REVIEW OF NITROGEN FERTILISER RESEARCH IN THE AUSTRALIAN SUGAR INDUSTRY

FINAL REPORT

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EXECUTIVE SUMMARY

The management of nitrogen (N) fertiliser is important to the Australian sugar industry, as it is an important nutrient for sugarcane production. However, over application results in reduced profitability and sugar quality, and results in high concentrations of N in soils and water of sugarcane growing areas. An extensive review of current and past research on N fertiliser management in the Australian sugar industry was undertaken to identify possible improvements in N fertiliser management and establish priorities for future research into sustainable management of N fertiliser.

The Australian sugar industry has a history of high N fertiliser usage, with applications increasing from the 1960s to the late 1990s. However, industry average sugarcane production has not kept pace with N fertiliser applications, resulting in a steady increase in N fertiliser applied per ton of sugarcane harvested. Historical and recently developed N management strategies rely on matching N applications to the predicted/expected yield of the forthcoming crop. Over-application of N fertiliser is a rational reaction by growers to uncertainty about the size of the coming crop and the **long-term** impact of N fertiliser on profitability – significant over-fertilisation reduces profits much less than significant under fertilisation. We suggest that past and current N fertiliser management strategies have not adequately accounted for these attitudes, and the resultant longer-term implications for soil and water quality and environmental impacts in sugarcane catchments.

While long-term under application of N fertiliser undoubtedly reduces profitability, there is considerable evidence to show that greatly reducing N fertiliser applications for a **single** crop will not significantly reduce sugarcane production. Thus, the short-term risk of crop yields limited by N deficits is possibly much lower than generally appreciated. If this is so, a new philosophy of N fertiliser management can be developed that remove the uncertainties that drive growers to over-apply N, and so allow closer matching of N inputs to N outputs from a sugarcane system. Rather than aiming to fertilise the coming crop, it may only necessary to replace the N lost from the previous crop, the majority of which is in harvested cane and therefore be easily estimated.

Over the past decade, there have been significant advances in our ability to simulate N (and carbon) dynamics in sugarcane production systems. We drew upon these advances to undertake a 'desktop' examination of this new 'replacement' N management strategy. Three N management scenarios were simulated: (1) the 'replacement' strategy, (2) the current recommended strategy and (3) the average amounts of N applied in the industry (i.e., 30 % greater than those recommended). The replacement strategy had similar productivity, greater profitability and lower environmental N losses, whether we simulated potential crop production or a more realistic level of production (resulting from the impact of pests, diseases, lodging, stool damage, etc.). Moreover, these advantages were greater in the simulations of realistic yields. The 'replacement' strategy is an evidence based, transparent and defensible N management strategy, all attributes that are important for the sugar industry to maintain self-regulation of N fertiliser management. We suggest that this strategy warrants further testing, through both simulation and field experiments.

Other questions remain unanswered in N fertiliser management. In particular is that of how to consider how N inputs from other sources, especially organic inputs such as mill by-products and fallow legumes. There are concepts used in the South African industry that may provide a useful approach for managing N in mill by-products in Australia. However, the issue for legumes requires some fundamental research, especially as legumes fallow are being actively promoted in the industry.

BACKGROUND

In common with other intensive agricultural production systems, large amounts of nitrogen (N) fertiliser are required to maximise sugarcane production in Australia (Keating *et al.*, 1997). Approximately 90,000 t of N was applied to the Australian crop in 2000 (Calcino, 2001; Chudleigh and Simpson, 2001). However, excessive applications reduce sucrose concentrations (Muchow *et al.,* 1996) and sugar quality (Mackintosh and Kingston, 2000), and are an unnecessary input cost for growers (Wood *et al.,* 1997). As well as its agronomic significance, N has considerable environmental significance. Losses of mineral N in gaseous form and/or by leaching can contribute to the greenhouse gas effect and reduce the quality of ground, river and marine waters. Thus, both the industry and the broader community benefit from high N fertiliser use efficiency. To help obtain such benefits, the sugar industry has a long history of researching the N requirements of crops, with current recommendations (Calcino *et al.,* 2000) having been developed on rates and methods of application for promoting sugar production (Chapman, 1994).

Despite these recommendations, there is uncertainty within the Australian sugar industry about the best management practices for supplying adequate N to sugarcane while, concurrently, minimising losses of fertiliser N to the environment. This uncertainty is manifest in the difference between the recommended N application rate (in most districts) of 160 kg/ha, and the recent industry average application rate of approximately 200 kg/ha (Keating *et al.,* 1997). Given that the recommended rate includes an ‘allowance’ for likely (and probably unavoidable) losses to the environment, the additional 40-50 kg/ha applied by the industry is likely to result in the detrimental agronomic and environmental impacts described above.

The industry periodically reviews the status of N fertiliser management (e.g., Anon., 1985; Chapman, 1994; Wood *et al.,* 1997; Keating *et al.,* 1997; Schroeder *et al.,* 1998) and these reviews summarise the progress of the industry’s N application recommendations and their derivation. In addition, the recent reviews pointed to the need to better match climate and soil conditions to crop requirements to increase nutrient use efficiency and reduce detrimental impacts in the resource base and the environment. These ideas have underpinned the goals of many of the projects undertaken in the industry in the past decade. It is timely to again reflect on the advances that have resulted from projects recently conducted on N fertiliser management, determine whether N fertiliser management can be improved in light of the results, and establish priorities for future research into sustainable management of N fertiliser in the sugar industry.

This project provides; (1) an overview of N fertiliser use and management, (2) suggests a new approach for best practice management of N fertiliser and (3) identifies some areas of limited knowledge that would benefit from future research.

OBJECTIVES

The objectives of this is project were:

- To review recent research into management of nitrogen fertiliser in the Australian sugar industry.

- To collate existing, and identify possible new, best management practices for sustainable use of nitrogen fertiliser in sugarcane systems.

- To determine knowledge gaps and suggest strategic directions for future research into sustainable and profitable management of nitrogen fertiliser in the Australian sugar industry.

All objectives of the project were achieved.

METHODOLOGY

There were three main activities undertaken in this project, as described below.

Summary of recent research on N mmanagement

Leaders of recent projects relevant to the management of N fertiliser in the Australian sugar industry were contacted to provide summaries of their projects. This ensured that information yet to be published was able to be considered in the review. To make this processs efficient, a workshop was conducted (24-25 March, 2002) to which project leaders were invited. Following the workshop, individual discussions were held with project leaders unable to attend or where more detail on the work presented at the workshop was required. Summaries of material collated during this activity (including the workshop discussion) are given in Appendix 1.

Review of literature

An extensive search of the literature to collate information published in ASSCT proceedings, journals, project final reports, etc. More than 300 references were obtained, and these are listed in Appendix 2.

Synthesis of research and literature

The research results and literature were synthesised to identify opportunities for improved management of N fertiliser and identify knowledge gaps and strategic directions for future research. To assist with this synthesis, different N management scenarios were simulated with the APSIM-Sugarcane cropping systems simulator (McCown *et al.,* 1996).

The APSIM model configuration consisted of modules for soil N and C (APSIM-SoilN; Probert *et al.*, 1998), soil water (APSIM-SoilWat; Probert *et al.*, 1998) and sugarcane residue (APSIM-Residue; Thorburn *et al.,* 2001a) dynamics, and sugarcane growth (APSIM-Sugarcane; Keating *et al.*, 1999). The modules are one-dimensional, use a daily time-step and are driven by climatic data. The dynamics of water, N, C and roots are simulated in soil layers, with water (and associated nitrate) moving between layers where gradients exist. The soil organic matter is divided into three "pools", with *fom* representing the fresh organic matter (i.e., roots and incorporated plant residues), *biom* representing the active biomass in the soil, and *hum* representing the humified material. Part of the *hum* pool is considered inert. The soil water module is a "cascading bucket" water balance model, with water between the drained upper limit (*dul*) and saturation draining to the layer below. The drainage rate is controlled by the parameter *swcon*, which was set to 0.4 in all layers. The lower limit of plant available water is defined by the parameter *ll15*. Evaporation from the soil follows Ritchie's (1972) two-stage evaporation model. The presence of plant residues on the soil surface affects runoff (and hence infiltration) and evaporation. The sugarcane module uses intercepted radiation to produce assimilates, which are partitioned into leaf, structural stalk, roots and sugar. The processes represented in the module are responsive to radiation and temperature, as well as water and N supply. Farming operations (such as fertilisation, planting, incorporation of crop residues through cultivation, or burning of crop residues) can be specified through the MANAGER module, to represent actual or hypothetical conditions.

Simulations were primarily based on a green cane trash blanketed (GCTB) treatment of the trash management experiment on a Brown Chromosol soil at BSES Mackay (Chapman *et al.,* 2001). This experiment was simulated by Thorburn *et al.,* (2001b) who found that measured sugarcane yields and soil organic carbon concentrations were well predicted by the model. Model parameters (Table 1) were based, wherever possible, on measured data. The soil profile was sampled to 1.5 m depth in 1997 and soil total C and N, mineral N and bulk density measured to initialise N and C in APSIM-SoilN. Measurements of microbial biomass (Robertson and Thorburn, 2001) were used to set the *biom* pool size. All other pools were set equal to values generally used in APSIM simulations of soil N dynamics in sugarcane production systems (Thorburn *et al.,* 2004b). The soil water parameters (saturation, *dul* and *ll15*) were estimated from the daily soil moisture data. Default parameter values (Keating *et al.*, 1999) for the sugarcane variety grown in the experiments (Q124) were used.

Table 1. Properties (0-0.2 m) of the Brown Chromosol soil used in the simulations.

Parameter	Brown Chromosol
Soil texture	Loam/clay loam
Organic C (%)	1.0
C : N ratio	18.0
Bulk density (kg/m^3)	1.51
Drained Upper Limit* (%)	30.0
Lower Limit* (%)	17.0

*Soil water parameters used in the SoilWat model (Probert *et al.,* 1998), analogous to field capacity and wilting point.

APSIM-Sugarcane simulates **potential** yields given constraints imposed by climate, soil water and soil N attributes, water and N fertiliser management and varietal characteristics. These yields are greater than those **actually** obtained in most blocks, where additional factors such as pests and diseases, lodging, stool damage, waterlogging, etc., which are not fully described in the model, reduce yields below potential. As N in harvested cane is one of the biggest net terms in the N balance of a site (Figure 1), it is desirable to predict realistic yields to describe a more realistic N balance (i.e., to have more realistic simulations of soil organic matter dynamics, environmental N losses, etc.). Simulations of both **potential** and **realistic** yields were thus undertaken for this study. The realistic yields were approximated in the simulations by using the lodging function in APSIM, which reduces radiation use efficiency and increases stalk death. The lodging command was issued within APSIM-MANAGER when a large rainfall event occurred after the crop had passed a dry weight threshold. The size of the rainfall event and the thresholds were regionally specific. The simulations were conducted over 100 years. For the 1st four crop cycles, the trash and N fertiliser management system was the same in all simulations – trash retained with 160 kg/ha of N fertiliser applied to ratoon crops and 75 % of that (i.e. 120 kg/ha) applied to plant crops. This allowed the simulated plant-soil system to come to equilibrium, and not be overly affected by the impacts of the initial values chosen for the model parameters. At the end of 25 years, different trash and N fertiliser management systems were introduced to the simulations. These systems are described below in the section *Future directions for managing N fertiliser*.

Outputs from the simulations were averaged over all crops (excluding the 1st four crop cycles) and included sugarcane yield, amount of N in cane and N lost to the environment (from both denitrification and leaching). As well as these biophysical outputs, the partial gross margin of sugar production in the simulation was also calculated. Gross margins were calculated assuming a sugar price of $250/t, harvesting costs of $7.50/t and N fertiliser costs of $1/kg/ha.

RESULTS

The need for N fertiliser applications

N is required by plants for photosynthesis and other metabolic processes. Sugarcane obtains almost all of its N requirements from mineralisation of organic matter in the soil or through fertiliser inputs, and a significant proportion (> 50 %) of N fertiliser inputs cycles through organic mater (Vallis *et al.,* 1996). N is lost from the sugarcane production system through (1) removal of harvested produce, (2) losses to the environment as a result of denitrification or leaching of nitrate below the root zone, and (3) trash burning if this is practiced (Figure 1). (N can also be lost through volatilisation of ammonia from urea fertilisers, but this will not be considered further as it is easily reduced by practical management practices.) Provided the soil N pools are in equilibrium, losses balance fertiliser inputs. There is evidence that total soil N is declining in some sugarcane producing regions (Wood, 1991), so the losses may be greater than the N fertiliser inputs.

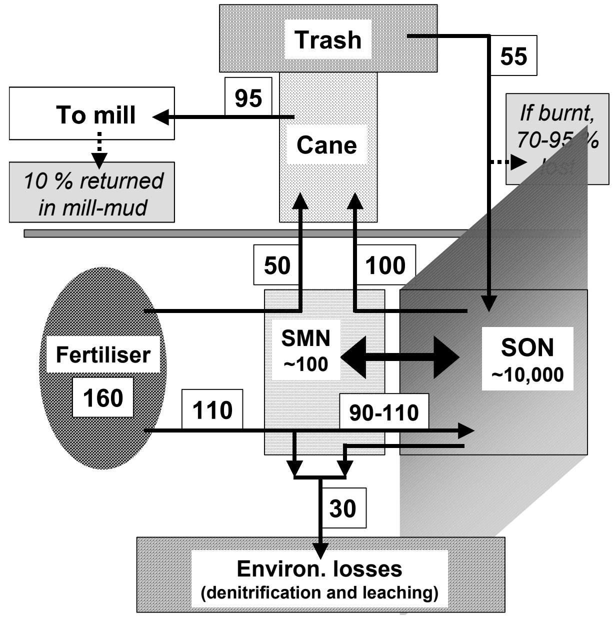

Fig. 1. Hypothetical flows of N in a sugarcane crop with the application of 160 kg/ha of N fertiliser and an assumed cane yield of 100 t/ha. Estimated amount of N (kg/ha/crop) flow shown in boxes. The amounts (kg/ha) of soil mineral N (SMN) and soil organic N (SON) to 1 m soil depth are also shown.

Mineralisation of N from organic matter cannot supply the N required for maximum crop growth indefinitely. For example, yields of sugarcane grown without N fertiliser inputs decreased to approximately 50 % of those receiving adequate N over five crops at Bundaberg (Figure 2). Furthermore, sugarcane production in the absence of N inputs reduces amounts of soil organic matter (Van Antwerpen *et al.,* 2001) and hence soil health. Thus, fertiliser N inputs are required to balance N outputs, and maintain productivity, profitability and soil health.

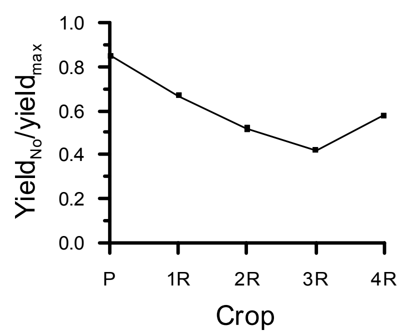

Fig. 2. Yields of sugarcane grown without N fertiliser inputs (yield$_{No}$) relative to crops receiving adequate N fertiliser (yield$_{max}$) over five crops (1996-2001) grown at Bundaberg (after Thorburn *et al.,* 2003).

N fertiliser use in the Australian sugar industry

Fertiliser N inputs have increased during the history of the Australian sugarcane industry (Figure 3): Inputs for the whole industry increased from 120 kg/ha in 1969 to approximately 200 kg/ha in the late 1970's, and have oscillated around that level since. The most readily available detailed data on N inputs, from the Herbert River region (Johnson, 1996; Wood *et al.,* 1997), support this industry-wide trend.

However, sugarcane (or sugar) production has not kept pace with the increased applications of N fertiliser (Figure 3), with the result that more N fertiliser is being applied per tonne of cane produced now than in the past. Pulsford (1993) estimated that the amount of N fertiliser applied in the northern part of the industry increased from 1.2 kg/t of cane harvested in the 1950's to 2.5 kg/t in the 1980's. The whole-industry data (Figure 3) show that it has been maintained at that level since. Keating *et al.,* (1997) suggested a 'rule-of-thumb' for estimating the amount of N required to adequately fertilise a sugarcane crop: 1.4 kg of N is required for each tonne of cane harvested up to 100 t, with 1.0 kg required for each tonne above that yield. Industry average inputs have been greater than this since the 1970's and approximately double this during the late 1980's (Figure 3). The net result of increased fertiliser applications is greater than necessary input costs, exports of N to mills (with implications for sugar quality) and environmental losses (Figure 4). These environmental losses increase exponentially when N fertiliser is applied at rates above that giving maximum sugarcane production.

