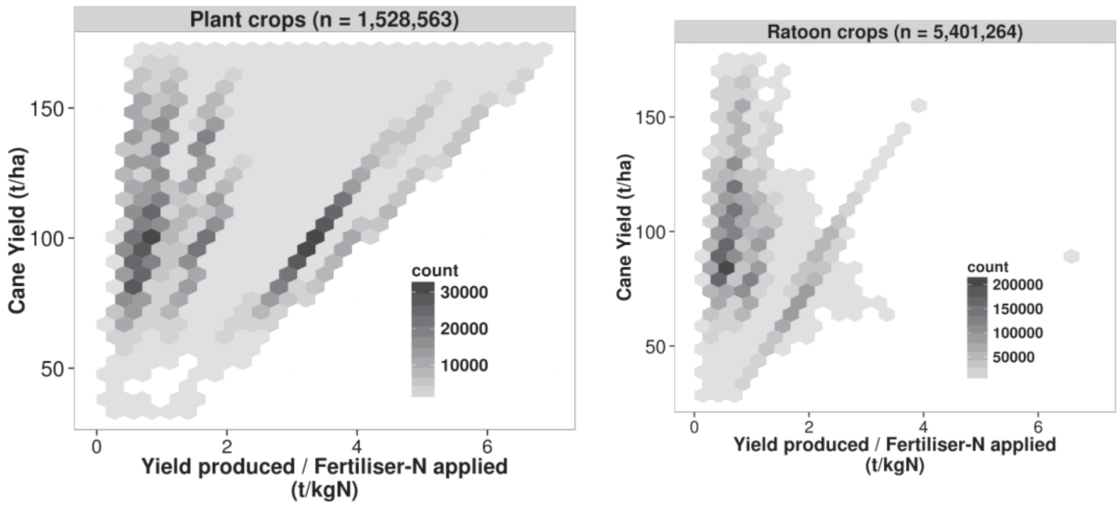


Figure 6.13. The NUE (yield produced/fertiliser N applied) for 6.9M sugarcane crops simulated across regions, soil types and management practices over 84 years (to 2011). Hexagons contain all the data points located in that region of the figure. The number of points plotted within each hexagon is indicated by the shade of grey of the hexagon (darker shades represent a higher number of points).

Factors that influence NUE

Given the wide range of NUE values that occurred in the simulations (Figure 6.13), it is valuable to identify which of the management factors included in the simulations (i.e. N fertiliser, timing of N fertiliser application, splitting N applications in plant crops, fallow management, tillage, and in-field traffic management) were associated with high NUE. To provide this information, the simulation results shown in Figure 6.13 were statistically analysed using 'data mining' techniques, i.e. cluster (Kaufman and Rousseeuw, 1990) and tree (Breiman et al., 1998; Therneau et al., 2013) analyses, to associate the management practices with NUE. The results are output as a 'tree diagram' that shows significant binary divisions between factors (such as management factors, regions, etc) associated with NUE.

Across the 6.9M simulated sugarcane crops, the average NUE was 0.91 t cane/kg N (Figure 6.14). Across all those crops NUE was significantly lower in ratoon crops (averaging 0.73 t cane/kg N) than plant crops (averaging 1.6 t cane/kg N).

For both ratoon and plant crops, the most influential factor was N fertiliser application rate. For ratoon crops, applying between fixed rates (i.e. that rate to every ratoon crop) of 160 and 320 kg N/ha/crop (denoted n160 and n320 in Figure 6.14), or using the Six Easy Steps system (denoted n6es in Figure 6.14) to determine N rate, had significantly lower average NUE (0.56 t cane/kg N) than applying <110 kg N/ha/crop or using the N Replacement system to determine N rate. The highest N rates (240 and 320 kg N/ha/crop) resulted in the lowest average ratoon crop NUE (0.39 t cane/kg N). Applying between 160 or 180 kg N/ha/crop or using the Six Easy Steps systems resulted in an average NUE 0.63

t cane/kg N. The third grouping of N rates for ratoon crops (applying <110 kg N/crop or using the N Replacement system) resulted in an average NUE 0.99 t cane/kg N. However, as N rates decreased and NUE increased, average cane yields decreased from 107 t/ha for the highest grouping of N management to 105 and 101 t/ha for the second and third lowest groupings. For ratoon crops, none of the other management factors (timing of N fertiliser application, fallow management, tillage or in-field traffic management) significantly influenced NUE.

For plant crops, there were only two significant groupings for N fertiliser rates: (1) applying between 160 and 320 kg N/ha/crop, and (2) applying <110 kg N/crop, or using the Six Easy Steps or N Replacement systems (Figure 6.14). The higher N rate grouping had an average NUE of 0.7 (t cane/kg N) and yield of 111 t/ha. For the lower N rate grouping, NUE was significantly determined by management of the preceding fallow, with bare fallow associated with lower NUE (average of 1.2 t cane/kg N) than fallows with a legume grown either as a grain or a cover crop. For the plant crops preceded with a legume fallow, the average NUE depended on multiple interactions between the specific N rates, type of legume (‘grain’ or ‘cover crop’) and region. For the different groupings, average NUE ranged from 1.6 to 3.7 t cane/kg N. Unlike the situation with ratoon crops, there was no trend in average cane yield between the different groupings, with the highest average cane yield (114 t/ha) occurring in the grouping with the highest average NUE. The lack of correlation between cane yield and NUE was affected by the N contained in the legume crops, which was available to the plant crop but not included in the calculation of NUE. As with the ratoon crops, other management factors (splitting N fertiliser applications, tillage or in-field traffic management) did **not** significantly influence NUE.

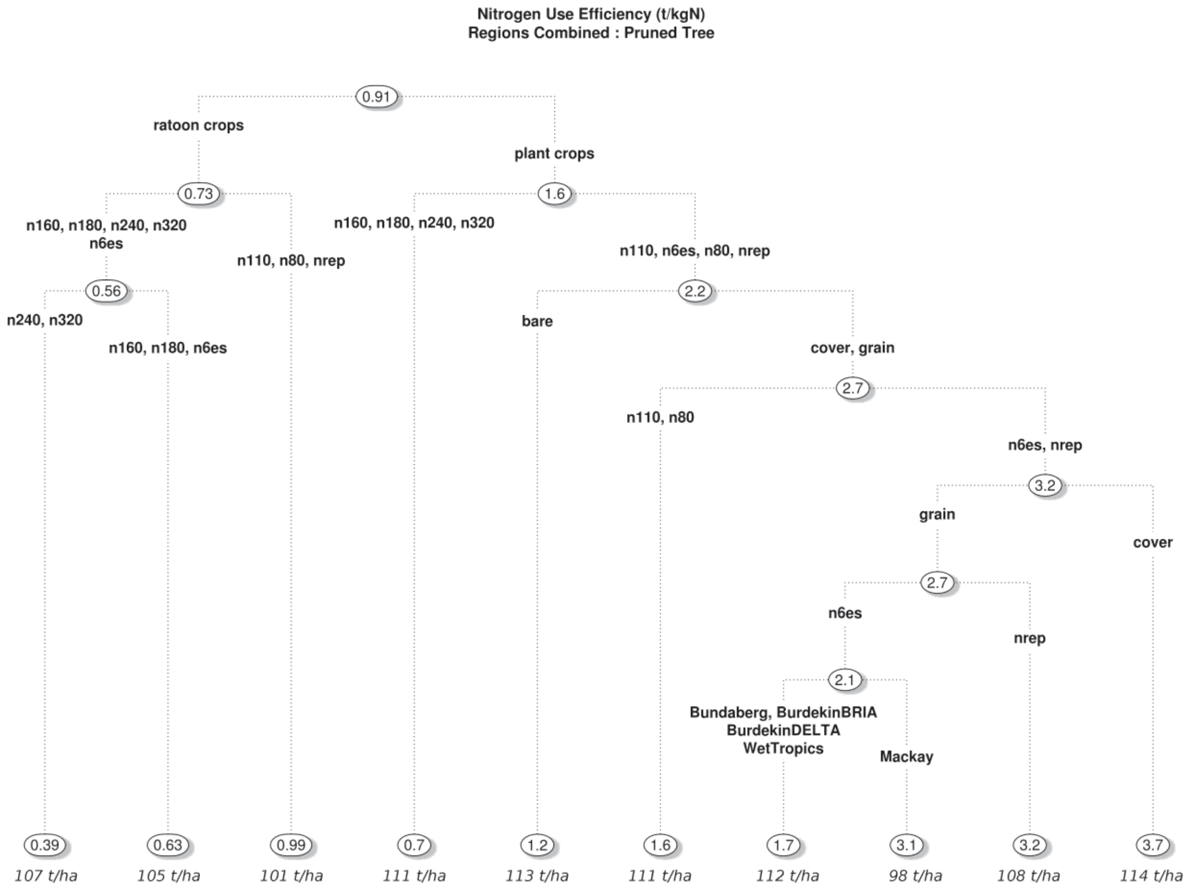


Figure 6.14. A regression tree analysis of the factors determining NUE (t cane/kg fertiliser N) predicted for 6.9M sugarcane crops simulated under a wide range of management practices, soils and climates over 84 years. Labels are explained in the text.

The data mining analysis was also conducted on simulations for each individual region (data not shown). As in the combined regions analysis, the factors most affecting average NUE were crop class (plant v ratoon crops) N rate and fallow management. However, there were differences in order of importance of these factors. For example, N rate was the primary determinant of NUE in Tully and Bundaberg, whereas it was crop class in the other regions. In the Burdekin Delta region, soil type was also a significant factor. The average NUE (across all crops) also differed between regions, being highest in the two Burdekin regions (which had the highest average yields) and lowest in Bundaberg (the lowest average yields). As with the analysis of the combined regions, timing of N fertiliser application, splitting N in plant crops, tillage and in-field traffic management did **not** significantly influence NUE.

6.6 Re-examination of the N fertiliser requirement

As described above, the N fertiliser requirement (which is the inverse of NUE) is a critical component of N management recommendation systems and a “rule of thumb” about N fertiliser requirements of sugarcane developed from an early application of the APSIM model (Keating et al., 1997) has been influential in the Australian sugarcane industry through its inclusion in the Six Easy Steps program

(Schroeder et al., 2010a). However, that “rule of thumb” was based on simulations under a single climate (Ingham), single management system and a limited range of soils (a range of N fertility levels, but uniform soil physical properties). There will likely be benefit in conducting their analysis under a wider range of climates, soils and management factors. As well, there have been developments in APSIM (described above) since that time that should result in more accurate representation of sugarcane N responses and may affect N fertiliser requirement. Thus, we determined N fertiliser requirement on the climates, soils and management factors described above using the same approach as Keating *et al.*, (1997).

Analyses

Overview

Analyses were preformed on a sub-set of the simulations undertaken for the analysis of NUE. As described above many of the management practices simulated (i.e. N fertiliser application date, splitting N applications in plant crops, tillage and in-field traffic management) did not significantly affect simulated NUE (Figure 6.14) so only a single level of these factors were include. As well, only bare fallows were simulated to avoid non-fertiliser N affecting simulated N fertiliser requirement. The resultant management system approximated a “C-Class” system (van Grieken et al., 2014, 2013b, 2010) with sugarcane growth simulated under a range of N fertiliser application rates. Functions (described below) were fitted to the predicted yield at each N rate to derive an ‘N response’ curve for each crop simulated for all the soil-region combinations. To further simplify the analysis, N response curves were only developed for ratoon crops (following Keating et al., 1997). The resultant number of individual N response curves ranged from ~500 for each of the two Burdekin regions to ~2,500 for Mackay. These curves were then used to determine the yield at maximum profitability, and the N rate (defined as the optimal N fertiliser rate: Keating et al., 1997) of associate with this yield, as described below.

Determining the optimal N fertiliser rate

One of three functions were fitted to describe the relationship between yield and the amount of N fertiliser: the Weibull model,

$$Yield = A + B \times e^{-e^{C} fert^{D}} \qquad (1)$$

a four-parameter Logistic model,

$$Yield = E + \frac{F-E}{1+ e^{(F-fert)/G}} \qquad (2)$$

or a simple logistics model,

$$Yield = \frac{H}{1+e^{(I-fert)/Jl}} \qquad (3)$$

where *Yield* is sugarcane yield (t/ha), *fert* is the N fertiliser rate (kg/ha) and *A, B, C, D, E, F, G, H, I* and *J* are empirical constants determined in fitting the curves. Three different functions were used as each is suited to fitting response curves of different "shapes", which varied from the 'classic' curves with a 'plateau' at high N rates to ones that that had no plateau.

From these curves, profitability at different N rates was calculated from partial gross margins (i.e. the difference between income from sugarcane and costs of N fertiliser and harvesting), with the N rate at which profitability was 99% of maximum then identified (e.g. Figure 6.1a). For the economic analysis the income from sugarcane was $30.14/t, the cost of N fertiliser was $1.38/kg N and harvesting costs were $7.73/t (van Grieken et al., 2014). Thus, for each simulated N response curve we identified the N rate at which profitability was 99% of maximimum (referred to as the optimal N rate) and the cane yield at this optimal N rate.

The N fertiliser requirement (kg N/t cane) is related to the slope of the relationship between the N optimal and cane yield at that N rate (e.g. Figure 6.1b). To determine the N requirement for each of the regions simulated, we fitted a linear quantile regression to the optimal N-cane yield results for each region. We fitted the regression to the 80th percentile: that is, for any given yield, there was an 80% chance that the optimal N rate was less than that implied by the quantile regression. To compare our approach with the original approach undertaken by Keating et al. (1997), we also fitted the quantile regression to their simulation data.

Results

Comparison with previous analysis

While we have broadly adopted the same approach as Keating et al. (1997) for determining sugarcane N fertiliser requirements, we have used different mathematical and statistical techniques to integrate the simulation outputs. To gauge the effect of these different techniques we analysed Keating's et al. (1997) simulation data with our approach. The N fertiliser requirement for Keating's et al. (1997) data resulting from our analysis was 1.2 kg N/t cane (Figure 6.1b), in contrast to their result of 1.4 kg N/t cane (yields <100 t/ha) and 1.0 kg N/t cane (yields >100 t/ha). Our analysis thus gives a lower optimal N rate at cane yields <100 t/ha.

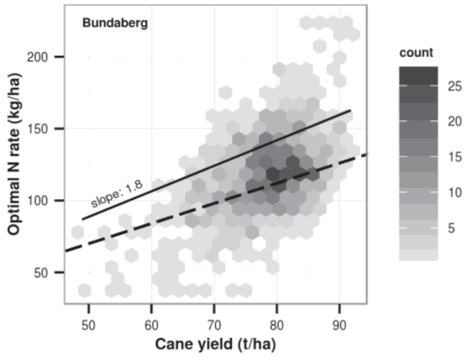
To assess the practical significance of the different N requirement analyses, we calculated the optimal N rate for a cane yield of 120 t/ha. This yield was selected as it is the yield potential identified for many regions in current industry N recommendations (Schroeder et al., 2010a). For this yield, Keating's et al. (1997) analysis gave an optimal N rate of 160 kg/ha whereas our analysis gave 144 kg/ha. The difference (16 kg/ha) is similar to the contribution of N from mineralised organic matter in soils with moderately low organic carbon (Schroeder et al., 2010a). Thus while our analysis produce different results from those of Keating et al. (1997), the results are in keeping with the understanding of sugarcane N requirements resulting from research conducted over the past 15 years (Schroeder et al., 2010a; Thorburn et al., 2011a).

Regional variation in N fertiliser requirements

For any given sugarcane yield our analysis suggests there can be a wide range in optimal N rates (Figure 6.15). The range is larger than that seen in the original analysis by Keating et al. (Figure 6.1b) likely due to the greater number of N response curves simulated and analysed in this study.

The N fertiliser requirement resulting from the quantile regression was 1.3 kg N/t cane in the Mackay and two Burdekin regions, 1.4 kg N/t cane in the wet tropics and 1.8 kg N/t cane in Bundaberg (Figure 6.15). The reason for the higher N requirement for Bundaberg is unclear, and its diagnosis beyond the scope of this study.

a



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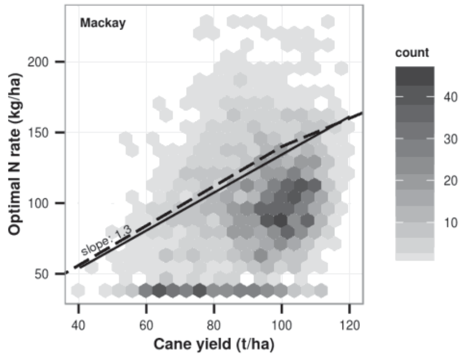

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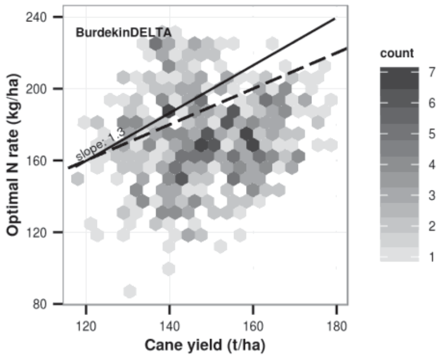

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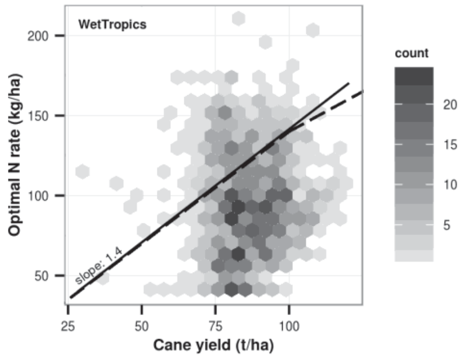

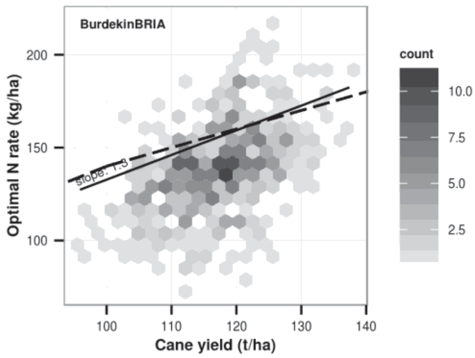

Figure 6.15 The variation in optimal N (i.e. the N fertiliser rates at which profitability is 99% of maximum) with yield predicted for ratoon crops over 84 years (to 2011) in five regions. In all simulations, crops were managed under "C-Class" practices. In each plot, hexagons contain all the data points located in that region of the figure. The number of points plotted within each hexagon is indicated by the shade of grey of the hexagon (darker shades represent a higher number of points. The solid line indicates the quantile regression fitted to the 80th percentile (with the slope shown), and the dash line is the "rule of thumb" for sugarcane N requirement (Keating et al., 1997)

6.7 How big is the sugarcane yield gap?

One possible way to increase NUE is to increase sugarcane yields. So in the context of increasing NUE it is relevant to ask what is the yield potential of sugarcane in Australia and how does that compare with actual yields? The difference between potential yields and those achieved by farmers is known as the yield gap (van Ittersum et al., 2013). Currently, there is substantial interest internationally in defining the magnitude and causes of yield gaps in a variety of crops (http://www.yieldgap.org/). Crop models provide a useful framework for investigating yield gaps. For example, Muchow *et al.*, (1997) undertook a yield gap analysis for sucrose production in the Australian sugarcane industry based on predictions from the APSIM-Sugar model. In the context of NUE, the potential yield of sugarcane rather than sucrose is of interest because the cane contains substantial amounts of N that are removed from the field at harvest. So a sugarcane yield gap analysis may provide insights into the extent that N uptake by crops could be increased.

Potential plant growth (for given genetic traits) is determined by the amount of intercepted solar radiation, with the conversion of that radiation into biomass (through photosynthesis) limited by temperature and atmospheric CO_2 concentration. These processes are represented in many crop models, so these models provide a basis to predict potential yields. However, yields are limited by many other factors (e.g. availability of water and nutrients, subsoil constraints to root growth and function, and the effects of pests and diseases), which is why potential yields are rarely achieved in practice. If crop models are able to represent these other limitations, and so simulate actual yields, they can provide insights into the yield gap.

Early modelling studies in the Australian sugarcane industry focussed, explicitly (Muchow et al., 1997) or implicitly (Keating et al., 1997), on potential yields as limited by water (rainfall or irrigation) availability. Some of the more recent studies have focussed on representing actual yields in simulations, through recognising subsoil constraints to root growth and incorporating the effects of lodging and/or water logging in simulations (Skocaj et al., 2013; Biggs and Thorburn, 2014; Meier and Thorburn, 2014; Thorburn et al., 2011). Comparing the predictions of yields with and without these constraints provides an indication of the yield gap in sugarcane production.

An extensive yield gap analysis was beyond the scope of this study. However, to provide first insights into sugarcane yield gaps, a subset of the simulations described above were run with no effects of water logging and/or lodging. The simulations consisted of two soils, each of contrasting texture, in the Bundaberg, Mackay, Innisfail and Tully regions. The Burdekin regions were excluded because of the complexity imposed by simulating furrow irrigation. The management system simulated approximated a “C-Class” system in each region.

The yields simulated with constraints to growth ranged from 82 to 97 t/ha (Figure 6.16). When these constraints were removed, simulated yields increased by 45 to 85 t/ha, being ~145 t/ha in Bundaberg and Mackay, and ~180 t/ha in the two wet tropics regions. Cane yields of this magnitude are rare or unheard of in these districts, and we are not suggesting they could be attained in practice. However, the simulated potential yields reflect the solar radiation received in these districts, which averages from 17 (in Tully) to >19 MJ/day/m^2 in Mackay (Muchow et al., 1997).

Added to this, in the wet tropics the abundant rainfall means crops are rarely water stressed so the potentials are high in these regions. This situation is similar to that of fully irrigated crops in the Burdekin region, which have potential yields of ~200 t/ha for (Muchow et al., 1994).

These results suggest there is a substantial yield gap in Australian sugarcane production. We have not sought to quantify the relative contribution to that gap from subsoil constraints, lodging and/or water logging in the simulations. However doing that would be straight forward, providing one path to better understanding and potentially minimising the cause of the yield gap in Australian sugarcane production.

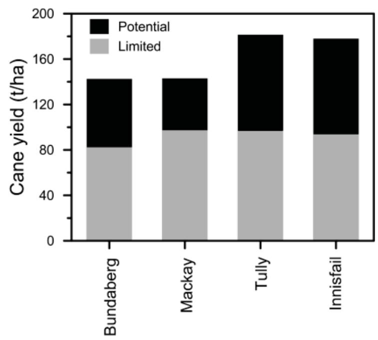

Figure 6.16. Average sugarcane yields at two sites in each of four districts simulated with and without ("Potential") limitations to crop growth.

6.8 Discussion

The Australian sugarcane industry has access, in the APSIM farming systems model, to a very well developed and tested capability for simulating many features of sugarcane production systems, including the growth of sugarcane (and associated rotation crops) under different climates and different levels of water and nitrogen stress. Representing these features is based on modelling crop and soil water dynamics and soil carbon-nitrogen cycling including losses of nitrogen to the environment. The model has been tested extensively in Australian and, increasingly, overseas environments.

Over the two decades in which this capability has been developed, modelling studies have had substantial impacts on our understanding of N-related issues in Australian sugarcane production systems. A major impact has been the incorporation of insights on sugarcane nitrogen requirement from early APSIM simulations into the SIX EASY STEPS guidelines for nitrogen management. APSIM simulation analyses of nitrous oxide emissions were also used by CANEGROWERS to promote the industry's position on impacts of potential greenhouse gas mitigation policy options. More recently, APSIM has been the basis for representing sugarcane production systems in the program evaluating the effectiveness of Federal Government grants made to farmers (for actions that include increasing NUE) to improve the quality of water leaving their farms. This work shows the positive off-farm impacts of cane farmers' moves to "BMP" nitrogen management and higher NUE. It has also underpinned development of informatics capabilities for undertaking and analysing results from large numbers of simulations (e.g. ~7 million simulated cane crops). These capabilities allow, for the first time, an approximate representation of the diversity of the block- or farm-level variability in behaviour of sugarcane production across the industry.

For this review, we re-analysed previously run industry-scale simulations to ask three questions: (1) What are the ranges of NUE are likely to occur in Australian sugarcane production under the range of climates, soils and common management practices found? (2) Which of these management practices result in high NUE? (3) Are there regional differences in sugarcane nitrogen requirement, and therefore the potential to regionally customise nitrogen management guidelines? The answers to these questions were:

1. The interactions between climate, soils and management produces a wide range of simulated NUE, ranging from ~0.3 t cane/kg N where yields were low (i.e. < 50 t/ha) to >5 t cane/kg N where yields were high and nitrogen fertiliser inputs low (mainly in plant crops). It is clear from these results that inter-annual variability in climate has a large effect on sugarcane growth and NUE.

2. Of the wide range of management practices simulated (i.e. variations in N fertiliser rates, timing of nitrogen fertiliser application, splitting nitrogen applications in plant crops, fallow management, tillage, and in-field traffic management) the **only** practice significantly influencing NUE in ratoon crops was nitrogen fertiliser application rate. Nitrogen fertiliser rate was also an important factor determining NUE in plant crops. For plant crops receiving low amounts of nitrogen fertiliser (i.e. < 110 kg/ha/crop), NUE was also affected by the management of the preceding fallow because the interactions between residual nitrogen from the fallow (lower for crops preceded by a bare fallow than a fallow with a legume, grown either as a grain or a cover crop) and the influence of the preceding fallow on nitrogen recommendation systems.

3. Sugarcane nitrogen requirement varied in the simulations from 1.3 kg N/t cane for Mackay and the Burdekin regions, to 1.4 kg N/t cane in the wet tropics and 1.8 kg N/t cane in the Bundaberg region. The reason for the higher requirement at Bundaberg was unclear. There was no evidence in the simulations for nitrogen requirement differing between low and high (i.e. >100 t/ha) yielding crops.

These simulation results have a number of implications for increasing NUE in the Australian sugarcane industry:

- They support current industry initiatives promoting adoption of SIX EASY STEPS guidelines for nitrogen that will reduce industry-average nitrogen fertiliser (which are above those recommended in all regions except the wet tropics) and increase NUE. They also support initiatives investigating new management technologies (e.g. use of enhanced efficiency fertilisers and/or application of precision agriculture) to facilitate reductions in nitrogen rates below those currently recommended in the SIX EASY STEPS guidelines.
- They also support current initiatives in integrating seasonal climate forecasting into nitrogen fertiliser management systems.
- They suggest that a decision support system based on the predictive capacity of APSIM may be valuable in assisting cane farmers accessing and incorporating climate variability and seasonal climate forecasting into their nitrogen management, as is being done in the Australia grains industry through YieldProphet® (Figure 6.17).

- The analyses of nitrogen requirements undertaken in this review illustrate a methodology that could help customise the sugarcane nitrogen requirements in the SIX EASY STEPS guidelines. For example, they could be used to determine soil specific nitrogen requirements that, if combined with the regional analyses described above, would align nitrogen requirements with the spatial scales of other aspects of SIX EASY STEPS (i.e. regional level for yield potential, soil level for nitrogen mineralisation). The simulation methodology could also support customisation of nitrogen requirements as SIX EASY STEPS is further developed to represent new initiatives to improve NUE, such as enhanced efficiency fertilisers, precision agriculture, etc.

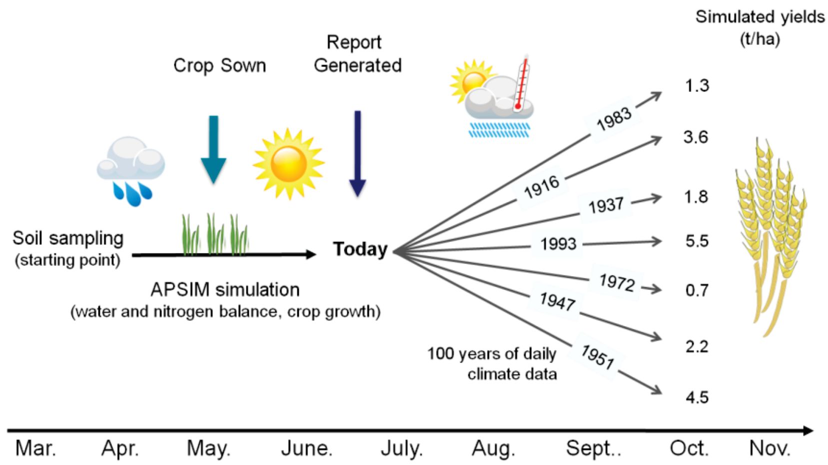

Figure 6.17. Schematic representation of a YieldProphet® forecast (after Hochman et al., 2009). A report (i.e. a prediction of crop growth) generated on a particular day shows the yield predicted to occur for all the climates in the past 100 years given the amount of soil water and mineral nitrogen at the time of planting, and nitrogen fertiliser applied to the crop. The yield benefits from adding more fertiliser can be assessed through YieldProphet® allowing farmers to assess their likely return on different amounts of fertiliser.

In recent simulations of Australian sugarcane production systems, it has become obvious that the yields obtained by cane farmers are, on average, substantially below those that could be achieved given the solar radiation and rainfall (and irrigation) under which crops grow: i.e. there is a substantial **yield gap**. A consequence of below potential yields is a reduction in NUE and an increase in nitrogen losses to the environment. Increasing cane yields is the ultimate “win-win” for the sugarcane industry. Yield gap analysis has been shown to provide a useful framework for understanding, and developing strategies to reduce the factors causing yield gaps (van Ittersum et al., 2013). The Australian grains industry is investing in yield gap analysis (Hochman et al., 2012), and there is likely a clear benefit to the Australian sugarcane industry from similar investments.