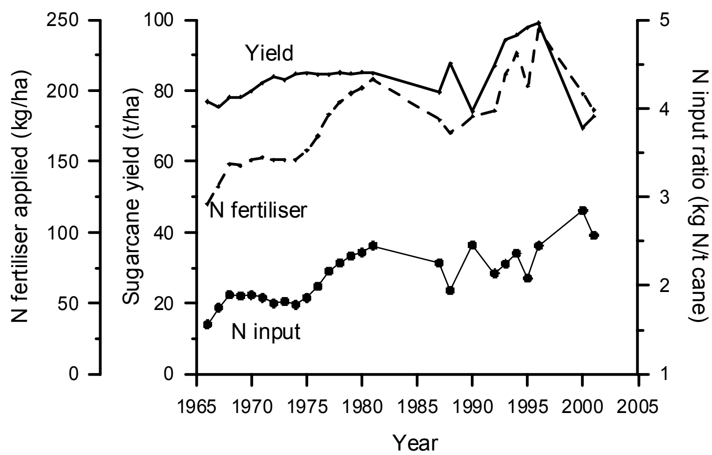

Fig. 3. Sugarcane yields, N fertiliser applied and N inputs relative to sugarcane production (N input ratio) for the Australian sugar industry. Note that there are periods of missing data. Data sourced from Anon. (1985, 1990, 1992, 1998, 2001a, 2002) and Calcino (2001).

Environmental impacts of nitrogen fertiliser use

Estimates of N losses to the environment

There are few direct measurements of N losses to the environment from sugarcane production systems. Most of those undertaken have been of gaseous losses (often employing N^{15} techniques) or lysimeter measurements of N leached from the root-zone. A trait of these studies is that they are generally undertaken at a single rate of applied N. Other approaches include measurement of partial N balances and simulation of N cycling, including denitrification and leaching losses, with cropping systems simulation models. These studies have considered the relationship between N application rates and environmental losses. Further details of these studies follow.

Gaseous losses

Volatilisation of N from urea has been extensively studied, with losses of up to 40 % of N fertiliser applied to a crop measured (Freney *et al.,* 1991, Prasertsak *et al.,* 2002). The environmental impact of this lost N is small in the Australian sugar growing areas, as ammonia (the gas produced during volatilisation) is not a greenhouse gas and much returns to the earth's surface in rainfall.

The main environmentally important gaseous loss of N is via denitrification. Weier *et al.* (1996, 1998) and Weier (1999) measured N losses through denitrification in the northern NSW, Mackay and Herbert regions and found up to 40 % of N fertiliser was lost via this pathway. Longer-term extrapolation of these generally short-term studies is difficult. However, they are consistent with whole-crop duration estimates of Prove *et al.* (1997) described below and simulations of long-term denitrification losses (Thorburn *et al.,* 2004a).

Leaching losses

There have also been estimates of leaching losses from the root zone of sugarcane systems. Prove *et al.* (1997) found 7 to 56 kg/ha of N leached below 0.6 m in lysimeter studies in the Johnstone River catchment. These losses, measured in three crops under two different management systems, equated to 4 to 33 % of N fertiliser inputs. They also measured N lost in runoff, but this was considerably lower 1-6 (kg/ha). Bohl *et al.* (2000a, 2000b, 2002) estimated N leaching losses in the Ripple Creek catchment of the Herbert region at a range of scales (paddock to sub-catchment) through water balance modelling combined with assumptions about the nitrate concentration of the water leaving the root zone. They generally found N losses equivalent to 15 % of fertiliser applications, but losses could be more than double that in plant cane on freely draining soil.

Partial N balances

Another experimental approach to determining N losses to the environment is to measure partial N balances in sugarcane system: This entails measuring N inputs, N outputs, and changes in soil N during an experiment. The difference between inputs and outputs plus soil N storage is assumed to be environmental losses. Prove *et al.* (1997) estimated N losses via denitrification equivalent to 0-80 % of N fertiliser applications by this method. Thorburn *et al.* (2003) estimated N losses (from all pathways) under a range of N fertiliser applications rates. Over five crops, they found N losses increased with increasing N fertiliser application rates to a maximum equivalent to ~ 70 % of N fertiliser applied. This study is the only experiment reported in the Australian sugar industry to explore N losses as a function of N fertiliser application rates. Other studies have been conducted at single N rates.

Simulation of N losses

Another approach to estimating N losses from sugarcane systems is to mechanistically model water and N dynamics and crop growth with cropping systems simulations models (Verburg *et al.,* 1996, 1998; Keating *et al.,* 1997; Thorburn *et al.,* 2001b, 2001c, 2004a). Simulations show the close link between N fertiliser application rates, sugarcane growth and environmental losses (both from leaching and denitrification) of N (Figure 4). They also highlight the extreme year-to-year variability of N leaching. At any rate of N fertiliser application, this variability has a 'random' component related to rainfall variability and the dynamics of nitrate (the mobile form of N) in the soil profile (Verburg *et al.,* 1998). There is also a systematic component. Thorburn *et al.* (2001c) simulated disproportionately high leaching losses occurring in plant crops at all rates of N, due to the combinations of N fertiliser applications and the accumulation of N during the preceding fallow. Simulated long-term environmental losses of N are also affected by soils and climates (Thorburn *et al.,* 2004a).

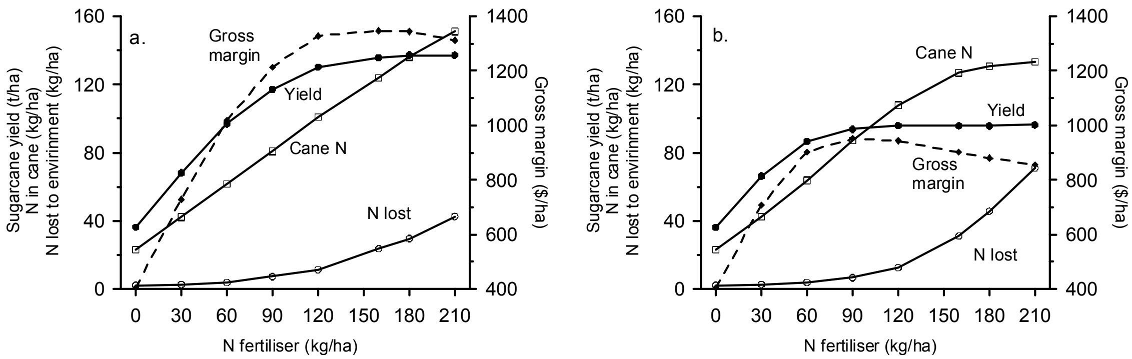

Fig. 4. Variation in long-term mean sugarcane yield, amount of N in cane, N lost to the environment and gross margin of sugar production simulated with the APSIM-Sugarcane cropping systems simulator (based on the green cane trash blanketed system at Mackay). Potential yields for the climate are shown in (a). More realistic commercial yields, approximating impacts of additional factors such as pests and diseases, lodging, stool damage, waterlogging, etc., are shown in (b).

N accumulations in the sugarcane growing environment

Apart from direct measurements and simulations of N losses to the environment from sugarcane systems, there is also evidence of elevated N concentrations in soils, groundwaters and stream waters and acidification of soils in sugarcane growing areas.

Deep soil profiles

In the Bundaberg area (Keating *et al.,* 1996) and the Johnstone River catchment (Rasiah and Armour, 2001) large amounts of N (from ~ 100 to 3,500 kg/ha) have been found stored deep in the soil profile, below the root-zone. The stores are consistent with the amounts of N leached from sugarcane production in these areas (Prove *et al.,* 1997, Verburg *et al.,* 1996). This stored N will gradually move to groundwaters, even if the N inputs from farming cease (Donn *et al.* – in Appendix 1). The transformations that occur to most forms of N fertilisers in the soil produce acidity, and there is evidence of increased soil acidity in sugarcane systems (Noble *et al.,* 1997)

Water bodies

With N in waters of sugarcane catchments, most studies concentrate on the mass of N discharged from the stream and discuss implications for all land uses in the catchments (e.g. Mitchell and Furnas, 1994, 1997; Williams, 2001). Commonly, more of the N comes from grazing than sugarcane production, because of the dominance of grazing lands in the catchments. However, contribution of N per unit area is generally greatest in sugarcane lands. Bramley and Roth (2002) related total N concentrations in streams in north Queensland to the area of sugarcane production in their catchments and found a significant positive correlation (Figure 5).

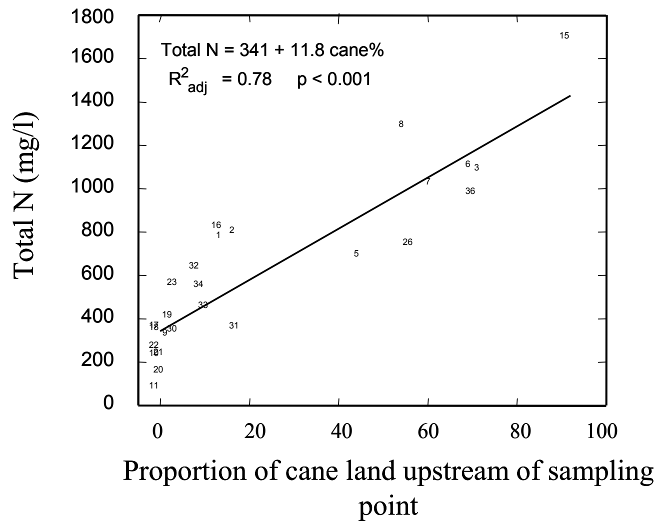

Fig. 5. Impact of sugarcane land area on total N in streams of the Herbert River catchment (after Bramley and Roth, 2002).

Thorburn *et al.* (2002a) surveyed groundwater nitrate-N concentrations from all sugarcane producing regions, except the Ord Irrigation Area. Overall, groundwaters were relatively free from excessive nitrate contamination (Table 2). However, of bores 11 % had elevated nitrate concentrations ($\geq$ 20 mg/L) with the greatest occurrence (14-21 % of wells affected) of elevated nitrate concentrations in the Burdekin, Mackay and Bundaberg areas. Nitrate in approximately half of these wells was likely to have come directly from fertiliser. In the Burdekin and Mackay areas, there was no general trend in groundwater nitrate concentrations over 2 years of monitoring of wells with initial nitrate concentrations > 20 mg/L. However, there was considerable variability within wells between sampling times and further monitoring is required. In Bundaberg, nitrate concentrations in 40 % of wells significantly declined over 6 years (1993-1999) of regular monitoring. The results for this area suggest that nitrogen fertiliser inputs during the monitoring period were not excessive relative to the local aquifer's nitrogen balance.

Table 2. Average annual rainfall, number of wells sampled and percentage of wells with nitrate concentrations in the ranges high (≥ 50mg/l, which is the drinking water standard), medium (≥ 20mg/l and < 50mg/l), or low (< 20mg/l) in each of the study areas (from Thorburn *et al.,* 2002a).

Area	Rainfall (mm)	Number of wells (% of total)	Wells in concentration categories (%)		
			Low	Medium	High
1. Mossman	2220	47 (3)	100	0	0
2. Tablelands	920	54 (4)	96	4	0
3. Gordonvale	2010	26 (2)	65	31	4
4. Wet tropics	4200-3500	82 (6)	95	5	0
5. Ingham	2060	57 (4)	93	4	4
6. Burdekin	1080	397 (27)	86	9	5
7. Proserpine	1800	106 (7)	93	6	1
8. Mackay	1680	165 (11)	79	15	5
9. Bundaberg	1130	423 (29)	79	17	4
10. Maryborough	1160	24 (2)	100	0	0
11. Ballina	1790	73 (5)	99	1	0
Total		1454	86	11	3

Factors influencing growers' decisions about N fertiliser management

There has been little specific research on decision making about N applications, but it is clear that growers (and advisors) use published recommendations as only one source of information. Other factors include soil types, varieties, farm management variables (e.g., irrigation, trash retention, availability of equipment), crop cycle length, weather, sugar prices and fertiliser costs (Johnson, 1995). It is also likely that information for a specific farm or block is more likely to influence growers' decisions than more general information (Johnson, 1995; Keating *et al.,* 1997; Wood *et al.,* 1997; Schroeder *et al.,* 1998). Keating *et al.* (1997) and Brennan *et al.* (1999) also argue that risk and uncertainty are major factors influencing growers' decisions about N fertiliser management.

Growers' profitability is influenced more by productivity than by the cost of N fertiliser: thus, gross margins are higher with above-optimal N inputs than substantially below-optimal inputs (Figure 4). As it is impossible to accurately forecast the yield of the forthcoming crop (due to uncertainties about the coming season, etc.), it is a 'sensible' **short-term** tactic to minimise risk of low production/profits by applying high rates of N fertiliser. Thus, over-application of N fertiliser is a rational reaction by growers to the uncertainty about the size of the forthcoming crop.

Implicit in growers' reasoning is the assumption that long-term average N response curves (such as those in Figure 4) apply to each **individual** year; i.e., applying little or no N fertiliser in any specific year will dramatically reduce yields. However, there is considerable evidence to the contrary. For example:

- Many of Chapman's (1994) experiments in Mackay show little response to N fertiliser at application rates greater than 40 kg/ha, especially for sugar yields.

- There was little difference in yield between N fertiliser applications of 0 or 160 kg/ha at three of nine sites studied by Vallis *et al.* (1994) in northern NSW and the Bundaberg area.

- There was only a 7 % and 16 % decrease in yield without application of N fertiliser in the plant crop and 1st ratoon crops, respectively, of the experiment reported by Thorburn *et al.* (2003, Figure 2).

- There was only a 10 % reduction in yield when N fertiliser was withheld in 2nd ratoon crops compared with applying 170 kg/ha on sandy soil (~ 10 % clay) in Bundaberg (Figure 6). In the same experiment, applying no N fertiliser in 1st and 2nd ratoon crops reduced the 2nd ratoon crop yield by ~ 25 % compared with applying at least 170 kg/ha to both crops.

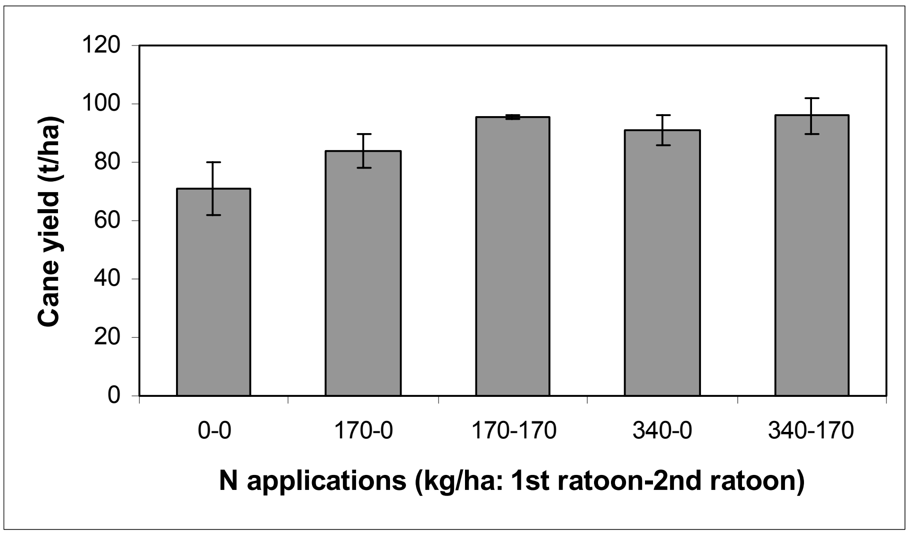

Fig. 6. Sugarcane yields in 1st and 2nd ratoon crops that had a range of N fertiliser applications, some of which were the same on each crop and some with reductions in the 2nd crop (after Vallis et al 1994).

These small negative effects from withholding N fertiliser in a single year may have arisen for a number of reasons, e.g., because there were large quantities of mineral N in the profile at the beginning of the experiment or the mineralising capacity of the soil was sufficient to supply much of the crops needs during the experiment. Whatever the reasons, these experiments show that rather than growers considering the N ‘petrol tank’ in the soil to be empty at the beginning of a crop, they could consider it nearly full. Thus, the risk of reduced crop yield due to **short-term** under application of N is likely to be much lower than generally considered.

However, there are other longer-term risks associated with sugarcane production, which also have the potential to substantially limit production and hence farm business profitability. (Brennen *et al.,* 1999). One is the risk of soil and water degradation, as described above. Another is institutional risk – that is the risk that society (through government) may regulate N management practice to reduce or prevent soil and water degradation. While self-regulation is the most common path taken in Australia, the recent draft water quality targets for rivers draining into the Great Barrier Reef lagoon (Anon., 2001b) show that the ‘threat’ of government regulation is real.

To minimise risks associated with soil and water degradation, N fertiliser applications need to be closely matched to the crop's requirements (Wood *et al.,* 1997, Keating *et al.,* 1997). To minimise institutional risks, N fertiliser management must be evidence based, transparent and defensible.

Traditional nitrogen fertiliser management recommendations

The industry standard N fertiliser management recommendations (Table 3) were derived by BSES and evolved over time (as described by Schroeder *et al.,* 1998). They are based on more than 200 experimentally determined regional 'N response curves' (Anon., 1985; Chapman, 1994) and the requirement that growers receive a 15 % return on investment in N fertiliser (Chapman, 1994). The results were collated into regional averages (for the north, Herbert, Burdekin, central and south regions) for plant and ratoon cane. However, regional N response curves and recommendations were similar and aggregated, except for the Burdekin region, which required higher N fertiliser. Some versions of the recommendations (Anon., 1985; Chapman, 1994) included variations for the price of sugar (above/below $300/t), soil types ('richlands' identified as requiring lower inputs) and areas of low rainfall (< 1,200 mm/yr). Some versions (e.g., Calcino, 1994; Calcino *et al.,* 2000) do not include the sugar price distinction, but recommend the range associated with the different sugar prices shown in Table 3 (e.g., Plant crop/Burdekin 135-150 kg/ha).

Table 3. Nitrogen management recommendations for sugarcane in Australia (Chapman, 1994)

	Crop class	N rate (kg/ha)	
		Burdekin	Other regions
Sugar price < A$300/t	Fallow plant	135	120
	Ratoon & replant	210	160
Sugar price > A$300/t	Fallow plant	150	120-150
	Ratoon & replant	270	160-200
Dry land or rich land	Fallow plant	-	80
regardless of sugar price	Ratoon & replant	-	120

Chapman (1994) acknowledged that the N responses at different sites were highly variable and presented information for 30 experiments conducted at Mackay that illustrated the variability. Maximum yields in ratoon cane approximately ranged from 50 to 110 t/ha with the response in cane yield to increasing N applications from 40 to 240 kg/ha approximately ranging between 0 and 30 t/ha. (The situation was similar for sugar yield as CCS was little affected by N application.)

A problem with these recommendations is that their basis is uncertain. This is because the data from which they were derived and the method of derivation have not been opened to peer scrutiny. The industry average N fertiliser application rates (Figure 3) have generally been greater than those recommended for much of the time since they were first published, suggesting that the recommendations are rarely followed. These recommendations have been criticised as being too broad and not adequately accounting for either soil fertility or nutrient use efficiency (Wood *et al.,* 1997). There is also no cognisance of the climatic impact on yield potential of the farm, apart from identifying higher general yield potential in the

Burdekin region. As described above, these are all factors growers take into account when making N management decisions.

Recent advances in nitrogen fertiliser management recommendations

Soil specific recommendations

To make fertiliser recommendations more site-specific and relevant to growers, Wood *et al.* (1997) and Schroeder *et al.* (1998) reasoned that soil type (and fertility) is a major factor determining the response of sugarcane yield to N fertiliser applications and must be accounted for when deriving recommendations for N fertiliser management. Soils with higher organic matter contents mineralise more N (represented by the thick double-headed arrow in Figure 1) and therefore should require less fertiliser inputs.

To address these issues, Wood *et al.* (2003) have suggested a new set of recommendations based on (a) target (potential) yield, (b) the N requirement of a crop of that size (using the 'rule-of-thumb' developed by Keating *et al.*, 1997), and (c) a 'discount' for N mineralised from soil organic matter (based on laboratory measurements of Schroeder and Wood, 2001). This system results in recommendations considerably lower than those currently published by BSES in all situations except for large crops grown on soil with low organic matter (e.g., Table 4). Wood *et al.* (2003) encourage growers to also undertake soil (Schroeder *et al.*, 1998) and leaf (Schroeder *et al.*, 1999) testing programs to monitor the N nutrition status of sugarcane crops.

Table 4. Proposed N fertiliser application rates (kg/ha) for the Herbert and Bundaberg districts assuming a yield potential of 120 t/ha (after Wood *et al.,* 2003)

N mineralisation index	Soil organic carbon (%)	Recommended application rate
Very low	<0.4	160
Low	0.41-0.8	160
Moderately low	0.81-1.2	140
Moderate	1.21-1.6	140
Moderately high	1.61-2.0	120
High	2.01-2.4	120
Very high	>2.4	100

This N management system has yet to be widely applied, so its success cannot yet be judged. However, there may be some potential problems with it. The first is that it is based on growers' assessments of target yield. While N fertiliser costs are a small proportion of total production costs, growers may well be optimistic about their target yields resulting in the calculation of large amount of N. The second problem is that the N requirement of a crop of a given size is not justified. Keating *et al.*'s (1997) 'rule-of-thumb' is not a well reasoned or tested metric. The third problem with this scheme is that the relationship between N mineralising capacity and soil C is not very precise (r^2 = 0.6) and overly simplistic. The relationship was developed by Schroeder and Wood (2001) in laboratory experiments, under controlled conditions of constant water content and temperature. Mineralisation of N from soil organic matter is well understood, and factors such as moisture content and temperature greatly affect it (Probert *et al.,* 1998). Thus, soil of a given organic matter content will mineralise more N in warmer and/or wetter environments. The difference can be up to 30 % (Meier *et al.,* 2003), similar to the range in application rates between the soil organic carbon groups (Table 4).

Novel monitoring of crop N status

In another approach towards site specificity of N fertiliser management, Keating *et al.* (1997, 1999) argued that the costs, both time and financial, make leaf and soil monitoring unattractive to growers compared with the costs of applying higher rates of N fertiliser. The development of easier and cheaper monitoring methods would facilitate better N fertiliser management. Given that the sugarcane stem is the most responsive part of the plant to N nutrition (Muchow and Robertson, 1994; Catchpoole and Keating, 1995; Wiedenfeld, 1995; Keating *et al.,* 1999) and that all harvested cane stalks pass through a sugarcane mill, the 'N status' of each sugarcane farm block could be monitored at sugarcane mills at negligible cost to growers. This information could then be supplied to growers with data on block yields, CCS, etc. Such a system could form the basis of monitoring, benchmarking and advisory actions for improving N fertiliser management. Rapid mill-based N monitoring techniques have been developed, and grower response to this information trailed in pilot studies in the Mossman mill region (Keating *et al.,* 2003).

N inputs from sources other than fertiliser

Legumes

Legume crop residues can provide an alternative source of N to that supplied by mineral fertiliser when legumes are grown in a sugarcane cropping cycle. It has been estimated that the above-ground biomass of a single crop of soybean can provide over 300 kg/ha of N to the soil (Garside *et al.,* 1996). Given that almost 30 % of the N produced by a legume may be stored below ground (Rochester *et al.,* 1998), this contribution may be increased further to provide an N input of approximately 400 kg/ha each fallow season. N in legume biomass can come from either mineral N in the soil or from the atmosphere through biological N_2 fixation (BNF). N in legumes will be released into the soil when residues from legume crops decompose. Thus, the presence of legumes in a sugarcane cropping cycle can greatly affect the N cycle, altering the patterns of soil mineral availability, and, possibly, increasing the total amount of N in the system.

Release of N in legume crop residues happens after the residues decompose, with the rate of this process primarily dependent upon the interaction between the climatic and soil environments and agronomic management practices. Garside *et al.* (1998) and Noble and Garside (2000) found that rates of N mineralisation rates soybean residues in the high rainfall area of Tully were more rapid when residues were incorporated into the soil than when they were left on the soil surface. However, sugarcane production spans many environments in Australia, so such site-specific studies contribute little to our understanding of the management requirements of legume residues in other locations. For example, it is not known whether residues would need to be incorporated when heavier soils, cooler temperatures, or lower rainfall conditions are found.

Another unknown is the temporal availability of N from a legume crop. The C:N ratio of legumes range with crop species and plant part but, in general, the C:N ratio of roots are in the region of 11 to 14 (Crawford *et al.*, 1997) and above-ground residues are commonly in the range of 16 to 20 for green manures and 20 to 30 for grain legumes (Evans *et al.*, 2003).

Compared to the relatively high C:N ratio of 120 for sugarcane (Robertson and Thorburn, 2000), the decomposition of legume residues is expected to be rapid. In addition, the low C:N ratio of legume residues is commonly thought to negate immobilisation of soil N stores, as happens with decomposing sugarcane residues (Ng Kee Kwong *et al.,* 1987, Basanta *et al.,* 2003). However, this remains to be quantified, especially in the tropical soils of sugarcane producing areas. Similarly, the potential effects of a possible increase in N supplied to the sugarcane plant by decomposing legume crop residues may, particularly during the later stages of growth, stimulate unwanted production of suckers, resulting in a reduction of crop sucrose concentration and CCS (Salter and Bonnett, 2000; Bonnett *et al.,* 2001).

Supplying atmospheric N to a sugarcane cropping system by BFN is attractive if it reduces the need for N fertiliser. Legumes have the potential to fix N, with up to 82 % of the N supplied by a legume derived from BNF in one study conducted by Bell *et al.* (1998). However, amounts of BFN can vary, being affected by many things, including the availability of soil mineral N. There are few other data on the relative contribution of N to a legume crop from BNF so it is difficult to judge how widely applicable are the results of Bell *et al.* (1998).

Given the potential benefits that may arise from including a legume fallow into the sugarcane cropping cycle, it is possible that the benefits of a legume crop may also be achieved on an ongoing basis through the introduction of a permanent legume forage understorey established beneath the cane crop. A greater understanding of the effects of competition for light, water and soil nutrients between the cane and legume crops is required in order to assess the efficacy of this practice to assist in sustainable sugarcane production.

The incorporation of legume fallows into the sugarcane cropping system is also know to produce a number of detrimental effects, namely an increase in soil acidification and increased leaching of nitrates (Noble and Garside, 2000). Whilst it is known that reduced rates of soil acidity can be achieved when legume residues are incorporated (Noble and Garside, 2000), further information on best-management practices for legume agronomy is required in order to minimise such negative impacts.

In any N fertiliser management system, it is necessary to estimate the amount of N that will be provided via a legume fallow or intercrop and deduct this from the estimate of N fertiliser applied. Garside and Bell (2001) suggest that there is no need to supply N to plant crops following a well-grown legume fallow. Calcino *et al.* (2000) recommend that N fertiliser application be reduced by 50-60 kg/ha following a fallow legume crop. However, the basis of this recommendation is uncertain, especially given the small amount of information that exists on the impact of legumes on N cycling in sugarcane soils. With the exception of the above studies, little is know about the temporal and spatial aspects of mineral N supply from a legume, and how this is affected by the accumulation of N by the legume via BNF and soil stores or the decomposition of above-and below-ground biomass. There needs to be a greater understanding of these issues on which to base N fertiliser management recommendations and decisions in sugarcane production systems that include legumes.

Biological N fixation

There is much interest surrounding the contribution of BNF to the N supply of sugarcane. Research undertaken in other sugar producing nations suggests that BNF has the potential to provide up to 72 % of the plant's N requirements (Boddey *et al.,* 2001). If there is significant

BNF activity in Australian sugarcane production, then this N source will have to be accounted for in N fertiliser management plans.

Of the many species of bacteria responsible for BNF in sugarcane, several of the key species have been isolated in Australian sugarcane plants and fields, including *Gluconacetobacter diazotrophicus, Herbaspirillum* spp and *Burkholderia* spp, (Murphy and Macrae, 1985; Li and Macrae, 1991, 1992a, 1992b; Chapman *et al.,* 1992; S. Robertson pers. comm., 2003). The populations of these bacteria vary between varieties (S. Robertson pers. comm., 2003) and in response to management factors. For example, Muthukumarasamy *et al.* (1999) suggest the amount of N_2 fixed is reduced by the application of N fertiliser but showed further that this trend was not uniform and was influenced by the form of the N fertiliser supplied (Muthukumarasamy *et al.,* 2002). While the studies mentioned have investigated populations of N_2-fixing bacteria, to date only a few Brazilian varieties have been shown to definitely fix N_2 (Urquiaga *et al.,* 1992).

Having N_2-fixing bacteria present in a plant does not necessarily indicate that BNF is taking place, so it is important to look for more direct evidence of N being supplied by BNF. The amount of BNF occurring is commonly determined in field studies from the ratio of the naturally occurring stable isotopes $^{15}N/^{14}N$ (expressed as $\delta^{15}N$) in leaves (Yoneyama *et al.,* 1997; Boddey *et al.,* 2001; Biggs *et al.,* 2002). The $\delta^{15}N$ values in leaves of the plant being studied are compared with values in leaves from nearby 'reference plants' (Boddey *et al.,* 2001; Biggs *et al.,* 2002) – plants of species known (or assumed) to either fix, or not fix N_2. $\delta^{15}N$ studies in Australian sugarcane systems have generally suggested that little or no N comes from fixation (Biggs *et al.,* 2002, Thorburn *et al.,* 2003). It might be argued that the higher rates of N fertiliser generally applied in sugarcane production in Australia, compared with overseas countries, may suppress N_2 fixation and so these results are an artefact of the Australian management system. However, Thorburn *et al.* (2003) found no evidence of BNF in a field experiment where sugarcane had received either high amounts (e.g., > 200 kg/ha/y) or **no** N fertiliser over the previous four years. More detailed process studies on BNF have also failed to reliably show significant contributions to the soil-crop N budget (S. Robertson, pers comm., 2003).

Thorburn *et al.* (2003) also pointed out an interesting feature of the $\delta^{15}N$ methodology that may result in overestimations of BNF. This feature raises the possibility that overseas studies of BNF in sugarcane using the $\delta^{15}N$ methodology, like those summarised by Boddey *et al.* (2001), maybe reporting inflated values.

A system of using N_2 fixing bacterial inoculants to supplement or replace N fertilisation has been developed for graminaceous crops, but is not yet able to replace N fertiliser application for meeting plant N demands (Andrews *et al.,* 2003). It is possible that a similar system could be developed for sugarcane in the future.

While having BNF occur in sugarcane is attractive for enhancing the N economy of sugarcane production systems, we conclude that it need not be considered in N fertiliser management plans in Australian sugarcane production at the current time.

Mill products

Mill mud/ash, a by-product of raw sugar manufacturing, has an historical role in the nutrition of sugarcane crops. At 'typical application rates', approximately 400 kg/ha of N are applied to the soil (Calcino *et al.,* 2000). Higher yields and leaf N concentrations have been found in response to the application of mill mud/ash where soils are N deficient (e.g. Kingston, 1999). Calcino *et al.* (2000) state that approximately 100 kg/ha of N will be available to the crop following application, but the availability of the remaining N is uncertain as it is in organic forms.

Despite its importance in the sugar industry, little has been published about the forms of N in mill mud/ash. This knowledge is a prerequisite for understanding the amount and timing of the availability of mill mud/ash, and hence developing guidelines for how mill mud/ash should be incorporated into N fertiliser management plans. Most recent work has been undertaken on stock piling mill mud/ash (Stacey, 2002; Bloesch *et al.,* 2003), and sheds no light on N dynamics following applications of mill mud/ash to sugarcane fields. The lack of understanding is reflected in vagueness of existing guidelines for the management of mill mud/ash. The South African industry has guidelines to account for N applications from mill by-products based on the N concentration and carbon to N ration of the by-product (Moberly and Meyer*,* 1987). It is important that a better process-understanding is developed of N cycling in sugarcane production systems following the application of mill mud/ash, leading to the development of sound guidelines, perhaps along the lines of those used in South Africa, for how mill mud/ash should be incorporated into N fertiliser management plans.