An important issue that has received little previous attention is the interaction between irrigation management and NUE, despite the fact that much of the Australian industry is irrigated. Irrigation increases cane yields (which will increase NUE) but can also enhance losses of nitrogen from the soil through leaching and denitrification (potentially decreasing NUE). Irrigation scheduling decision support systems are available to help cane farmers optimise irrigation management. However, they do not include nitrogen cycling, so can not be used to increase both irrigation efficiency and NUE. It would

be useful to determine the value of expanding irrigation management decision support systems to include nitrogen management.

Finally, models and simulation capabilities are only as good as the information on which they are based. There are a number of attributes of nitrogen in Australian sugarcane systems that are not represented in APSIM because they are not adequately understood and quantified at a processes level. A good example is the occurrence of NH_4 in coastal soils (especially north of Townsville) and the kinetics of ammonium uptake by sugarcane. The "computer code" exists in APSIM to represent these processes; it is the values of the governing parameters that are unknown. There has also been little activity over the past 15 years on parameterising new sugarcane varieties. Strategic investment into understanding these and other agro-ecosystem functions will underpin an enhanced simulation capability available to the sugarcane industry.

6.9 Acknowledgements

The work reviewed in this paper came about through projects funded by many sources. These include The CRC for Sustainable Sugar Production, Sugar Research Australia, the former Land and Water Australia and, more recently, the Australian Government. We thank these organisations for their support. We also acknowledge support from Australian Government and Sugar Research Australia for the development of this paper, and the constructive comments of Dr Mike Bell.

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7. PART I: Use of enhanced efficiency fertilisers to increase fertiliser nitrogen use efficiency in sugarcane

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7.1 Abstract

Enhanced efficiency fertilisers are fertilisers that release nitrogen (or other nutrients) more slowly than conventional fertilisers like urea, or temporarily stabilise the nitrogen in a form less liable to losses. When the slow release or stabilisation is synchronised with plant nitrogen uptake it can potentially reduce nitrogen losses, improve fertiliser use efficiency and increase yield. This chapter describes the different types of enhanced efficiency nitrogen fertilisers and reviews experimental evidence for their control of nitrogen release or stabilisation as well as for benefits derived from their use in sugarcane as well as other industries. The chapter also considers data on crop nitrogen demand, modelling opportunities and economic analyses.

Research and development of enhanced efficiency fertilisers has been going on for 40-50 years and many different mechanisms have been explored to achieve either slow release or stabilisation of fertiliser nitrogen. As the early studies did not demonstrate clear yield benefits, the interest in these more expensive fertiliser products waned. Recent years have, however, seen further trialling worldwide driven by concerns about low fertiliser use efficiency and nitrous oxide emissions and leaching losses. Most of these more recent experimental trials have focussed on a subset of product types, namely polymer or polymer-sulfur coated slow/controlled release fertilisers or urease and nitrification inhibitors, which temporary stabilise the nitrogen in urea or ammonium form.

The results from the limited trials to date in Australian sugarcane suggest that enhanced efficiency fertilisers may have agronomic and environmental benefits in at least some situations. As the effectiveness of enhanced efficiency fertilisers is affected by a complex set of interacting soil, crop, climate and management factors, season-to-season and site-to-site variability contributes to inconsistencies in the experimental findings suggesting that further and more in-depth investigations are warranted. Reviews covering experiences in other industries and overseas also highlight the inconsistent agronomic and environmental benefits from enhanced efficiency fertilisers, although the on average positive effects obtained in recently published meta-analyses are cause for optimism.

Various recommendations for further research and improved trialling are summarised at the end of the chapter, including the need to better characterise release patterns or stabilisation periods and how these are affected by climatic and soil factors and to incorporate such measurements in experimental trials. Considerations relating to interpretation of meta-analyses and opportunities for cropping systems modelling to both interpret and extrapolate experimental findings are also discussed. More in-depth trialling and modelling will be able to provide a better understanding of the system interactions and the drivers for nitrogen loss in different environment and management situations. An assessment of the role for enhanced efficiency fertilisers in the sugarcane industry and recommendations on the relative suitability of different product types for different environment or management situations will

depend on this. As adoption of enhanced efficiency fertilises will depend on the balance between cost and achievable benefits, economic analyses will need to be included too.

7.2 Introduction

Increasing fertiliser nitrogen (N) use efficiency is of interest to the sugarcane industry in terms of optimising N supply and reducing environmental losses. Studies using labelled ^{15}N fertiliser have suggested that maximum recoveries in the sugarcane crop and surrounding soil may be just over 60% of N applied (Chapman et al. 1991; Vallis and Keating, 1994, Keating et al. 1997, Prasertsak et al. 2002, Wood et al. 2010). Loss of N from the soil before the crop can utilise it is assumed to be a key reason for the observed low efficiencies.

Key loss pathways of fertiliser and soil N affecting N use efficiency in Australian sugarcane are volatilisation, denitrification, nitrate leaching, surface runoff and erosion (Wood et al. 2010). The relative magnitude of these losses varies, however, depending on soil type, landscape position, amount and timing of rainfall, crop demand, and the form and method of fertilisater application. For example, ammonia volatilisation losses are largest when urea is surface applied (Prammanee et al.1989; Prasertsak et al. 2002) and under conditions of frequent minor wetting (Denmead et al. 1990; Freney et al. 1992b), denitrification losses are largest under waterlogged conditions in the presence of enough of soil carbon (Weier et al. 1996, 1998; Chen et al. 2008b) and nitrate leaching losses are largest in permeable soils (Verburg et al. 1998b).

While the relative importance of loss pathways may vary from place to place and time to time, they all have in common that (temporary) surplus N in the soil or on the surface increases the risk and magnitude of losses. This has led to the concept of improving N use efficiency by better synchronising N supply with crop demand (e.g. Shoji and Gandeza 1992; Coale et al. 1993; Myers et al. 1997; Robertson 1997; Cassman et al. 2002; Crews and Peoples 2005). In turn, this concept of synchronisation, has prompted the development of enhanced efficiency fertilisers which either release the N more slowly (e.g. by encapsulating the fertiliser in a coating) or stabilise it in a form less liable to losses for longer by temporarily blocking or reducing a particular N transformation step (e.g. urease and nitrification inhibitors). The ideal enhanced efficiency fertiliser would provide nutrients in a form or at such a release rate that would minimise losses but also ensure crop uptake was not limited by nutrient supply (Hauck, 1985; Shoji and Gandeza, 1992; Morgan et al. 2009).

Reviews by Chen et al. (2008b) and Wood et al. (2010) have highlighted the potential role for these enhanced efficiency fertilisers in improving the efficiency of N fertiliser use in Australian agriculture and Australian sugarcane, respectively. These reviews have supported a renewed interest in enhanced efficiency fertilisers in Australia, characterised by an increasing number of experimental trials over the past 5-6 years using a variety of enhanced efficiency fertilisers.

This chapter reviews experimental findings relating to the use of enhanced efficiency N fertilisers in sugarcane to improve crop performance, increase N use efficiency, and/or decrease N losses. It is intended to help identify research needs and opportunities for the Australian sugarcane industry, but goes beyond the immediate experimental findings in Australian sugarcane trials to draw lessons from experiences in other countries and other industries.

This review firstly presents the different types of enhanced efficiency N fertilisers and how they control the amount and type of N supply. It then examines the experimental evidence for this control in the form of release patterns and stabilisation duration as well as considering responses to environmental factors such as soil water and temperature, microbial populations, etc. Two subsequent sections summarise the experimental evidence for any benefits derived from the use of enhanced efficiency fertilisers in Australian sugarcane as well as lessons that can be drawn from experiences elsewhere. As synchrony between N supply and N demand or stabilising applied N in forms less prone to loss would, at least theoretically, provide the best chance at improving fertiliser N use efficiency consideration is also made of crop N demand patterns, before commenting on modelling opportunities and relevant economic analyses. The chapter concludes with a statement covering outstanding questions and future opportunities.

7.3 Enhanced efficiency N fertilisers and their mode of control of N release or form

The in-principle or *prima facia* advantages of enhanced efficiency fertilisers have been understood for a long time and an enormous amount of work has been carried out in this area over the past 40-50 years (see, for example, the reviews by Lunt 1971, Prasad et al. 1971, Parr 1972, Hauck 1985, Shaviv and Mikkelson 1993, Shaviv 2001, Chen et al. 2008b; Chien et al. 2009 and Trenkel 2010). Despite this and the fact that a number of well-developed enhanced efficiency fertiliser technologies exist, their use amounts to less than 0.5% of total world fertiliser consumption (Shaviv 2001, Trenkel 2010) and tends to be restricted to specialised fields of application (Shaviv 2001).

Enhanced efficiency fertiliser technologies are, in essence, methods intended to provide nutrients (particularly N) in a form, at a rate, or in a pattern which increases uptake by the plant while minimising losses to the environment. The means by which this can be achieved are very diverse. The methods can be classified in a variety of different ways, but a common distinction is made between slow – and controlled release fertilisers, and stabilized fertilisers (Figure 7.1, Table 7.1; Trenkel, 2010; AAPFCO, 2013).

As the name indicates, slow- and controlled release fertilisers release nutrients at a decreased rate. This can be achieved in a number of ways. The most popular method uses a barrier/retarding layer to control fertiliser release. This is achieved by coating fertiliser cores or granules (most often urea) with non-organic coatings (e.g. sulfur coated urea - SCU), organic polymers (polymer coated urea (PCU); e.g. thermosetting resin or thermoplastic polymer) or a combination of multiple layers (e.g. polymer coated SCU – PSCU) (Shaviv 2001, 2005; Chen et al. 2008b; Trenkel 2010). Less commonly, the fertiliser may be embedded within a matrix of polymeric material, which leads to either a continuous or incomplete network of barriers to release (Shavit et al. 1995).

Slow release of crop available N can also be achieved by using organic or inorganic N compounds that react slowly in the soil to release available N. The slow reaction can involve microbial decomposition (e.g. urea formaldehyde - UF), chemical decomposition (e.g. Isobutylidene Diurea - IBDU), or sollubilisation (e.g. $MgNH_4PO_4$). Physical restrictions are also used to slow down the availability of the N. Examples of the latter include using a low surface to volume ratio (e.g. super granules), incorporation (dispersion) into an inert matrix that results in slowed diffusion or release through a tortuous path, and physical adsorption of N (usually NH_4) by exchange with charged compounds and

surfaces, including polymers (Lunt 1971), hydrogels (Tong 2009), clays, zeolites and organic compounds.

Table 7.1 tentatively includes in this category the product Black urea, a urea product coated with what Advanced Nutrients Australia (2014), its producers, describe as an "an organic complex specifically manufactured to contain a unique ratio of oxidative functional groups and cofactors of biological oxidation." It is suggested (Advanced Nutrients Australia (2014) that as the fertiliser dissolves ammonia hydrolysed from the urea bonds to the coating and in addition the materials of the coating promote the increase in microbial communities that temporarily immobilise the nutrients, providing effectively a slow release of N to the plant. The reported benefits of black urea (Australian Sugarcane 2010; Advanced Nutrients Australia 2014) and pot trials (Janse van Vuuren and Claassens 2009) with other crops sound promising, but the lack of published, experimental research experiments and trials that quantify the processes involved make it difficult to draw conclusions about the role such products could play as enhanced efficiency fertilisers in Australian sugarcane. The use of organic compounds to stabilise N fertilisers has been explored before (e.g. Garcia Serna et al. 1996, Siva et al. 2000) in the context of reducing ammonia volatilisation losses. It is important that claimed benefits of fertilizer additive products are examined both in terms of product and soil chemistry and agronomic effectiveness, as was done by Chien et al. (2014) for another copolymer product.

The terms slow release and controlled release are sometimes used interchangeably. Others have referred to the coated products as controlled release and the other methods as slow release. In recent years there has been some push (e.g. Shaviv 2001, 2005) to reserve the term controlled release for those products "for which the factors determining the rate, pattern, and duration of release are known and regulated during fabrication" (Chien et al. 2009). This has typically limited it to polymer coated fertilisers whose release is supposed to only be temperature dependent.

Stabilised fertilisers are "fertilisers amended with additives that reduce the transformation rate of fertiliser compounds, resulting in an extended time of availability in the soil" (Chien et al. 2009; AAPFCO, 2013). The enhanced efficiency of these fertilisers is not defined by their release, but is achieved by maintaining the released N in a form that is less susceptible to loss. Principal N transformation reactions targeted by these stabilisers are urea hydrolysis and nitrification. Urea hydrolysis is of interest, because this reaction raises the pH of the soil which along with high concentrations of ammonium (NH_4) can lead to considerable losses of gaseous ammonia (ammonia volatilisation). By inhibiting the urease enzyme, urease inhibitors reduce the rate of hydrolysis or delay the hydrolysis.

Nitrification inhibitors inhibit or slow down the biological oxidation of NH_4-N to nitrate-N (NO_3-N). As NO_3-N is in most soils more mobile than NH_4-N, this has the potential to reduce nitrate leaching during the inhibition period. In addition it may reduce the denitrification losses.

A few enhanced efficiency products combine two or more mechanisms. For example, in maize and cotton studies in the US reported by Halvorson et al. (2014, Hatfield and Parkin (2014) and Watts et al. (2014) two products were used that contained both urease and nitrification inhibitors (SuperU, AgrotainPlus). Trenkel (2010) provided an example of a Dd Meister®, a urea product which had a coating of nitrification inhibitor and a second coating of polyolefin. Another example are calcium

carbide products coated with wax and shellac (Mosier 1994) or embedded in a polyethlyene matrix (Freney et al. 2000) which provide a slow-release source of acetylene gas, a nitrification inhibitor.

Table 7.1 provides a comprehensive outline of the various types of enhanced efficiency fertilisers, together with some indication of the mechanism by which they are thought to act, and products representing these mechanisms. While only a limited number of products are currently trialled in the Australian sugarcane industry, the information is provided to indicate that a large variety of products is available, that different mechanisms will have inherent strengths and weaknesses, and that many different ways could be pursued to improve on the currently available products. Cost will of course be an issue for commercialisation and adoption (see Section 7.7).

There are many excellent reviews in the literature that describe these products, from that of Parr (1972) to Goertz (2000) (which provides rare detail on the manufacture of the different enhanced efficiency fertilisers), to the almost-encyclopaedic work of Trenkel (2010). Landis and Dumroese (2009) give a brief but useful summary of the types of enhanced efficiency fertilisers that are available and the commercial options for coated products for use in forestry. Shaviv (2001) provides an excellent summary of the issues and challenges which surround enhanced efficiency fertilisers, even today. It should be noted that controlled release is a field undergoing continuing development and there is, for example, interesting work being published in the area of targeted delivery systems in pharmaceuticals (Siepmann 2008, Davidson 2012) but only time will tell if these concepts will prove to be suitable or commercially viable in agriculture.

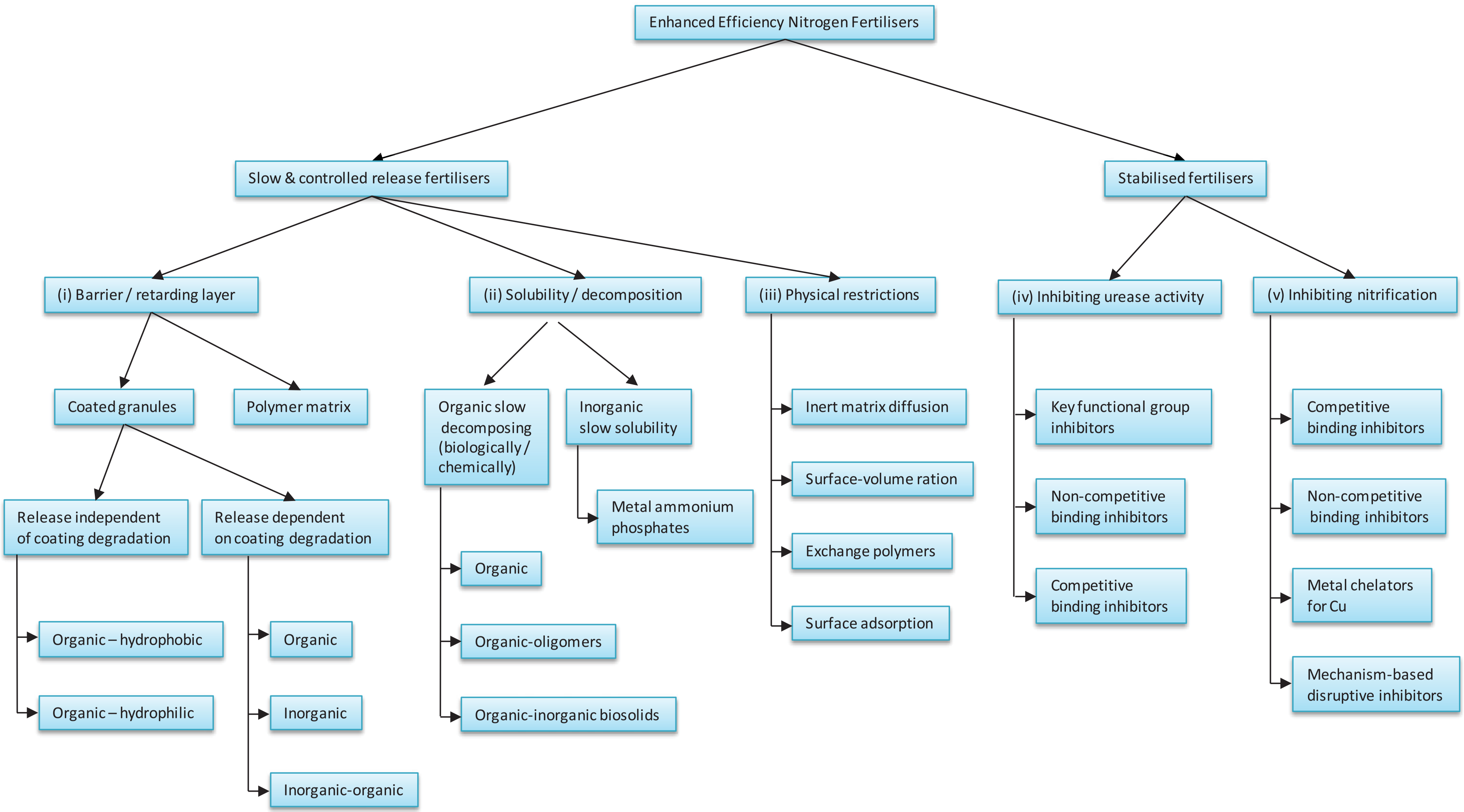

Figure 7.1. Classification of enhanced efficiency fertilisers by mechanism (adapted from Azeem et al. 2014). See Table 7.1 for more detail.

Table 7.1. Types of enhanced efficiency fertilisers and their mechanisms.

(i) Barrier/retarding layer

a) Description and Mechanisms
A (generally inert) layer covers the nutrient (normally urea) and acts as a diffusion barrier to inhibit release. Implementations vary from those applied as a molten coating (e.g. wax, sulfur or thermoplastics such as polyolefins) to resin-types (which are generally applied from solvents such as xylene and include thermosets (such as rubber) and reaction of separate monomers with the fertilizer prill (so-called reactive layer coating or RLC) (Gossett et al. 1993). Occasionally, products disperse granules of soluble fertilizer in a continuous matrix which is itself insoluble or partially-soluble are also considered in this category (Shaviv 2001).

Ideally, the inert layers are not affected by soil properties (such as pH, salinity, texture, microbial activity, redox potential, ionic strength of the soil solution) but only by temperature and the permeability of the polymer coating to moisture (Trenkel 2010). Release from RLC products is, for instance, mainly temperature related (Shaviv 2001). In the case of sulfur coatings, release is claimed to be due to water penetration through micropores and coating imperfections (Goertz et al. 1993, Goertz 2000) and/or rupture caused by increased osmotic pressure (Parr 1972, Gordonov et al. 1996. Shaviv and Mikkelson 1993). Alkyd-resin types or thermosets (eg Osmocote) are also swelled by osmotic pressure, stretching the layer and enlarging micropores in the coating thus enabling fertilizer release (Shaviv 2001).

Types

Release independent of coating degradation

Organic – hydrophobic

polyolefin, ethylene vinyl acetate (EVA), wax (hydrocarbon or plant-derived), styrene butadiene rubber (SBR), polyurethane, alkyd, RLC, fatty acid salts (Hudson et al. 1995, Trenkel 2010), copolymers of glyceryl esters of unsaturated acids with dicyclopentadiene (DCPD), epoxy-polyester resins, urethanes and polystyrenes etc) (Gordonov et al. 1996)

Organic – hydrophilic

hydrogels, super adsorbent polymer (SAP), polysaccharide etc.

Release dependent on coating degradation

Organic starch, polyacrylates, polyacrylamides etc

Inorganic sulfur coated urea, struvite etc.

Inorganic-organic sulfur-wax coated urea, polymer-sulfur coated urea (PSCU) (Shaviv 2001, Trenkel 2010)

Available commercially as

alkyd-resin; Osmocote® [Scotts/ICL], coated NPK fertilizer

polyolefin; Nutricote® [Chisso], Meister® [Chisso], polyolefin coated urea (Trenkel 2010), etc.

RLC; Polyon® [Pursell], ESN [Agrium], E-Max [ICL]

polyurethane; Polyon (Shaviv 2001, Trenkel 2010), Plantacote and Multicote (Shaviv 2001)

fatty acids/paraffin; Multicote [Haifa]

PSCU; Poly Plus PSCU 39N [Lesco], TriKote [Agrium/Pursell], Poly-S PSCU38.5-40N [Scott], A/F AntiFloat [Sumitomo] (Trenkel 2010), Lebanon Pro, Agrocote [Everris/ICL]

polyacrylate; Luquasorb [BASF]

polyacrylamide; Stockosorb [Evonik]

(ii) Solubility/decomposition

Description and Mechanism

The solubility of the principal fertilizer is chosen or chemically modified so the release characteristics of the principal nutrient are slowed. The modified form of N (i.e. urea formaldehyde, UF etc.) is primarily broken down by microbial action (Goertz 2000, Shaviv 2001, Guertal 2009) and

release is dependent on those factors that affect soil biological activity, including pH, moisture and temperature (Prasad et al. 1971, Goertz 2000, Shaviv 2001); Isobutylidene diurea (IBDU), on the other hand, is broken down by non-biochemical hydrolysis (Goertz 2000, Guertal 2009) and is primarily related to granule size (Goertz 2000, Shaviv 2001), moisture (Goertz 2000, Shaviv 2001), soil pH (Goertz 2000, Shaviv 2001) and to a lesser extent soil temperature (Goertz 2000). Cyclodiurea (CDU) is broken down by both hydrolysis and microbial action (Goertz 2000, Shaviv 2001). Oxamide, a direct substitute for urea, is broken down by microbial action (Goertz 2000). Inorganic materials such as struvite deliver N based on inherent solubility.

Types

Organic; oxamide (Parr 1972, Rubio and Hauck1986, Mikkelsen et al. 1994), oxamide-polyvinylalcohol composites (Takada et al. 1992).

Organic – oligomers; Organic oligomers made using urea. Generally urea-aldehyde condensates, such as urea-formaldehyde [UF], isobutylidene diurea [IBDU] (Goertz 2000), cyclodiurea or urea-acetaldehyde condensate [Crotonylidene DiUrea or CDU] (Goertz 2000, Shaviv 2001), triazone (Guertal 2009) or melamine

Organic/inorganic biosolids; crop residues, manures, composts, sewage sludge**,** blood and bone, hoof/horn/bone meal etc.

Inorganic;Struvite

Available commercially as

Urea-aldehyde; Nutralene, METH-EX 40, HD Super Fairway, CoRoN28-0-0, METH-EX 38, Nitro 26 CRN 26-0-0, FLUF 18-0-0, Plantodur, Plantosan, Azolon [Aglukon](Trenkel 2010) Nitroform [NOR-AM],Organiform, Granuform, Pro Turf [ICL], Osmoform[ICL], HiTech, Scotts (Goertz 2000)

Triazone; Formolene Plus [Tessenderlo Kerley Inc], N-Sure [Tessenderlo Kerley Inc]

IBDU; Par-ex IBDU

CDU; CDU [Chisso Asahi], Crotodur [BASF] (Goertz 2000)

(iii) Physical restrictions

Description and Mechanism

Fertilizer release is limited by a low surface-volume ratio, or physically restricted due to incorporation into an inert matrix with tortuous release paths, or is electrostatically adsorbed to surfaces or ion exchange media.

Types

Inert matrix diffusion; Physical dilution of nutrient in an inert material, sometimes as matrix compacts with discontinuous barrier networks throughout (e..g. Driessen et al. 2013)

Surface-to-volume ratios; (eg supergranules) reduce the rate of dissolution for a given mass of nutrient (Parr 1972, Trenkel 2010). Compacts such as briquettes, spikes, sticks etc. used for fertilizing trees and shrubs (Shaviv 2001) and increasingly used in irrigated paddy rice applications (Geethadevi et al. 1991, Gour et al. 1990, Raju et al. 1989).

Exchange polymers; (Lunt 1971) or hydrogels (Tong 2009) require sufficient moisture and concentration on anions/cations to release the nutrient form from the polymer or hydrogel. Neem.

Surface adsorption; (i.e. clays, zeolites) to restrict release, again relying upon an exchange of anions/cations to exchange at adsorption sites.

Available commercially as

Urea supergranules [MHI, Mitsubishi], pressed locally from urea in Asia.

Black Urea; Urea coated with organic acid matrices (Ecotech 2002, Advanced Nutrients 2014).

(iv) Stabilised: Inhibiting urease activity

Description and Mechanism

Slow the rate of hydrolysis of urea to NH_4 by inhibiting the activity of the urease enzyme (Trenkel 2010). Decreasing the rate of hydrolysis also favours increased NH_4:NH_3 due to corresponding decrease in the rate of increase in soil pH. This decreases the risk of volatilisation losses due to loss of NH_3 gas (Cameron et al., 2013). The most common approach is to develop structural analogues of urea (Competitive inhibitors).

Types

The three key inhibition mechanisms (Watson, 2005; Medina and Radel, 1988) are classified as;

Key functional group inhibitors; compounds are developed to modify the shape of the enzyme by interacting with specific functional groups (i.e. sulphydryl reagents)
Non-competitive binding inhibitors; compounds that complex at the active sites such as Ni-hydroxamate and arylorganoboron-carboxylate complexes.
Competitive binding inhibitors; based upon structural analogues of urea, these compounds compete directly against urea for access to the enzyme. Inhibitors in this category include: *N*-(*n*-butyl) thiophosphoric triamide (NBPT), N-(2-nitrophenyl)phosphoricacidtriamide (2-NPT), ammonium thiosulphate (ATS), phenylphosphorodiamidate (PPD/PPDA), hydroquinone (Bremner 1995).

Available commercially as

Competitive binding inhibitors; NBPT [Agrotain] (Watson 1990, Trenkel 2010), NBPT [Arborite AG-NT, Gavilon]

Combined with nitrification inhibitor; Agrotain Plus, SuperU [Agrotain] (Watts et al. 2014. Halvorson et al. 2014)

(V) Stabilised: Inhibiting nitrification

Description and Mechanism

Slow the rate of nitrification by suppressing the function of bacteria involved in the oxidation of NH_3 to nitrate. Detailed discussions of the complex mechanisms associated with nitrification inhibitors may be found in the literature (Subbarao 2006). Subbarao (2006) suggested that there were over 60 compounds identified that could perform as nitrification inhibitors. The most common approaches rely on the ability to restrict the ammonia monooxygenase (AMO), a Cu-containing enzyme, from converting ammonia to hydroxylamine.

Types

Competitive binding inhibitors: substitution of compounds that compete with NH_3 for sites on AMO
Non-competitive binding inhibitors: of alternative sites within the enzyme
Metal chelators for Cu: targeted to reduce the effectiveness of Cu (i.e. mercapto compounds)
Mechanism-based disruptive inhibitors: compounds that act have specific roles in stopping AMO function, suppress or inactivate Nitrosomonas bacteria. i.e. AMO converts acetylene (from calcium carbide) into a highly reactive epoxide, which then reacts with key proteins that act as catalysts for NH_3 conversion, irreversibly damaging AMO function. Nitrapyrin has a bacteriocidal effect on *Nitrosomonas* bacteria (Trenkel 2010). Dicyandiamide (DCD) acts to suppresses the respiration of *Nitrospira* and *Nitrosomonas by* interfering with cytochrome oxidase function (Cameron, 2013).

Available commercially as

Mechanism-based disruptive inhibitors: Nitrapyrin [Dow]/N-Serve [Dow], 4-amino-1,2,4-6-triazole-HCl (ATC) [Ishihada], 2,4-diamino-6-trichloro-methyltriazine (Cl-1580) [Cyanamid], DCD [Showa Denko] and DCD-triazole [Alzon, SKW Stickstoffwerke Piesteritz], 1-mercapto-1,2,4-triazole (MT) [Nippon], 2-amino-4-chloro-6-methyl-pyramidine (AM) [Mitsui Toatsu], 3,4-dimethylpyrazole phosphate (DMPP) [BASF, Entec], 1-amide-2-thiourea (ASU) [Nitto], ATS (Subbarao 2006, Trenkel 2010), 5-ethylene oxide-3-trichloro-methly1,2,4-thiodiazole (Terrazole) [Olin Mathieson], calcium carbide (Trenkel 2010).

Combined with urease inhibitor; Agrotain Plus, SuperU [Agrotain] (Watts et al. 2014. Halvorson et al. 2014)

7.4 Experimental evidence of control of N release or form

Patterns of release from slow and controlled release fertilisers

Nutrient release curves are typically proprietary information of the fertiliser manufacturers (Simonne and Hutchinson 2005). The information sheets provided with the fertilisers provide an expected release time, usually to 80% of release, in some cases differentiating between release time in different (colder or warmer) climates (Figure 7.2).