Capabilities of cropping systems models aid N fertiliser management

The characteristics of the N cycle in sugarcane production systems suggest that a sugarcane cropping system model with crop and soil N capabilities able to respond to management practices and climate would be a valuable tool in examining/deriving improved N management strategies. It is likely that such a model will be one-dimensional and operate on a daily time step (Probert and Keating, 2000). To be useful, such a model should include representation of crop growth as affected by N supply, inputs to and losses from crop residues as a result of biological (e.g. senescence and detachment/decomposition) and mechanical (e.g. harvesting/burning or incorporation during tillage) processes, and description of the major N transformation in the soil (Figure 7).

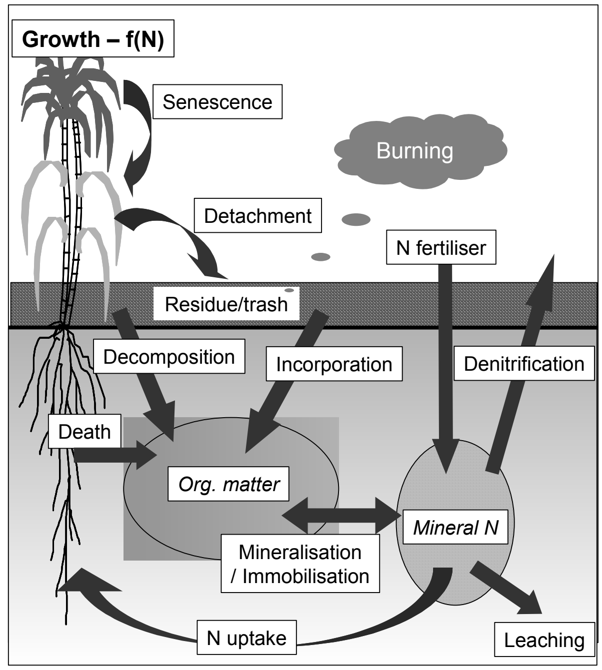

Fig. 7. Diagram of the different process that need to be represented to model N dynamics in a sugarcane cropping system.

A detailed review of the models available to simulate these processes in presented in Appendix 4. Accurate simulation of soil water is also critical because of its importance in modelling crop growth and soil N processes, i.e. its role in mediating microbial dynamics, and direct impact on losses of N by nitrate leaching, denitrification and ammonia volatilisation. Soil water processes needed in such a tool were considered by Probert and Keating (2000), and so will not be considered further here.

The sugarcane cropping system has features, such as the long time over which crops grow, production of high amounts of low quality crop residue, the infrequency of fallows in the cropping system, and the need for large amounts of N to reach potential yields, that set it apart from many other cropping systems. These features place special demands on a system for modelling N dynamics in a cropping system. To date, only APSIM-Sugarcane has these features. APSIM-Sugarcane has been shown capable of predicting many of the important attributes, such as the dynamics of yield, crop residue, and soil N and C, of a sugarcane system in the context of N management. The model has provided important insights into (1) soil organic matter and N dynamics under different residue management practices, (2) optimising the management of N fertiliser where residues are retained and in irrigated systems, and (3) losses of N to the environment.

There are refinements that could be made to improve the model's performance for these scenarios. More importantly, however, there are processes that are not represented in the model that are required to better address questions such as gaseous losses of N and the impact of N on sucrose yield. Some of these issues have been partly overcome by use of other models to refine inputs to (e.g. account for volatilisation of N from urea fertiliser) or outputs from (e.g. partitioning gross N losses during denitrification into N_2O and NO_x emissions) the model. The detail required to incorporate these process into the model may be too great in relation to the other crop, soil and management processes represented in the model. There are also other challenges that have not been discussed in this paper. One in particular is the scaling of one-dimensional models to catchments or landscapes. This problem is not unique to the issue of N dynamic in sugarcane cropping systems.

Future directions for managing N fertiliser

A factor in current N fertiliser management recommendations is the link, implicit or explicit, between fertiliser applications and the yield of the forthcoming crop. This yield is notoriously hard to predict and, as stated above, growers have sound reasons for not wanting their crop yields to be N-limited. So it is understandable that growers apply amounts of N fertiliser appropriate for large crops – this is seen as insurance against yields being limited by N deficiency. But what is the real probability of the yield being limited by inadequate N supply? As stated above there is considerable evidence suggesting that, in many cases, the N mineralisation capacity of the soil and/or soil mineral N reserves are sufficiently high that little N fertiliser is required to provide an adequate N supply for a **single** crop. Rather than thinking that the soil N 'petrol tank' is nearly empty, there is good reason to think that in many cases it is more likely to be nearly full.

By making this assumption about soil N supply, the philosophy of N fertiliser management can be changed. N fertiliser need not be thought necessary to ensure the yield of the forthcoming crop, but to replace the N removed from the site via the previously harvested crop. Thus, **uncertainty** surrounding the yield of the forthcoming crop is replaced by the **certainty** of N removed in the previous crop. For each block, the off-take of N can be readily estimated from the measured cane yield in combination with either (a) knowledge (e.g., Catchpoole and Keating, 1995; Muchow *et al.,* 1996) or 'rules-of-thumb' (Keating *et al.,* 1997) about N concentrations in cane, or (b) direct measurements made at mills (e.g., Staunton *et al.,* 1999).

To further explore the implications of the 'N replacement' concept of N fertiliser management, long-term simulations were run using the APSIM cropping systems simulator for three different N fertiliser management strategies: (1) N replacement, (2) current recommended N fertiliser management (Calcino *et al.,* 2000) and (3) current industry average management. The recommended system had 120 and 160 kg/ha of N applied to plant and ratoon crops, respectively. The industry average management had 155 and 210 kg/ha of N applied to plant and ratoon crops, respectively. In the replacement system, the amount of N applied to a crop equalled that contained in the cane at harvest of the previous crop (assuming a cane N concentration of 0.3 %) and an allowance for unavoidable environmental losses of N. Not making this allowance results in continual under application of N fertiliser and increasing N deficiency in the crop. Losses were initially assumed to be 10 % of the N contained in the previous crop, resulting in a total N application of 110 % of that in the previous crop. This 'rule' was applied to plant and ratoon crops and no account was taken of the impacts of fallows between crop cycles.

For both potential (Figure 8a) and realistic (Figure 8b) yields, there was little difference in simulated sugarcane yields in any of the N management systems for the Brown Chromosol soil and Mackay climate. However, the gross margin (i.e., the income from sugarcane less the costs of fertiliser and harvesting) in the N replacement system was higher than in the other two systems (Figures 8c and d), particularly where realistic yields were simulated (Figure 8d). The increased gross margin was a result of lower rates of N fertiliser applied to the N replacement system, especially with realistic yields (Table 5). The lower N fertiliser applications in the N replacement system resulted in lower total environmental losses of N simulated for both potential (Figure 8e) and realistic (Figure 8f) yields. The maintenance of cane productivity with lower N fertiliser inputs did not degrade soil organic matter: There was little difference in simulated soil organic matter amounts in any of the N management systems (data not shown).

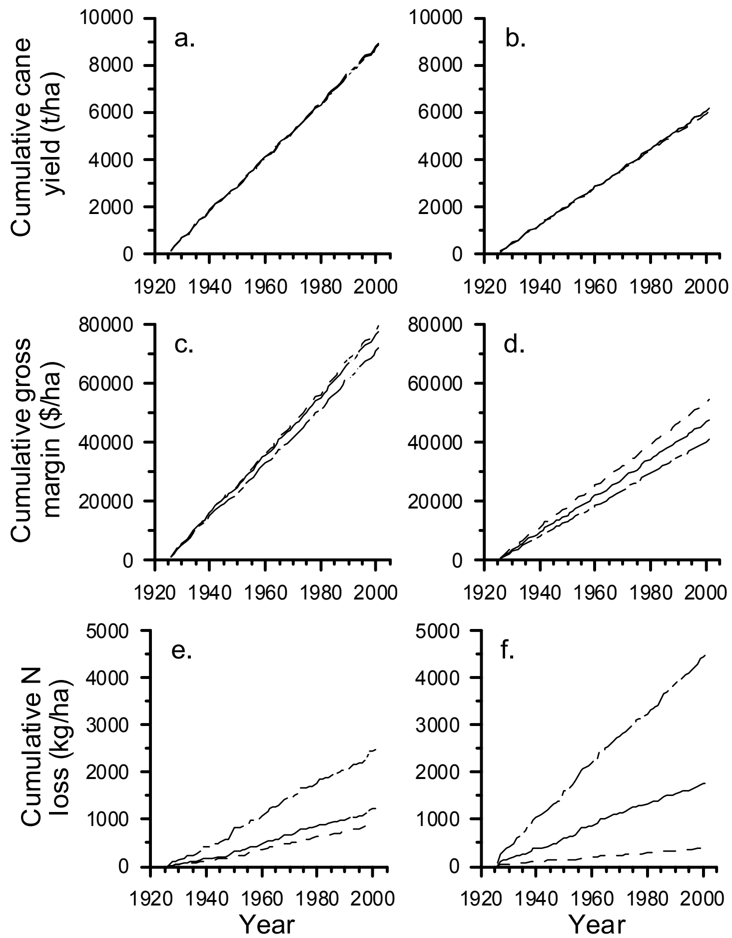

Fig. 8. Cumulative cane yield, gross margin and N losses simulated for three different N fertiliser management systems (recommended – solid line, industry average – long dashes, replacement – short dashes) under potential (a, c, e) and realistic (b, d, f) yield conditions.

Table 5. Average N fertiliser applications per crop (kg/ha) and per tonne of cane produced (kg/t) for three different N management systems simulated for potential and realistic yield conditions.

N management system	N applied per crop		N applied per tonne of cane	
	Potential yields	Realistic yields	Potential yields	Realistic yields
Recommended	152	152	1.1	1.6
Industry average	199	199	1.4	2.1
Replacement	137	94	1.0	1.0

DISCUSSION

N fertiliser applications are necessary to maintain sugarcane productivity, profitability, and soil health. Rates of fertiliser application should, ideally, be block specific and related to crop yields to minimise losses of N to the environment and the deleterious effects of high N concentrations on crop agronomy and sugar quality. In order to retain self-regulation, fertiliser management needs to be evidence based, transparent and block specific. Traditional N fertiliser managements recommendations used in the sugar industry do not fulfil these criteria.

The simulations undertaken in this project (e.g. Figure 8) support the proposition that an N fertiliser management system based on replacing the N exported from farm blocks in harvested cane could maintain productivity and soil quality, improve profitability and decrease N losses to the environment. It would also be evidence based, and defensible. Simulations were only conducted for a limited range of sugarcane management systems and the replacement concept could benefit from wider desktop testing. However, such an exercise was beyond the scope of this review.

An uncertainty with the N replacement system is how to account for N losses from sources/processes other than harvested cane. In simulating this system, an assumption was made about environmental losses (that they equalled 10 % of applications), and it proved to be satisfactory for the system simulated. However, environmental losses may be district specific, and accounting for areas where N losses are high from either nitrate leaching or denitrification may be important. Environmental losses of N decrease rapidly with decreasing applications of N fertiliser (e.g., Figures 4a and 4b), and so these losses will be minimised under a management system that closely matches N applications to N requirements. The difference between districts may be less than expected, given that the majority of our knowledge on environmental losses of N has been unintentionally derived from over-fertiliser experiments (e.g., 160 kg/ha of N applied to a crop yielding ~ 80 t/ha; Prove *et al.,* 1997).

A replacement system, like other N fertiliser management systems, would benefit from monitoring crop and soil N status to ensure N deficits or excesses did not occur in the crop, and that soil quality was maintained. Systems are available or under development to perform this monitoring (Schroeder *et al.,* 1999, 2002; Keating *et al.,* 1999, 2003).

Other knowledge gaps in the area of management of N fertilisers centre on questions of how to account for N inputs from sources other than fertilisers. These inputs can come from N fixation in legume crops grown during fallows, N applied to soil through mill mud/ash or N applied to the soil via irrigation water containing N. Fertiliser applications should be discounted for these inputs. N from irrigation water is regularly accounted for in N fertiliser recommendations made in the Burdekin (G. Ham pers. comm.), the district where the problem is most relevant (Thorburn *et al.,* 2002a). However, as described above, there is still considerable uncertainty about the amount and timing of N release from legumes and mill mud/ash. It is important that more information is gained about these issues and soundly based N fertiliser management guidelines developed. These uncertainties are important in all N management systems.

Management strategies such as slow-release N fertiliser products and splitting of N applications will provide no improvement in N use efficiency under current N fertiliser management practices because of the general over-supply of N currently occurring. However, they may be useful tools in a replacement strategy where N use efficiency is inherently much higher.

OUTPUTS

There were several outputs from this project:

- Notes from the workshop on *Management of N Fertiliser in ihe Australian Sugar Industry* (Appendix 1).
- A database of references obtained during electronic and manual searches of literature on N fertiliser management in ihe Nustralian sugar industry (Appendic 2). This database has been sent to people actively researching this issue.
- There were two publication arising from this project:

Thorburn, P.J., Park, S.E. and Biggs, I.M. (2003). Nitrogen fertiliser management in the Australian sugar industry: strategic opportunities for improved efficiency. *Proceedings of the Australian Society of Sugar Cane Technologists*, 25: 12pp.

Thorburn P.J., Meier E.A. and Probert M.E. (2004). Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications. *Field Crops Research*, submitted.

EXPECTED OUTCOMES

Expected outcomes from this project include:

- The ‘N replacement’ concept – that a viable N fertiliser management system might be based on the premise of replacing N losses from the previous crop.
- Improved understanding of N cycling in sugarcane systems, especially relating to environmental loses of N.
- Clearer definition of knowledge gaps in the areas of N fertiliser management.
- Stimulated debate about appropriate ways to manage N fertiliser in the Australian sugar industry.

These outcomes should underpin an ultimate improvement in the management of N fertiliser in the Australian industry, leading to greater profitability and sustainability of the industry and increased acceptance by the public of the N fertiliser management practices of the industry.

FUTURE RESEARCH NEEDS

This project has identified several areas where future research is required. Firstly, the N replacement concept should be subject to further testing, through both simulations and field experimentation. The aims of this research should be to:

- Better define the amount of N lost through harvested cane, trash burning (where applicable) and unavoidable environmental losses in different regions (from the wet tropics to NSW), under different conditions (e.g., irrigation and dryland) and different farm management practices (e.g. N carrier, N application technique).
- Demonstrate whether replacing these losses provides a reliable and profitable cane supply.
- Developing the knowledge base within the grower and advisor community to underpin adoption of the 'replacement' N management practices.
- Defining benchmarks for the industry and broader community of the amount of N needed for sustainable sugarcane production.

Other areas where research is required include:

- Developing methods for accounting for N contributions from organic sources, such as mill mud or fallow legumes, to sugarcane N supply, and
- Applying and refining in-mill and other methods of monitoring the N status of sugarcane crops.

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APPENDIX 1: Report of Workshop on Best Management of Nitrogen Fertiliser in the Sugar Industry

Workshop on:
Best Management of Nitrogen Fertiliser in the Sugar Industry
Townsville, 7th-8th March, 2002

Introduction

Despite the long history of investment in N fertiliser management research supported by both SRDC and R&D providers, there remains uncertainty regarding the best management practices for supplying adequate N to sugarcane while, concurrently, minimising losses of fertiliser N to the environment. The industry needs to be environmentally responsible and adopt management practices that minimise off-site impacts. At the same time industry must look to maximise profitability, by matching inputs to outputs. SRDC wishes to review recent progress in N fertiliser management research to document current best management practices, and determine and prioritise remaining knowledge gaps.

This workshop was held to collate information on work yet to be reported, or still in progress, that is relevant to the review. Researchers who have been actively involved in research and development of N management practices in recent times were invited to share their conclusions (rather than the details) of their work with the workshop group. Following the workshop, more detail of their work was obtained and incorporated into this review.

This report consists of the workshop program, workshop summation, and the summaries of the research presented at the workshop. Research relevant to the review but unable to be presented at the workshop is also summarised.

WORKSHOP ON:
Best Management of Nitrogen Fertiliser in the Sugar Industry

Townsville, 7th-8th March, 2002

PROGRAM

THURSDAY 7TH MARCH

From - to	Topic	Presenter
12:30 - 13:30	**Lunch**	
13:30 - 13:50	Introduction	Doug McGuffog/ Peter Thorburn
13:50 - 14:05	Herbert nitrogen by variety trials	John Reghenzani
14:05 - 14:20	NUTMAN and Maintaining Soil Fertility	Greg Shannon/ Kylie Webster
14:20 - 14:35	N fixation in sugarcane	Sue Robertson
14:35 - 14:50	Yield decline studies - implications for N fertiliser management	Alan Garside
14:50 - 15:05	Impact of trash management on N fertiliser management	Fiona Robertson
15:05 - 15:20	**Discussion**	
15:20 - 15:35	**Afternoon tea**	
15:35 - 15:50	Monitoring N at the mill to improve management on the farm	Ian Biggs
15:50 - 16:05	Impact of trickle irrigation on N fertiliser management	Sam Stacey
16:05 - 16:20	Current status of modelling N dynamics in sugarcane systems	Peter Thorburn
16:20 - 16:35	Development of a potential N mineralisation index	Elizabeth Meier
16:35 - 16:50	Environmental association of nitrate-N retention in deep soil profiles in Queensland wet tropics.	Ras Rasiah
16:50 - 17:05	On-farm measurement of deep drainage quality and its implications for the Burdekin delta groundwater	Phil Charlesworth
17:05 - 17:30	**General Discussion**	
19:00	**Dinner**	

FRIDAY 8TH MARCH

From - to	Topic	Presenter
8:30 - 8:40	Welcome new attendees	Peter Thorburn
8:40 - 9:00	Re-cap of Thurs	
9:00 - 9:15	Trends in N use in the sugar Industry	Garry Kuhn
9:15 - 9:30	The "external environment"	George Rayment
9:30 - 9:45	"Science directions" in N research	Graham Kingston
9:45 - 10:00	N dynamics and leaching - studies in Bundaberg	Keith Bristow
10:00 - 10:15	**Morning tea**	
10:15 - 10:30	Economic opportunities for enhancing N fertiliser management	Thilak Mallawaarachchi
10:30 - 11:45	Economics of non point source of pollution - N	Ejaz Qureshi
11:45 - 12:15	Group/s discussion on future directions	
12:15 - 12:30	*Wrap up*	Peter Thorburn
12:30 - 13:00	**Lunch**	

N-review Workshop – Group discussion on future directions

The final task of the workshop required attendees to divide into three discussion groups of around 7 or 8 people. Each group was assigned a subject area (socio-economic, agronomic and environmental) as context within which to discuss issues relating to sustainability and profitability, knowledge gaps and implications for N-fertiliser management. The notes that flowed from these discussions highlighted the many facets of the subject and apparent conflicting perceptions of agents. Although each group was requested to discuss issues pertaining to only one subject area, the necessity to incorporate issues relating to other subject areas became apparent. The following summary attempts to draw out the main themes covered by the three discussion groups.

Externalities/Community

- The fear of external regulation is one of the two main drivers likely to effect change in the present N fertiliser management practices (the other being cost of production).
- Growers bare all of the risk of potentially low yields in the short-term as a result of reduced N fertiliser application rates, whilst the community accrues the lion's share of the benefits from less fertiliser use (at no cost to themselves). Need for a move away from risk reduction strategy by the grower, to risk sharing by the wider community.
- Need for the community to be accepting of the sugar industry for not only the financial benefits that it provides to rural communities, but also to the environmental impacts that are associated with cane growing and sugar production.
- There is potential for a fertiliser tax to be levied on growers as an incentive to reduce application rates.
- A reduction in the use of less productive and marginal land could be achieved through a buy-back scheme funded by the wider community.
- Need for more informative and effective education and communication to the local and national community to improved the perception of sugarcane industry.
- Growers need to be more aware of the link between on-farm management and off-farm impacts.

Cane growers as business managers (perceptions and knowledge)

- Growers need to be given a financial incentive to induce them to reduce fertiliser inputs – the present notion of using excess N as a low-cost insurance policy needs to be exposed as non-viable in the long-term.
- A move towards determining N fertiliser application rates using the maximum gross margins concept needs to be fully incorporated into farm management decision making and assessment (although it is recognised that the gross margin is a moving target).
- A broader view of the determinants of yield needs to be accepted by growers – present widespread perception that N is the sole determinant of yield, regardless of other resource limitations.
- Need for more informative and effective education and extension programmes to facilitate the implementation of new findings/practices. This may challenge some "traditional" notions of how to grow sugarcane. The aim would be to build the confidence of growers to understand the information and apply it to their farm.

Agronomic

- Need to increase nutrient use efficiency – this requires an integrated nutrient management approach.
- Need for easy on-farm determination of crop and soil N status and the subsequent application of this knowledge into nutrient management decision making.
- Additional mill N status data would aid nutrient management decisions (particularly NIR technologies).
- Other sources of N (e.g., mill mud, trash, N_2 fixation, irrigation water, fallows) need to be quantified and accounted for when calculating N fertiliser application rates.
- Current N fertiliser recommendations need refining (current recommendations are general) – need recommendations that take into account site, soil, variety, and climate.
- Requirement for increased adoption of alternative fertiliser application technologies.
- Information on the cane crop's temporal demand for N lacking in current knowledge base.

Monitoring nitrogen at the mill

I. M. Biggs, B. A. Keating and T. J. Webster
CSIRO Sustainable Ecosystems

Summary

Techniques, such as crop logging, leaf analysis, chlorophyll measurement, petiole sap NO_3^- concentration have been utilised as tools to aid N management in sugarcane agriculture. While these methods offer insight into the crop N status, due to complications in their sampling, analysis and interpretation no one method has provided the grower with reliable rapid information to apply to their crop management. The result is that growers apply additional N fertiliser as an insurance against N-limitation of crop yield. The monitoring of N at the mill project aims to deliver a rapid measurement of the N content of harvested cane arriving at the mill and relate this to crop N status. This can then be fed back to the grower with other mill data. In the light of this information, and incorporating knowledge of the history of the farm and assistance from extension officers, the grower can modify their N fertilising strategies.

The development of a methodology to assess the adequacy of N supply in relation to crop requirements was at the core of this project. These crop requirements are in turn strongly driven by yield potential, N supply from soil and other non-fertiliser sources and N losses, principally via volatilisation, denitrification and leaching. The project built upon a pilot study which showed that the level of nitrogen (in particular N in the form of amino-N) in sugarcane stems at harvest time was responsive to the supply of N the crop experienced during its life cycle. This observation opened up the prospect to monitor N levels in cane delivered to mills, relate this back to specific blocks of cane and use this information to adjust nitrogen management in future seasons.

The relationship between juice amino-N concentration and cane yield has been used to construct diagnostic curves for target juice amino-N values. 'Low' juice amino-N concentrations (< 100 µg amino-N ml^{-1} juice) could indicate N deficiency but there is not yet enough evidence to support this and there appear to be many other factors which can cause low juice amino-N while not impacting on crop yields. 'Target' juice amino-N is a region of 100 to 300 µg amino-N ml^{-1} juice. In this region the relative sugar yield is starting to plateau out and as the juice amino-N concentrations increases over 300 µg amino-N ml^{-1} juice there is no increase in sugar yield, the 'Excess' range.

The major outputs of this project relate to the knowledge necessary to underpin a monitoring technique aimed at assessing the N status of blocks of sugarcane at harvest time. Specific elements of this knowledge include:

(a) That variation in N supply (such as arises from differential N fertilisation practice) has the dominant influence on the amino-N concentration in cane stems at harvest time
(b) That all the varieties tested to date exhibit the phenomenon of elevated amino-N levels in cane stems/juice in response to excess N supply, although there were some varietal differences in the absolute concentrations that are observed under elevated N supply.
(c) That water stress has a modest influence, in the form of elevated amino-N concentrations in crops that have experienced yield-limiting levels of water deficit.
(d) That amino-N levels in cane stems exhibit a modest downward trend as a crop ages, but the age related differences within a typical harvest window are small and of little consequence in terms of interpretation of amino-N monitoring information.

(e) That all factors impinging on amino-N concentrations in cane stems can be interpreted via a conceptual model of demand for N for new growth (biomass) and supply of N from N compounds stored in stem tissues (principally amino-N) and where relevant, continued uptake from soil sources.
(f) A diagnostic relationship between relative sugar yield and amino-N concentrations which can be used to define three zones of N supply, namely excess, target and potentially deficient.

These outputs are complimented by the experiences on-farm, which highlight the generally limited responsiveness of cane and/or sugar yield to small changes in fertiliser N inputs. Earlier reports have noted this phenomenon (eg. Catchpoole and Keating, 1995) and attribute it to the significance of other sources of N such as soil organic matter mineralisation. This suggests that a longer-term view of N fertilisation practice is justified, rather than a short term "fine-tuning" of N rates on a year-by-year basis. The use of an amino-N assay as an indicator of the N status of the preceding crop is complimentary to this longer-term view. Over a period of years the monitoring of N status of crops as they are processed in the mill should enable patterns of N supply to be discerned, and these patterns can be used to make progressive adjustments to N management strategy on a block specific basis.

Industry outcomes as such remain in the future and will be achieved via other projects, in particular CTA045. The results of this project have reinforced the science underpinning the "N at the Mill" concept and justify the efforts in CTA045 to develop a practical method of implementing "N at the Mill" monitoring.

The significance of the project for the Australian sugar industry and wider community is that, assuming the practical monitoring challenges being addressed in CTA045 can be overcome, a "universal" monitoring of the N status of every block or rake of cane grown in the industry is within sight. This would be of immense value in terms of (a) better targeting N fertiliser inputs and in some cases, identifying savings in input costs to growers, (b) in demonstrating to the wider community the industry's intent to apply concepts of benchmarking and best practice, and (c) ultimately reduce N leakage from cane fields thus delivering improved water quality to the groundwaters and surfaces waters that surround the Australian sugar industry.

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An investigation of sugarcane nitrogen physiology: sources, uptake, and metabolism.

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Summary

Research in to the basic physiology of sugarcane metabolism has stalled in recent years compared to the period pre 1970. This is especially evident in nitrogen research, where advances in nitrogen biochemistry and plant nitrogen metabolism have progressed in other plant species but not sugarcane.

Nitrate versus ammonium uptake preference trends were investigated via aerated hydroponic culture. Plant biomass measures showed no clear preference for either nitrogen form. Soluble nitrogen pools in roots, leaves and xylem sap were followed. These showed that under nitrate nutrition, up to 1.0 mM external concentration, Q141 sugarcane was able to carry out the majority of NO_3^- reduction in its roots and transport predominantly assimilated nitrogen as amino acids in the xylem stream. At external nitrate concentrations greater than 1.0 mM, high amounts of nitrate were seen in the xylem sap stream, though nitrate levels in leaves remained relatively low. When supplied with NH_4^+, root assimilation was capable of handling high external concentrations. Only at high external NH_4^+ concentrations did relative ammonium concentrations in the xylem sap start to increase but this was mainly due to a decrease in total amino acid concentration in xylem sap. This was possibly due to a general decrease in plant health at higher external NH_4^+ concentrations. The main amino acid present was found to be asparagine. This was particularly apparent when high-nitrogen fertilised, field-grown sugarcane was compared with low-nitrogen fertilised, field-grown sugarcane. This supports earlier findings of other researchers. The activities of the rate-limiting nitrogen assimilation enzymes, nitrate reductase and glutamine synthetase, were measured in two *Saccharum* species and six *Saccharum* hybrid varieties. Both enzymes had higher activities in leaves compared to roots, though these differences were more pronounced in nitrate reductase compared to glutamine synthetase activity. There were significant differences in the leaf activity of nitrate reductase between the different varieties and species but not in the root activity. Differences between varieties and species in glutamine synthetase activity were not significant for either leaves or roots.

The potential for nitrogen input into sugarcane from atmospheric N_2 via endogenous symbiotic bacteria was investigated by measuring the natural abundance of ^{15}N ($\delta^{15}N$). Reports from overseas claim high potential nitrogen incorporation via this pathway and past studies have confirmed the presence of the N_2-fixing bacteria in Queensland commercial sugarcane plants and sugarcane fields. Overall the $\delta^{15}N$ measures did not show biological N_2 fixation to be a major nitrogen source for Queensland commercial sugarcane. The results did show the influence of high nitrogen fertilisation applications on plant $\delta^{15}N$ values. The drop in $\delta^{15}N$ value following the application of nitrogen fertilisers can potentially result in an incorrect interpretation of the N_2 fixation potential of the plant under investigation. This is due either to partitioning on uptake of nitrogen via the roots or the foliar uptake of volatilised NH_3 from surface applied urea fertilisers.

This study has shown that sugarcane can use either nitrate or ammonium inorganic nitrogen sources but does not rely on N_2 fixation. In aerated, solution cultures, external NH_4^+ had a detrimental effect on plant growth especially at high concentrations and where the plant is

grown for extended periods on these concentrations. This may have implications for the fertilising strategy of single high doses of urea fertilisers to sugarcane fields at a time when growers are attempting to establish a crop at the start of the season. Investigation of both organic and inorganic nitrogen pools in various plant parts indicate a capacity to assimilate the majority of nitrogen taken up by the plant in roots and then the transport of this assimilated nitrogen throughout the plant in predominantly asparagine form. Stem storage of assimilated organic nitrogen is also predominantly as asparagine. These results show the roots of sugarcane plants to have a central place in the assimilation of inorganic nitrogen in sugarcane metabolism. The lack of research in to sugarcane root physiology then is seen as an area requiring readdressing in future sugarcane nitrogen research.

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Contemporary nitrogen balance for mill regions of NSW canelands

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Summary

Nitrogen balances for canelands (Table 1) and for sugar mills (Table 2) of the 3 mill regions of northern NSW (Harwood, Broadwater, Condong) were constructed to guide awareness and sustainable nutrient management in the region. These balances derived from the best available measured data and estimates where experimental data were not available. Estimated inputs to canelands from N_2 fixation, irrigation water and in cane setts were ignored, as were N losses in runoff. It was assumed there was no net change in the soil store of N, as cane-cropping practice had not changed significantly in recent years. For the mills, NO_x emissions from the combustion of bagasse were included but any N in bagasse transferred to Harwood Refinery from the three mills was not considered.

Nitrogen inputs into the NSW canelands was dominated by fertiliser N (92%) followed by filter mud and ash (7%). Other inputs were minor. The major nitrogen outputs from NSW canelands were dominated by millable cane (31%), burning of cane (28%) and denitrification (27%). Minor outputs included soil in millable cane (4%), NH_3 loss from fertiliser N (3%), leaching (4%) and sediment losses (2%). Whatever time period is selected a closed system cannot be obtained for the canelands of NSW due to two year cropping. At the beginning of the time period, outputs are captured without their corresponding inputs and the reverse applies at the end of the time period. Since the area cropped is increasing with time, there are more unmatched inputs that outputs. Thus N inputs exceed outputs for the canelands N balance sheet.

For the sugar mills N enters the mill in the form of millable cane and leaves it mainly in filter mud/fly ash (36%), molasses (34%). NO_x emissions from burning bagasse account for 19% of N outputs followed by N in raw sugar (11%). In contrast to the canelands the sugar mills N budget should balance. However about 13% of N entering the mill fails to appear in the outputs.

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Table 1. N budget for mill areas of NSW. Annual average for the 4 year period from 1992 to 1995.