Brand NAME	80% Release (days at 20°C)	80% Release (days at 25°C)
MEISTER-5	50	30
MEISTER-7	70	40
MEISTER-8	80	50
MEISTER-10	100	70
MEISTER-15	150	100
MEISTER-20	200	140
MEISTER-27	270	180
MEISTER-40	400	270

POLYON 43
TEMPERATURE RELEASE RATES

60°F = 16-18 weeks
70°F = 10-14 weeks
80°F = 6-8 weeks

Average Soil temperature	Basacote Plus 3M	Basacote Plus 6M	Basacote Plus 9M	Basacote Plus 12M	Basacote Plus LR
15 °C	4 – 5 M	6 – 7 M	9 – 10 M	12 – 14 M	16 – 18 M
21 °C	3 – 4 M	5 – 6 M	6 – 9 M	10 – 12 M	14 – 16 M
27 °C	2 – 3 M	4 – 5 M	7 – 8 M	9 – 12 M	12 – 14 M

Figure 7.2. Indicative information on release timeframes provided with different products (clockwise; JCAM AGRI.co. n.d., bestfertilizer.com 2007, Compo Expert 2010) (60°F = 15°C, 70°F = 21°C, 80°F = 27°C).

A number of experimental studies have examined the release patterns of slow and controlled release fertiliser products (e.g. Oertli and Lund, 1962; Snyder and Gascho 1976; Prasad, 1976; Gandeza et al. 1991; Shaviv 1996; Medina et al. 2008; and several more). Figure 7.3 illustrates the variety of release patterns using a selection of products. Note that these fertilisers were not specifically developed for use in sugarcane and many are indeed not used in sugarcane.

Temperature is a factor that, often by design, can impact on release quite strongly as shown for the Meister and ESN polymer coated products in Figure 7.3b and d. The temperature dependence may vary significantly with product type and release mechanism. The use of coating thickness to control release time is illustrated in Figure 7.3f for the Agrocote product. Some sulfur coated products release a proportion of the fertiliser very rapidly, a phenomenon sometimes described as 'burst' (Shaviv 2001, 2005; Trenkel 2010) (see e.g. Figure 7.3g,h). The extremely slow release of the last ~30% in some products has been referred to as "lock off" (e.g Figure 7.3h) and limits, or may prevent entirely, the use of this portion of the fertiliser by the crop. The extent of "lock off" is controlled by the thickness of the sulfur coating. Soil moisture and the method of placement have also shown to affect release (e.g. Prasad, 1976; Du et al. 2006), but information on this is limited. Some of the product descriptions for polymer coated fertilisers claim that moisture is not a factor after the initial absorption of water. Others claim that as long as the soil is not drier than crop wilting point, soil moisture is not a factor (Christianson 1988; Shoji 1999; Golden et al. 2011), but this is not well defined and may not apply to all products due to their different release mechanisms (see e.g. Husby et al. 2003). Slow release fertilisers that rely on microbial breakdown of the coating, may have more

variable release rates from one soil to another and the patterns may vary under fluctuating field conditions (Halvorson et al. 2014). Due to their dependence on environmental factors, the release patterns may vary from season to season, an aspect that warrants further investigation.

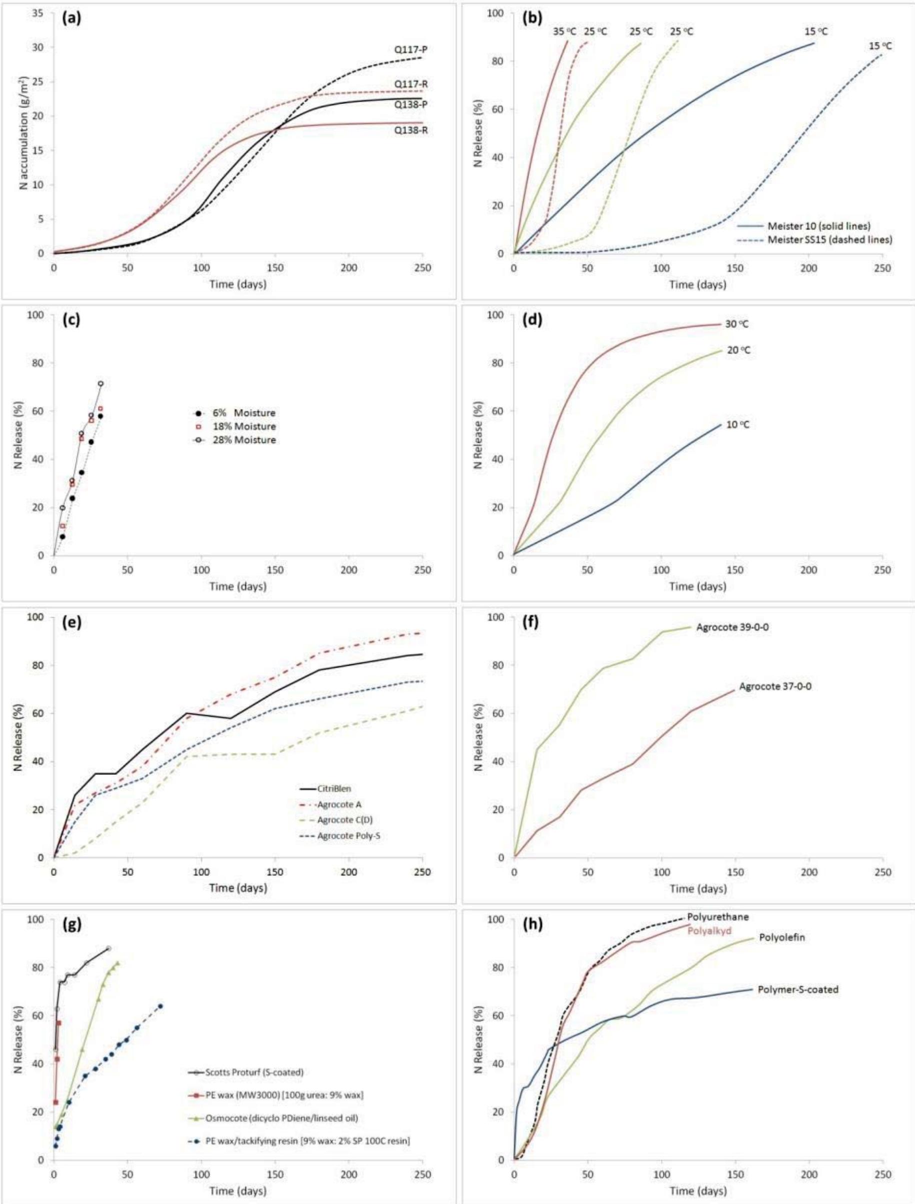

Figure 7.3. Examples of fertiliser release patterns from controlled and slow release fertilisers (b-h) compared with the time frame of above ground N accumulation observed in a sugarcane trial under non-stressed conditions in Ingham N Qld (a) (see Section 7.6 for further details). Data from (a) Wood et al. (1996); (b) Trenkel (2010); (c) Christianson 1988; (d) ESN, Ellison (2012); (e) .Medina et al. (2008); (f) Sam Stacey pers.comm.; (g) Gossett et al. (1993); (h) Shaviv (2001). Note, many of these fertilisers were not developed for use in sugarcane and most are indeed not used in sugarcane.

It is clear from the release patterns shown in Figure 7.3 that a simple description of the time required for 80% to be released, on its own, does not provide sufficient information about the timing of N supply to the crop. The patterns of release up to the point where 80% is released are quite different and range from parabolic to linear and sigmoidal (Shaviv 2001). The match between the pattern of release and crop N demand could affect N loss as well as crop response. Many of the polymer coated controlled release fertiliser products have a release pattern that is initially linear and then declines (often referred to as the 'linear type'), with few reflecting the sigmoidal shape of the N accumulation curves typical of most crops. The synchrony with crop N uptake is discussed in more detail in Section 7.6.

Siepmann et al. (2008) reviewed the means of altering release patterns through the combination of two or more polymers with varying characteristics. By simply varying the blend ratio of polymers with different physicochemical characteristics (permeability, solubility, mechanical stability) broad ranges of film properties can be developed. Controlled release fertilisers can also be applied blended with conventional fertilisers (e.g. Medina et al. 2008; Noellsch et al. 2009; Kryzanowski 2012; Dowie 2013; Di Bella et al. 2014). This is how Agrocote (Figure 7.3f) is often applied in the Australian sugarcane (see Section 7.4). Release patterns from blends would be different from that of the controlled release component(s) and reflect the mixed nature of the product, as shown in Figure 7.3e for the CitriBlen® product used in the Florida citrus industry. It combines three controlled release fertilisers with different release patterns and a soluble fertiliser component.

A factor contributing to the slow release patterns is the issue that coated fertiliser granules are not completely uniform and that coating thickness will vary. This variation results in the fertiliser effectively consisting of a population of granules with varying release characteristics (Shaviv et al. 2001, 2003b). It has been suggested that for some products that rely on breakdown of the coating, it is the characteristics of the population that determines the release pattern (Oertlli 1974; Shaviv 2001). Material science characterisation techniques may be able to shed a light on the exact release mechanisms, by studying the coatings during release.

Measuring N release from controlled and slow release fertilisers

There is considerable variety in the way N release from controlled and slow release fertilisers is determined, which complicates comparisons. There have been some proposals to standardise these methods (e.g. Sartain et al. 2004a,b; Trenkel 2010; Ozores-Hampton and Carson 2013; Medina et al. 2014b,c). Given, however, that the design of methods is a function of the objective of the evaluation and that these are not always the same, these attempts have not yet been successful (Simonne and Hutchinson 2005).

A method commonly used in the fertiliser industry for determining fertiliser release is to measure nutrient release in water. This is useful to compare or quickly screen controlled release fertilisers (Ozores-Hampton and Carson 2013). However, this may not correctly reflect the release of fertiliser products in the field, particularly for products that rely on microbial action to break down the coating (Samuel Stacey, pers. comm.). In addition, the release of N from some products may differ when exposed to the chemical or microbial conditions of soils.

Incubations with soil can be used to study a range of soil and environmental factors (see e.g. Golden et al. 2011). Sometimes these incubations are performed in small leaching columns to collect the released urea, ammonium and nitrate (Sartain et al. 2004a; Medina et al. 2014a). Soil moisture content conditions are a consideration in these incubations with Du et al. (2006) finding that release under saturated conditions can be higher than in a soil at field capacity. To study release under variable soil moisture conditions others have used designs that sampled the soil N (Fujinuma et al. 2009) or the proportion of N remaining in the fertiliser prills that were kept in small rumen bags buried in containers with soil (Golden et al. 2011).

The approach of burying mesh bags containing fertiliser granules in the soil, periodically removing some of these, and determining the amount of fertiliser remaining also lends itself for measuring release in the field (Wilson et al. 2009a). This method is relatively simple and being a field based method can be used in parallel with evaluations of agronomic or environmental benefits of the product. The results obtained would be specific to the field conditions encountered during measurement and hence may not easily extrapolated to other conditions.

Due to the (intended) slow release of nutrients from slow and controlled release fertilisers, characterising their behaviour can take time. Some studies have attempted to accelerate the release by the use of higher temperatures (Warrender et al. 2010; Wang et al. 2011; Median et al. 2014b), but care needs to be taken in extrapolating such measurements to real life behaviour, particularly as different products often display different temperature responses. For example, Adams et al. (2013) reported that Osmocote, which has a thermoset polymer coating, had a relatively controlled gradual response to temperature, whereas Nutricote, based upon a thermoplastic polymer showed uncharacteristically high releases at increased temperature.

Longevity of inhibitor action

Inhibitors work by 'stabilising' N – keeping it in a form that is less prone to losses. This means there is not a release as such, and if the 'stabilised' form of N can be used by the crop (as is suggested for uptake of NH_4 by sugarcane in chapter 4), it is not limiting nutrient availability.

Longevity of nitrification inhibitors

Longevity of nitrification inhibitor action depends on the persistence of the inhibitor and its bioactivity in soil (Keeney 1980; Chen et al. 2008b). In turn the persistence is affected by sorption, degradation, volatilization and/or leaching processes, and the bioactivity by the persistence, activity of the sorbed phase, and nitrifier population and activity (Keeney 1980; Slangen and Kerkhoff 1984). Many of these processes are affected by environmental and edaphic factors such as pH, temperature, organic matter content, clay content and type, soil moisture content and aeration (Keeney 1980; Prasad and Power 1995; Chen et al. 2008b). Longevity of nitrification inhibitors will, therefore, depend on the product type and soil and climate conditions.

A calcium carbide polymer matrix tested by Freney et al. (2000) as a release source acetylene gas was shown, in laboratory studies, to inhibit nitrification for 90 days and considerably slowing the oxidation of ammonium for 178 days. In a field trial with irrigated maize the same calcium carbide polymer matrix was found to retard nitrification for at least 48 days (Randall et al. 2001). Halverson et al. (2014) suggested the longevity of the nitrification inhibitor action can range from 4 to 10

weeks, referring to literature sources discussing the three most actively studied (Chen et al. 2008b) products: nitrapyrin, dicyandiamide (DCD), and 3,4-dimethylpyrazole phosphate (DMPP). This matches indicative ranges provided by Trenkel (2010) for DCD of 4 to 10 weeks, and Nirapyrin (N-Serve) of 6 to 8 weeks in warm soils, extending to 30 weeks or longer in cool soils (in the US) in late fall or winter. Product information for ENTEC® (containing DMPP) suggests activity ranges from 4 weeks or less under warm field conditions to more than 10 weeks under cool field conditions (Figure 7.4).

Data collected by Chen et al. (2010) in incubations spanning up to 42 days and comparing two products (DMPP and 2-Chloro-6-(trichloromethyl)-pyridine based), suggested the effect of soil temperature should be characterised in conjunction with soil moisture. At 40% water filled pore space, both inhibitors were effective for at least 42 days at all temperatures (up to 25°C), whereas the effectiveness of DMPP declined markedly after 14 days under warm, moist conditions (25°C and 60% water filled pore space). In a recent sugarcane study in tropical Queensland, however, a DMPP-based nitrification inhibitor proved effective in reducing soil nitrate concentrations for over 12 weeks (Wang et al. 2014), suggesting stabilisation time frames may be longer than expected.

Laboratory studies carried out at the University of Melbourne have evaluated a range of nitrification inhibitors and found that in the majority of soils nitrate production and N_2O emissions were reduced effectively, but that the inhibitors were less effective in a highly organic, acidic clay loam dairy pasture soil, and had a higher impact in less organic, higher pH soils of varying texture (Suter 2013). Increasing temperature tended to decrease inhibitor performance but not always and this depended upon the soil and inhibitor (Suter 2013). Work is continuing to investigating this in more detail and is focused on identifying soil parameters most likely to affect inhibitor performance (Suter 2013).

Variability in effectiveness in different soils is also linked to their microbial communities. Various soil microorganisms can be involved in the nitrification process (Cameron et al. 2013; Suter 2013) and not all of these are inhibited or inhibited to the same extent by the inhibitor products (Di et al. 2010; Kleineidam et al. 2011; Cameron et al. 2013; Wakelin et al. 2014). With inhibitor action, nitrification and N_2O emissions all sensitive to soil conditions such as moisture content, pH and nutrient status and linked to the dynamics of microbial communities (Cameron et al. 2013) this is currently a very active space of research (e.g. Di et al. 2014; Robinson et al. 2014; Florio et al. 2014) that may provide some more clarity in the near future including the development of tools to predict the efficacy of nitrification inhibitors in different soils (Wakelin et al. 2014).

Average soil temperature (*C) where fertiliser is placed	Usual time for 50% of ENTEC stabilised nitrogen to be nitrified
<12	10 weeks +
12 – 18	4 – 10 weeks
19 – 30	4 weeks or less

Figure 7.4. Indicative information on temperature effects on the ENTEC product; longevity is shorter at higher temperatures (ENTEC Fertilisers 2011). More recent findings indicate stabilisation time frames may be greater than indicated at warmer temperatures (see text).

Longevity of urease inhibitors

The longevity of urease inhibitor effectiveness tends to be much shorter, usually in the order of 7-14 days in field experiments (Trenkel 2010). Longevity of effectiveness reduces with increasing temperature (Chai and Bremner 1987; Carmona et al. 1990; Suter et al. 2011). The lab incubation study by Suter et al. (2011) suggested that the effectiveness of the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) was also strongly dependent on soil chemical properties. In an acidic soil with high urease activity and high organic carbon content the inhibitor had little impact on urea hydrolysis, whereas in an alkaline soil with lower urease activity and lower organic carbon content the inhibitor was effective for at least 14-15 days (the duration of the experiment) at 5°C and 15°C. At 25°C the NBPT effectiveness declined more rapidly with <2% of applied urea remaining at 14-15 days.

The relatively short period of effectiveness means that the urease inhibitors are mainly suited to minimise volatilisation losses from surface applied urea. When urease inhibitors are successful in delaying and/or slowing down urea hydrolysis, this provides a chance for rainfall or irrigation to transport the urea into the soil, ammonium to diffuse into the soil, leaching and dilution, and the nitrification process to offset the increase in micro-site soil pH caused by the hydrolysis of urea, reducing the potential for ammonia volatilisation losses.

7.5 Evaluation of enhanced efficiency fertilisers in Australian sugarcane

Enhanced efficiency fertilisers were first trialled in the Australian sugarcane industry in the early 1990s. This work formed part of attempts to increase the efficiency of use of fertiliser N by reducing N losses such as volatilisation and denitrification. It coincided with the development of industry wide fertiliser application recommendations (see chapter 2).

As these early studies did not demonstrate clear yield benefits, the interest in these more expensive fertiliser products waned. Recent years have, however, seen further trialling of enhanced efficiency fertilisers driven to an extent by the need for the industry to consider environmental impacts of N fertilisation, namely greenhouse gas N_2O emission as well as nitrate leaching and runoff contributing to excess N loads to the Great Barrier Reef.

Here we summarise the findings of the various trials and experiments with published or publicly presented results.

Early work on reducing ammonia volatilisation losses

In response to observations of large ammonia losses after application of urea (Prammanee et al. 1988, 1989; Denmead et al. 1990; Wood et al. 1990; Freney et al. 1994) and concerns that surface applications of urea in conjunction with trash retention, a management practice gaining acceptance in the late 1980s and early 1990s, could further exacerbate this, a number of early studies on enhancing the efficiency of fertilisers focussed on reducing ammonia volatilisation. They attempted to limit the pH increase of the soil or the crop residues caused by urea hydrolysis by using a mixture of urea with ammonium sulphate (Prammanee et al. 1989; Obcemea et al. 1993) or through attempting to bind the ammonium from urea to anions (chloride or nitrate) and the carbonate of urea hydrolysis with base cations (calcium or magnesium).

This latter approach was tested by Kong et al. (1991) who mixed urea with potassium chloride or muriate of potash to evaluate soil N recovery and ammonia volatilisation losses. Field microplots in a freshly harvested cane field in Ingham using a mixture of urea and analytical grade potassium chloride suggested improved soil N recovery (evaluated over a 39-day period) (Kong et al. 1991). The use of a commercial mixture of urea with muriate of potash in a field micrometerological study, however, resulted in higher volatilisation losses. This was ascribed (Kong et al. 1991) to the alkalinity of the muriate of potash (pH of 9.2 vs. pH of 6.0 for analytical grade potassium chloride when dissolved in water) suggesting that the success of the approach is sensitive to the actual product used.

Mixing ammonium sulfate with urea to reduce ammonia volatilisation losses was more successful. A micrometeorological study by Obcemea et al. (1993) in a freshly harvest green cane field showed that if there was sufficient water in the system, more than that from dewfall alone, the dissolved ammonium sulfate could reduce the pH and reduce emission losses. The interaction with moisture proved, however, an important factor in the effectiveness of the approach. Dew formation which did contribute to volatilisation was not sufficient to dissolve the ammonium sulfate, limiting its ability to reduce losses until sufficient rainfall was received. This also meant that the lab measurement of pH was not reflective of the field situation due to its method allowing the complete dissolution of ammonium sulfate and hence providing an overestimation of the reduction in pH (Obcemea et al. 1993, Obcemea 1994). Additional work reported by Obcemea (1994) also highlighted that effectiveness was dependent on the mixture containing sufficient ammonium sulfate (suggested to be 50%).

An earlier study by Prammanee et al. (1989) had also included a urea+ammonium sulfate treatment, but the focus of this paper was on applying the urea fertiliser below the soil and trash. This approach proved highly effective and gained adoption later in the 1990s. The paper also flagged the possibilities of trialling enhanced efficiency fertilisers to reduce N losses. A pilot study using microplots and sugarcane trash was included in Prammanee (1991). It included 9 forms of N (granulated urea, ammonium sulphate, ammonium nitrate, urea ammonium nitrate (UAN), urea + analytical grade KCl, urea + urease inhibitor N-(n-butyl) thiophosphoric triamide (NBTPT; converting to its active oxygen analog N-(n-butyl) phosphoric triamide NBPT)), urea large granule, 70-day (to 50% at 25°C) organic polymer coated urea and 100-day organic polymer coated urea) applied to the surface of the trash with recoveries determined after 39 days. All products achieved higher recoveries than granulated urea, but the two polymer coated fertilisers were particularly effective achieving close to 100% recovery, although only about 86% of the fertiliser had released during this time, so the author noted a possible concern about early N supply to the crop. The trial with KCl prompted the further work by Kong et al. (1991) above.

Obcemea (1994) also trialled two types of polymer coated urea, a zeolite coated urea, and four phosphoryl triamides acting as urease inhibitors. The field study involving the polymer and zeolite coated urea products was conducted in a trash blanketed sugarcane field in the Herbert River District, Ingham, North Queensland. The trial went for 28 days and monitored ammonia volatilisation as well as pH of the trash. Over this short time-frame the zeolite coating proved ineffective, but the polymer coatings did reduce ammonia volatilisation (by 20 and 85% for the two different products). Obcemea (1994) noted the need to consider the rate and time of release of the fertilizer in selection of a suitable product. A subsequent laboratory experiment demonstrated

zeolite applied on top of urea could be effective, but was sensitive to the rate applied, with the higher, more effective rate (5 t/ha) possibly having an unacceptably high cost-benefit ratio (Obcemea 1994).

The four different urease inhibitors were only compared in a laboratory study, but this highlighted differences in effectiveness between products, with the most effective products being cyclohexyl phosphorlc triamide (CHPT) and N-(n-butyl) thiophosphoryl triamide (NBTPT) showing 100% inhibition at day 1, decreasing to 82-88% inhibition at day 3 and to 15-32 % at day 15), warranting further evaluation in the field (Obcemea 1994).

Active industry communication of the magnitude of the ammonia volatilisation losses and the science behind it, along with the development of fertiliser applicators with coulters that could cut through trash (e.g. Calcino et al. 1988) led to a change in practice from the mid-1990s onwards to band the urea subsurface below the trash (Wood, pers. comm. Oct 2014). This has reduced ammonia volatilisation losses dramatically, so that work relating to enhanced efficiency fertilisers in sugarcane since then has focussed less on reducing ammonia volatilisation and more on denitrification, leaching and runoff N loss processes.

Early work evaluating yield impacts

While the experiments by Prammanee (1991) and Obcemea (1994) could demonstrate effects of the enhanced efficiency fertilisers on ammonia volatilisation and N and pH dynamics, it did not evaluate impacts on yield. A study considering the effect of different N fertiliser formulations on sugarcane yield was carried out as part of an SRDC project supervised by Myers and Vallis (1994). The study was performed in southern Queensland and northern NSW and included seven experimental trials (1989-1993) on four different soil types. The fertiliser treatments included two coated urea products with six different release times (estimated to range from 36 to 160 days at 23-25°C based on the supplier's data), urea plus zeolite, urea plus calcium carbide coated with shellac and wax, as well as urea with a nitrification inhibitor. Treatments were replicated 3-5 times. Actual release times were not determined as part of the project, nor were N losses measured. No significant yield differences were observed. Possible reasons for the lack of yield differences mentioned in the report included a lack of N response in two of the experiments and the fact that ^{15}N studies in the same project indicated that a large proportion of crop N uptake came from mineralisation of soil N (Myers and Vallis, 1994). The authors also noted that the low precision inherent to experiments like those carried out meant that yield differences of more than 12 t/ha were required for statistical significance (Myers and Vallis, 1994).

Another SRDC funded early trial (Randall et al. n.d.) tested a nitrification inhibitor in a 3rd ratoon crop field trial near Mackay in 1996/97. This detailed trial included 5 rates of N fertiliser, 5 rates of inhibitors and 4 replicates of each. It monitored soil N throughout the season and also measured crop N and estimated N losses in microplots using ^{15}N. The inhibitor, based on a calcium carbide polymer matrix (Freney et al. 2000) was effective in delaying the conversion of ammonium to nitrate. This effect lasted between 8 and 10 weeks and had disappeared by 15 weeks (Randall et al. n.d.). Crop yield and sugar yield were, however, not affected by the inhibitor. The authors suggested that in this case the delayed conversion to nitrate did not result in reduced losses, possibly due to the conditions not being conducive to large losses in the period that the inhibitor was effective

(Randall et al. n.d.). The authors also noted that it was possible that benefits would be obtained in seasons with different rainfall patterns and that further field assessments should be based on a clearer idea of where and when N losses would likely be important, possibly through simulation modelling. John Freney, a co-investigator on the project, also commented that factors other than N may have played a role (pers. comm. Oct. 2014).

Recent controlled release N efficiency trials in the Herbert catchment

These (0.5–1.0 ha) field trials commenced in 2011 and are comparing the relative efficiency of a polymer-sulfur coated fertiliser with conventional urea. In the first year (2011-12) four paired sites (two clay soils and two solodic soils each with all treatments replicated twice) were established in green cane trash blanketed, 1st ratoon sugarcane (Di Bella et al. 2013). During the very wet summer (2400 mm between Nov 2011 and Apr 2012) all sites recorded severe waterlogging and 151 mm rainfall was recorded just 9-12 days after fertiliser applications – well within the release periods of the controlled release fertiliser products used, which had nominal release times of 80% release in 3 months in the clay soil trials and 80% release in 6 months in the solodic soil trials). Di Bella et al. (2013) reported for 2011-12 a statistically significant increase in average cane yield at similar rate applications (on average 5-6 t/ha across N rates or approximately 10%) and sugar yield was increased when averaged across both soil types (0.5 t/ha). The 80 or 90 kg N/ha applications of controlled release fertiliser were statistically equivalent in terms of cane yield to 160 kg N/ha urea. On the clay soil this was accompanied by a clear response to N (90 vs. 160 kg N/ha) for both urea and controlled release fertiliser, whereas on the solodic soil there was only a response to N with controlled release fertiliser (Di Bella et al. 2013). It was assumed (Lawrence Di Bella, pers. comm. Sep. 2014) that the lack of N response in the urea treatments was due to the urea fertiliser being largely lost due to the very wet conditions.

The second season (2012-13; 2nd ratoon sugarcane) was significantly drier (only 15 mm rainfall in the first month since ratooning), but the trial results were similar with a significant increase in average cane yield at similar rate applications (similar magnitude as in 2011-12), statistically equivalent yields for 120 kg N/ha controlled release fertiliser and 160 kg N/ha urea, and again a clear N response at the clay sites, but none at the solodic sites (Di Bella et al. 2014). The response to controlled release fertiliser, but absence of N response at the solodic sites would warrant further investigation into the types, timing and relative magnitude of N losses, but those data were not collected as part of this initial industry trial.

Recent trials with controlled release fertiliser blends

Fertiliser blends with between 15 and 50% polymer-sulfur coated fertiliser (80% N release over four months) mixed with conventional urea were trialled at one site in the Herbert in 2011-12 and five sites with different soil types in 2012-13 in the Herbert, Burdekin and Mackay areas (summarised in Di Bella et al. 2013, 2014). Plot sizes between 0.3 and 0.7 ha were used, replicated three times at each site. In commercial practice, blends are often used to ensure readily available N at the start of the season. It also reduces the cost of the fertiliser. In 2011-12 (Herbert area site) yields were not statistically different at $P \leq 0.05$, but at $P \leq 0.1$ the 25% CRF-N blends applied at 120 and 150 kg N/ha resulted in statistically higher yields than that of 160 kg N/ha urea (Di Bella et al. 2013).

In 2012-13 there were no significant differences in cane or sugar yield for the various blends used compared with conventional urea use at all but one of the sites. This site in the Burdekin (dry tropics, irrigated sugarcane, sandy loam soil, Dowie 2013) presented a mixture of results. At the highest rates (200 kg N/ha) the various blends (25:75, 50:50, 75:25 CRF-N to urea N) all outperformed the urea in terms of yield (by an average 12 - 18 t/ha or 10-15%) and increased sugar yield (1-2 t/ha) in two of the three blends. The data showed a strong correlation (r^2=0.88) between the proportion of CR N in the blend and cane yield (Dowie 2013; Di Bella et al. 2014), although not all yield levels were statistically different. At 160 kg N/ha application rate there was no statistical difference between the 50:50 blend and urea, and at 120 kg N/ha application rate the 50:50 blend performed worse than conventional urea in both cane yield (by an average 19 t/ha) and sugar yield (3t/ha) (Dowie 2013; Di Bella et al. 2014). uDespite a blend having been used, this was likely related to issues with early vigour and insufficient N availability (Dowie 2013). The trial used two different sugarcane varieties, with one used for all treatments of 1 replicate and the other for the other 2 replicates of each treatment. While varieties may have different N uptake patterns and responses, this design minimised the impact from variety specific responses.

Two other, unpublished trials with controlled release fertiliser blends were carried out in Cairns and Silkwood, Qld. The trials included both urea and a (3-month) polymer-sulfur coated urea in a 50:50 blend at three different rates (80, 120, 160 kg N/ha) replicated 3 times. There was no significant difference in either trial for cane or sugar yield, but there was a significant interaction between product and rate on Commercial Cane Sugar (CCS) in the trial at Cairns (Derek Sparkes, pers. comm.).

Other agronomic trials with controlled release fertiliser

A trial in the Mackay area (Farmacist 2013) in 2012-13 on a deep sandy soil compared topdressing with 134 kg N/ha urea and 89 kg N/ha polymer-sulfur coated fertiliser. The applications were made 4 week post-ratooning after a uniform 1st application of 46 kg N/ha at 11 days post-ratooning. Despite the lower rate for controlled release fertiliser no statistical difference in cane yield, CCS or sugar yield between treatments were found, but as these were the only rates applied, it cannot be established whether this was due to the slow release of N or lack of N response.

Another trial on a duplex soil subject to waterlogging (Farmacist, 2013) also used an initial uniform application (39 kg N/ha) followed by applications of 121 kg N/ha urea, a further split application of 90+31 kg N/ha, an application of 121 kg N/ha 25% blend, and an application of 81 kg N/ha straight controlled release fertiliser. Cane yield, CCS and sugar yield were again not statistically different between treatments, but as in the above trial, this could be a consequence of fertiliser type or lack of N response, without N response data this cannot be established. Subsequent trials have included N response tests, but data has not been published yet (R. Sluggett, pers. comm.).

We are aware of at least one more trial with enhanced efficiency fertilisers which did not result in significant differences in crop performance, the details of which can, however, not be shared as this was a confidential report. It is quite likely that more trials with inconclusive or non-significant outcomes (like e.g. Randall et al. n.d. and Myers and Vallis (1994) have not been published.

Nitrous oxide emission trials

Wang et al. (2008) reported on two experiments at Murwillumbah, NSW (2005-06) and Mackay Qld (2006-07) comparing the effects of fertiliser form (conventional urea, polymer coated urea controlled release fertiliser and urea with nitrification inhibitor, DMPP) on nitrous oxide emissions measured using manual chambers. They found that polymer coated urea reduced cumulative emission for the season by on average 30% at the Murwillumbah site (Wang et al. 2008). The use of a nitrification inhibitor did not result in a significant reduction at plot level (P=0.05), but within the fertiliser band, where it was active, the emission rates were consistently lower. At the Mackay site, emissions from treatments with polymer coated urea were initially lower during the second and third weeks after fertiliser application, but exceeded those of the conventional urea treatment during the subsequent 7 weeks which coincided with wetter conditions and higher emissions. As a consequence the average cumulative emission from treatments with polymer coated urea for the season was increased by 50% (Wang et al. 2008). As at the Murwillumbah site the use of nitrification inhibitor did not result in a significant change in cumulative emission for the season.

While the different rainfall regimes may have played a role in determining the different effectiveness of the polymer coated fertiliser, the authors also explained that the product used at Mackay released N more slowly than that used at Murwillumbah (described as having 'about half the solubility'), so that could also have played a role, depending on the time of release relative to crop uptake and rainfall. No details were provided on the release pattern of the product. The authors suggested that the ineffectiveness of the nitrification inhibitor in Mackay was probably due to the higher temperatures leading to faster decomposition than in more temperate climates, although they flagged that soil properties such as sand content, pH and microbiological properties could also play a role (Wang et al. 2008). Indeed current interpretation of the findings (Rob Dwyer, pers. comm.) leans more towards an explanation that the low soil pH (pHwater = 4.7) caused other nitrifying bacteria (i.e. those not inhibited by the nitrification inhibitor) to dominate and hence the reduced effect of the nitrification inhibitor,

Over the 2010-11season the effectiveness of a nitrification inhibitor (DMPP) to reduce nitrous oxide emissions was evaluated in a plant crop at a site near Mackay, Qld. The experiment, which included both manual and automated measurements of emissions, was part of a larger trial investigating the effects of soybean cropping during the fallow period of the sugarcane system and is described in detail by Wang et al. (2012). Due to above average rainfall the site was saturated for prolonged periods in the six months following N fertiliser application. Nitrous oxide emissions from N fertiliser were effectively reduced by the use of urea with a nitrification inhibitor compared with urea alone, particularly in the first 2–3 weeks after fertiliser application (Wang et al. 2012). Cumulative emission was reduced by 4.2 kg N_2O-N/ha as compared to the use of conventional urea ($P < 0.05$) (Wang et al. 2012). Effects of reduction in N losses (N_2O and N_2) on yield have not been published yet, but in another trial at the same site the effects were not statistically significant (Salter et al. 2013).

Wang et al. (2014) reported on a 2012-13 trial at Ingham using both polymer-coated urea and nitrification inhibitor-treated urea. Despite lower mineral N concentrations during the first 1-2 and 1-3 months, respectively, there were no significant differences in annual cumulative nitrous oxide emissions, nor did it affect sugar cane yield (in a same rate comparison). The inhibitor treatment also maintained sugar yield levels with lower application rates. The authors also comment that 'further

studies are required to investigate the optimal management practices such as application time and rate in relation to soil and climatic conditions'.

On one of the clay sites of the Herbert controlled release N efficiency trials (see above) manual gas sampling was undertaken during the 2012-13 season to estimate nitrous oxide emission levels in treatments of 122 kg N/ha urea or 119 kg N/ha controlled release fertiliser as well as a zero N fertiliser treatment (Di Bella et al. 2014). Gravimetric soil moisture and soil NH_4 and NO_3 were determined at each gas sampling. During the first two, dry months the nitrous oxide emission losses were minimal and not statistically different. After the December rainfalls, the nil treatment has significantly lower emissions than the fertilised treatments. The differences between urea and controlled release fertiliser treatments were not significantly different ($P \leq 0.05$) at any occasion, but the authors reported a higher rate of emissions during a short, 2-week period in January (just over 2 months after fertilisation; Di Bella et al. 2014). While there was no clear relationship between emissions and soil NH_4 or NO_3 concentrations, the soil N concentrations during this period tended to be higher in the controlled release fertiliser treatments (Di Bella et al. 2014).

A trial of urea, urea plus a nitrification inhibitor (DMPP) and polymer- sulfur coated urea fertiliser (all at 95 kg N/ha) on nitrous oxide emissions from a plant crop on a black cracking clay (Farmacist 2013) also demonstrated a strong increase in the manually measured emissions to opening summer rainfall. At any measurement time the differences in emissions were not statistically significant, but the data suggest that within the fertilised row the timing of N_2O emissions from treatments with enhanced efficiency fertilisers may have been slightly delayed relative to that of the urea treatment, suggesting the delayed release /nitrification could not prevent N_2O losses.

On-going trialling

A number of the trials mentioned above are ongoing and several new ones are commencing. In addition farmers are doing their own trialling.

Overseas sugarcane experience

Sugarcane is growing in a number of other countries around the world (e.g. US, Brazil and Japan), but in relation to the possible use of controlled release fertiliser the Australian sugarcane industry has probably looked most at the work done in recent years in Florida. Sugarcane in Florida is grown in close proximity to the Everglades National Park, a RAMSAR wetland of international importance. N losses to the environment are therefore a concern; a situation not unlike that of northern Queensland and the Great Barrier Reef. Sugarcane was originally grown on the organic ('muck') soils of the Everglades Agricultural Area, an area of 700,000 acres of farmland, created from the drainage of the northern Everglades. Due to problems with organic soil subsidence, sugarcane expanded into the adjacent sandy ('mineral') soils (Gascho and Snyder 1976; Obreza et al. 1998) from the mid to late seventies onwards and this area now represents 20% of the total area of sugarcane in Florida (McCray et al. 2014). On the organic soils, little or no N is required (Rice et al. 2010), due to the high supply from soil N mineralisation and high nutrient retention capacity. The sandy soils (>97% sand and <2% organic matter; Sato and Morgan 2008), however, have poor water and nutrient retention capacities (Morgan et al. 2012), raising the concern about N leaching to groundwater.

Multiple split applications (4-5 for plant crops and 3-4 for ratoon crops), are common practice on these soils (McCray et al. 2014) especially after Obreza et al. (1998) not only demonstrated yield benefits, but also suggested this practice was economical. The last two of these applications may be aerial applications. The use of enhanced efficiency fertilisers on these sandy soils, therefore, can also provide cost saving through a reduction in the number of applications (Morgan et al. 2012).

Gascho and Snyder (1976) compared sulfur-coated urea (SCU), then a relatively new product, with multiple split applications (half applied at planting in November and the remainder over 3 split applications in March, May and June). The slower of two SCU products, both applied at planting, had the higher yields, but neither matched the performance of the split application system, due to most N being released before the warm summer when the N was required in the highest quantities. The accompanying publication (Snyder and Gascho 1976) that determined the release patterns suggests a reasonably smooth release, but the first measurement was not until 3 months after planting and 10-20% did not release after 12 months. It is now known that SCU products suffered from both 'burst' and 'lock off' (see Section 7.3). Gascho and Snyder (1976) concluded that the release patterns needed to be optimised or their application time adjusted, e.g. to just before canopy closure.

The use of SCU in greenhouse experiments with sugarcane carried out by El Wali et al. (1980) resulted in significant reductions in N leaching compared with urea. Crop yield and N uptake were, however, not affected. A nitrification inhibitor was found to be less effective in reducing N leaching losses, possibly because N was also lost in the ammonium form.

Elsewhere, Isobe (1971) obtained higher cane yields in Hawaii when using sulfur-coated urea (SCU) instead of five split applications of uncoated urea. In another field test Isobe (1972) showed that under conditions of high rainfall the use of SCU instead of uncoated urea allowed the N rate to be halved. Similarly, in India, Panje et al. (1974) observed a positive effect of the use of urea acetaldehyde instead of urea on cane dry weight with N leaching reduced by 50%. Yadav et al. (1990) in a study in India did not find statistical differences in yield amongst a range of enhanced efficiency fertiliser products, but mentioned an effect on plant density that may be worth exploring. As in Queensland, more recent studies have looked at N_2O emissions, including Vargas et al. (2013) who reported on significant decreases observed in N_2O emissions by using nitrification inhibitors or a polymer-sulfur coated controlled release fertiliser in Brazil.

In recent years trials have been undertaken in Florida controlled release fertiliser to reduce N leaching losses and increase yield in sugarcane, alongside work in citrus and tomato (project led by K.T. Morgan, http://portal.nifa.usda.gov/web/crisprojectpages/0213493-improved-nutrition-of-citrus-sugarcane-and-vegetable-crops-grown-on-sandy-soils-in-southwest-florida.html; Gunter Ward pers. comm.). Some promising results appear to have been obtained as judged by a conference abstract by Morgan (2007), who reported increased cane yields, sugar yields and N use efficiency compared with soluble fertiliser sources. Unfortunately no conference or journal papers were found to document these findings in more detail. A recent study on sugar cane yield response to N on sandy Florida soils (McCray et al. 2014) does not present any results from controlled release trials either, although it does mention that this work is being undertaken.

7.6 Evaluation of enhanced efficiency fertilisers in other industries

Enhanced efficiency fertilisers have been trialled in a range of other agricultural industries. A number of reviews, including Hauck (1985), Mikkelsen et al. (1994), Bremner (1995), Shaviv (2001), Chen et al. (2008b), Chien et al. (2009) and Trenkel (2010) not only describe the different enhanced efficiency fertiliser products, but also provide snapshots of some of findings in this rapidly growing field of research and development. In this section we do not attempt to review the complete body of evidence, but highlight some of the work and findings that may inform future evaluations within the Australian sugarcane.

Australia

Most published experimental evaluations of enhanced efficiency fertilisers come from overseas. Within Australia published studies of trials involving controlled release fertilisers are particularly limited. Apart from those in the sugarcane industry mentioned in Section 7.4, very few studies have been published. One exception is that by Chen et al. (2008a) who reported on the use in irrigated cotton of two polyolefin coated urea fertilisers with different release times (nominally 70 and 270 days after application at 20°C). Small observed yield differences were not statistically significant, but, compared with urea, the faster product did reduce nitrate concentrations in soil and increased the apparent recovery efficiency of fertiliser N. The slower product, on the other hand, did not release N fast enough to supply the crop's needs, emphasising the importance of getting the release time-frames right.

Another study is the early work by Mason et al. (1985) testing the use of sulfur coated urea (SCU) in 9 wheat trials in Western Australia. The four SCU fertilisers used did not show any yield advantages over urea. Delayed urea application (by 4-6 weeks) proved a more effective means of reducing leaching losses and increasing yields. As the SCU fertilisers were topdressed onto the surface of the soil, concerns were expressed that the wetting-drying conditions or the limited contact with the soil and its microbes may have hampered release (Mason et al. 1985). Unfortunately release (or N remaining in fertiliser prills) was not measured directly.

More work has been done with urease and nitrification inhibitors. For example, a significant body of work by Freney, Rochester and co-workers in irrigated cotton (e.g. Freney et al. 1992a, 1993; Chen et al. 1994; Rochester et al. 1994, 1996; Rochester and Constable 2000), who successfully used nitrification inhibitors to reduce the considerable denitrification N losses that are often observed in this system. Not all nitrification inhibitors were equally effective, but encouragingly there was a strong association between each compound's ability to inhibit nitrification and its capacity to improve N fertilizer recovery (Rochester et al. 1996). The product used in the Rochester et al. (1994) study (etridiazole) retarded nitrification of ammonium for more than 2 months and resulted in significant increases in crop N uptake and lint yield.

Early work by Osborne (1977) in wheat had demonstrated that a nitrification inhibitor slowed down the nitrification of ammonium for 140 days, but wheat yield was not impacted. Freney et al. (1992a) used a wax coated calcium carbide to provide a slow release of acetylene to inhibit nitrification in an irrigated wheat system, the same product that was also tested in cotton and sugarcane (see Section 7.4). The inhibitor proved effective and prevented N loss by denitrification for 75 days, increased N accumulation by the wheat plants, increased grain N and resulted in a 46% greater recovery of

applied N in the plant-soil system at harvest. No increase in grain yield was, however, obtained due to waterlogging affecting the crop. Smith et al. (1993) built on this work and looked at the soil N dynamics more closely to conclude that 'the increased recovery of applied N in the plant-soil system in the presence of acetylene was due not only to a reduction in gaseous N loss, but also to a decrease in the rate of net mineralization of organic N in the soil.'

As in Australian sugarcane, recent years have seen renewed interest in experimentation with inhibitors. For example, Turner et al. (2010) and Suter et al. (2013) who both used urease inhibitors to reduce ammonia volatilisation in temperate climate studies. The study by Turner et al. (2010) of urea top-dressing applications in dryland wheat observed a reduction in ammonia losses by using a urea product containing the urease inhibitor NBTP (7.6 kg N/ha down to 0.8 kg N/ha). Suter et al. (2013) compared two forms of the same inhibitor on ryegrass, with both proving effective in reducing losses, but neither increasing the agronomic efficiency or recovery of applied N, presumably due to the presence of sufficient available N.

In Western Australia Lester et al. (2012) compared the effectiveness of a nitrification inhibitor (DMPP) and urease inhibitor (NBPT) in reducing N_2O emissions from dryland wheat. The authors reported that the nitrification inhibitor substantially reduced N_2O fluxes from the fertiliser bands following winter rains two months after sowing and that the urease inhibitor still had some effect too. No statistically significant effects on biomass or grain yield were observed. De Antoni Migliorati et al. (2014) evaluated a DMPP based nitrification inhibitor in a wheat-maize system in sub-tropical Australia. It proved to be effective in reducing N_2O emissions during the maize summer season, when conditions were favourable for high nitrification and denitrification rates. Yield increases, were, however, not observed here either.

There are a number of current or recently completed projects funded by GRDC, DAFF and others that focus on the use of enhanced efficiency fertilizers to reduce greenhouse gas emissions. These studies have been in cropping (Victoria and NSW), maize-wheat rotations and sugarcane (Queensland), vegetables, dairy and pasture (Victoria, Queensland) and irrigated cotton (Queensland). Research groups include Chen, Suter and Lam at the University of Melbourne, Wang at Qld DSITIA, Bell at UQ, Rowlings at QUT, Harris and Kelly at DPI VIC, Li at NSW DPI and Quayle and Yeates at CSIRO). This will be a worthwhile space to watch for publications in the near future. The DAFF program also includes work on a fertiliser based on clay-modified activated charcoal by the University of Newcastle (Scott Donne).

In addition to these larger funded projects, there are smaller experiments and trials by individual scientists, farmer groups and individuals. For example, in the Lower Eyre Peninsula there has been an interest in controlled release fertilisers to reduce nitrate losses and allow fewer fertiliser applications (Ware et al. 2013) and in Tasmania there is some work trialling focussed on the use of controlled release fertilisers to improve fertiliser N use by crop in waterlogged situations (Johnson and Acuna, UTAS).

Experiences overseas

Drawing general conclusions from the large body of trial results in other industries proves difficult. In a few industries these fertilisers are widely adopted (lawns, golf courses, fruit trees, and vegetables; Shaviv 2005), suggesting more consistent benefits may be obtained in these industries, but in most

of the other industries adoption is low and the trials have demonstrated mixed results (see e.g. Chen et al. 2008b; Trenkel 2010).

To provide a flavour of the range of experimental evaluation outcomes the following is a summary of findings presented in a recent special issue of the Agronomy Journal (Vol 106, Issue 2, Mar-Apr 2014) from a coordinated effort to evaluate the effects of enhanced efficiency fertilisers on N_2O emissions and agronomic performance (Hatfield and Venterea, 2014):

- Halvorson and Bartolo (2014) evaluated the effects of a polymer coated urea and a stabilised urea with nitrification and urease inhibitors on yield, plant N uptake, and N use efficiency of furrow-irrigated maize on a silty clay soil. The polymer-coated urea had a N use efficiency and yield advantage over urea in two of the three years, but only at N rates below maximum yield. At some of these rates greater economic returns were obtained with the polymer-coated fertiliser than with urea. The stabilised urea fertiliser did not have yield or N use efficiency benefits.
- Parkin and Hatfield (2014) compared the effects on N_2O emissions from a fine loamy soil cropped to rainfed maize fertilised using conventional fertiliser (urea ammonium nitrate (UAN)) and enhanced efficiency fertilisers (UAN containing the urease and nitrification inhibitors, urea containing urease and nitrification inhibitors, controlled-release polymer-coated urea). They observed no reductions in cumulative seasonal N_2O emissions from treatments fertilized with the enhanced efficiency fertilisers in any of the three study years, but in one of the years the controlled release fertiliser had a significantly higher emission than the two treatments with UAN. This was attributed to the episodic nature of N_2O emissions induced by rainfall events later in the season.
- Maharjan et al. (2014) compared the effects of controlled-release polymer-coated urea, stabilized urea with urease and nitrification inhibitors and three split applications of UAN and urea on N_2O emissions from a loamy sand soil, NO_3 leaching, and yield for fully irrigated and minimum-irrigated maize. The split application of UAN and urea resulted in the highest grain yield and N use efficiency, while the inhibitor product performed similar to the split application in both leaching and emission N loss. The controlled release fertiliser had higher N losses and lower crop performance.
- Halvorsen et al. (2014) summarised the findings from a number of studies comparing the effectiveness of several enhanced efficiency fertilisers in reducing soil N_2O emissions from a clay loam soil under irrigated maize. Across all the studies significant reductions were obtained with both controlled release fertilisers and stabilised (inhibitors) products. They noted, however, a lack of (average) effect on conventional till systems (as compared with no-till and strip-till).
- Dell et al. (2014) compared N_2O emissions and grain yield between four enhanced efficiency fertilisers during a 4-yr field study in rainfed maize on silt loam soils. The fertilisers included a controlled release fertiliser, two stabilised products based on urease and nitrification inhibitors and a product based on cation stabilised amine-N. All but the latter were found to delay nitrate accumulation, but cumulative growing season N_2O emissions and grain yield were similar for all N sources in each year of the study. Inconsistency in rainfall was seen as leading to highly variable N_2O emissions. Crop production was found to be limited by water stress during extended portions of the growing seasons resulting in N not being the most limiting factor.

- Asgedom et al. (2014) compared the effects of a controlled release fertiliser and a stabilised urea fertiliser with urea on N_2O emissions from soil under canola and wheat. Cumulative emissions were lowest for the controlled release fertiliser and similar for the urea and stabilised urea fertilisers. N availability to canola and spring wheat by the controlled release fertiliser was, however, insufficient to meet crop demand, resulting in reduced yield and N uptake compared with urea and the inhibitor product, highlighting the challenge of matching release to demand.
- Watts et al. (2014) compared enhanced efficiency fertilisers (controlled release and inhibitor based stabilised products) to conventional N fertilisers (urea, ammonium sulfate (AS), urea-ammonium sulfate (UAS)) in a high-residue conservation cotton production system on a sandy loam soil. Generally, no significant differences in cotton lint yield were observed and while N source affected fiber quality, the effects varied among years.
- Burcazo et al. (2014) evaluated the use of a nitrification inhibitor in maize on a fine silty loam. The authors reported that N use efficiency (defined as the grain yield differential with the zero N treatment) was significantly increased by the use of the inhibitor, but that yield itself was not significantly increased. This apparent contradiction resulted from including the effect of the inhibitor at the zero N rate, which had a small, negative, but not statistically significant effect on grain yield. Whether grain yield and N use efficiency would have been significantly improved compared with a zero N without inhibitor cannot be established from the published data, but if there was an effect it would have been small.
- Sistani et al. (2014) compared grain yield and nutrient uptake resulting from conventional and enhanced efficiency fertilisers in a maize system on a silt loam soil. They found no significant difference in maize grain yield or dry matter among the N sources.
- Hatfield and Parkin (2014) compared conventional and enhanced efficiency fertilisers on grain yield and biomass at the beginning of the grain-filling period, leaf chlorophyll index measurements, spectral reflectance, and leaf area index throughout the growing season of a rainfed, continuous maize system. The authors found no significant effect of enhanced efficiency fertilisers (inhibitor products as well as controlled release fertiliser) on the biomass or leaf area indices at the end of vegetative development; however, there were consistently higher yields with the enhanced efficiency fertilisers, which were related to increased leaf chlorophyll index values during the grain-filling period. The enhanced efficiency fertiliser materials decreased the rate of leaf senescence, leading the authors to conclude that the increases in grain yield were linked to the increased ability of the maize canopy to maintain green leaf area and intercept photosynthetically active radiation.

The mix of findings in the above studies illustrate the difficulty in drawing general conclusions about the effectiveness of enhanced efficiency fertilisers, even from 3-to 4-year experimental studies with a coordinated approach as in this special issue. In the sections below we make some further observations on specific aspects of experimental evaluation from the broader literature on enhanced efficiency fertilisers.

Recent meta-analyses

In an attempt to identify patterns across multiple studies, a number of recently published papers have carried out meta-analyses. Among them are the studies by Akiyama et al. (2010) and Halvorson et al. (2014) who tried to quantify the average effectiveness of different types of enhanced efficiency fertilisers on reduction of nitrous oxide emissions, by Abalos et al. (2014) who used it to characterize the response of crop productivity and N use efficiency to the application of urease and nitrification inhibitors, and by Linquist et al. (2013) who focussed on yield and N uptake in rice systems.

Akiyama et al. (2010) considered a total of 113 datasets from 35 different field experimental and peer-reviewed studies. Across these datasets from different land uses ('upland', grassland, paddy, and fallow) from around the world and representing different soil, climate, crop and management combinations, nitrification inhibitors were found to significantly reduce N_2O emissions: on average by -38%, with a 95% confidence interval ranging from -44% to -31% (Akiyama et al. 2010). Polymer coated fertilisers also significantly reduced N_2O emissions (on average by -35%, with the 95% confidence interval ranging from -58% to -14%), whereas urease inhibitors did not reduce N_2O emissions compared with conventional fertilisers (Akiyama et al. 2010). The effectiveness of nitrification inhibitors was found to be relatively consistent across the various types of inhibitors and land uses, although overall effectiveness was greatest in grassland. The controlled release fertilisers exhibited more contrasting results across soil and land-use type than the nitrification inhibitors, although the authors noted uneven representation of different soils and regions and some dominating soil-land-use associations. The lack of effect from urease inhibitors on N_2O emissions is not surprising, given its short longevity and intended use to reduce ammonia volatilisation losses (Section 7.3). In situations, however, where N_2O emissions largely happen within the first month after fertilisation urease inhibitors have shown an impact (e.g. Abalos et al. 2012).

Halverson et al. (2014) reported on a smaller regional meta-analysis based on 41 datasets from 6 sources comparing both controlled release and stabilised fertilisers with urea and UAN. It included the results of a series of N source comparison studies by Halvorson and co-workers in sprinkler-irrigated, maize-based cropping systems in the central Great Plains of Colorado, US. The average reductions in N_2O emissions relative to urea were similar to those reported by Akyama et al. (2010): on average -42% for a controlled-release, polymer coated product, -46% for a stabilised urea source containing urease and nitrification inhibitors and -57% and -61% for a slow-release - and a stabilized urea ammonium nitrate (UAN) source, respectively.

The study of Abalos et al. (2014) evaluated the effects of four inhibitors (nitrification inhibitors DMPP and DCD, urease inhibitor NBPT, and a combination of NBPT and DCD) on crop productivity and Fertiliser N uptake efficiency ($NUpE_{Fert}$ (chapter 3). Across a wide range of crops, climates, and soils, the overall effectiveness of the inhibitors to increase both productivity and $NUpE_{Fert}$ was found to be significant, although there were differences in significance and mean effect sizes depending on inhibitor type, crop type, soil and management factors. Larger responses were found in coarse-textured soils, irrigated systems and/or crops receiving high N fertilizer rates. In alkaline soils (pH ≥ 8), the urease inhibitor produced the largest effect size, not unexpected given the high ammonia volatilization losses from these soils.

The finding of a significantly higher response in crop productivity to the inhibitors in irrigated compared with rainfed systems were linked by the authors to the higher leaching and denitrification losses in the irrigated systems. They did note that several of their rainfed studies came from low rainfall Mediterranean areas, which highlights the difficulty of representing the wide range of environments in meta-analyses. The study by Parkin and Hatfield (2014) above highlighted instead the episodic nature of rainfed systems as limiting effectiveness, while others have emphasised the farmer control over irrigation (Hartz and Smith 2009). Quemada et al. (2013)used meta-analysis to conclude that irrigation management may be a more effective means to reduce nitrate leaching than the use of enhanced efficiency fertilisers.

In rice systems Lindquist et al. (2013) also found that the use of enhanced efficiency fertilisers increased yield and N uptake, but the average effects were modest (< 10%). There was no significant difference among the products either in terms of yield or N uptake, but analysed separately their responses relative to the control varied (Lindquist et al. 2013). The slow and controlled release class (including both coated and organic slow decomposing products; Table 7.1) exhibited high variation, but the authors indicated that the number of studies in this class was low. Soil pH proved an important factor in determining effectiveness in these systems, with the responses in acidic soils not significant, whereas those in alkaline soils were.

A few observations can be made in relation to these meta-analyses and serve as lessons for any future meta- analyses that may be proposed for the Australian sugarcane industry:

- Meta-analyses provide a quick overview of the significance of effects that are seen across the included datasets. The positive ‘overall’ effects seen in the above studies across the various environments, systems and products are encouraging and provide a balance to the mixed observations highlighted elsewhere in Sections 7.4 and 7.5. Apart from the expected strengths of urease inhibitors on high pH soils, the above meta-analyses have, however, not provided clear indications of environments, soils or management systems where particular types of products can be predicted to be most effective.
- The finding of ‘no significant effect’ provides information about the average effects across all conditions and environments tested. A ‘no-significant effect’ does not mean that effects do not occur – they may in some situations. Depending on the uniformity of conditions included in the analysis, this information will be more or less valuable.
- In the study by Akiyama et al. (2010) both the nitrification inhibitors and polymer controlled release fertilisers were found to be more effective in reducing the (higher) N_2O emissions from grassland compared with their effect in other land uses. To develop specific industry recommendations, meta-analyses that concern a single land use like Lindquist et al. (2013) and Halverson et al. (2014) may provide more insights, albeit limited to that land use.
- A large % reduction in N loss does not necessarily mean a large reduction in the magnitude of N loss. The magnitude of N loss reductions will need to be reported to inform industry of the ability to reduce fertiliser application rates, e.g. to off-set price premiums of enhanced efficiency fertilisers. With N_2O emissions a small amount of N loss may itself not have a large impact on N budget, but it does have an environmental impact and if caused by denitrification, will be accompanied by N_2 loss.