Budget components	Units	Mill area			NSW	Source
		Harwood	Broadwater	Condong	Total	
Area						
Area under cane	ha	9809	10609	7051	27468	Mill statistics
Area fertiliser	ha	5911	6562	5701	18174	Mill statistics
Inputs						
Fertiliser	t N	1279	1454	1141	3874	Fertiliser Industry Statistics (J. Pulsford, pers. comm.)
Rainfall	t N	12	16	12	39	Avg. annual rainfall and average of N conc. in rainfall (Hart *et al.*, 1987 and Fellar, 1981)
Dry deposition	t N	4	4	3	11	Rate of 0.6 kg N/ha (Denmead *et al.*, 1993) and area fertilised
Filter mud/Fly Ash	t N	97	112	90	300	Mud/ash equivalent to 10% of cane crushed (Peter Nielsen, pers. comm.) & product analysis (G. Barry, pers. comm.)
Total	t N	1392	1586	1246	4224	
Outputs						
Millable cane	t N	307	363	289	959	Mill statistics & analysis of Broadwater millable cane (0.048% N on wet wt basis)
Soil in millable cane	t N	28	61	30	120	Soil content (P. Summerville, Broadwater mill (pers. comm.)) & Soil analysis (G. Barry, pers. comm.)
Burning	t N	281	299	281	862	Mitchell *et al.* (2000)
NH_3 loss (fertiliser)	t N	32	36	29	97	2.5% of fertiliser N. (Biggs *et al.*, 1996)
Sediment	t N	14	25	24	63	Model of Neil and Yu (1995) and average total N in top 10cm soil for each mill area (Barry, pers. comm.)
Leaching	t N	43	47	37	127	Leaching for heavier textured soil at Ripple Creek (Bohl *et al.*, 2000) modified linearly for rainfall
Denitrification		275	303	242	820	Loss of up to 5 kg N/ha per significant rainfall event (Weier *et al.*, 1996) reduced to 25% when cane not fertilised
Total	t N	980	1134	932	3047	

Table 2. N budget for the sugar mills of NSW. Annual average for the 4-year period from 1992 to 1995.

Budget components	Units	Sugar Mill			NSW	Source
		Harwood	Broadwater	Condong	Total	
Inputs						
Millable cane from mill area	t N	307	363	289	959	Mill statistics & Analysis of Broadwater millable cane (0.048% N on wet wt basis)
Intermill cane transfer	t N	7	0	2	9	Mill statistics & Analysis of Broadwater millable cane (0.048% N on wet wt basis)
Total	t N	314	363	291	968	
Outputs						
Raw sugar	t N	31	36	30	96	Mill statistics & 0.04% N in raw sugar (Coale *et al.*, 1993).
Molasses	t N	89	109	84	282	Mill statistics and weekly analysis of molasses at Broadwater in 1999 (0.47% N)(Barry, pers. com.).
Burning bagasse NOx emissions	t N	52	60	48	160	0.28g N/kg wet bagasse based on USEPA (Anon., 1993) and Bilger and Flood (1974) and millable cane contains 28.5% bagasse.
Filter mud/Fly Ash	t N	97	112	90	300	10% of cane crushed & product analysis (0.15% N wet wt) (G. Barry, pers. comm.)
Total	t N	269	317	252	838	

On-farm measurement of deep drainage quality and its implications for the lower Burdekin delta groundwater.

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Summary

The lower Burdekin delta is a prime sugarcane growing region due to plentiful sunlight and water. However, concerns have been raised about the quality of water leaving sugarcane fields (though deep drainage and runoff), the intrusion of sea water into the underlying aquifer, rising water tables and salinity. The Lower Burdekin Initiative (LBI) was established to coordinate a research effort designed to ensure the longer term economic sustainability of the region. Furrow irrigation is the main irrigation method practiced in the Burdekin and better management of furrow irrigation is one method to improve water use efficiency (WUE) and help sustain the groundwater resources.

Deep drainage quality and quantity were investigated using the APSIM-SWIM model. APSIM simulations of the water/nutrient balance for different soil types and farmer management were analysed. APSIM closely simulated measured values for evapotranspiration, runoff, drainage, and yield. Simulated N leaching ranged from 4 to 30 kg NO_3-N ha^{-1}.

The effect of N-fertiliser management on the quality of deep drainage water was investigated by comparing single N-fertiliser application with nine applications via fertigation. With water application constant, the fertigated treatment leached less than 50% of the single N application treatment.

While the initial APSIM simulations are promising, the next season will focus on gaining drainage water quality measurements to verify the model runs. As confidence in the model outcomes increases further scenario analysis will be performed.

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Factors influencing the retention of nitrate at depth

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Summary

This research program was intended to provide an understanding of the mechanisms controlling the retention of nitrate by anion exchange in highly weathered soils from north Queensland. In addition, studies have been undertaken to elucidate the fate of retained nitrate under a range of management conditions; for example, when gypsum is applied to the soil, or following the cessation of farming. These studies are intended to provide a better understanding of any environmental risk posed by the retained nitrate.

Central to this aspect of research is the soil solution, as it is the mobile phase in the system and plays an important role in many aspects of soil chemistry, including the extent to which surfaces develop charge. Ions present in the soil solution exist in equilibrium with a number of soil constituents (i) free, soluble salts, (ii) exchangeable ions and (iii) precipitated minerals. In addition to the relationship between soil solution composition, and exchange site occupancy by ions, the ionic strength and pH of the soil solution influence the magnitude and sign of charge present on variable charge minerals (Uehara and Gillman, 1981). Therefore knowledge of ionic strength, pH and the composition of the soil solution is needed to underpin an understanding of exchange reactions.

The ions present in a soil solution, which is leaching down a profile, are in equilibrium with exchange sites present on the soil surfaces. Thus the monitoring of changes in soil solution concentration provides a non-destructive, indirect method for monitoring changes in exchange concentration. These measurements were made on four columns containing soils sampled from the Johnson River catchment (see V. Rasiah in this appendix).

Soil solution concentrations of cations and anions for four profiles were similar to that previously reported in tropical Australian soils. Soil solution nitrate concentration showed a similar profile distribution to exchangeable nitrate, arising from the equilibrium between the soil solution phase and the exchange phase. The addition of an artificial rainwater solution resulted in the leaching of nitrate and other anions and cations from soil columns. On the basis of this result, it is expected that the exchangeable nitrate will be released slowly over a period of greater than 10 years if no further additions occur. Upon addition of the artificial rainwater the ionic strength of the soil solution decreased, lowering the surface charge density on the variable charge soil components present, thus releasing exchangeable ions into the soil solution. Changes in charge density with pH were also shown to exist, with organic matter dominating the charge development in the surface samples and variable charge minerals becoming less dominant with increasing depth, thus lowering the AEC and increasing the CEC. Competition experiments are ongoing, but results to date indicate that sulfate is the dominant anion while nitrate and chloride have a similar selectivity.

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Yield decline studies – implications for N fertiliser management

A. Garside

Summary

The Sugar Yield Decline Joint Venture (SYDJV) has concentrated on two areas of research relevant to N nutrition in sugarcane production; the potential contribution of N derived from legumes, and the interaction between soil health and N nutrition. Whilst some insight has been gained into both areas, many questions still remain.

Contribution of N from legumes
The tops from a successfully grown crop of soybean can contribute up to 300 kg/ha N, around 60% of which is produced via biological N_2-fixation. Although not yet quantified, it is hypothesized that an additional approximately 30% can also be supplied from the roots of legumes. As a result, plant crops, and potentially some of the subsequent earlier ratoon crops, do not require applications of mineral N fertilizer to obtain acceptable yields. However, the mechanisms underlying the longevity of these benefits are not yet fully understood and the benefits to subsequent ratoon crops are not yet quantifiable.

It is recognized that N is readily leached from the permeable soils present along much of the wet coast and that these losses may be reduced through surface management of the residues of legumes such as soybean. However, sugarcane production in Australia spans many environments and extends over a vast distance. Little is known about the management requirements of soybean residues in the full range of environments that sugarcane is grown. For example, it is not known whether residues would need to be incorporated on the heavier soils or the drier climates typical of some regions.

Whilst legumes may appear to offer many benefits to the sugarcane production cycle, care must be taken to avoid viewing them as the panacea to all nutrient management ills. For example, further research is required before we fully elucidate the mechanisms underlying the acidification and NO_3 leaching known to result from the use of legume fallows.

Interaction between soil health and N nutrition in sugarcane
Many experiments have been conducted during the duration of the SYDJV. In particular two are reported here. Experiments conducted in the Mackey region looked into early plant establishment and found that the difference in the early shoot number of plants was associated with the duration of a break, rather than break type. Also, the differences in early shoot number paralleled differences found in the soil biota. In a rotation experiment located in the Burdekin region, sugarcane crops were grown on areas of land previously under a range of management regimes, including continuous cane production, bare fallow, legumes and pasture. The number of shoots produced at 58 days after planting showed no response to the rate of N applied across all management history treatments. By 80 days after planting there was a large increase in the number of shoots associated with secondary tiller development across all history treatments, although only the continuous cane production management history showed a significant effect to the application of N. In summary, it would appear that the establishment and early growth phase of sugarcane is independent of N, whilst secondary and higher order tillering is highly dependent on N.

The implications of these and other findings suggest that N can be used to mask the adverse effects of poor soil health. Indeed, there is a fair indication that growers are in fact using excessive applications of N-fertilizer to this effect. This body of research suggests that more attention should be paid to attaining good soil health. This will allow a reduction in the amount of N applied and/or more efficient use of N in sugarcane cropping systems. Furthermore, it is hypothesized that good soil health will improve the future resilience of the sugarcane system and this will have implications of both environmental and economic importance.

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Looking for the big issues

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Summary

The uptake of N should be assessed in relation to its utilisation for biomass production and commercial yield. The uptake of N depends on:

- Crop class (Meyer & Wood, 1984; Wood *et al.*, 1996). Find more biomass per kg N in plant crops compared to ratoon crops
- Genotypic differences. General recognition that genotypes require individual N fertilisation strategies to acquire optimal yield and cane quality. 'Vigorous' canes (eg Q138) able to produce yield targets with lower inputs and uptake of N compared to 'less vigorous' canes (eg Q117) (Wood *et al.*, 1996).
- Age and biomass accumulation. There is a period of rapid N accumulation 50 to 120 days after planting or ratoon, which is substantially complete after 180-200 days.

Nitrogen use efficiency (NUE), how is the best way to measure this?
Yield efficiency = Recovery efficiency x utilisation efficiency
(Uptake N/applied N)

Find that sugarcane is an efficient user of acquired N (Yield Efficiency Ratio (YER) = 250-586 kg biomass kg^{-1} N). This is much higher than for other crops, due in part to the longer growth period of sugarcane. Optimal YER is 1.1-1.2 kg N t^{-1} cane, which is close to the Australian recommendation of ~1.4 kg N t^{-1} cane. Brian Keating put forward the figure of 100 t cane ha^{-1} as a target yield or 1 kg N t^{-1} cane.

While sugarcane is an efficient user of acquired N it is not an efficient acquirer of fertiliser N. In Australia find 24-41% recovery of applied fertiliser N in the season of application, compared to 27-36% in South Africa, and 23-40% in Taiwan. The balance of N required by the crop comes from the mineralisation of soil N reserves.

International N fertiliser recommendations show Australia to be higher than most other sugarcane growing countries.

Country	Plant crop (kg N ha^{-1})	Ratoon crop (kg N ha^{-1})	
Australia	80-150	120-250	
Brazil	50	100	Other inputs
South Africa	60-120	100-200	Site dependent
USA - Florida	0-200	0-200	Site dependent
USA – Hawaii	224	224	

Improved knowledge will lead to opportunities for the definition and adoption of fertiliser friendly products with better management of N applications. A greater understanding of the soils will also help in this. Another area where N management can be improved is if realistic

expectations of yield targets are accepted and fertilisers applied accordingly. There is a need to acknowledge and quantitatively define the N sources available to a sugarcane crop. These potential sources include: soil N, legumes, recycled plant material, associative N_2 fixation, irrigation water, organic additives (e.g. biodunder, mill mud), and industrial fertilisers. If the risks were better defined and predicted then growers may not opt for worst-case scenarios in their fertiliser management strategies.

While other yield limiting factors have to be recognised and addressed, opportunities for better N management exist. This can be achieved through continued refinement of fertiliser applications for individual regions and farms, and forecast weather conditions. There exists a potential to reduce potential loss processes through recognition of risks and split N fertiliser applications. Recognition that different varieties should be managed individually will also help.

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Country	Soil category	N Mineralising capacity	Crop class & kg N/ha		Comments
			Plant	Ratoon	
Australia	Fertile	-	80	120	
	General	-	120-150	160-250	Range depends on expected yield
Brazil	General	-	50 + fixation, legumes & wastes	100 + fixation, legumes & wastes	
South Africa	Org. matter <2%	Low	120-140	140-200	Range depends on agro-climatic & moisture environ.
	O.M. 2-4%	Moderate	100-120	140-160	Range "
	O. M. 2-4%	High	80	120	Range "
	O. M. >4%	Very high	60	100	Range "
Florida	Sandy	Low	200	200	Sandy soils -split applications
	O.M.<35%	Moderate	123	123?	Sandy muck soils
	O.M.35-85%	Very high	34	34?	Mucky sand soils
	O.M.>85%	Very high	0	0	Muck soils
Hawaii	General	-	224	224	Mostly as split applications in drip irrigation

Trends in nitrogen fertilizer use in sugarcane

G. Kuhn
Incitec Fertilizers

Summary

The fertilizers used in Australia are mostly imported. Those that are manufactured in Australia are priced at import parity.

In Queensland, fertilizers are imported into Brisbane, Mackay, Townsville and Cairns.

The following table shows the analyses and sources of nitrogen-containing fertilizers commonly used in sugarcane. Nitrogen prices have been indexed against that of urea, as at July 2002. The phosphorus in DAP (Di-ammonium phosphate) has been costed at the same price as that in Triple Superphosphate (TSP). No value has been attributed to the sulfur (S) in Gran-am (granulated ammonium sulfate) or calcium (Ca) in Calcium Ammonium Nitrate (CAN or Cal-am) or TSP.

Analyses, Source and Comparative Price (per kg of N) of Fertilizers used in Sugarcane (July 2002).

Product	% N	% P	% S	% Ca	Source	Nitrogen Price Index
Urea	46				Brisbane, Imports	1.0
Nitram®	34				Newcastle	1.6
Cal-am	27			8	Imports	2.0
Gran-am	20.2		24		Brisbane	2.5
DAP	18	20			Mt Isa	0.2

Note. Nitram is available ex Brisbane only. It is not available ex Mackay, Townsville or Cairns.

Given the distance over which fertilizers are transported, freight is a major component in their landed cost. Not surprisingly, the fertilizers with the highest analyses, i.e. urea (46% N) and DAP (18% N, 20% P) are the most economical and the most widely used. Not only is there less to freight and handle, less fertilizer has to be applied, which speeds up fertilizing operations on farm.

Urea and DAP also have other advantages.

The next most concentrated nitrogen fertilizer, Ammonium nitrate (AN) or Nitram (34% N) is not only more expensive per kg of nitrogen (N), it is classified as a Dangerous Good (Oxidising Agent), which imposes restrictions on how it is stored and handled.

Nitram, which is manufactured at Newcastle, is not available in sufficient quantity to meet the local demand. CAN is imported to make up for this shortfall. In CAN, the ammonium nitrate is diluted with calcium carbonate, so that the end product is not classified as a DG.

AN and CAN are more hygroscopic than urea, which makes them less suitable for use in humid environments and in blends than urea. Use of AN and CAN is largely confined to ratoon cane trash blankets to which nitrogen fertilizer is applied without incorporation (by mechanical means or overhead irrigation). Ammonia volatilisation losses from AN or CAN

are negligible, while they can be substantial from urea in these circumstances if follow-up rain is not received soon after application.

Up to the 1950s, by-product Sulfate of Ammonia was the only nitrogen fertilizer available to canegrowers. These days, Sulfate of Ammonia is rarely used as a straight nitrogen fertilizer on account of its low analysis, high price (per kg of N), and acidifying effect on soil pH. Granulated ammonium sulfate (Gran-am) is mainly used as a blend ingredient to supply the necessary amount of sulfur, the balance of the nitrogen being applied as other products.

DAP rates are likewise dictated by the amount of phosphorus that is required.

Blends are popular in sugarcane as they allow several nutrients to be applied in a single pass, saving time and labour in application. Not all fertilizers are compatible in dry blends. Urea, for example, is compatible with DAP but cannot be mixed with superphosphate.

In the foreseeable future, there will be no major changes in product choice and the market mix. The slow release fertilizers presently available are expensive, and urease and nitrification inhibitors are short-lived in their effects under wet tropical conditions. The factors that have made urea and DAP the preferred ways to apply nitrogen and phosphorus, i.e. high analysis, competitive price, compatibility in blends, will not change.

Nitrogen fertilizer rates in sugarcane in Australia peaked in the 1980s and early 90s, and have fallen somewhat in recent years.

Canegrowers have traditionally erred on the high side with fertilizer rates, in the knowledge that more money can be lost through under-fertilizing than over-fertilizing. For example, an extra 20 kg/ha of nitrogen as urea may cost around $20, but a yield loss of anything more than a tonne of cane per hectare will leave the farmer out of pocket.