- It is well known that meta-analyses can suffer from publication bias due to the fact that trials that did not result in significant treatment differences are less likely to be published. Both Akiyama et al. (2010) and Abalos et al. (2014) tested for publication bias using Rosenthal's and Orwin's fail-safe number tests (Rosenberg et al. 2000), and concluded most of their findings were not affected by publication bias. These tests calculate the number of non-significant, unpublished or missing studies that would need to be added to the meta-analysis to change the results from significance to non-significance (Rosenberg et al. 2000). While being a simple and intuitive approach, the method has received some criticism (see e.g. Becker, 2005). A critical step in the methodology is the assumption about the likelihood that unpublished studies exist; in other words, deciding what a large fail-safe threshold number would be. The check for bias would also need to be done for all comparisons (as reported by Akiyama et al. 2010), not just for the dataset as a whole. Given the experience in sugarcane in Queensland (Section 7.4), where a number of the trials with no significant difference were not formally published, the publication bias is an issue that needs to be kept in mind when summarising published treatment effects.
- As the fail safe number approach does not correct the magnitude of the presented effect sizes, these need to be interpreted with care. Conclusions should focus on the significance of effects. Significant differences between factors can be confounded if the mean effect sizes are affected by publication bias. Alternative methods for bias correction that do correct effect sizes are available (Rothstein et al. 2005).
- It could be argued that the study by Halverson et al. (2014) does not include publication bias as it is effectively a summary of a defined set of trials for a specific cropping system in a specific climate. It does mean that care needs to be taken in extrapolating their reported effect sizes to other industries or environments, especially given that the authors suggested that their results could be used by policymakers to determine mitigation potentials and help determine financial credits that may encourage their use.
- It is tempting to conclude from the similar percentage effect sizes obtained by Akiyama et al. (2010) and Halverson et al. (2014) for nitrification inhibitors and controlled release fertilisers and the lack of significant product differences in the meta-analysis by Abalos et al. (2014) and Lindquist et al. (2013) that there is no strong case for one above the other. Apart from any issues of publication bias or extrapolation beyond the tested dataset, it is important to realise that such a conclusion relates to average results across the tested dataset. Knowing that the effectiveness is determined by the interactions between climate, soil, crop and management, it is likely some product types will suit certain conditions better than others. The suggestion in both Lindquist et al. (2013) and Akiyama et al. (2010) that slow release products may have more variable responses is worth exploring further. It is the analysis of effects from different soil, management and crop factors as attempted by Lindquist et al. (2013) and Abalos et al. (2014) that may proof more informative in this respect.
- Effects from the use of enhanced efficiency fertilisers need to be compared with those that can be obtained through water and nutrient management (Lindquist et al. 2013; Quemada et al. 2013). Understanding the best management practices that will maximize the effectiveness of enhanced efficiency fertilisers is important to allow effective comparison with other practices that increase crop productivity and N use efficiency (Abalos et al. (2014).

Interactions with management

A number of studies have highlighted interactions with management. For example, Halvorsen et al. (2014) found that a controlled release polymer coated fertiliser consistently reduced N_2O emissions in a no till and strip till system, but not in a conventional till system. When applied in subsurface bands the effectiveness of this fertiliser was found to be variable and inconsistent (Halvorson et al. 2014), although an explanation for this behaviour was not provided. On the other hand, Sato and Morgan (2008) showed that subsurface application increased cumulative N recovery relative to surface-applied controlled release fertiliser in a controlled environment experiment.

While no clear trends can be distinguished from the available data, it is a point to consider. In particular it is important to investigate how the differences arise and answer questions like: Does the tillage or placement action affect the longevity of the release or inhibitor action? Does the management influence factors that determine release rate, rate of breakdown or effectiveness of the inhibitor action?

Another example of the interaction with management is that of fertiliser application timing. In a study comparing controlled release fertilisers with different release patterns in potato, Rosen et al. (2012) concluded that the slower release product would require a pre-plant application whereas the faster release product needed to be applied at emergence. Conversely, the most suitable timing for fertilisation may determine the type of release pattern required. It is hence important that these release patterns are understood. Rosen et al. (2012) used fertiliser mesh bags to get a direct assessment of the release during the experimental monitoring season.

Agrium (http://www.smartnitrogen.com/how-esn-works/use-recommendations) provides separate guidelines for the application of their controlled release fertiliser by region and industry incorporating recommendations around suitability for autumn vs. spring fertiliser applications for different locations. For example, for wheat grown in the southern humid US corn belt, spring applications are not recommended due to the higher temperatures not sufficiently retarding the release.

Whole season vs. start of season

A few experimental trials with controlled release fertilisers have noted that the initial decrease in N_2O emissions was followed by increased N_2O emissions later during the growing season, causing an increase in cumulative N_2O loss over the season as a whole. This was not a consistent finding, with the studies only reporting it for one trial (Wang et al. 2008) or one season (Parkin and Hatfield 2014). Most of the time, the differences in emissions are not statistically significant, despite the visual differences between the cumulative N_2O emission curves (e.g. Di Bella et al. 2014; Farmacist (2013).

For a different season, the results shown in Figure 7.5a in the study by Parkin and Hatfield (2014) illustrate that delayed N_2O losses can occur with both controlled release fertilisers and stabilised fertilisers. From day (of year) 151 until day 178 cumulative N_2O loss from the urea treatment was significantly higher than that of the controlled release fertiliser and stabilised fertiliser (nitrification and urease inhibitors). Cumulative N2O emissions from the latter two treatments increased more rapidly from then on, causing the seasonal cumulative amounts to not be significantly different.

While in this case the later increases in N_2O losses did not cause an increase in seasonal N_2O emission, the data highlight an important point. If the delayed release or stabilisation of N leads to elevated nitrate concentrations later, there is a risk of increased losses then if conditions conducive to losses occur then. Parkin and Hatfield (2014) referred in this context to the episodic nature of rainfall events causing the N_2O losses during the growing season in rainfed systems. An understanding of the (typical) timing of N loss processes in sugarcane systems in different environments and on different soil types will prove informative. The risk of losses will reduce when release or stabilisation is better matched with crop N uptake.

A similar 'catching up' has been observed with ammonia volatilisation losses and the use of urease inhibitors (Figure 7.5a). In this case, however, it seems that the delay or reduced rate of urea hydrolysis leads to a more consistent seasonal benefit (e.g. Cantarella et al. 2008; Soares et al. 2012). Risk of ammonia volatilisation is greatest when the hydrolysis of urea leads to an increase in both pH and ammonium concentration. Delaying or slowing this process, allows for equilibration with the surrounding soil, rainfall washing urea below the soil surface and compensation from nitrification, which consumes ammonium and reduces pH. This means the later increases in volatilisation are of reduced magnitude. With surface application the use of a nitrification inhibitor can, however, keep ammonium concentrations elevated and lead to increased volatilisation losses (Figure 7.5b).

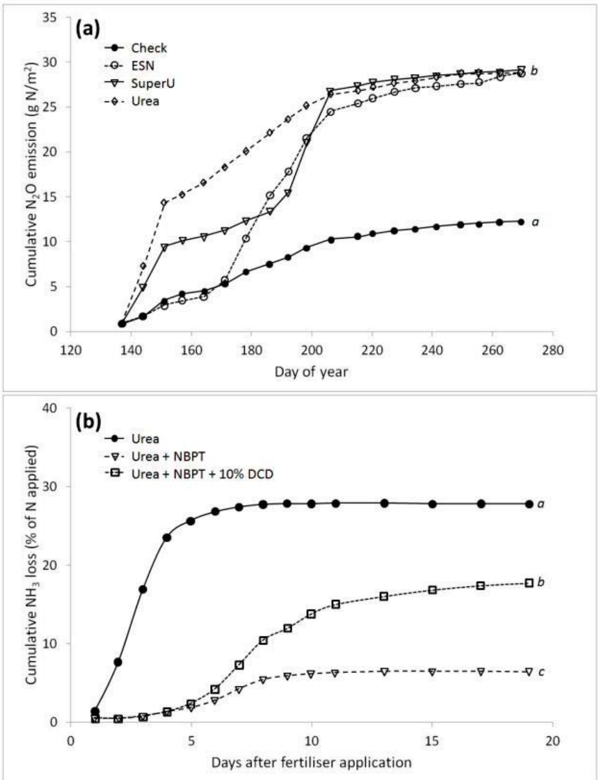

Figure 7.5. (a) Cumulative N_2O-N emission loss under rainfed maize in the US using urea, a polymer coated fertiliser ESN, a stabilised fertiliser SuperU (urease and nitrification inhibitors), and a N0 check (selected data from Parkin and Hatfield (2014) 2011 trial); (b) cumulative ammonia loss in volatilization chambers under controlled conditions following application of urea, urea and a urease inhibitor (NBPT) and urea with both a urease inhibitor (NBPT) and a nitrification inhibitor (DCD) (selected data from Soares et al. 2012 experiment 1). Different letters for the final cumulative amounts are significantly different ($p \leq 0.05$).

Based on the findings in the special issue of the Agronomy Journal (see above) Hatfield and Venterea (2014) concluded that N_2O emissions are often reduced for a period following application (usually the start of the season), but depending on timing of rainfall during the latter part of the season when N is released or the N fertiliser no longer protected by inhibitors the responses become less predictable. This implies that to achieve an accurate assessment of N loss reductions, monitoring needs to continue throughout the season and not be extrapolated from a shorter period immediately post-application. As will be discussed later (Section 7.8), monitoring beyond the season may be warranted as well, if N is left behind by the crop.

Understanding effectiveness requires understanding of systems dynamics

The experimental findings in sugarcane in Section 7.5 and those documented above for other industries highlight that the goals of reducing N loss, increasing N efficiency and increasing crop yield are not always achieved simultaneously. Reduced N loss has the potential to increase yield, but only if the crop is N limited (see e.g. Verburg et al. 2013, Dell et al. 2014; Halvorson and Bartolo 2014).

As pointed out by Venterea et al. (2012) N management practices that achieve the highest recovery of fertiliser N in crop biomass may also result in the highest N_2O emissions (Fujinuma et al. 2011; Gagnon et al. 2011) and practices or conditions that reduce one N loss pathway, may increase that of another (Venterea et al. 2012, Prammanee 1991). For example, reducing volatilisation losses may make more N available for denitrification or leaching losses, if the N is not taken up by the crop prior to these losses occurring.

The effectiveness of enhanced efficiency fertilisers in relation to N loss, N use efficiency and crop performance is affected by a complex set of interacting soil, crop, climate and management factors (Mosier et al. 2002; Chen et al. 2008b) that affect the amount and timing of release or availability in the mobile nitrate form relative to the magnitude and timing of N loss processes and relative to the magnitude and timing of N demand and its effect on crop performance and yield. Landscape position has also been suggested as a factor affecting the effectiveness of enhanced efficiency fertilisers (Noelsch et al. 2009). As a consequence findings have not been consistent across seasons, soils, cropping systems and management practices (Chen et al. 2008b, Venterea et al. 2012).

An understanding of the key drivers is, however, critical in order to determine the role that enhanced efficiency fertilisers can play. That such an understanding can be powerful is best demonstrated using the study by Hartz and Smith (2009) who analysed the California experience with controlled release fertilisers for vegetable production. Realising that the potential advantage of controlled release fertilisers is maximized in production systems in which in-season N losses are significant but beyond the control of the grower, and where there are cultural constraints on in-season fertiliser application (Hartz and Smith, 2009), they concluded that, in that system, the in-season N leaching losses were driven by irrigation, due to the majority of rainfall falling out of season, and hence within control of the grower. In addition, the high water holding capacity of soils favoured for vegetable production also reduced the risk of N leaching losses. With respect to management, the widespread adoption of drip irrigation would allow for efficient irrigation as well as the option of multiple applications of less expensive N fertilisers, reducing the case for controlled release fertilisers which despite 30 years of research in the industry indeed had a very low adoption rate.

It would be valuable to do a similar assessment of drivers in the sugarcane systems of Australia, but due to regional differences in climate, soils and management, the analyses are likely to be more region specific. In addition, the highly variable climate means that the system's interactions are difficult to capture in experimental trials of just 3-4 years. Linking the trials with modelling may provide a better option (see Section 7.8 below).

Trial design

An experimental trial set up specifically for scientific purposes usually contains multiple treatments that may not only compare the fertiliser products of interest, but also include one or more fertiliser rates. Sometimes the rates reflect the recommended rate as well as a lower rate (e.g. Pack et al. 2006), at other times full N response curves are determined (e.g. Halvorson and Bartoli 2014)). Often a zero N treatment is included to determine the N supply from the soil (carry-over from previous season and soil mineralisation) or the background N losses. The effects from the enhanced efficiency fertilisers are typically compared with those from conventional fertilisers at the same applied rates.

As one potential advantage of enhanced efficiency fertilisers includes the possibility of using enhanced efficiency fertiliser at a lower rate, some studies, especially demonstration trials, have compared conventional fertiliser at a certain (e.g. best management practice) rate with enhanced efficiency fertiliser at a lower rate (see e.g. Section 7.5). Achievement of similar crop performance may then suggest that the enhanced efficiency fertiliser delivered benefits. The dilemma with this approach is that it does not provide information about N responsiveness. More specifically, it does not answer the question whether the use of a lower rate of conventional fertiliser may also have resulted in the same crop performance. While a full response curve provides the best information to assess the true value of fertiliser product comparisons, it is not always feasible to include them in farmer led trials. A simple trial that generates a definitive outcome (Lawes 2011) may be preferred so that it is important to define the test question well and select the control treatment carefully. In the above example of the comparison between conventional urea at a higher rate and enhanced efficiency fertiliser at a lower rate, it will be more useful to add a treatment of conventional urea at the lower rate, than to include a zero N treatment, which does not provide information about the relative responsiveness to N between the two rates. Zero N treatments or strips can help assess the contribution from soil N and are critical for N use efficiency calculations (see Chapter 2).

As shown by Halvorson and Bartolo (2014) and also by the preliminary simulations in Section 7.7, the responses in yield will more likely be observed at sub-optimal N rates. Trialling with rates that include both sub-optimal and supra-optimal rates provides insights into any shifts in the inflection point on the yield response curve. Trialling only at sub-optimal rates is more likely to show yield effects (Chen et al. 2008b; Frye 2005), but the positive effects do not necessarily extrapolate to higher fertiliser rates where yield may be limited by other factors.

7.7 Understanding crop N demand patterns

Accomplishing synchronisation requires an understanding of crop N demand patterns and how these are influenced by seasonal conditions, soil properties and cropping systems management. Synchronisation from a crop supply perspective to avoid N stress is particularly relevant for slow and controlled release fertilisers. Nitrogen stabilised by nitrification inhibitors is available to the sugarcane due to its ability to use both nitrate and ammonium. Therefore, inhibitor stabilised N, would not be expected to limit the crop. To minimise the risk of N losses, however, delaying the availability of nitrate N until the crop's demand for N can effectively 'compete' with N loss processes would still be relevant.

Under Queensland conditions, N accumulation in aboveground biomass of sugarcane was found to follow a sigmoidal function. The rate of N accumulation appears to be most rapid for a period of approximately 80-120 days occurring between 70 and 280 days post crop initiation (Figure 7.6). It has been noted that uptake often ceases well before crop biomass reaches its maximum, even under conditions high N supply (Wood et al. 1996; Kingston et al. 2008). A number of Australian and overseas studies have indicated that uptake of N by sugarcane is affected by crop class (plant or ratoon cane), crop age, genotype as well as seasonal and management effects that affect biomass accumulation. Given the observed effects of N supply levels (Figure 7.6c,d,e), it is possible that crop response and N demand may also change in response to timing or form of N supply. A systematic analysis of the effect of seasonal, crop and management factors on the variation in N uptake

patterns does not appear to have been published and could be informative for the evaluation of enhanced efficiency fertilisers, in particular for choice or design of controlled release fertilisers.

Different N demand patterns may require different release patterns to achieve synchronisation. Hauck (1985) commented that 'because uptake and use patterns vary considerably among different plant species grown under similar conditions of N supply, it is unlikely that any single pattern of N release from a material will satisfy the N requirements of all cropping situations.' Therefore a product that suits one crop, may not suit another, and hence care must be taken when extrapolating experimental findings from one crop to another. Whether the differences in uptake patterns between plant and ratoon crops in sugarcane will necessitate products with different release patterns will require further assessment as timing of application (relative to planting or ratooning) can also play a role (Section 7.6).

Many of the more readily available controlled release fertilisers (not necessarily developed or recommended for sugarcane) follow the linear-declining release pattern, with only a short delay prior to release commencing (Section 7.4). Nitrification inhibitor longevities at the lower end of the scale (< 4 weeks or even < 10 weeks; see Section 7.4) would also allow nitrification to occur ahead of the period of high N uptake. Compared with the sigmoidal uptake patterns in Figure 7.6 his suggests there may be room to improve the synchrony, although how much difference that would make depends on the timing of N losses and any (temporary) immobilisation of fertiliser N in the soil. In reviewing data on the comparative recovery of basal N to paddy rice, Shoji and Kanno (1994) reported on the significantly higher recovery from a sigmoidal product (79%) compared with 22-23% from urea and 48-62% from the linear-declining release product, although the comparison was based on data from three different sources, so other factors could have played a role too.

One point of note is that most data on crop N accumulation only consider the aboveground biomass. Root N requirements are less well understood. Given suggestions that controlled release fertiliser products may not supply sufficient N to ensure early vigour (prompting the use of blended products), the (early) N demand by roots requires further investigation.

Optimising the synchrony between supply and demand also needs to consider the impacts of the timing of N availability may have on CCS. A number of studies have suggested that high N supply can decrease sucrose concentration in fresh millable stalks, decreasing the commercial value of the stalks. The lower sucrose concentration on a fresh weight basis has been linked to decreased stalk dry matter content, as the effect on sucrose concentration in dry millable stalks was found to be small (Muchow and Robertson, 1994). Where a premium is paid on CCS this results in a possible trade-off between N supply effects on cane yield and fresh weight sucrose content. Changing the timing of N supply will potentially add another dimension to this balance.

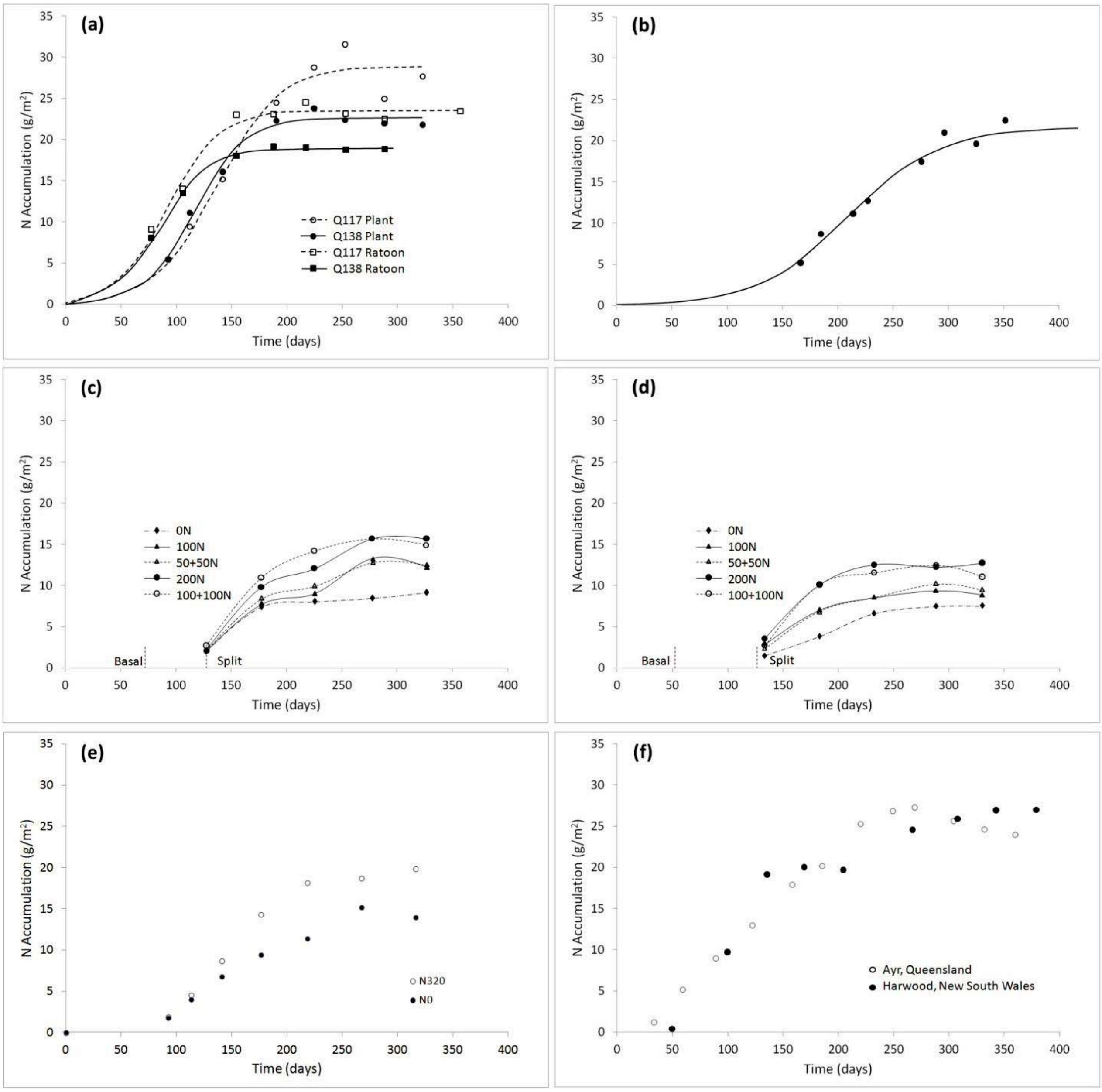

Figure 7.6. Examples of N accumulation patterns observed in Australian sugarcane. Data from Wood et al. (1996) for (a) two varieties of a plant and first ratoon crop grown in Ingham N Qld and (b) a plant crop (Q96) grown in Ayr, N Qld (experiment by Muchow et al. 1994), all under conditions of high N input and unlimited water; Kingston et al. (2008) for (c) third ratoon and (d) fourth ratoon crops (Q155) grown in Rocky Point, S Qld under irrigated and water logging conditions with a range of fertiliser management treatments; Verburg et al. (1996) for (e) a first ratoon (CP51-21) grown near Bundaberg, S Qld under irrigated conditions and two N rates; Keating et al. (1999) for plant crops (Q117) grown at Harwood, NSW (experiment Hughes et al. 1995) and Ayr, N Qld (Muchow et al. unpublished experiment) under conditions of irrigation and high N inputs.

7.8 Opportunity for modelling

The release patterns from controlled release fertilisers have been modelled using empirical regression functions (Jarrell and Boersma 1979, 1980; Gandeza et al. 1991; Fujinuma et al. 2009). Typically such functions are specific to a product and constant environmental conditions, such as constant temperature. While useful to provide an estimate of release times in contrasting environments, it does not capture the changes in temperature typically experienced within seasons. Gandeza et al. (1991) presented an approach to calculate cumulative release with time in the presence of daily variations of temperature by switching between the regression curves for cumulative release at different temperatures.

Where the mechanism of release is well understood, for example with polymer coated controlled release fertilisers, conceptual models provide a better alternative. Shaviv (2001) described the release from polymer coated controlled release fertilisers as a three-stage process (Figure 7.7) consisting of an adsorption stage during which water enters the coated granule, but no release occurs, a linear release stage while solid fertiliser is dissolving maintaining constant osmotic pressure and hence release, and a declining stage when the all solid fertiliser has dissolved. A number of product descriptions, e.g. Pursell Industries (1992) and Haifa (nd) use this same conceptual model. Bear et al. (1998), Shaviv (2001) and Shaviv et al. (2003a) used it as the basis for detailed mechanistic process models, simulating e.g. water absorption, temperature dependence, membrane solute permeability and diffusion from a spherical granule. The approach was extended further by applying population statistics to take into account that there will be variation in coating thickness and properties of individual granules, and hence release patterns, within a fertiliser application (Shaviv et al. 2003b; Du et al. 2008).

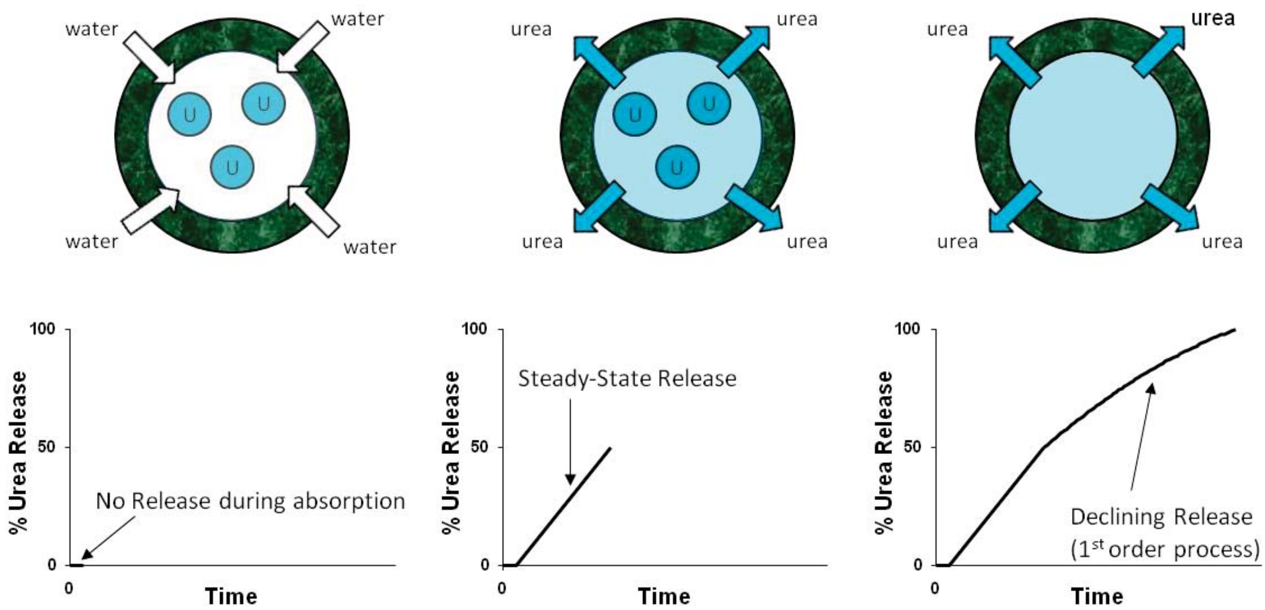

Figure 7.7. Conceptual three-stage process for release from controlled release polymer coated fertilisers.

Verburg et al. (2013) also adopted the three-stage conceptual model, but without the detailed process descriptions, simply defining the release rate of the linear phase and linking that of the subsequent 1st order declining release phase to it. A user defined Q10 temperature effect allows for rates to increase with increasing temperatures, e.g. a Q10 = 2 results in a doubling of the rate with a 10 degree increase in temperature (Figure 7.8). This approach allows the release throughout a season with fluctuating temperatures to be simulated dynamically. Like Bear et al. (1998), Shaviv et al. (2001), (2003a), this model allows description of release from the so-called linear-declining products (Section 7.4), but would need to be adapted for sigmoidal release or release that is governed by factors other than temperature.

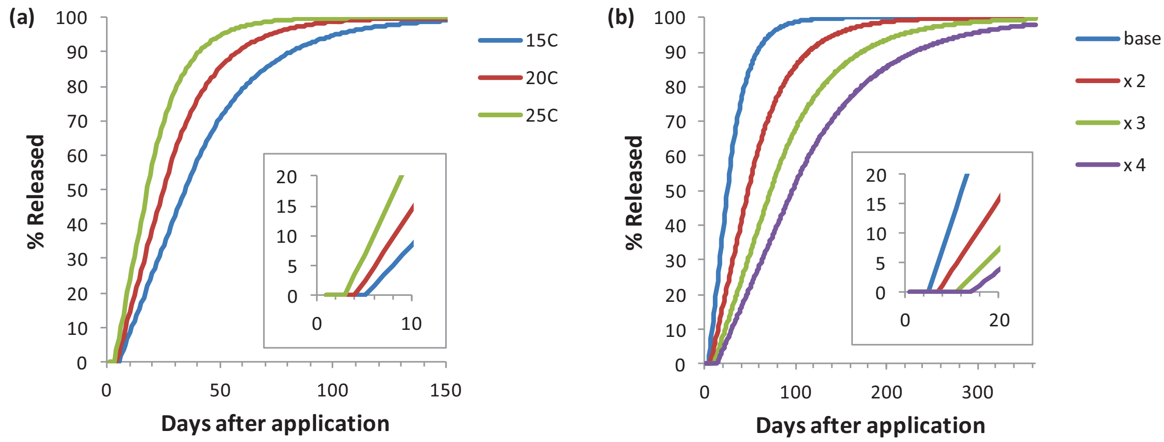

Figure 7.8. Modelled release as a function of time; (a) base product at different temperatures, (b) products with different release rates at 20°C (base product and x 2, x 3 and x 4 times slower).

Verburg et al. (2013) built their model into the Agricultural Production System Simulator (APSIM; Keating et al. 2003). By integrating the release model within this cropping systems model, the interaction (and relative timing) of release and other system processes such as crop N uptake and N losses, as well as climate impacts and management practices can be studied. Preliminary simulations for a number of cropping systems confirm the value of a system's approach (Verburg et al. 2013). Simulations with an earlier version of the model (Verburg et al. 1998a) of sugarcane systems confirm some of the findings from earlier simulations with split N fertiliser application (Verburg et al. 1998b), namely:

- Yield benefits are only achieved on the slope of the N response curve, i.e. at sub-optimal N rates (see Figure 7.9), but they result in the yield plateau being reached at lower N rates. This compares well with findings by Halvorson and Bartoli (2014, Section 7.6).
- Yield benefits can be highly variable from year to year (see Figure 7.9), depending on the magnitude and timing of N losses, which are similarly variable (see e.g. Verburg et al. 1998b)
- Simulating over longer times frames, of multiple seasons, highlights the effect of carry-over of unused N, which may be liable to loss at some later time, e.g. early in the next season or during the fallow. When longer timeframes are considered, the environmental N losses are, therefore, only reduced if the reduction in N loss is accompanied by either an increased in N uptake by the crop or a reduced application rate. The use of controlled release fertiliser at rates beyond the demand of the crop does not further reduce the N losses in the long term (Figure 7.10).

The implication of these findings for experimental evaluations is that one must be careful when extrapolating from growing season measurements. Any reductions in N loss demonstrated during the experiment, may in fact accumulate in the soil if not used by the crop or lost through another process. The impact of carry-over N on future N losses would be of particular concern in those trials where enhanced efficiency fertilisers reduced the N losses but did not improve crop response (e.g. De Antonio Mighorati et al. 2014).

The implication of the findings for management is that N fertiliser rates, complemented by N supply from the soil, still need to match crop N demand. This means that recommendations on fertiliser rates would need to accommodate an estimate of the reduced N losses through the use of enhanced efficiency fertiliser, which could be a challenge with high year-to-year variability in N losses.

Modelling allows extrapolation in time, but also in space. Preliminary simulations of multiple split applications, as an approximation for controlled release, suggest the responses to controlled release fertilisers may vary significantly with soil and locations (see Figure 7.11). In addition, modelling allows the internal system interactions to be explored in more detail, e.g. through the output of intermediate variables. This would also allow, for example, the study of crop N demand patterns compared with fertiliser release patterns, including year-to-year variability.

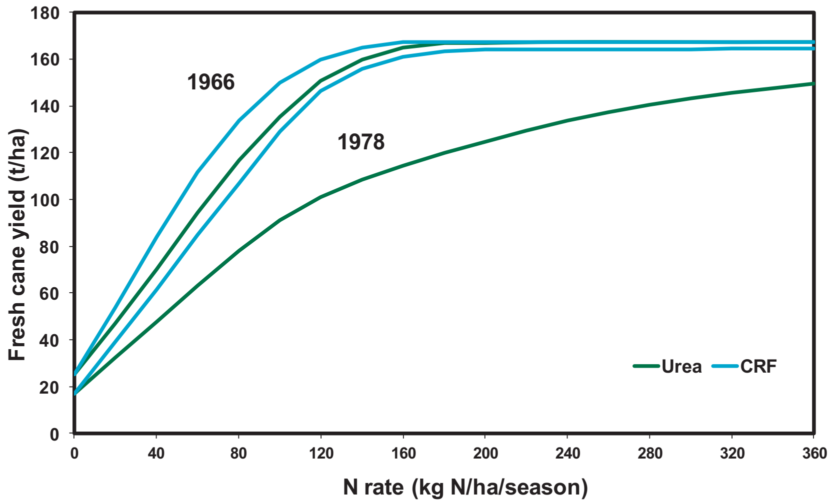

Figure 7.9. Preliminary simulations of controlled release fertiliser in sugarcane demonstrating yield response to N supplied by urea or controlled release fertiliser in two different years. (Location and product details not supplied due to preliminary nature of the simulations) (Verburg et al. 1998a).

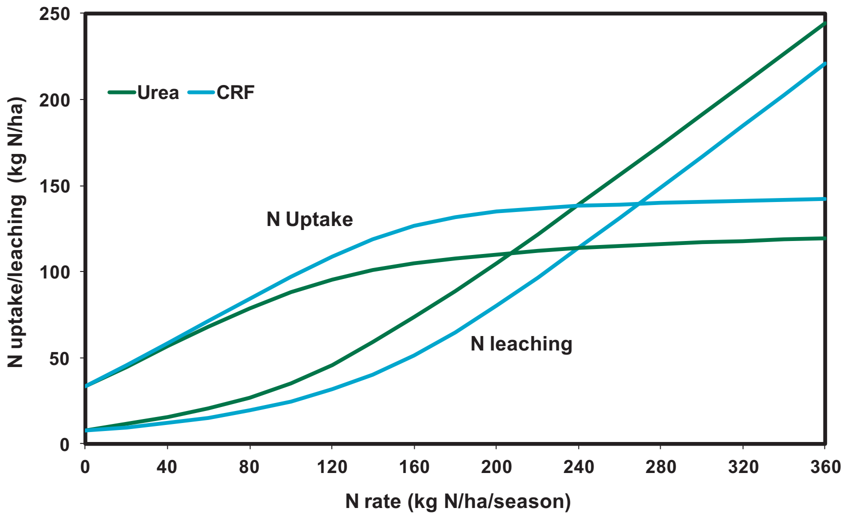

Figure 7.10. Preliminary simulations of controlled release fertiliser in sugarcane demonstrating the response of average N uptake and N leaching to N supplied by urea or controlled release fertiliser over a period of 98 years. (Verburg et al. 1998a).

Modelling has not been limited to slow or controlled release fertilisers. Cichota et al. (2010) developed and tested an APSIM module to simulate the effect of nitrification inhibitor DCD on nitrification. Vogeler et al. (2010) and Cichota et al. (2013) have used the model to explore the role of DCD in reducing nitrate leaching from grazed pastures. The N dynamics model DNDC (denitrification decomposition; http://www.dndc.sr.unh.edu/model/GuideDNDC95.pdf) can simulate the effects of both urease and nitrification inhibitors. It has been used to simulate the effect of nitrification inhibitors on N_2O emissions in grazing pasture systems (Giltrap et al. 2010, 2011) and on emission losses (NH3, N2O, NO) from a wheat-maize cropping system (Cui et al. 2014)

For simulation analyses to be meaningful, they need to capture the key N loss processes as well as crop N demand and response, along with the effects of various factors of influence such as soil characteristics and seasonal weather. The APSIM model has been shown to perform well in a range of contexts and for a variety of sugarcane systems and locations (see Chapter 6), but model verification is an ongoing process that benefits from careful and detailed experimental measurements. Areas that warrant further attention in the context of simulating enhanced efficiency fertilisers in sugarcane include early vigour/root N demand by the crop, denitrification losses, ammonium vs. nitrate uptake preferences, and the behaviour of the different enhanced efficiency fertilisers in response to the soil environment.

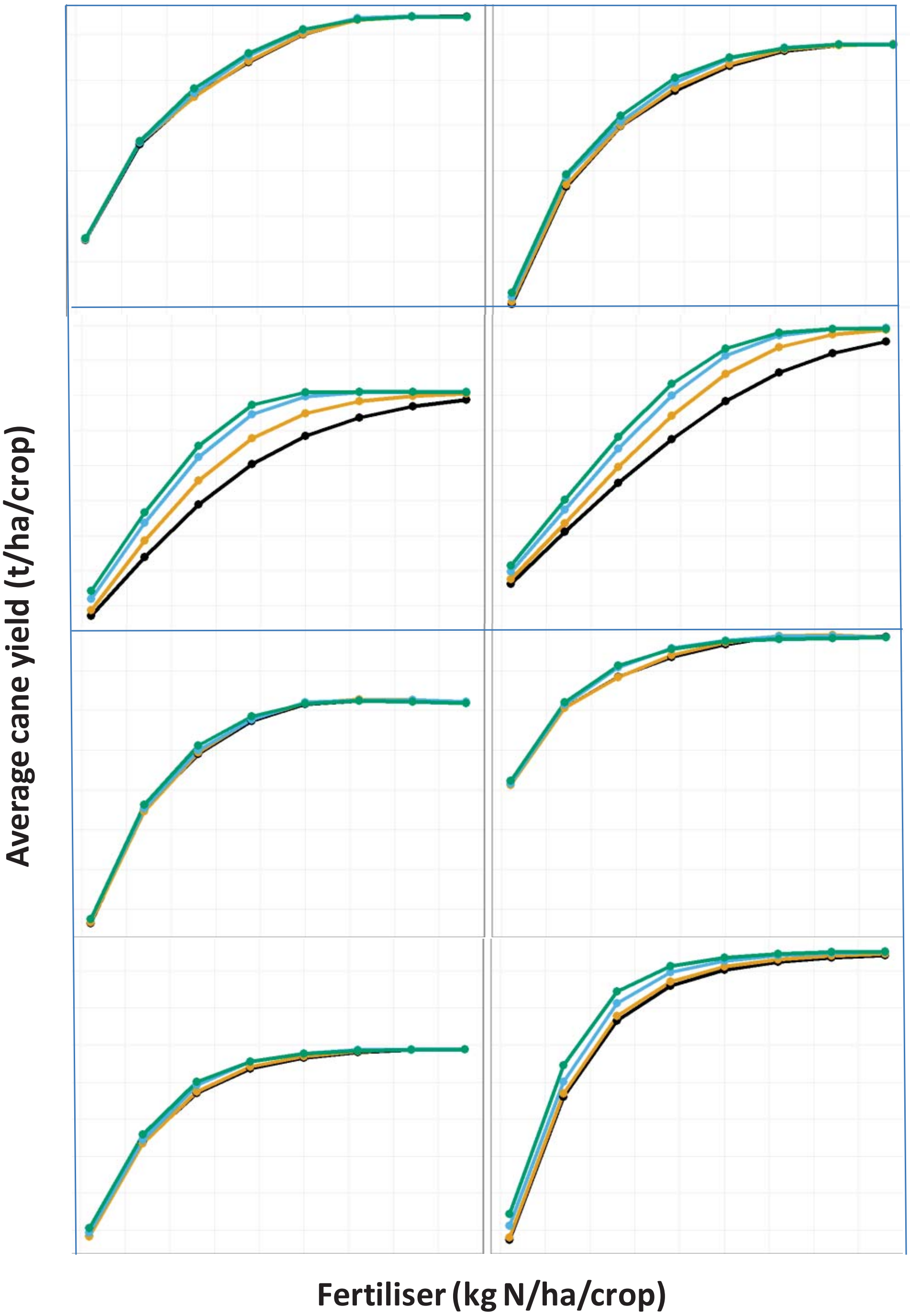

Figure 7.11. Simulated sugarcane yields in response to fertiliser N applied in 1 (black), 2 (orange), 3 (blue) and 4 (green) split applications for 8 soil/climate/management scenarios (locations and soils as well as axes scales not supplied due to preliminary nature of the simulations).

7.9 Economics of enhanced efficiency fertiliser use

Enhanced efficiency fertilisers are relevant to the management of two key pressures facing the Australian sugar industry: a cost-price squeeze, through downward trending sugar prices and rising input costs (Smith et al. 2014); and the need to reduce pollution in the Great Barrier Reef marine ecosystem from N and phosphorous exports from sugarcane land (van Grieken et al. 2013).

The cost-price squeeze, whereby the rate of inflation in production input costs is not matched by a proportionate increase in commodity prices, is not new or confined to the Australian sugar industry. The traditional strategies that have been employed to offset the decline in real incomes that these worsening trade terms implies have been to seek ongoing productivity gains – fertiliser management falls into this category. The price of urea on average has grown at much the same rate as CPI inflation over the last twenty years, but with a significant price spike across 2007-2009 (Smith et al. 2014). Fertilisers make up a significant component of farm business variable costs, averaging about 20% of the variable costs across the cropping cycle (Brennan McKellar et al. 2013), although this can vary depending on the fertiliser price and other inputs used in the production process. Enhanced efficiency fertiliser may present an opportunity to increase profits from cane production by enabling reductions in the quantity (and therefore cost) of fertiliser applied, or increase cane yield without a corresponding increase in fertiliser costs. The relative advantage of using these fertilisers compared to conventional forms will also depend on whether these efficiencies in fertiliser result in benefits that outweigh the higher per unit cost of these fertilisers.

On a unit for unit comparison, enhanced efficiency fertilisers are more expensive to purchase than conventional fertilisers, although published estimates are limited to the international literature and the quoted differences vary widely. There does appear to be consensus that controlled release fertilisers are currently more expensive than nitrification inhibitors. Lammel (2005) presented data that suggest nitrification inhibitors were 1.3-1.6 times as expensive as conventional NPK, slow release fertilisers were 4-6 times as expensive and controlled release fertilisers 8-12 times (Trenkel 2010). Shaviv (2001) and Chen et al. (2008b) suggested controlled release fertilisers may be 3-10 times the cost of conventional fertiliser. Such comparative cost assessments are snapshots in time. Prices are subject to change over time, e.g. in response to market forces and volumes traded. For example, the price premium for ESN controlled release fertiliser products (Agrium Inc 2014) in the US and Canada has recently been reported to be in the range of 15-30% (Gagnon et al. 2012), considerably less than that suggested by the earlier studies. The cost of enhanced efficiency fertilisers in Australia will differ due to the smaller market. Chapter 7 PART II provides a statement from Australian Fertiliser Industry on the current situation. As indicated above, these prices and price differentials may change over time.

Another uncertain aspect in the economic evaluation of enhanced efficiency fertiliser (and indeed conventional fertiliser) is identifying the economically optimum application rate which maximises the net return to fertiliser use. This can also be expressed as the rate in which the marginal return from an additional unit of nutrient equals the marginal cost. Determining the functional relationship between yields and fertiliser levels for a given crop is a key issue in determining the value of enhanced efficiency fertilisers because this underpins the economic responsiveness of varying the level of nutrient applied to a crop. For example, a gross margin curve exhibits may exhibit ‘flatness’ around the optimum fertiliser rate, reflecting the underlying yield response to fertiliser. For

moderate variations changes in fertiliser input levels, the implication of flatness around the economic optimum is that it will most likely result in only a small change in profit. Brennan et al. (2007) conducted a study in the Australian northern grains industry and found 'flatness' of the response curve was generally restricted to supra-optimal rates, with the implication that suboptimal N rates are more costly to get wrong than supra-optimal.

The issue of 'flatness' of the fertiliser response curve around the optimum is a well-documented finding in agricultural economics literature, dating back to the 1950s. Pannell (2004), however, notes the lack of recognition and discussion among many current agronomists (and even among agricultural economists) of the 'far-reaching' but 'under-recognised' implications of flat payoff functions. These concepts have also been explained and illustrated in the context of sugarcane by Brennan et al. (1999).

A key source of uncertainty affecting the economic outcomes from fertiliser use is that a manager's knowledge of the yield response to N (or any other nutrient) for any given soil type is imprecise because it depends on uncertain weather conditions. This means that the manager cannot choose with certainty the optimal rate of N to apply to each soil type to maximise profit for a given season. Other sources of uncertainty affecting the economic outcomes from fertiliser use can be alleviated by managers but at a cost (e.g. soil testing) which must be weighed up against the expected benefits.

Uncertainty, and the value of information to reduce it, is relevant to the economics of enhanced efficiency fertilisers, just as it is to conventional forms of fertiliser, and there is a body of literature that has addressed this e.g. Brennan et al. (2007); Oliver and Roberston (2009); Yu et al. (2008).

Economics of enhanced efficiency fertilisers in the Australian sugar industry

To date only one published study appears to have considered the economics of enhanced efficiency fertiliser use in Australian sugarcane. This study by Di Bella et al. (2014) (based in part on Dowie 2013) calculated net returns ($/ha) for trials with controlled release fertiliser blends mentioned in Section 7.5. The trial was established in 2012 and harvested in 2013, and examined a limited range of application rates. Calculations were performed for each fertiliser treatment in the trials (conventional urea and various blends of urea and controlled release fertiliser).

Net returns for sugarcane were calculated using the Cane Payment Formula (Government of Queensland, 1983) to establish the cane price, assuming a sugar price of $420/t and harvesting costs of $7.50/tonne of cane harvested. The calculation was:

Net Returns ($/ha) = (Cane price ($/t) - harvesting costs $/t) * yield t/ha – fertiliser costs $/ha.

The authors did not report the unit costs of the controlled released fertiliser or urea, but calculated from the data presented they differed by a factor of 2.9. Returns excluded irrigation, chemical and fixed costs, which implies that these would not change under alternative fertiliser regimes.

The study identified that at one site and at the highest rate of N (200 kg N/ha) controlled release N trials had higher cane productivity and N-efficiency (t cane/kg N applied) compared to urea. Of these treatments, only the blend with the lowest percentage (25%) controlled release fertiliser had a higher net return (12%). The blends with higher percentages of controlled release fertiliser decreased the net returns, despite producing higher cane and sugar yields. This result will be

sensitive to the price premium on the controlled release fertiliser. The study did not present an economic comparison of straight (100%) controlled release fertiliser because it was assumed to be unviable.

Other economic studies

There have been a number of studies overseas concerning other crops that have included measures of net returns, and economic efficiency associated with enhanced efficiency fertiliser use (e.g. Gagnon et al. 2012; Khakbazan et al. 2013; Zvomuya and Rosen 2001; Noellsch et al. 2009; Wilson et al. 2009b; Arrobas et al. 2011; Farmaha and Sims 2013). The studies are context dependent to particular crops and locations, vary in their specific conclusions about the economic advantages of enhanced efficiency fertiliser, and the economic analyses cannot be translated directly to sugarcane. What the studies have in common is the conclusion that enhanced efficiency fertilisers do not provide a consistent economic advantage compared with conventional application. The economics of enhanced efficiency fertiliser could improve if used in conjunction with conventional fertilises (e.g. Farmaha and Sims 2013; Zvomuya and Rosen, 2001).

However, relevant issues identified in these studies can guide further enquiry in the sugarcane context. These include:

- The price deviation between conventional and enhanced efficiency fertiliser is influential in economic outcomes, as inferred from the studies above
- The economic benefits of enhanced efficiency fertilisers vary according to weather conditions between seasons (e.g. Zvomuya and Rosen 2001)
- Economic outcomes for enhanced efficiency fertilisers vary spatially within a landscape as well as seasonally (Noellsch et al. 2009)

Economic-environmental considerations

The Great Barrier Reef is situated adjacent to the Queensland coast, and the Queensland sugar industry is located in the coastal river catchments that drain into it. Water quality in the GBR has declined significantly since European settlement and sugarcane production is regarded as a major source of pollutants (Queensland Government, 2013). The Queensland and Australian governments have responded to address diffuse source pollution in the GBR through the Reef Plan (Queensland Government, 2013). Changing agricultural land management in catchments adjacent to the reef has been a focus of the Plan. The Great Barrier Reef Protection Amendment Act (GBRPAA) 2009 is one of several policy instruments being used in the GBR catchments to achieve Reef Plan's targets and goals for water quality improvement to the GBR lagoon. The Act regulates a number of specified activities, including those on sugar cane properties in catchments in the Wet Tropics, Burdekin and Mackay–Whitsunday regions (see http://www.ehp.qld.gov.au/reefprotection/). In regulated catchments, the Act requires landholders to determine crop requirements for N and phosphorous before application, and to compile and comply with an environmental risk management plan (van Grieken et al. 2013). Soil N testing and nutrient management regulations apply to all properties that have at least 75% of their cane producing land within the boundaries of the regulated catchments. In addition, development of and compliance with environmental risk management plans is mandatory

for sugarcane farmers in the Wet Tropics with 70 hectares or more of their land under cane production (van Grieken et al. 2013).

Van Grieken et al. (2013) conducted an economic analysis in two catchments that identified the likely changes that landholders made when complying with the GBRPAA 2009 requirements, the potential costs and benefits for the landholder of these changes, as well as the potential consequences for pollutant exports. Based on the results in two catchments studied, it was concluded unlikely that the regulations would achieve the Reef Plan's target of 50% dissolved inorganic N load reduction by 2018 in either catchment, unless further land management changes were made. The study quantified the economic trade-offs in moving to more aspirational practices in order to further reduce dissolved inorganic N, which showed an increase in the total private costs to landholders to achieve reductions in the annual load of dissolved inorganic N.

The 'aspirational' scenario analysed by van Grieken et al. (2013) represented a suite of innovative practices that are documented in the Queensland Government's ABCD Management Framework 2013-2014 , with the ABCD classification defining scales of improvement from dated practices(D), conventional practice (C) best industry-promoted practice (B) through to future aspirational or new and innovative practices (A). (see http://www.reefplan.qld.gov.au/measuring-success/methods/management-practices.aspx). The use of enhanced efficiency fertiliser products in high risk areas or during identified high-risk periods has been identified in the A suite of practices (DAFF 2013). Van Grieken et al. (2013) did not however isolate the differences in economic outcomes between enhanced efficiency fertilisers and conventional forms.

The possible economic benefits of enhanced fertilisers may also depend on future guidelines or legislative frameworks that might be imposed around water quality and agricultural emissions. Given sugarcane's proximity to the Great Barrier Reef, N run-off and other threats to water quality, place pressure on growers' and industry's social licence to operate (Canegrowers 2014). The adoption of a new practice that limits nitrous oxide emissions may, in future, have the potential to generate revenue proportional to the value placed on carbon. These off-site aspects do not appear to have been considered in any economic analyses of enhanced efficiency fertilisers.

Further economic research

In relation to the sugar industry context, there appear to be a number of gaps in the literature for possible future inquiry. These include:

- The economic performance of enhanced efficiency fertilisers under different relative price differences between conventional and enhanced efficiency fertilisers, and under other price assumptions;
- The functional relationship between yield and enhanced efficiency fertiliser input, and from this relationship between fertiliser and economic response.
- Risk and net returns from enhanced efficiency fertilisers in the presence of temporal and spatial variability
- Economic-environment tradeoffs between net returns and nutrient export to the Great Barrier Reef under enhanced efficiency and conventional fertilisers

7.10 Summary and concluding remarks

Review findings and lessons

The results from the trials to date in Australian sugarcane suggest that enhanced efficiency fertilisers may have agronomic and environmental benefits in at least some situations. Inconsistencies in these benefits indicate further and more in-depth investigations are warranted (see Section 7.5). Reviews covering experiences in other industries and overseas also highlight the inconsistent agronomic and environmental benefits from enhanced efficiency fertilisers (e.g. Chen et al. 2008b; Hatfield and Venterea 2014), although the on average positive effects obtained in recently published meta-analyses (Section 7.6) are cause for optimism.

The delayed release of N or stabilisation of N in a form less susceptible to loss can often be demonstrated (see Section 7.4) with enhanced efficiency fertilisers, but this does not always translate in a reduced N loss. If the period of delayed or reduced availability (compared with conventional fertiliser) does not coincide with conditions conducive to N losses, reductions in N loss will be minimal. This is particular the case with N_2O and N_2 emission losses as well as nitrate leaching and N runoff losses which, depending on conditions, can happen throughout the season. The effectiveness of enhanced efficiency fertilisers (in particular urease inhibitors, but potentially also slow and controlled release fertilisers) to reduce ammonia volatilisation losses appears to be more consistent due to its usually shorter time frame and the fact that a slower hydrolysis process modifies the soil environmental factors that contribute to ammonia loss (see Section 7.5). In Australian sugarcane their role in reducing volatilisation losses will need to be assessed against other practices, such as incorporation of the fertiliser into the soil. Due to their shorter longevity (see Section 7.4) compared with nitrification inhibitors, urease inhibitors are less effective in minimizing other N loss pathways, although a number of studies have nevertheless evaluated them for N_2O reductions and on occasions where N_2O losses occurred early during the season they have proven effective (see Section 7.6).

If the delayed availability of N in nitrate form (from slow or controlled release fertilisers or following stabilisation using nitrification inhibitors) coincides with a time that the system is susceptible to N losses this can cause increased losses later (see Section 7.6). Hatfield and Venterea (2014) concluded in this respect that initial effectiveness can often be demonstrated during the period immediately following application, but that rainfall patterns during the rest of the season determines the overall efficacy. Given that it is this whole season scale which would usually determine the agronomic benefits and that to assess environmental benefits we might even need to go beyond that (Section 7.8), it is important that the responses over such time frames become better understood.

The key to elucidating the impact of variable seasonal conditions – from year to year and from site to site – is to consider how they impact on drivers for N losses from the system and what these drivers are in the first place. Complex system interactions between rainfall pattern, soil water and N dynamics, and timing of crop N accumulation are at play and these vary from site to site and often from season to season as well. As illustrated by the example of the California experience with controlled-release fertilisers for vegetable production (Hartz and Smith, 2009; Section 7.6), understanding the system interactions and the drivers for N loss can help elucidate the case for enhanced efficiency fertiliser in a system.

The importance of a system's view is also highlighted by the observations that the reduction in N loss via one mechanism may make more N available for loss via other mechanisms if the reduction in N loss is not taken up by the crop (Section 7.6). It follows that knowledge of the synchrony between N release or stabilisation patterns and crop N uptake is important, but surprisingly very few field trials include an assessment of the release or stabilisation patterns of the product used. Very few assessments of the synchrony between release and N demand by the crop have been made (see Section 7.7). Based on the release and stabilisation patterns of commercially available products (section 7.4), there seems to be room for improvement and it has been demonstrated that better synchrony can translate into higher N recovery by the crop. This will require a better understanding of the response of crop N demand patterns as a function of seasonal and management conditions.

As suggested by the results of a number of trials (Sections 7.5 and 7.6) a reduced N loss does not necessarily result in increased crop N use efficiency or a yield benefit, depending on the driver for yield potential. A response to the improved N supply is a necessity for a yield benefit to be recorded. Therefore, when comparisons between conventional fertiliser at a higher rate and enhanced efficiency fertiliser at a lower rate are made it is important that the response to N between these two rates is measured too (Section 7.6). Without it, a statistically equal response cannot necessarily be ascribed to the use of enhanced efficiency fertiliser. The finding by Di Bella et al. (2013) that N response was lacking with urea but present with enhanced fertiliser, provides an interesting challenge in this respect. While possibly reflecting a special case, it points to the need to complement agronomic measurements with other evidence that can link the agronomic outcome to a cause. The finding, both experimentally (Halvorson and Bartolo 2014; Section 7.5) and through simulation (Verburg et al. 1998a; Section 7.8), that yield benefits are only achieved at sub-optimal N rates, suggests trials using such rates are more likely to demonstrate treatment effects. Care must, however, be taken in extrapolating the results at sub-optimal N rates to supra-optimal N rates. A shift of the optimal N rate to lower application levels may, however, prove useful from an economic perspective.

Where yields are limited or affected by other factors, this can mask or override the response for enhanced efficiency fertilisers. Indeed, when these other factors, including e.g. water availability, supply of other nutrients, and negative crop responses to water logging, pests and diseases, express themselves in a high field variability this may prevent statistically significant results, as raised by Myers and Vallis (1994; Section 7.6).

The mixed results worldwide (Sections 7.5, 7.6) suggest that no blanket recommendations about the effectiveness of enhanced efficiency fertilisers can be made. The presence and magnitude of benefits will vary depending on season, crop, location (soil and climate) and management system, as well as interactions between these. For some cropping systems the benefits are clearer and indeed we do see adoption in industries like paddy rice, horticulture and turf grass, where losses are clearly significant (e.g. due to waterlogged systems, sandy soils, or shallow rooted crops) or fertiliser application cost reductions are more obvious given current practice of multiple split applications. Based on the limited trialling to date within the Australian sugarcane industry, the benefits are likely to be variable – site or region specific and quite possibly seasonally variable as well. The available experimental evidence reviewed here does, however, not provide sufficient information to tease out exactly where and when benefits would most likely be obtained and how significant they may be.

Looking at the number of trials involving enhanced efficiency fertilisers worldwide, it is disappointing how few conclusions can be drawn about why benefits are obtained under some circumstances, but not in others. We are still faced with the same questions as expressed 20 years ago by e.g. Hauck (1985) on needing to better understand the relationships between fertiliser form, rate of N uptake and use by plants, and to delineate cropping systems where enhanced efficiency fertilisers may have definite value and their advantage may justify the higher cost.

A number of trials appear to have been opportunistic, testing only one enhanced efficiency fertiliser product against a conventional fertiliser and often in just one or two seasons and locations. Many of the agronomic trials include very few additional measurements that may help explain the findings, such as changes in soil N, crop N accumulation or an assessment of N losses. Even the most obvious measurement, an assessment of the pattern of the fertiliser release or stabilisation is often not included. With the effectiveness of enhanced efficiency fertilisers clearly dependent on system interactions, it would be desirable that trials do not just test a product but that they also attempt to explain observed effects and that they for that reason take more of a system's approach. Such studies do, however, require substantial funding, which is often not available.

As shown in Section 7.8 and Chapter 6, agricultural systems modelling can provide a means to extrapolate experimental seasons in space and time as well as explore systems interactions. Preliminary work to date simulating split applications and controlled release fertilisers (Section 7.8) confirm that variable responses are likely to be obtained across the Australian sugarcane regions. The simulations also highlight that yield responses are only obtained in N responsive situations (i.e. on the slope of the N response curve) and that the use of enhanced efficiency fertilisers does not eliminate the need for matching total N supply (including soil N supply and after subtraction of N losses) to crop N demand. Carry-over of any excess N where the total N supply exceeds demand may lead to N losses in a subsequent season or during the fallow.

There is a surprising lack of publicly available data on release patterns and how these may differ for different soils. Slow or controlled release products are typically characterised by time to 80% release, which does not provide any information on the shape of the release pattern, which could include significant early release, or 'lock off' of a certain percentage of the fertiliser (see section 7.4). Data are typically provided for a few key temperatures (e.g. 15, 25 and 35 °C), whereas in reality the temperature will change throughout the season. Measuring and modelling of the release patterns and factors of influence (such as temperature) may provide an assessment of the seasonal variability in release.

Characterisation of release is also often done under lab conditions that bear little resemblance to field conditions, e.g. through dissolution in water or in saturated soil suspensions. For some products or situations this may give an incorrect impression of release time, in particular where microbial action is involved in the release process or other factors (soil pH, water availability) affect it. Similarly little is known about interactions with soil management actions such as tillage and placement (Section 7.6). There is a role for lab incubations, in particular to tease out processes and some factors (e.g. temperature), but at some point the link with release under field conditions need to be made. Standardised protocols for such lab and field characterisations have not yet been developed, although attempts are being made (Section 7.4).

Achieving benefits with enhanced efficiency fertilisers will require a good understanding of the system as a whole, including crop, soil, climate and management interactions. Outcomes will be sensitive to timing of release or stabilisation relative to crop N demand and accumulation and timing of loss processes.