The assignment system that operated for many years also encouraged farmers to maximise yields. Canefarmers did not have the option of planting additional land to sugarcane, as most other primary producers had, to increase production. Furthermore, those farmers who consistently grew over-quota cane were in a better position to take advantage of industry expansions when increases in quota were allocated.

In seeking to improve nitrogen fertilizer use efficiency, gains are more likely to come from improvements in the ability to predict appropriate nitrogen application rates, and how and when fertilizers are applied, than from new fertilizer products.

Predictive tools are required that will allow farmers to reduce nitrogen fertilizer rates with confidence, in the knowledge that yield will not be sacrificed. On-line NIR determinations of the nitrogen status of cane delivered to the mills, coupled with existing predictive tools, shows promise of allowing this to happen.

Nitrogen is split-applied in plant cane, but is usually applied in a single pass soon after harvest in ratoons.

Split applications of nitrogen in ratoons may be warranted in soils and environments in which the risk of leaching or denitrification is high. In season diagnostic tools that allow blocks in need of supplementary nitrogen to be identified will be of value.

An integrated strategy to enhance profitability and environmental compliance in the Australian sugar industry

T. Mallawaarachchi
CRC for Sustainable Sugar Production

Summary

As a mature industry, the Australian sugar industry faces a new set of challenges. While striving for profitable production, addressing environmental impacts of industry practices in a manner acceptable to the broader community is a difficult task. Achieving these twin goals in the medium to long term requires strategies and actions to guide optimal resource use. Cleaner production strategies that offer incentives to promote efficient production and minimise net social costs of industry operations are needed. This paper examines how to solve the problem of clean production in cane growing. As a component of a broader study, this paper identifies the essential dimensions for designing a strategy to minimise the total cost of compliance. Policy insights are derived in the light of an integrated economic-environmental analysis applied to nutrient management, employing best available scientific information. The broader study moves away from the traditional reactive management approach towards a strategic preventive regime aimed at developing an integrated safeguard system to achieve triple-bottom-line performance in the industry.

Reports/publications

Development of a potential nitrogen mineralisation index

E.A. Meier and P.J. Thorburn
CSIRO Sustainable Ecosystems

Summary

A potential nitrogen (N) mineralisation index was developed with the objective of investigating at a conceptual level soil nitrogen fertility in response to both climate and crop demand. The index was developed using the Agricultural Production Systems Simulator (APSIM) model's ability to simulate organic matter (OM) decomposition as a function of soil water content and temperature. Different climate and sugarcane crop management scenarios were simulated using 100 years of climate data. For the purposes of index development, soil moisture and temperature output from the simulations was limited to that of the surface layer of soil (20 cm) due to the limited influence of soil lower in the profile upon OM decomposition. Soil temperature and moisture were individually scaled between 0 (complete inhibition of OM decomposition) and 1 (no limitation to OM decomposition) using established relationships within the model. The temperature and moisture factors thus calculated were combined to form an index in which averaged monthly values were calculated to smooth daily fluctuations in soil conditions. The term "potential nitrogen mineralisation index" was coined in recognition of the close relationship between the carbon and nitrogen cycles, and that the index explicitly considers conditions for potential mineralisation only.

Two scenarios were presented for use of the index. The dominant effect of climate in the wet tropics on potential soil N fertility compared to other areas was highlighted by a consistently greater index at Babinda compared to Bundaberg (Fig. 1), despite the impact of different trash management practices. At both locations, indices showed higher values during the summer months in response to higher rainfall and temperatures at this time. Trash removal by burning also lowered the index at both sites due to increased evaporation. However, although trash retention both increased the supply of OM as a potential N source as well as enhancing the conditions under which that N could be released at individual sites, climate had a greater overall effect on potential soil N fertility.

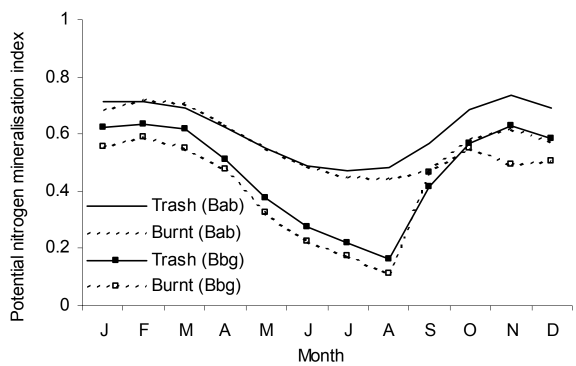

Fig. 1. Effect of trash burning and retention compared to climate on the potential nitrogen mineralisation index of a crop ratooned on 1 September at Babinda (Bab) and Bundaberg (Bbg)

The possibility of enhanced matching of potential soil N supply with crop N demand was explored through comparison of the potential N mineralisation index with a second index of N limitation experienced by the crop. The plant N limitation index was calculated from a combination of factors that weighted the effect of N limitation on photosynthesis and cell expansion, and was similarly scaled 0-1. In this second scenario, the application of the indices to the management practice of split fertilizer application in Babinda was explored (Fig. 2). The effect of splitting the fertilizer application in this simulation was to induce an early N limitation in the crop, but this effect was one of timing only as the maturing crop under both fertiliser treatments showed similar levels of N adequacy. By comparison, the potential N mineralisation indices were highly similar for both fertilizer regimes, indicating that the effect of the crop on soil water content was the same and hence that the crop size was in the long term unaffected by the change in timing of fertilizer application. Consequently, the index was able to show that the split application of N fertiliser on the crop ratooned on 1 September in Babinda did not improve matching of soil supply and crop demand for N compared to the single application.

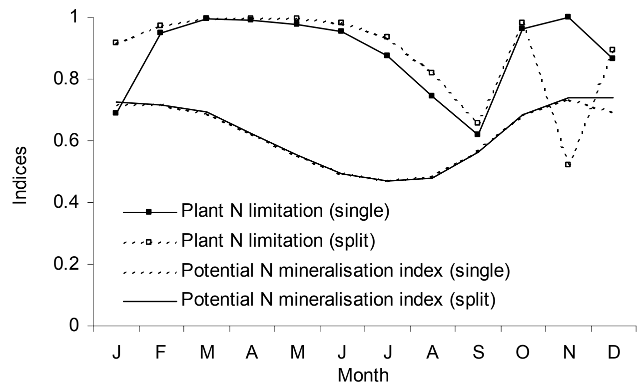

Fig. 2. Potential nitrogen mineralisation and plant nitrogen limitation indices at Babinda under fertiliser applications applied 30 days after ratooning on 1 September (single) or split between time of ratooning and 90 days later (split)

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Publications

Environmental association of nitrate-N retention in deep soil profiles in Queensland wet tropics.

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Background

Nitrogen mass-balance studies for the major cropping systems (sugarcane, banana, and pasture) in the wet-tropical Johnstone River Catchment (JRC) of Far North Queensland (FNQ) have shown that 30 to 50% of the fertiliser-N applied to the ferrosols leached below the crop root-zone (< 0.75 m) as nitrate-N (Moody *et al.,* 1996; Prove and Moody, 1997). The leached nitrate-N might have been adsorbed at anion exchange sites or denitrified or entered streams/rivers, by lateral-flow, and deep groundwater. Though the physical conditions (rainfall, deep profile and conductivity) prevailing in JRC are favourable for both vertical and lateral transport of nitrate, the anion exchange capacity (AEC) and other chemical attributes of the ferrosols on the other hand are conducive for adsorption in soil matrix (Rasiah and Armour, 2001; Gillman and Abel, 1987; Black and Waring, 1976a, 1979). However, the adsorption at AEC may be limited by the maximum potential nitrate-N retention capacity (MPNRC) of the soil. Retention of the nitrate-N leaching below the root-zone may help in reducing the risk of contamination of on- and off-site water bodies. In this context Yellowlees (1991) suggested that nutrient transport from cropland might be associated with Great Barrier Reef (GBR) ecosystem health.

The leaching of 30 to 50% of the applied fertiliser-N below the root-zone is an economic input loss to producers. Quantitative information on nitrate-N accumulation at catchment scale may help in encouraging producer groups to improve N fertiliser management practices. The cropping systems in JRC use relatively large quantities of N fertiliser. The annual application of fertiliser-N in sugarcane ranges from 100 to 200 kg N/ha, 100 to 900 kg N/ha for banana, and 20 to 500 kg N/ha for grazed pasture. In JRC, ≈ 45,000 ha of pasture, 16,000 ha of sugarcane, 7,000 ha of banana, and another 2,000 ha of other fruit crops receive N fertiliser at the aforementioned rates. Thus, in a relatively high N fertiliser input system, quantitative information on nitrate-N retention at catchment scale is required to address, at least partially, the economic, sustainability, and environmental health issues.

Materials and methods

Site description

Thirty soil cores to a depth of 10 to 12 m were taken from the JRC between 1998 and 2000. Twenty-seven out of the 30 cores were from under sugarcane, one each from banana, pasture, and rainforest. The cores under sugarcane were taken from major representative soil types in the catchment, but majority of them were from ferrosols (Pin Gin soil type), which is the predominant soil type in JRC. Cores represented different trash and fertiliser management systems, different slope aspects on the landscape, and vicinity to drainage systems. On average, the sugarcane paddocks received 125 kg N/ha annually during the last15 years.

Soil cores (0.05 m dia.) were taken from the sites at 1.5 m depth increments, using a hydraulic rig. The cores were placed in split PVC tubes, and segmented at 0.5 m depth increments. Sub-samples were taken from each segment immediately after coring and stored at < 4^oC for nitrate-N and ammonium-N determination in the laboratory. The 0.5 m segmented cores were air-dried material and ground to < 2 mm. These samples were analysed for CEC, AEC, pH, EC, Ca^{2+}, Mg^{2+}, K^+, Na^+, soil organic C (SOC), SO_4^{-2} and Cl^- (Rayment and Higginson, 1992).

Results and discussion.

Nitrate-N concentration in the 10 to 12 m profiles under cropping ranged from 0 to 105 mg/kg soil compared with 0 to 0.45 m/kg under rainforest. The typical distribution (Fig.1) indicates that most of the N accumulation was found below the root-zone at depths > 1 m. The N-load in the profiles ranged from 16 kg/ha/10m to 4700 kg/ha/10m. In 12 out of the 30 profiles the N-load was between 1000 to 4700 kg/ha, between 150 to 1000 kg/ha in 10 profiles and <100 kg/ha in 6 profiles compared with 20 kg/ha under rainforest. Exclusive of only at one location, the N-load at the other 29 sites was greater than rainforest. Nitrate-N accumulation occurred under 8 out of the 9 major soil types and under trash burnt and retained systems. Nitrate-N accumulation and retention in JRC seems to be widespread and amounts retained were modified by soil type and probably by landscape position, and proximity to drainage discharge.

Weak but significant positive correlation existed between profile nitrate-N distribution and AEC. The negative association between nitrate-N and CEC or pH, Ca or Mg was weak but significant. The positive association between nitrate-N and Cl was very strong, but no significant association existed nitrate-N and SO_4. Multiple regression analysis indicated that Cl, pH, and electrical conductivity (EC) accounted for 51% of the variability in nitrate-N distribution in soil profiles. Though nitrate adsorption occurred at anion exchange sites, the AEC nevertheless seems not a limiting factor in N-accumulation as suggested by the aforementioned regression. The AEC's non-limiting role was probably masked by the maximum potential nitrate retention capacity (MPNRC) of soil. For example in AJ134 the maximum potential retention capacity was 9.8 t/ha whereas the amount retained was only 0.36 t/ha. On the other hand, in RC135, the PMNRC was 22.7 t/ha, whereas the amount retained was 3.6 t/ha (Fig. 2). In general, the MPNRC in JRC ranged from 6.1 to 31 t N/ha, suggesting the major soils in JRC possess large capacity to adsorb, accumulate and retain nitrate-N. This implies these soils are serving as a temporary nitrate-N filter, thereby reducing the transport of nitrate-N in lateral-flow and/or deep groundwater and denitrification.

Computations show the N-retention at catchment scale averages to ≈ 920 kg N/ha under cropping. We mentioned elsewhere in the text that leaching below the root-zone ranged between 30 to 50% of the applied N, which ranged from 100 to 200 kg N/ha/yr. Assuming low N-input (100 kg N/ha/yr) and minimum leaching (30% of the applied N or 30 kg N/ha/yr), it is evident that it would have taken at least 30 yr for 900 kg/ha of N to accumulate, provided that all the N leached below the root-zone was adsorbed and retained. This is an unlikely scenario. On the other-hand, at least some of the nitrate-N leached below the root-zone might have entered lateral-flow or deep groundwater or denitrified. Further, the potential for adsorption and accumulation to occur is high when the profile is relatively dry. On the other hand, the long saturated hydrological conditions that prevail in JRC during the wet season may favour the nitrate-N in the shallow fluctuating groundwater to be transported in lateral-flow and/or into deep groundwater rather than being adsorbed at AEC. Preliminary results indicate the N-load in the shallow fluctuating groundwater that developed during the wet season ranged from 40 to 110 kg N /ha. The potential for this heavy N-load being discharged into GBR is a serious concern. While the high MPNRC is serving as a temporary filter in reducing the risk, at least partially, of contamination of water bodies, appropriate N fertiliser management practices that will minimize N leaching below the root-zone should be developed.

Summary and implications

- Nitrate-N retention under cropping, more specifically under sugarcane, seems to be widespread in JRC. This suggests that N fertiliser management practices need to be refined to minimise nitrate-N leaching below the root-zone (through slow release N use, legume green manure N).
- The unresolved issue on the fate of large quantities of the un-adsorbed nitrate-N in deep soil profiles need urgent attention in relation to on- and off-site ecosystem environmental health issues. The unaccounted nitrate-N is potentially available for transport in lateral-flow and to deep groundwater.
- **The economics of the N leaching below the root-zone should be addressed with producer groups, to encourage them to switch over to cost-effective N-input practices that will reduce N leaching.**
- **Nitrate-N derived from ammonia-based fertilisers and leached below the root-zone also poses subsoil acidification risk.**

Acknowledgment
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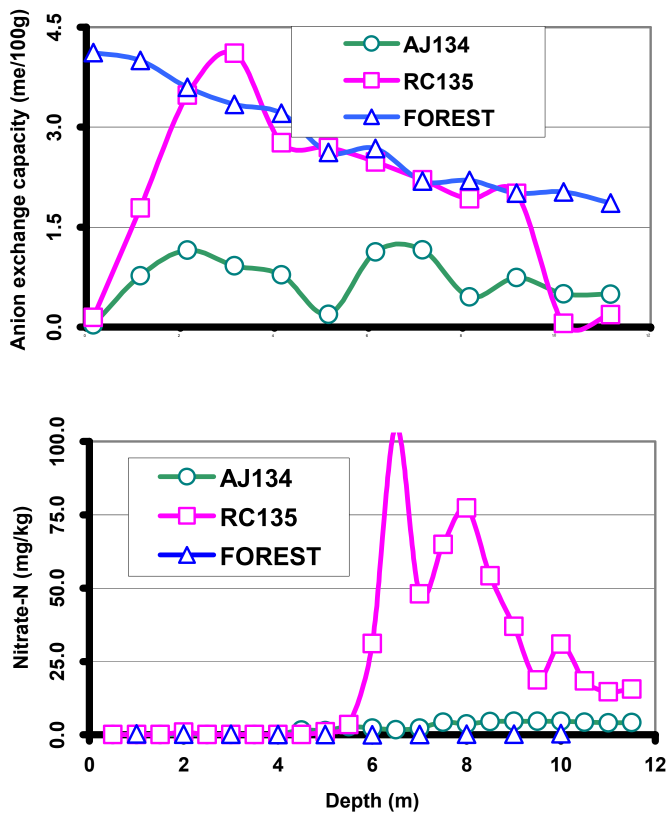

Figure 1. Nitrate-N and anion exchange distribution in typical soil profiles.