For controlled and slow release fertiliser products, if timing of release is too early, effects may be limited or non-existent, if timing is out and occurs during a wet period it may increase losses, if timing is too slow it may affect early vigour of the crop and if timing is too late, then it may limit the crop or even leave N behind (Rosen et al. 2012). With sugarcane the impact of timing of N availability on CCS needs to be considered too (Section 7.7). For nitrification inhibitors use in sugarcane, the timing of stabilisation is likely less of an issue in relation to crop N supply, but still relevant from the perspective of reducing the risk of N losses.

For slow and controlled release fertiliser use in the Australian sugarcane industry, the level of precision required to optimise crop performance and minimise losses is likely to be a challenge. In addition, unpredictable variations in seasonal conditions that affect both N losses and N uptake patterns mean that achieving a perfect match is unlikely. Nevertheless the positive experiences in some industries and countries (e.g. Japan) and the example of application guidance provided in the USA for some controlled release fertiliser products (Section 7.6) suggest that it may be possible to derive region/soil/landscape position specific rules of thumb and link these to product choices.

Based on the findings documented in this review the challenge for nitrification inhibitor use in the Australian sugarcane industry will be to ensure sufficient longevity in warm climates and under a range of soil conditions (pH, organic matter, etc.). For urease inhibitors it will be their effectiveness in different temperature, soil and trash conditions, as well as benefits relative to other practices that reduce volatilisation losses. Adoption of all of the products will depend on the balance between cost and achieved benefits.

Review recommendations

This review of the use of enhanced efficiency fertilisers to increase N use efficiency in sugarcane suggests the following needs and opportunities:

- Despite the mixed experimental evidence obtained so far, slow release or stabilisation of N that is better synchronised with plant N accumulation would appear to provide an opportunity to reduce N losses and increase N use efficiency, especially in high loss (wet) environments. There is, therefore, a case for further trialling of both types of enhanced efficiency fertilisers.
- At least some of these trials need to combine agronomic measurements and assessments of N loss pathways, so that cause and effect can be better established. Emission, runoff and leaching loss pathways should be considered. Trials should also include an assessment of the release / stabilisation patterns of products used and consider the synchrony with crop N accumulation. Ideally multiple products that rely on different release/stabilisation mechanisms are included in each trial to allow a proper comparison and bring us a step closer to determining their relative strengths and weaknesses. As described above, achieving and quantifying crop responsiveness to N is important.

- Where trials are limited to agronomic evaluations only, the lessons that they can provide could be extended considerably by inclusion of an N rate comparison to demonstrate N responsiveness and by an assessment of the release pattern of the product used. To encourage the latter, simple protocols should be developed that can provide information on release or stabilisation patterns experienced during the field trial. Zero N treatments should be encouraged in order to allow an assessment of N supplied by the soil (from carry-over from previous season and soil mineralisation).
- Given the high season-to-season and site-to-site variability in Queensland, cropping systems modelling should be linked to the experimental trials to help interpret the results and extrapolate the findings more broadly.
- To support the site selection and design of trials as well as future adoption, a systematic assessment of N loss drivers and timing and likely benefits from enhanced efficiency fertilisers should be carried out to identify region/soil/season/crop/management (irrigation/fertiliser placement) combinations that would most likely benefit from their usage and what this means in terms of product requirements. The position within the landscape (topography) should also be explored as a possible factor.
- To address the lack of publicly available data on release patterns and fill knowledge gaps on responses in different soils and management systems more work is needed to characterise the release patterns and factors of influence for different controlled and slow release fertilisers. The information needs to allow an assessment of release pattern relative to major N loss events and of its synchrony with crop N accumulation.
- Characterisation of the longevity of stabilisation patterns of different nitrification inhibitors is equally desired, including an assessment of interactions with microbial dynamics in different soils and of longevity of stabilisation in the hotter climates of tropical Queensland.
- The limited available data on release patterns from current, commercially available enhanced efficiency fertiliser products suggest that there is room for improvement to achieve better synchrony between fertiliser N release and crop N demand. Improving the synchrony will not be a trivial exercise, however, as, especially in rainfed systems, the products would need to cater for climatic influences on crop growth, e.g. rapid growth and presumably N demand in response to rainfall. Developments on this front would be best informed by a better understanding of the behaviour and limitations of current products in Australian sugarcane systems (through the above trials and modelling) and definition of 'ideal product' requirements that could be informed by modelling (even if the ideal product itself may not exist).
- To add to the discussion on appropriate N rate selection methods and recommendations for the industry (Chapter 2), the use of enhanced efficiency fertilisers will not only require an assessment of where this is likely beneficial, it will also require a judgement of levels of reduction in N application that may be achieved with enhanced efficiency fertilisers to avoid carry-over of excess N.
- With economics being a key driver in adoption, it is important that the economic performance of enhanced efficiency fertilisers is further investigated. The investigations should consider different relative price differences, risk and net returns in the presence of spatial and temporal variability, and economic-environment tradeoffs. Due to seasonal variability, economic analysis

in conjunction with modelling is needed to extrapolate the cost-benefit assessments in experiment trials.

- It is recommended that the science behind the performance of enhanced efficiency fertilisers in different situations is (continued to be) communicated widely and at different levels within both the sugarcane and fertiliser industries to encourage a systems understanding and evidence-based decision making for trialling and adoption.

7.11 Acknowledgements

This chapter draws on the experimental findings of many. In addition we received input, comments and feedback from a number of people. We would like to acknowledge their contributions and mention in particular the following people: John Freney, Therese McBeath, Mike Wong, CSIRO Agriculture Flagship; Andrew Wood, Tanglewood Ag Services; Lawrence Di Bella, HSCP; Michael Nash, Terrain; Philip Moody,Weijin Wang, Queensland DSITIA; Derek Sparks, Queensland DAFF; Jayson Dowie, Farmacist; Robert Sluggett, Farmacist; Samuel Stacey, Everris Australia; Gunter Ward, Everris US; Rob Dwyer, Charlie Walker, Incitec Pivot Fertilisers; Rob Norton, International Plant Nutrition Institute; Jeff Kraak, Fertilizer Australia; Alan Garside, Agritrop Consulting. The manuscript benefitted significantly from extensive feedback on an earlier version by Andrew Wood, Rob Dwyer, Charlie Walker, Samuel Stacey and Rob Norton. We thank Mike Wong for reviewing the second last version.

We acknowledge funding from Sugar Research Australia and CSIRO.

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PART II: Commercial Context for Enhanced Efficiency Fertilizers (EEF) in the Australian Sugarcane Industry

J Kraak, S Stacey, C Walker, R Dwyer and N Drew

7.13 Introduction

This summary provides an overview of the current commercial situation with respect to enhanced efficiency fertilizers (EEF) in the Australian sugarcane industry. Case study examples are provided for two EEF products which have gained a level of commercial traction in the market place. The technical aspects of EEF products are covered in PART I of chapter 7 of the Nitrogen Use Efficiency in Sugarcane review and so will not be discussed here.

The concept of EEF is not new. For example, one slow release nitrogen (N) product (urea formaldehyde) was patented in Europe in 1924, with production in the U.S. beginning in the 1950s. EEF have long been used in specialty applications such as turf and ornamentals. However it is in the last few years that these products have begun to gain commercial traction in the Australian sugarcane market.

7.14 EEF overview in Australian sugarcane

Sources of nitrogen fertilizer

In the sugarcane market, there are three main sources of N fertilizer i.e. urea, ammonium sulphate and ammonium phosphates (mainly DAP), with lesser amounts of urea ammonium nitrate solution (UAN) and calcium ammonium nitrate (CAN). Urea is the dominant N fertilizer applied to sugarcane. EEF technology is applied to urea, ammonium sulphate and in some cases (with respect to coatings) potassium fertilizers.

A large proportion of the N fertilizer (including both standard urea and EEF treated urea) is applied in a blend with other fertilizer products such as potassium chloride and DAP to provide other nutrients required by the crop (typically potassium and phosphorus).

Pricing trends

A number of considerations will influence the price of EEF products.

These include:

- Cost of treatment: The current EEF products used in sugarcane are applied to existing fertilizer products, typically urea. The fertilizer cost, EEF product cost and increased product handling during manufacture contribute to the total cost.

- Logistical considerations: A large proportion of the standard urea used in Australia is imported in bulk ships and may then be treated with EEF product. Some EEF products are also imported as a finished product (e.g. polymer coated urea). The volume of finished EEF product in the

Australian sugarcane market is currently insufficient to justify the use of bulk shipping so it is shipped as containerised freight which is significantly more expensive. Shipping distance from the point of manufacture for standard urea and some EEF products can also be significantly different.

- Patents: Most EEF's are initially covered by patents. History would indicate that as product patents expire and technologies become main stream, the cost of the technology typically falls, particularly as demand / volume increase.

Whilst the factors influencing price will be different for each EEF technology / product, ultimately the economics of global supply and demand will determine the price of EEF products. Whilst it is difficult to predict future price trends with certainty, the relative price of EEF products to standard urea may decline as demand volume increase and technologies / products compete with each other in a free market.

The price of nitrogen (urea) also has a significant impact. The higher the nitrogen cost the greater the benefit of efficiencies gained through the use of EEF products and the lower the relative additional cost of treatment.

Current market share

The proportion of nitrogen fertilizer treated with EEF is estimated at 4 – 6% of cane fertilizer blends in 2014. Indications are that volumes will increase in the coming years.

7.15 Case study examples

Two products account for a large proportion of the EEF currently used in sugarcane; Agrocote® (a controlled release fertilizer) and Entec® (a nitrification inhibitor). Currently Entec® is a patented product, while Agrocote® is not covered by a patent. The information below has been supplied by the companies involved in promoting these products in Australia. The use of these examples does not represent a recommendation or endorsement by Fertilizer Australia. There are other EEF products on the Australian market with more likely to be introduced in the future. Fertilizer Australia members are committed to only making product efficacy claims that are capable of substantiation, either by trial work or reference to accepted scientific literature.

Agrocote® (information supplied by Samuel Stacey of Everris Australia Pty Ltd)

Product description

Agrocote® is a coated controlled release fertilizer. The outer coating restricts the absorption of water and therefore the dissolution rate and diffusion of the fertilizer into the soil. Whereas uncoated urea will dissolve within hours of application to moist soil, potentially releasing from 150 to 220 kg N/ha in one day (typical industry application rates), Agrocote® releases urea N over a period of three to six months depending on the product analysis chosen. By slowing urea dissolution, Agrocote® can reduce the environmental loss of nitrogen in sites where leaching or denitrification processes cause poor efficacy of conventional urea (Hutchinson et al., 2003; Pack et al., 2006; Shoji et al., 2001).

The release rate of nutrients from Agrocote® is proportional to the coating weight, which is controlled at the manufacturing stage. Agrocote® is currently supplied in three different longevities that will release nitrogen over periods of 3 months, 4.5 months or 6 months. While all three products may improve nitrogen use efficiency in high loss environments compared to conventional urea, the 4.5 month release period is likely to be well synchronised to nitrogen demand in sugarcane (Wood et al., 1996).

Replicated field trials have shown that, in nitrogen responsive sugarcane, crop yields can be significantly ($P \leq 0.05$) increased by providing between 25%-100% of the nitrogen as Agrocote® (Di Bella et al., 2013; Di Bella et al., 2014). Growth responses due to improved nitrogen use efficiency were likely due to reductions in nitrogen leaching and denitrification, as measured during previous and subsequent studies (Pack et al., 2006; Moody P, Wang W & Pu G (2014) [study of nitrous oxide emissions], unpublished raw data). Further work is being undertaken to compare nitrogen losses from conventional and controlled release fertilizers via leaching, denitrification and surface runoff across multiple sugarcane growing regions.

Typical use on sugarcane farms

Agrocote® is typically blended with conventional uncoated fertilizers prior to application. Blending provides more complete nutrition as sugarcane crops often also require supplementary phosphorus, potassium and sulphur to optimise growth rates, depending on the existing fertility of the soil. Agrocote® can be blended with most conventional fertilizers that are used on sugarcane farms such as uncoated urea, ammonium sulphate, DAP, MAP, potassium chloride and potassium sulphate. Blends for sugarcane crops typically contain between 25% and 40% of the N as Agrocote®. The addition of uncoated N may assist with early crop establishment and also reduce the cost to growers, while still containing sufficient controlled release N to provide a measureable improvement in efficiency (Di Bella et al., 2014).

Like other granular fertilizers, Agrocote® blends can be banded into the soil during planting and applied to ratoon crops through stool splitters. Subsurface application is preferred to minimise the chance of physical movement of the fertilizer granules in the event of heavy rainfall and flooding. Subsurface application will also reduce the risk of volatilisation from conventional N fertilizers that may be present in the blend.

Pricing

Controlled release fertilizers can be significantly more expensive per unit of nitrogen compared to conventional fertilizers. The higher cost is due to a combination of factors, including the cost of the coating, increased product handling during manufacture and poorer freight efficiencies.
Despite the higher cost relative to conventional nitrogen, farm net margins can be increased by using Agrocote® in situations where environmental losses from conventional nitrogen sources are significant. For example, in a replicated trial located in the Burdekin delta region, a blend containing 25% Agrocote®-N and 75% urea-N significantly ($P \leq 0.05$) increased sugarcane yield by 12.45 t/ha and net margins by $460 /ha compared to urea alone (Di Bella et al., 2014). An ongoing challenge will be

to better identify sites where the efficiency of existing fertilizer practices is poor and where controlled release fertilizers will have maximum benefit.

Indicative rate of application

The optimum rate of Agrocote® application relative to conventional N fertilizers depends on both the degree of nitrogen loss typically experienced and the potential for nitrogen response in the crop. For example, in situations where conventional fertilizers do not supply sufficient N to optimise sugarcane production, due to very high environmental losses, the use of Agrocote® at the same N rate as conventional fertilizers is likely to increase crop yield. For example, Agrocote® blends increased sugarcane production in the Burdekin Delta region by 17.6 t/ha compared to urea at the same nitrogen application rate (Di Bella et al., 2014). However, where growers are able to supply sufficient N from conventional fertilizers to maximise crop yield, but environmental N losses are still significant, the use of an Agrocote® blend may allow growers to reduce N application rates without reducing crop yield. For example, Agrocote® supplied at 75% and 50% of the conventional N rate provided similar sugarcane yield to 160 kg urea-N/ha on clay and solodic soils, respectively (Di Bella et al., 2013). In both situations sugarcane productivity per unit of N applied was increased by using Agrocote® blends. However, farm profitability is usually greatest where significant yield increases can be realised.

Key reasons canefarmers are choosing the product

The main motivation for applying fertilizer to sugarcane farms is to increase productivity and farm profitability. However, nitrogen loss from fertilizers is a significant problem from some sugarcane fields and has both environmental and social implications. The greatest losses are typically from sites prone to waterlogging, where nitrogen is lost via denitrification, and from permeable soils, where nitrogen is principally lost via leaching.

Where N losses are significant, growers can maintain productivity by either increasing nitrogen application rates or by using enhanced efficiency fertilizers that help to minimise losses. Due to social pressures being placed on the sugarcane industry to minimise environmental harm, growers can no longer afford to inefficiently apply high nitrogen rates and need to look at more sustainable ways to optimise productivity. For this reason, canefarmers that limit nitrogen application rates according to best-practice recommendations, and have cane blocks prone to either denitrification or leaching losses, are the most likely to benefit from the use of controlled release fertilizers such as Agrocote®.

Thus key motivations for growers to use controlled release fertilizers such as Agrocote® are a desire to:

- Minimise nitrogen leaching on permeable soils.
- Minimise nitrogen loss from denitrification on flood irrigated soils or those prone to waterlogging, and to
- Optimise productivity without applying unsustainable rates of nitrogen fertilizers.

Entec® (information supplied by Charlie Walker and Robert Dwyer of Incitec Pivot Fertilisers)

Product description

Entec® is the brand name for 3,4-dimethylpyrazole phosphate (DMPP) which is a nitrification inhibitor. Entec® temporarily suppresses the activity of nitrifying bacteria in the soil through a bacteriostatic action (not bacteriocidal action). This retains nitrogen in the ammonium form which is still plant available but not subject to the leaching or denitrification losses that can occur to nitrate with excess rain or irrigation. According to Robinson et al (2011) ammonium nitrogen is preferred by sugar cane – they concluded that discrimination against nitrate and a low capacity to store nitrate in shoots prevents commercial sugarcane varieties from taking advantage of the high nitrate concentrations in fertilized soils in the first three months of the growing season, leaving nitrate vulnerable to loss.

Typical use on sugarcane farms

In Sugarcane response to Entec® treated fertilizer has been summarized at http://www.incitecpivotfertiliser.com.au/Incitec%20Pivot%20Fertilisers%20Dealer/More%20cane%20more%20gain. This data includes trails where favourable responses were evident and also sites where little or no response was observed.
In other market segments IPF recommend that Entec® treated fertilizer represent at least 60% of the nitrogen in a blend – in some cases this will mean that just the urea component of the blend is treated with Entec® while in other cases both the urea and ammonium sulphate component may be treated. For sugarcane ratooning fertilizer blends and plant cane sidedressing fertilizer blends, all the urea within the fertilizer blend requires Entec® treatment.
As a component of product stewardship for Entec®, advisers must pass an accreditation course before they can recommend or distribute Entec® treated products. Entec® is recommended for use in situations where leaching and/or denitrification potentials exist during the timeframe over which the active ingredient has activity. These situations are numerous & varied, especially with respect to denitrification & the fact sugarcane is sequentially harvested over a season.

Pricing

As blends vary in their composition it is difficult to give an exact price premium, but at present the premium for common urea based cane blends averages around $80 – 90/tonne (Ex GST) or $0.33 per kg N present as urea.

Indicative rate of application

This again varies – in some cases growers will maintain N rates with an expectation of better outcomes using Entec® while in other cases growers will cut back their N inputs to keep fertilizer costs around the same as a conventional fertilizer program with the expectation of similar (if not better) outcomes as a conventional fertilizer program. The majority of trial data indicates that Entec® treatment whilst maintaining the nitrogen rate as outlined within the industry's BMP (i.e. Six-Easy-Steps) delivers the best productivity outcomes.

Key reasons canefarmers are choosing the product

There is proof that the technology works in cane i.e. demonstrates both agronomic, environmental and economic benefits in independently conducted replicated trial work. There is also no doubt about the duty of care by growers, who are endeavouring to minimise potential off-site impacts by utilising nitrification inhibitors.
Interest in Entec® is being observed in all cane regions with a focus product being applied close to the onset of the wet season in north Queensland.

Entec® is now freely available within the cane market although further rapid growth may test the capacity of treatment facilities – this is only expected to be a short term issue however, as distribution sites are geared up to treat fertilizers. It was initially thought that the efficacy of Entec® was compromised by high soil temperatures, however recent studies by Melbourne University and CSIRO are showing excellent results under high soil temperatures and challenging conditions in cane soils and under irrigation in the Burdekin.

Entec® is a registered trademark of EuroChem Agro GmbH

7.16 References

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8. Fertilizer N use in the sugar industry – an overview and future opportunities

MJ Bell and P Moody

8.1 Fertilizer N use in the sugar industry – productivity, profitability and agronomic efficiency

The Australian sugar industry operates in challenging environments, with high rainfall and variable soil types contributing to difficult conditions in which to efficiently manage a mobile nutrient like nitrogen (N). However, one of the immediate observations from an overview of fertilizer N use in the sugar industry is the lack of clarity with which the industry has so far approached this issue. It is widely recognized that in any crop, the demand for N is determined by the size of the crop and the fundamental efficiency with which that crop produces a unit of biomass or harvested product from a kg of acquired N (N use efficiency – NUE) (e.g. Cassman *et al*. 2002; Ladha *et al*. 2005). Therefore a good understanding of yield potential at the spatial scale of the productivity unit (i.e., farm, several blocks of similar productivity, individual blocks or within-block) about which N fertilizer management decisions (rate, form, placement, timing) are made is required, along with an understanding of how that varies with seasonal conditions. Collectively, this could be called seasonal 'block' (or productivity zone) yield potential, and it will produce a crop N demand that varies significantly from year to year. The sugar industry is currently operating at the district level (generally comprising several thousand cropped hectares across variable soil types and landscapes), and basing N demand for all growers in the district on the best farm yield ever achieved over a 20 year time frame. Consistent over-estimation of N requirement is an obvious outcome.

In addition, the industry has very little documented information about how efficiently the crop can use N to produce biomass or sugar. At least part of the reason for this is the inappropriate efficiency index benchmarks being used by industry to assess fertilizer N performance. These are currently based on a measurement that is recognized internationally as the 'partial factor productivity of N' (PFP_N) (Dobermann 2005) which is simply the total productivity (i.e., harvested product) divided by the fertilizer N applied or t cane/fertilizer N rate). The application of such a measure to explore fertilizer NUE is clearly misleading, as it represents an integration of the effects on productivity of both indigenous (i.e., soil N) and applied N sources, and an increase in either indigenous or applied N can be equally important in determining PFP_N.

The uncertainty created by applying this broad NUE benchmark to a consideration of specific constraints or improved management strategies for improvements in fertilizer NUE is obvious. Without an understanding of the source of acquired crop N and a quantification of the incremental response to applied fertilizer N, no appropriate measure of fertilizer NUE can be derived. This is why the widespread adoption of what is effectively the inverse of PFP_N (i.e. kg N/t cane yield) derived by Keating *et al*. (1997) and applied in the 6ES (Schroeder *et al.* 2010) and refined in the N replacement concept of Thorburn *et al.* (2007) can result in widely different perspectives on the agronomic efficiency of fertilizer N use (compare Chapters 2 and 3 of this review).

This overview examines industry N use and decision support systems (DSSs) from the point of view of: (i) the extent to which fertilizer N applications reflect crop N demand; (ii) the ability of existing DSSs to maximize productivity by maximizing fertilizer N crop recovery and optimizing efficiency of internal N use in biomass production; and (iii) opportunities for future research and development to improve profitability, productivity and environmental performance.

8.2 Matching N supply to crop demand

The quantum of N required

While management inputs can moderate the effects of the different climatic conditions experienced by the Queensland sugar industry to some extent (e.g. use of irrigation in drier areas; improved drainage in wetter areas), intrinsic regional productivity differences do exist across the industry and these are reflected in the Estimated Highest Average Annual District Yields (EHAADY) shown in Schroeder *et al.* 2014 (Table 2.3 of Chapter 2 of this review). Perhaps of greater interest though is the variability in average yields in each production region in response to different growing seasons and biotic influences. These are illustrated for the different production regions for the period 1990-2008 in Chapter 2 (Figs. 2.4-2.9) and for 2003-2012 in Chapter 3 (Fig. 3.2) of this review, and are summarised in Figure 8.1 below.

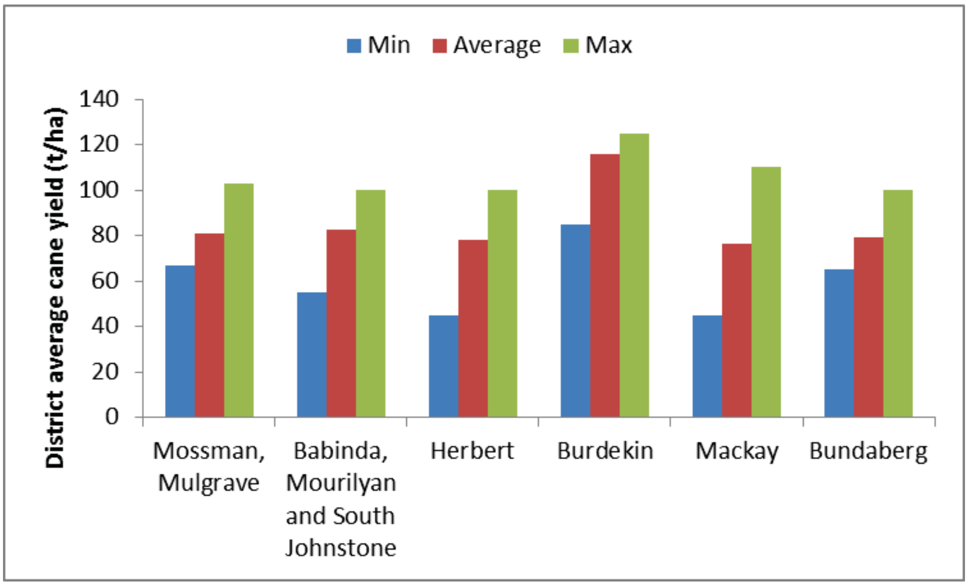

Figure 8.1. District average cane yields for the period from 1990-2008 (derived from Schroeder *et al*. 2010) for cane-producing regions across the Queensland sugar industry. Data are presented as a mean and a maximum and minimum for the monitoring period.

While average productivity is similar across most regions except the irrigated Burdekin, seasonal variability is large. The variability between high and low yielding years is *ca.* 50% in the Burdekin, Bundaberg and the Northern districts, 80% in the Wet Tropics and >100% in the Herbert and Mackay (Central) districts. The majority of this variability is related to rainfall (both the quantity and the seasonal distribution) and associated solar radiation, in combination with availability of supplementary irrigation water in some seasons in the southern and central regions in particular.

These strong climatic influences on crop yields, and hence crop N demand, suggest that an opportunity exists to integrate seasonal climate forecasts, especially in environments like the Wet Tropics and possibly the Central region, to modify seasonal yield potential and hence crop N requirements. This approach has been embraced by the grains industry in Australia, with climate forecasts embedded in decision support tools like Yield-Profit as a key factor in determining seasonal yield potential, and hence crop N demand (Hunt *et al*. 2006). While the current work of Skocaj *et al*. (2013a, 2013b and 2014, covered in some detail in Chapter 2) is exploring the relationship between climate signals and seasonal yield potential in the Tully region, there is considerable scope to both extend this work to other regions of the industry, and also to refine the nature of the investigations.

One area for refinement is to re-assess the current focus on the 'optimum N fertilizer rate' in response to climate signals in the work (Schroeder *et al.* Chapter 2). Given the evidence of (generally) poor fertilizer N recovery by crops across the industry (described as $NUpE_{Fertilizer}$ in Chapter 3), and the extent to which predicted N losses via leaching or denitrification can vary with season and soil type (modelling Chapter 6 Thorburn *et al*. 2014), it would seem logical that an outcome of such research should be a focus on improving $NUpE_{Fertilizer}$ under wetter seasonal conditions. A simple focus on N rate-yield response, as reported in Chapter 2, will not result in implementation of a decreased fertilizer N requirement commensurate with lower yield potentials in wet seasons. Instead, 'optimum' N rates based on achieving a fixed relative yield (95% in the case of the Tully site results in Chapter 2) irrespective of the actual yield potential will simply counter greater environmental losses in wetter seasons. In such situations, the opportunities afforded by Enhanced Efficiency Fertilizers (EEF, Verberg *et al.* 2014, Chapter 7 PART I) would seem to provide considerable scope for future investment, especially in environments where yield potential is almost always constrained by seasons being very wet (e.g. the Wet Tropics) or where excessively wet seasons can occasionally occur and climate signals may be able to indicate their occurrence.

While the concepts of EHAADY and district yield potential (DYP = EHAADY + 20%; Schroeder *et al*. 2010) for assessing likely crop N demand have resulted in some rationalization of industry fertilizer rates (see Forward by Wood *et al.* this review), there is a clear need for these figures to be updated to better reflect current climate sequences and commercial production trends (as suggested by Schroeder *et al.* in Chapter 2). For example, the district average annual cane yield in Proserpine-Mackay ranged from 63-86 t/ha for 2003-2012, while the values for EHAADY and district yield potential have remained constant at 110 and 130 t/ha, respectively (Chapter 2, Fig. 2.8). These values were based on a high productivity seasonal sequence in the mid-late 1990s, with this level of productivity not seen since. Similar dips in district productivity are evident in the Mossman-Mulgrave (Chapter 2, Fig. 2.4) and Bundaberg (Chapter 2, Fig. 2.7) data, although the magnitude is less than that for Mackay.

A more effective approach for improving N use efficiency is to better match fertilizer N rates to crop N demand by basing N requirements on a realistic yield potential. This can be achieved by moving from DYP to a target yield at the finer spatial scale of farm or preferably block management units. At present, the concept of DYP ensures that more than 90% of growers in at least 18 out of 20 years apply fertilizer N rates that are greater than required to meet crop N demand. This extremely conservative approach to N fertilization represents an unacceptably high risk of either off-site losses or depressed crop quality (low sugar content, lodged or suckered crop). Most growers have, or can obtain, productivity data at farm or possibly individual block scale from the mills for preceding years.

The relative differences in yields across seasons will integrate the effects of farm/field management as well as underlying constraints of landscape position, soil type and other yield-influencing factors on crop performance. As such, growers may be able to obtain more realistic assessments of the yield potential for their blocks and management style and so better define the likely crop N demand in each management unit. Development of a suitable approach to handling large crop to crop variability in yields at this scale will require careful analysis and testing, but may deliver significant improvements in NUE.

The application of block or even within-block productivity zone information to determine fertilizer rates is increasingly common in the grains industry (Robertson *et al*. 2012). Precision agriculture technology and variable rate fertilizer equipment offer the opportunity to vary N rates for productivity zones within fields or to vary top dressing rates 'on the go' in response to proximal sensors that monitor real-time canopy N status (Robson *et al*. 2014 Chapter 5). The challenge with applying this technology in the sugar industry is: (a) to identify the real cause of the yield variability and determine the most appropriate management response (i.e. address the yield limitation or lower the yield expectation and fertilize accordingly); and (b) in the case of the use of proximal sensors, having a reliable enough indicator of overall crop N status at a time when field management interventions are still possible (i.e., before the cane crop reaches the 'out-of-hand' stage at *ca*. 3 months of age). The latter prerequisite may not be achievable in the sugarcane cropping system because, as pointed out by Bell *et al.* in Chapter 3 of this review, at out-of-hand stage the crop comprises only about 10-15% of the final biomass and crop N content, and the period of rapid crop N accumulation is just beginning.

Improved synchronising of N supply and demand

Improved synchrony of N supply (from all sources, including fertilizer) is recognized as a key step in improving N use efficiency in other cropping systems (especially cereals and rice) at regional, national and international scales (e.g., Cassman *et al.* 2002; Doberman 2005). Considerable benefits have been reported in those systems from adoption of various management strategies including a reduced reliance on anticipatory (pre-season) in favour of responsive (in-season) N applications, more accurate predictions of mineral and organic soil N reserves and their likely mineralization rates, improved guidelines for splitting N applications according to phenology and N demand, and by the use of EEF or controlled released fertilizers.

For the sugar industry it is apparent that improving the synchrony of N supply with crop demand holds the key to improving fertilizer N recovery by the crop and improving agronomic efficiency (t additional cane produced/kg fertilizer N applied). Given the potential to incur large N losses due to extended periods of heavy rainfall (see Thorburn *et al*. 2014, Chapter 6), the vulnerability of N supply (from soil, fallow legume, soil amendment or fertilizer sources) is obvious, with the overview in Chapter 3 documenting consistent observations of large N losses and low fertilizer N recovery. Attempts to minimize losses by using split N applications (e.g. at planting/prior to ratooning and then again before 'out of hand' stage) with traditional fertilizer N products have generally provided limited benefits (e.g., Chapman *et al*. 1996) and the broader evaluation of this practice in the modelling chapter (Thorburn *et al*. 2014 Chapter 6) concurs with the limited returns from this strategy. However this work has not been conducted with the new generation of EEFs, which may offer some significant advances in this regard. These products should be of considerable interest to

the sugar industry, where opportunities to apply N later in the season during the period of peak uptake are limited (due to both the size of crop and often the coincidence of this stage with the wet season). Therefore an ability to apply a product at the start of the rapid N uptake period (*ca.* 3 months after planting/harvest) and use the fertilizer product attributes of physical barriers (e.g. polymer coats) or microbial activity inhibitors (e.g. nitrification inhibitors) to slow the accumulation of mineral N species vulnerable to leaching or denitrification loss (i.e., NO_3-N) has the potential to deliver improved synchrony and fertilizer N recovery by the crop. This is clearly an area for an expansion of research effort.

Reports of variable N benefits from fallow legumes can also be related to poor synchrony of N release coinciding with major loss events before the cane crop could utilize the residual legume N (see Figs. 2.27 and 2.28 in Chapter 2), with tillage and legume residue management between the legume and cane phases one opportunity to influence the rate of legume decomposition and N mineralization (e.g. Garside and Berthelsen 2004; Bell *et al.* 2006). There may also be opportunities to improve the synchronization of release of N from legume residues by use of nitrification inhibitors applied onto legume residues (Weijin Wang 2014, unpublished data) and further research in this area would be of interest.

8.3 Frameworks for improving the efficiency of fertilizer N use

If the industry is to make progress in improving fertilizer N management, it must develop a set of terms, definitions and methodologies that allow an unequivocal assessment of fertilizer use efficiency and agronomic and environmental performance. The benefits of this comprehensive approach can then be promoted to industry using networks and decision support tools similar to those used in rolling out the 6ES framework over recent years. However it will require a considerable investment in up-skilling growers, advisors and productivity staff involved in fertilizer management.

This new approach will target the key performance indicators that allow quantification of current and future fertilizer N management strategies and will involve four components that are relevant across all crop industries – (i) a clear differentiation between indigenous (soil) N supply and the crop performance that engenders, versus the additional crop performance derived from applied N fertilizer; (ii) quantifying the efficiency with which applied N is recovered by the crop and the residual value of unused N left in the soil; (iii) determining the efficiency with which N accumulated by the crop is converted into biomass and yield; and (iv) quantifying the marginal return for each additional kilogram of fertilizer N applied in terms of productivity (i.e., kg/ha of grain yield, kg/ha cotton lint or, in the case of the sugar industry, t/ha sugarcane or sugar), and profitability ($ gross margin/ha). Each of these components of N use efficiency will involve both a re-examination of existing information as well as the initiation of new R, D and E.

Contribution of indigenous versus applied N to crop productivity

Quantification of the contribution of indigenous N to crop N content and yield (both harvested cane and sugar) is an essential prerequisite to determining an appropriate rate of fertilizer addition. In the grains industry, pre-plant or early-season soil sampling is used extensively to indicate a starting quantity of profile mineral N which is used to discount the N fertilizer requirement to meet the target yield (e.g., Bell *et al*. 2013). Further discounts are based on an estimate of in-season mineralization, although in most cases this represents only a small proportion of the crop N budget. The pre-plant mineral N measurements are less relevant in the sugar industry due to unreliability of using profile N at planting as an indicator of available N over the following 6-8 months in a high rainfall environment. Conversely, in-season mineralization of N would appear to be of much greater importance due to the extended time periods, warm temperatures and moisture availability combined with higher soil carbon and greater residue loads. While there is some acknowledgement of the contribution to indigenous N mineralized from soil organic matter in the current 6ES framework (see Chapter 2), basing the generalised 'discount' on the correlation between a 14 day laboratory incubation (extrapolated to field conditions industry-wide over a 6-12 month growth period) and the single, fairly unresponsive indicator of soil organic carbon concentration is, at best, a first approximation only and leaves a lot of room for improvement. Indeed, there are already exceptions to this generalized correction factor in extremely acidic, high C soils in both NSW and NQld.

There appears to have been little attention paid to the magnitude and variation in crop and sugar yields generated in the limited number of field trials where a 0N rate was deployed (such treatments should be a mandatory inclusion in any future N research program) coupled with the lack of measurement of the crop N accumulated in such treatments. Results from 0N treatments in field experiments that are linked back to laboratory incubations and prognostic soil tests would give a much more robust and defensible relationship between soil characteristics and the likely net contribution of indigenous soil N to crop performance and crop N accumulation. For example, data presented in Bell *et al*. 2014 (Chapter 3, Table 3.2 and Fig. 3.6) indicate that indigenous N accumulated by crops (i.e., in 0N treatments) ranged from as low as 35-40 kg N/ha to as high as 130-150 kg N/ha, and was accompanied by a similarly wide range in unfertilized cane yields (45-115 t fw cane yield/ha). Crop N derived from the soil reserves was generally greater in the plant than ratoon crops and tended to be higher in soils from the southern regions than in the Central region, Burdekin or the Wet Tropics, presumably because the rainfall distribution and amount were more conducive to crop N recovery rather than environmental losses.

Even using a re-analysis of data from trials conducted as part of the 6ES program and presented in Chapter 2 (Schroeder *et al.*, this review), the relationship between cane yield in the 0N treatments and soil organic C gave no indication of a unifying relationship between soil organic C and crop performance (and presumably N availability) (Fig. 2.2), and the variation in cane yield (and presumably N content) around the commonly occurring 1-1.5% organic C content is particularly obvious. Crop N content was not reported in these studies.

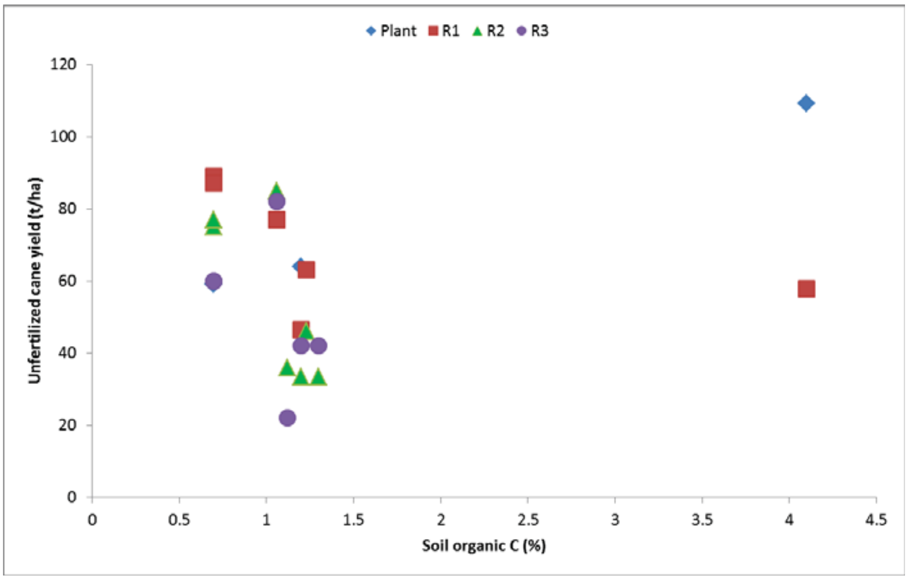

Figure 8.2. The relationship between cane yields without applied N fertilizer and soil organic C concentration in soils at the experimental sites conducted in the 6ES field program and reported in Schroeder et al. 2014 (Chapter 2).

Given the importance of an accurate assessment of mineralisable soil N for the subsequent determination of fertilizer N requirement, it should be a priority for future industry investment to develop a more robust indicator of in-season mineralization in different soils and climates and prediction of the crop yield that could be supported by this component of the crop N balance. Preliminary work in this area was undertaken by Meier *et al*. (2003), who compared potential N mineralisation indices in contrasting climates (Babinda and Bundaberg) using simulation approaches benchmarked against limited measurement of soil mineral N in surface layers of farms at Babinda. The encouraging results suggest further work should be undertaken in conjunction with all agronomic trials involving N management. This would necessitate a 0N treatment, and plant biomass and soil samplings to determine soil N mineralization and crop N accumulation. Given the importance of timing of N availability on positive yield-determining processes like tillering and tiller retention, as well as on possible negative impacts through suckering, lodging and a reduction in CCS (Chapter 3), such investigations should focus both on the rate and quantity of N mineralized throughout the growing season as well as the pattern of crop N accumulation.

Efficiency of recovery of applied N

As noted by Bell *et al*. 2014 (Chapter 3) there is limited information documenting the recovery of fertilizer N in above-ground crop biomass, whether in response to varying rates of N fertilizer or to use of soil amendments or legumes in the crop rotation, and almost no data on N accumulation in roots and stools below ground. Even where studies have been conducted in more recent years, there has often been no 0N rate to allow differentiation between soil and fertilizer N contributions (e.g., the studies comparing 6ES and the N replacement concepts covered in Chapter 2 and the work by Connellan *et al*. in the Burdekin cited in Chapter 3) and few determinations of crop N content – other than measures of N concentrations in juice or stalks (Thorburn *et al*., 2011).

While this lack of data has severely limited the ability to get reliable estimates of fertilizer N recovery ($NUpE_{Fert}$) across the diversity of seasons and soil types present in the industry, the available data

reviewed in Chapter 3 suggested recoveries in the plant crop averaged only 20% and the ratoons slightly higher at 30-35%, with no real evidence of additional recovery in subsequent years of a crop cycle. This compares very poorly with the suggested median crop N uptake by cereals world-wide of 55% in the year of application, with a further 5-10% recovery in subsequent seasons (Ladha *et al*. 2005). While at least some of the residual N is retained in the stool and roots and soil organic matter, the lack of benefits in subsequent years of a crop cycle suggest what is not lost is immobilized for some time.

There is therefore a clear priority for the industry to focus on strategies that will improve recovery of applied N fertilizer. Improved fertilizer technology (Verberg *et al*. 2014; Chapter 7 PART I) will obviously play a role in this by reducing losses and improving the synchrony of N supply and demand. Similarly, a better understanding of the contribution of indigenous N supply to crop N acquisition and crop yield will allow a clearer quantification of crop N requirements and so allow a rationalization of fertilizer N inputs in some environments. Finally, a better understanding of the impact of improved root health (delivering a more functional and efficient root system) on crop N accumulation may provide further impetus for changes to the sugarcane farming system that will deliver improved $NUpE_{Fert}$ as well as improved profitability and sustainability.

Agronomic and physiologic efficiency of use of applied N

As noted in both Chapter 3 and earlier in this overview, the inappropriate use of what amounts to PFP_N or its inverse in discussions about fertilizer NUE in the Australian and international sugarcane literature has clouded the interpretation of agronomic studies of fertilizer N requirements in the sugarcane crop. This lack of clarity has also affected the design and interpretation of the limited studies on the physiology of N use in sugarcane, which already suffers from being fragmented, assessed from a limited number of genotypes and targeting different objectives (Livingstone *et al.* 2014 Chapter 4). There are examples of both limitations in this review –

<u>Agronomic NUE</u>: The 6ES and N replacement frameworks (Schroeder *et al*. 2014, Chapter 2) use the inverse of PFP_N (kg applied N/t fw cane yield) in discussions about fertilizer NUE, with all the resulting ambiguity introduced by uncertainties about the source of the crop N and also the actual yield increment due to a fertilizer N application. As discussed in Chapter 3 (Bell *et al*. 2014), in the absence of measurements of crop N acquisition, the appropriate metric for agronomic NUE should be derived from the yield increment resulting from the application of fertilizer N (i.e. $Y_N – Y_{0N}$) and the N rate used to deliver that yield increment (i.e., the agronomic efficiency of applied N or $AgronEff_{Fert}$). For consistency with current industry benchmarks the inverse of $AgronEff_{Fert}$ (kg N applied to deliver an additional t of cane yield) can be adopted.

When this approach is used to re-examine the available information in the published literature (see Chapter 2) or in the derivation of the 6ES N requirement (Chapter 2) the apparent 'consistency' in NUE reported across many field trials (1.0-1.5 kg N/t cane – Schroeder *et al*. 2014 Chapter 2) disappears and a wide range in values of $1/AgronEff_{Fert}$ can be observed. In the literature reviewed in Chapter 3, the majority of values ranged from 7.5-15.0 kg N/t cane in plant crops and 2.7-19.0 kg N/t cane in ratoons when the district fertilizer N rate was used. Lower values were obtained when the optimum N rate for each site (derived from the fertilizer N rate response surface) was substituted.

The N response trials conducted during development of the 6ES framework and reported in Chapter 2 provided another opportunity to derive 1/AgronEff $_{Fert}$ data. Each of these trials contained a range of N rates in addition to a 0N treatment and equations describing the response surface were presented, allowing the yield of each N rate (Y_N) in each crop class to be described in relation to the maximum yield at that site and year (i.e. Y_{max}). The relationship between the relative yields for each N rate and site year (i.e., Y_N/Y_{max}, expressed as %) and the efficiency with which that N rate produced additional cane yield (1/AgronEff$_{Fert}$) was then explored. Data were subdivided into yield response classes based on whether the respective N rates achieved 60-80%, 80-90% or 90-100% of Y_{max} for that site-year combination and the relationships between Y_{max} and 1/AgronEff$_{Fert}$ are plotted for each relative yield class in Fig. 2.3.

This analysis illustrates three key points. Firstly, data suggest the higher the achievable yields (Y_{max}) the stronger the N demand and the more efficiently applied N fertilizer is used to produce cane yield (i.e., 1/ AgronEff$_{Fert}$ is low). If crop yield categories of <80 t/ha, 80-100 t/ha and >100 t/ha are considered, the average efficiency of N fertilizer use (i.e., 1/ AgronEff$_{Fert}$) for the rates required to maximize yields (i.e. Y90-100%) were 24 kg N/t, 18 kg N/t and 11 kg N/t cane yield increase, respectively.

Secondly, as progressively higher N rates deliver yields approaching Y_{max} the efficiency with which applied N fertilizer produces cane yield decreases. The average of 1/AgronEff$_{Fert}$ for Y60-80%, Y80-90% and Y90-100% averaged over all yield categories was 3.9, 7.5 and 19.6 kg N/t cane yield increase, respectively.

Finally, as the site Y_{max} decreased the variation in of 1/AgronEff$_{Fert}$ generally increased, suggesting that when other factors were limiting yields the efficiency of fertilizer N use was much more variable.

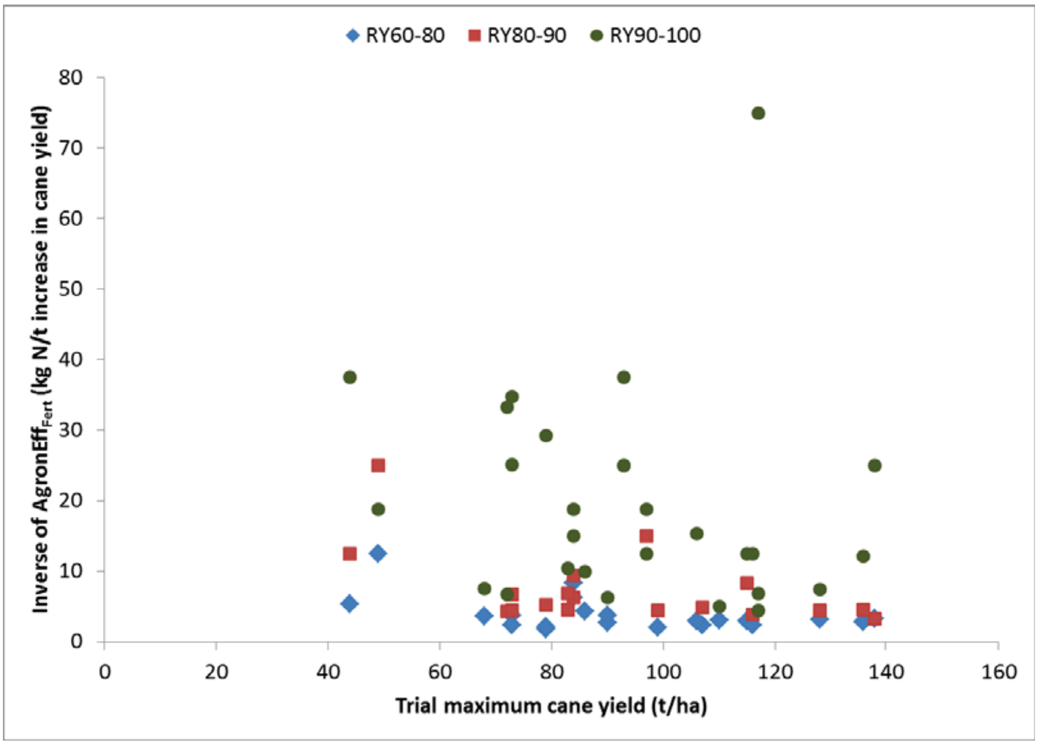

Figure 8.3. The relationship between maximum cane yields (Y_{max}) and the inverse of $AgronEff_{Fert}$ for each N fertilizer rate from trials presented in Chapter 1. Data are subdivided into N rates producing relative yields that were 60-80%, 80-90% and 90-100% of Y_{max} for each site-year combination.

The data in Figure 8.3 are an aggregate of regions, soil types and climates across the industry. An example of a similar analysis conducted at a finer resolution is shown in the simulation data in Thorburn *et al*. 2014 (Chapter 6, Fig. 6.11), which explores the variation in cane yields, the inverse of AE and total N losses for particular combinations of soil type and regional climates at a constant N rate. Collectively these analyses show how a structured approach to analysing NUE and the parameters influencing it in different production regions can provide real insights into how N management approaches might be modified in different parts of the industry.

<u>Physiological NUE</u>: A clear priority would seem to be a better understanding of the processes of N accumulation and cycling in a sugarcane crop and the internal use efficiency of N to produce biomass, cane and sugar yield (defined as NUtE in Chapter 3). There is little published information on NUtE – either in field-grown crops of commercially-available clones (Bell *et al.* 2014, Chapter 3) or for genotypes and breeding populations grown with varying N status (Robinson *et al.* 2014 Chapter 4). Using genetic solutions to lower fertilizer N requirements via selection for improved NUtE is well advanced in the major grains crops, but there has been little attention paid to biomass crops like sugarcane (Robinson *et al*. 2014 Chapter 4). Given the demonstrated capacity of the crop to accumulate luxury amounts of N, especially in the stalks which are sent to the mill (see Chapter 3), development of NUtE benchmarks could develop clearer indicators of the crop N content required to achieve yield targets as well as facilitate the selection of genotypes that are more efficient at producing biomass or cane yields per unit of accumulated N.

While some elegant studies of genotypic variation in NUtE (kg crop N uptake/t biomass or cane yield) under contrasting N supply have been described from short term (3 month) assays under

controlled conditions by Livingstone *et al*. 2014 (Chapter 4), extending this work to the field is proving challenging. Examples are the studies reported by Livingstone *et al*. 2014 (Chapter 4), where fertilizer N supply alone was used to establish 'high' and 'low' N supply in field trials to evaluate relative genotypic performance across a crop cycle. At the Burdekin site, where significant yield responses to applied N were recorded throughout the crop cycle, plant crops in the 'high N supply' background only accumulated an additional 20-25 kg N/ha on average compared to those receiving only 20 kg N/ha. Poor fertilizer recovery in the 'high N' background (<15%), presumably due to environmental losses, resulted in only limited differences in crop N status against which to assess any genotypic differences in NUtE. In contrast, the Mackay site showed limited fertilizer N response in the plant and 1R crop, presumably due to a previously unidentified high soil mineralisable N content. The implications of declining N supply through a crop cycle may identify very different genotypic characteristics to those in situations where the early crop establishment and stool development are occurring under reasonable N supply.

These problems are clear examples of some of the broader N management uncertainty that is plaguing the Australian sugar industry. The tools to identify fertilizer N requirement at a site are inadequate, and the current N fertilizer management strategies cannot guarantee that because fertilizer N has been applied it has necessarily been available for crop uptake. However the assessment of genotypic differences in NUtE is an area with considerable potential to deliver both improved frameworks against which agronomic practices can be developed and benchmarked while also making a longer term contribution to reducing fertilizer N requirements in sugarcane cropping systems. The experimental approaches under which this work is conducted need to be clearly defined, with any future work conducted in an environment where crop N supply can be more closely regulated, either through in-crop N management (e.g. via trickle irrigation) or under conditions where N losses are likely to be much lower.

8.4 Future research priorities in relation to fertilizer N management

This overview of N management in the Australian sugar industry has indicated that nitrogen fertiliser use efficiency (t cane or sugar produced per kg applied N) should be able to be greatly improved without compromising productivity (total tonnes cane produced). Improved N fertiliser use efficiency will increase grower profitability (higher sugar yield for the same N rate, or the same sugar yield for a lower N rate) and have environmental benefits by ensuring more of the applied N is recovered by the crop, thus reducing off-site N movement and impacts on water quality and/or greenhouse gas emissions. However there are significant areas for future investment in R and D before these win-win outcomes can be achieved.

The key initiatives (and likely timeframe for underpinning R and D outputs) that will improve N use efficiency can be grouped under several themes –

Understanding crop N requirements

(a) Determining achievable yield potential for the productivity unit about which N fertilizer decisions are made (*viz*., several blocks, an individual block or a productivity zone within a block) and using this to determine crop N requirement. This yield potential would be based on past performance of the productivity unit (mill records or remotely-sensed stable yield potential) and take account of seasonal forecasts to adjust the target yield. It would need to be demonstrated to industry (using case studies based on actual block/productivity zone data) that

the methodology used to determine the achievable yield potential would not adversely impact productivity. *(Short-medium timeframe)*

(b) Quantifying differences in N utilisation efficiency (tonnes cane or sugar produced per kg accumulated crop N) in existing commercially available clones and then across a broader genetic base in conjunction with existing plant improvement programs. The research to develop this knowledge needs to be undertaken in environments where researchers can be sure of achieving differential crop N availability and acquisition, given the evidence that 'high N' application rates do not necessarily lead to high crop N accumulation in conditions conducive to large environmental losses. Such studies need to be extended to include exploration of genotypic differences in the ability to recover applied N (e.g., root system characteristics), but the interactions between root system activity and soil health observed in other studies on soils with a sugarcane history could cloud interpretation of this work. *(Medium-long timeframe)*

(c) Developing an appropriate N multiplier (kg applied N to produce a tonne cane/sugar) that is not confounded by differential contributions from indigenous N, takes into account potential yield and possibly varietal effects, and contains a clearly identifiable estimate of unavoidable losses associated with soil type and position in the landscape. Much more R and D is required to refine this multiplier, and field experiments will need to follow a benchmark methodology that includes a nil applied N treatment so that crop N uptake can be apportioned between N uptake from indigenous soil N and N uptake from applied fertilizer/amendments. Field experiments will also require biomass harvests to determine at what growth stage, and how much, of the applied N was recovered by the crop. *(Short-medium timeframe)*

(d) Develop an improved understanding of below-ground N accumulation during a cane cycle and the dynamics of subsequent mineralization and contributions to the indigenous N pool available for crop uptake. *(Short-medium term)*

Fertilizer N management

(e) Develop a more robust and soil type/regional specific framework that allows fertilizer N requirement to be discounted by a realistic estimate of the contribution from indigenous soil N. This will require further R and D to develop a more sensitive indicator of soil N mineralisation potential than is provided by soil organic C measurement alone, and benchmarking these estimates against net N recovery by unfertilized crops in the field under contrasting environments, seasonal conditions and at different stages in the crop cycle. (*Short-medium timeframe*)

(f) Conduct an intensive investigation of the effectiveness of different controlled release/enhanced efficiency fertilizers in better synchronizing soil N availability with crop N acquisition and improving NUE. This should be conducted in collaboration with industry partners and should be a lot more comprehensive than simple product comparisons at a limited number of rates and should use not only crop/sugar yields, but also crop N recovery as effectiveness benchmarks. This work could also be extended to include management of legume residues to maximize subsequent recovery by the cane crop. (*Short-medium timeframe*)

(g) Identify the sugar-producing regions (characterised by seasonal effects, soil type, crop management) best suited to the effective performance of EEFs with different attributes and modes of action. Once the fundamental knowledge generated by activity in (f) has been distilled, simulation studies should be quite effective in this regard. (*Medium timeframe*)

(h) Explore the interactions between NUE and irrigation management/water use efficiency (WUE) in key production environments like the Burdekin. It is highly likely that maximising irrigation WUE will also maximise NUE by reducing the risk of N losses, and this needs to be demonstrated. (*Short-medium timeframe*)

(i) Explore the opportunities to adopt precision agriculture techniques to further refine N management within productivity zones. This would involve combinations of remotely sensed productivity zones (or yield stability maps once effective yield monitors are developed) to determine likely fertilizer N demand, with fine-tuning afforded by in-season canopy assessment and variable rate fertilizer applications. The feasibility of the latter would need to be demonstrated before substantial investment was considered, due to the restrictions in timing of crop access relative to crop N demand. *(Medium-long term)*

Development and refinements to DSSs

(j) Developing a decision support framework that allows growers to match the most effective EEF with a given season/soil type/crop management situation. *(Short-medium timeframe)*

(k) Develop a simple tool that will allow growers to conduct economic analyses to assess the profitability of improved N management systems. This tool needs to be based on the economic return from an increment of applied N because it is apparent that the productivity efficiency of applied N decreases as the cane/sugar yield plateau is approached. *(Short-medium timeframe)*

(l) Incorporate the above new information into the 6ES. The principles of 6ES provide the industry with a robust BMP framework, and continuous updating of the interpretive guidelines of the framework provides industry with a vehicle for implementing improved N use efficiency. It is suggested that promoting a 'nitrogen budget' approach to improving NUE may facilitate grower engagement by improving their understanding of how N fertiliser inputs are but one component of the soil N cycle. The N budget approach is effectively a 'systems approach' that integrates information about synchrony between nutrient supply and crop demand, crop N uptake and distribution above and below ground, N export to the mill, N loss pathways and risks, and the effects of fertiliser form, rate and placement, and efficient irrigation (water) management on these N budget components. *(On going)*

Education and outreach

(m) Develop a communication strategy to convey the complexity and economic realities of improving NUE to the broader community. This will involve quantifying the risks from economic as well as environmental perspectives of applying an additional increment of N, and conversely the economic cost and environmental benefits of reduced N applications. An appreciation of the economic value of N provided by mineralisation of soil N is also required. *(Short-medium term*)

(n) Develop a concept paper to facilitate the better coordination and communication of industry and government research investment and extension activities. Since the Industry Nitrogen Forum in February there have been discussions amongst interested parties, and in-principle agreement, about the need to form an NUE Steering Group to provide coordination and structured governance into the future, to enhance linkage between industry needs and objectives and the development of government policy and plans to implement and realise environmental management targets. It proposed that core members would come from key stakeholder groups such as SRA, CaneGrowers, EHP, DAFF and the Federal Department of Agriculture and the Federal Department of the Environment. The Steering Group should be able to draw on relevant expertise as required from leading research organisations, sugar industry Productivity Services Boards and NRM groups including the services of the Science Leader. (*On going*)

8.5 Conclusions

This extensive overview of all aspects of N management in the Australian sugar industry has identified several areas for improvement in existing management approaches, but also identified some new technologies and approaches that offer real, ' game-changing' opportunities to reduce N fertilizer rates while improving crop recovery efficiency and maintaining or improving crop productivity. The targeted program of R&D investments outlined will provide the necessary information and tools to realize these opportunities and foster industry adoption.

An additional important opportunity exists to bring the broader community along on this efficiency drive, with considerable long term benefits for the industry's environmental credentials. In some ways this could be analogous to the campaign run by the cotton industry to demonstrate its high level of environmental stewardship with the adoption of integrated pest management strategies. The step-change technology in that instance was the development of transgenic (insect resistant) cotton varieties and the management systems that were developed around them. The sugar industry could learn from that approach, with improved fertilizer technology the potential step-change that can potentially reduce fertilizer rates, reduce off-site impacts, and maintain or improve productivity and profitability. If such an approach was successful, the cotton industry may well be an interested observer, given the issues that industry has with N use inefficiency and denitrification losses!

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