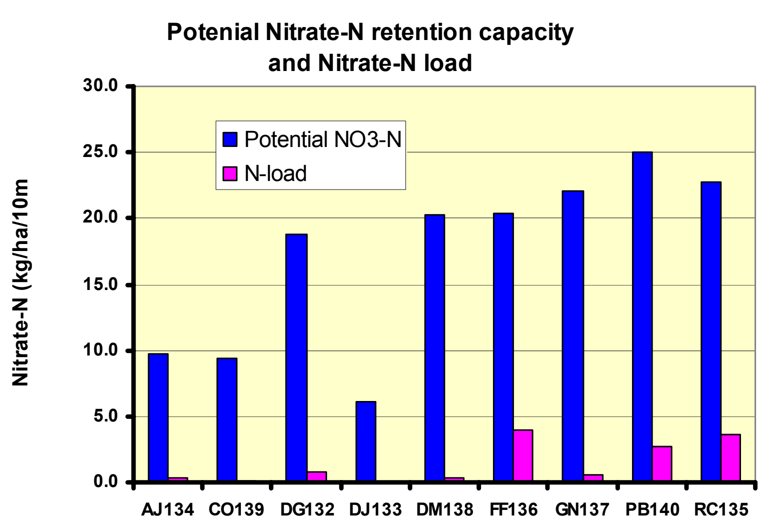

Figure 2. Potential nitrate-N retention capacity and the current N-load in soil profiles.

The “external environment”

G. Rayment
Qld Government, DNR and CRC sugar

Summary

Large reductions in N runoff are sought from all users along the Queensland coast, both agricultural and urban. The instigation by the Federal Government of targets has resulted in decreases of up to 39% in N discharges. Sugarcane in Queensland and NSW occupies only 1.5% of the total land area but is placing pressure on water quality from high N-fertiliser inputs, resulting in sub-soil NO_3^- runoff and leaching. There is sound evidence that NO_3^- concentrations are increasing as water passes through intensive sugarcane growing regions (Hunter et al.).

There is evidence that recommended N-fertiliser rates are 50-75 kg N ha^{-1} too high. In the wet tropics find NO_3^--N is of special concern. Approximately 50% of N (and ~80% P) flux in the Johnstone River is attached to sediments. Annually sediment flows down rivers in Queensland amount 8,800 t (Mulgrave/Tully Rivers 1400 t, Johnstone River 1400 t). Rainforests were shown to contribute ~10% NO_3^--N to these flows, while sugarcane contributes 50% of NO_3^--N. There is a need to consider river flows in drought periods compared to wet periods to investigate dilution effects. Find N:P concentration ratios in drought as high as 10.4:1 as NO_3^- from soil stores is released, while in wet periods this ratio drops to 3.3:1.

Assessment of groundwater quality (in Queensland sugarcane growing regions) showed that only 3% of 1028 bores monitored exceeded drinking water health limits. Not all of these bores were from sugarcane growing regions so some of the N must be coming from other sources. Bohl et al (2000) quantified subsurface N flows from sugarcane fields in the Lower Herbert at 20-30 kg ha^{-1} yr^{-1} lost to groundwater along riparian zones while 0-10 kg ha^{-1} yr^{-1} lost via overland flow. Such high measured and potential N inputs into groundwaters signal community concerns in regard to groundwater quality and these concerns must be addressed.

What are needed are diagnostic tests for growers to monitor their N use. APSIM simulations of yield responses show that 44 kg N ha^{-1} is the optimum N rate. Better statistical fitting of yield x N rate curves to elucidate optimum N recommendation rates will help support these fertiliser recommendations. The development of critical value tests with judgement balanced by economic rationale is required.

A possible way forward is for a small team is to gather N rate trial data from across the sugar industry, where trials have at least five N rates. Use APSIM to fit models to the data designed to define the minimum N non-response yield point. These findings should then be exposed to economic assessment. A follow up workshop will be held to communicate results to the industry.

Reports/publications

References

Bohl et al (2000)
Hunter et al (year)

Herbert nitrogen by variety trials

J. Reghenzani
Bureau of Sugar Experiment Stations

Summary

A survey conducted 5 years ago in the Herbert Region showed over 50% of sugarcane growers were applying N-fertilizer rates far in excess of those recommended. This has implications for both the off-farm environmental effects and the economic sustainability of the industry given the recent downturn in sugar prices. However, it is hypothesized that maximum profit per unit area may be achieved using new varieties of sugarcane and lower rates of N than are currently applied. A series of N x variety trials was conducted in the Herbert District to quantify the N-fertiliser requirements for a range of newly released varieties.

Each year over a 3-year period, a trial was established in either the Lower Herbert, Upper Stone or Mutarnee area. This ensured that a variety of environmental conditions were represented in the trial. The six varieties grown at each site were chosen for their suitability to local conditions, with three varieties being common to all sites. The six rates of N-fertiliser used in the trials (0, 9, 27.5, 83, 150 and 250 kg/ha) were based on a logarithmic progression and selected to elucidate the lower end of the yield x N response curve. The experimental design at each site was identical and consisted of three replicates containing fully factorial treatments of N and site-specific varieties. A variety of agronomic measurements were taken, including soil analysis prior to planting, third leaf samples for N status and critical N levels, yield components (stalk counts, height and diameter), CCS and juice amino N. Analysis concentrated on cane, sugar and CCS response and also included a calculation of gross economic margin for each treatment.

A field day tour was attended by local Herbert growers prior to the commencement of the trials in 1999. The aim of the field day was to demonstrate the advantages of lower N applications in terms of fewer adverse environmental effects, higher CCS, reduced lodging and extraneous matter, and a reduced cost of production. In particular, growers were encouraged to consider evaluating fertilizer response in terms of gross margin ($/ha), rather than tonnes of cane produced per hectare (TCH), with $/ha calculated as:

$$\$/ha = TCH * VC - CHL - CN$$

where VC is the value of the cane per tonne ~ CCS, sugar price, CHL is the cost of harvesting and levies ~ t/ha, and CN is the cost of N fertiliser ~ N rate.

Trial results
Plant crop yield showed that both variety and N had a highly significant effect on tonnes of cane per hectare, tonnes of sugar per hectare, gross margin ($/ha) and foliar N. There were no significant interaction effects. The variety x N data showed a non-linear response of cane yield to N-fertiliser rate, with the maximum yield in some treatments sometimes being obtained at lower rates of N. Moreover, different varieties displayed a different response to the rate of N-fertiliser applied. Given the non-linear response, it was concluded that ANOVA may not be suitable for identifying N * variety effects.

Quite surprisingly, yield was found to respond to very low rates of N-fertilizer (e.g. 9 kg/ha). Additional analysis suggested that endogenous N fixation by the sugarcane plant may have been responsible. This will be investigated further.

There was an increase in the rate of foliar N with increasing rates of N-fertilizer. The current critical N is 1.8%, however this may range from 1.7% to 1.9% for some of the varieties included in the trial.

Across all varieties CCS increased over the period May to August to an average of 16.29 in the plant crop. In general, the effect of N and variety progressively reduced with time, with only the Lower Herbert site displaying a significant linear effect of N on CCS early in the season. The different varieties showed different patterns of CCS accumulation over time and different varieties produced the highest and lowest CCS at each site. There was a negative relationship between CCS and the rate of N applied to the crop. Early measurements of CCS showed that increasing rates of N depressed CCS in all three sites. The average early CCS loss being 0.39 units for each 2 additional bags of urea applied (114 kg N/ha).

When the gross margin was calculated for all treatments, maximum returns were generally found at the lower rates of N. The parabolic relationship between gross margin and rate of N was also variety-specific. In four of the varieties maximum gross margin could be obtained when N was applied at a rate of ≈ 150 kg/ha and for two of the varieties, when N was applied at a rate of < 100 kg/ha. This suggests that N-fertiliser application rates should be tailored to each variety individually and that in many cases N-fertiliser may be reduced below present rates of application in order to gain maximum profit per unit area.

It is intended that research will continue at the present sites and the results will be extended to the wider Herbert region. Future work will aim at identifying those varieties most suited to regional climatic conditions and requiring the lowest rates of N. Growers will continue to be encouraged to use gross margins to evaluate N management options.

Reports/publications

Modifying N Fertiliser Application for GCTB

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[1]Bureau of Sugar Experiment Stations
[2]CSIRO Sustainable Ecosystems

Summary

Research based on field experiments at 5 locations has shown that the GCTB system can gradually increase total soil N, and that this is not necessarily accompanied by increased soil net N mineralisation. Long-term projections based on the field experiments suggested that GCTB would result in small increases in total soil N (4-25% in the soils studied) and increases in net N mineralisation equivalent to the annual trash-N inputs (40-100 kg N/ha/year), and that it could take 10-35 years for the system to approach this new equilibrium. The total N eventually built up under GCTB and the time to equilibrium would depend on trash, climate, soil and management factors which were not specifically identified, but incorporated into a concept called 'soil retentivity'. 'Best bet' recommendations for N fertilisation under GCTB have been developed from this work and presented to industry (see Table). These recommendations assume that crop yield and N losses under GCTB are the same as under a burnt system.

Time since adoption of GCTB	BSES recommendation less …
1-2 crop cycles (5-10 years)	None
2-3 crop cycles (10-15 years)	10-15%
≥4 crop cycles (≥20 years)	20-25%

Reports/publications

N fixation in sugarcane

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Summary

Research undertaken by other sugar producing nations suggests that biological N_2 fixation in sugarcane has the potential to provide up to 72% of the plant's N requirements. However, research conducted in Australia suggests a substantially lower supply of N can be acquired from this process. This research has been conducted to quantify the process of biological fixation and further our understanding of the relationship between bacteria and biological N_2 fixation in sugarcane.

Three species of bacteria responsible for N_2-fixation in sugarcane have been isolated and identified as *Gluconacetobacter diazotrophicus, Herbaspirillum* sp and *Burkholderia* sp. An ecological study of the bacteria suggests that sugarcane plants contain significant populations of N_2-fixing bacteria and that these populations vary between varieties. The addition of inorganic N-fertilizers reduces the populations of bacteria and nitrogenase activity. A factorial experiment showed there to be an interaction between genotype, N_2-fixing bacteria and the environment (N-fertilizer application).

Nitrogenase assays confirmed a variety response to inorganic N application, identified a critical level of N required for plant growth (approximately 120 kg/ha), and a decrease in nitrogenase activity with increasing levels of inorganic N. The populations of bacteria found in aboveground biomass were greater than those present in the root and stubble of sugarcane plants. The presence of bacteria were considered responsible for the "stay green" effect found in sugarcane.

Whilst the amount of N produced by N_2 fixing bacteria has not yet been quantified in this study, further work is proposed. This research will consider genotype N use efficiency and the interaction between N use efficiency and endogenous N fixation. This research will offer significant potential for identifying the balance between the genotype-specific minimum N-fertilizer application rates necessary for plant growth, and the maximum rate of N-fertilizer that will enable maximum biological N_2 fixation.

Reports/publications

An integrated approach to nutrient management in the Australian sugar industry

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Summary

On-farm nutrient management in the Australian sugar industry has in the past been based on general recommendations for use across regions and soils. This approach, although simple to use, does not reflect the large diversity of conditions and soils that exist in the industry. Fertiliser inputs have historically been aimed largely at maximising cane production and achieving short-term economic gain rather than focussing on the long-term health of soils and the production system. More recently it has increasingly been recognised that sustainable sugar production is an essential component of on-farm profitability combining the maintenance of soil fertility and minimisation of off-site effects. It is now agreed that in a sustainable system fertiliser inputs should be used as a means of balancing the total nutrient resource available for optimum sugar production.

Over the past six years, scientists in the Cooperative Research Centre for Sustainable Sugar Production (CRC Sugar), of which BSES and CSR Sugar are participants, have been developing a multi-faceted approach aimed at achieving sustainable nutrient management. An integrated approach to nutrient management has been developed which combines longer-term nutrient management strategies and a number of tactical 'tools' (such as regular soil testing, leaf analysis and some useful 'rules of thumb') into a set of soil and site-specific nutrient recommendations.

In developing this approach, research, development and technology transfer initiatives have focused on five key areas:

- A review of the basis of fertiliser recommendations (Wood *et al.*, 1997; Schroeder *et al.*, 1998a) and fertiliser practise in the Australian industry (Schroeder *et al.*, 1998b; Schroeder *et al.*, 1999).
- Recognition that soil type (based on easy to recognise field properties – colour, texture and position in the landscape (Wood *et al.*, 1997; Bruce, 1999; Schroeder, 1999; Schroeder and Kingston, 2000), and soil chemical properties (Nelson *et al.*, 1999) be used as the basis for varying rates of nutrients applied within the integrated approach.
- Development of soil/site specific fertiliser recommendations based on the re-evaluation of past data and the results of recent field, glasshouse and laboratory investigations (Schroeder and Wood, 2001; Schroeder and Wood, 2002). Simple but useful pedo-transfer functions are also being developed to enable extrapolation of recommendations to the industry as a whole.
- An extensive education program aimed at training extension and advisory staff in the principles of sustainable nutrient management. In excess of 200 people have successfully completed courses presented by CRC Sugar over the past four years.

- Encouraging growers to use soil testing (Schroeder *et al.*, 1998b), leaf analysis for advisory and nutrient trend purposes (Schroeder *et al.*, 1999) and better record keeping for more informed decision-making on-farm.

One example of advances made within the integrated approach to nutrient management is the development of soil specific nitrogen fertiliser recommendations. An important development was the recognition that soils in the Australian sugar industry differ in their ability to mineralise N according to organic matter content (Wood and Stewart, 1985; Schroeder and Wood, 2001). This used in combination with N requirement based on yield target, as suggested by Keating *et al.* (1997) – 1.4 kg N tonne^{-1} on cane up to 100 tonnes ha^{-1} and 1 kg N tonne^{-1} of cane thereafter – provides a logical basis for fine-tuning nitrogen inputs (Table 1).

Table 1. N application rates based on yield target (Keating *et al.*, 1997) and N mineralising potential (Schroeder and Wood, 2001).

Yield target (tonnes cane ha^{-1})	**N requirement (kg N ha^{-1})**
70	100
85	120
100	140
120	160
140	180
Organic C (%)	**Reduction in N application rate (kg ha^{-1})**
<0.8	0
0.8-1.6	20
1.6-2.4	40
>2.4	60

Leaf analysis is an example of one of the tools available to growers in an integrated approach to nutrient management. Used in conjunction with soil analysis it can provide a useful check on the adequacy of fertiliser recommendation and nutrient inputs. It enables nutrient imbalances to be identified and corrected, and trends to be monitored at the block, farm and regional levels.

For the nutrient management system to be fully integrated, nutrient recycling associated with trash retention (Mitchell and Larsen, 2000; Robertson and Thorburn, 2000), nutrient additions due to the use of by-products (Barry, 1999), and nutrient losses associated with certain soil, environmental conditions and fertiliser carriers (Bruce *et al.*, 1999; Reghenzani and Armour, 2002), will also need to be considered and accommodated in the package when and where necessary.

The integrated approach to nutrient management developed to date allows for sufficient flexibility to cover the range of on-farm management styles that exist in the Australian sugar industry. It also allows for future modifications to be easily introduced as further information becomes available. Future work is planned to incorporate the advances into a use-friendly decision support package that will assist growers and their advisors to make informed and logical decisions about nutrient inputs and application rates. Importantly the package will focus on supplying advice to ensure fully balanced nutritional management (covering all essential nutrients). Not only will implementation of this system improve productivity on-farm, but it will also signal the on-going willingness of the sugar industry to be environmentally responsible.

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NUTMAN and maintaining soil fertility

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Bureau of Sugar Experiment Stations

Summary

It has long been suspected that sugarcane growers have been using fertiliser rates in excess of those recommended by BSES. A program of research was designed to (a) quantify the cost of different N-fertiliser rates on productivity per unit area, (b) assess the trend in N-fertiliser use over the period 1996 to 2000, and (c) encourage responsible nutrient management in the sugar industry. The research included field trials, surveys and the development and delivery of a short course on maintaining soil fertility to cane growers.

In order to quantify the importance of N-fertiliser rate on the financial returns to growers, a number of field trials were conducted during the period 1995-2001. The trials were undertaken in sugar growing regions spanning the Queensland coast from Bundaberg to Mossman. The field trials were based on one cane variety and assumed a uniform soil type and commercial harvesting and milling operations across all regions. The fertilizer rates used in the trials were 120, 165 and 220 kg/ha.

Results were similar across all regions and data for Mulgrave are presented as an example. The results showed that in terms of the financial returns to growers (expressed in $ / ha), there was a trend for different fertiliser rates to have little or no effect on the returns obtained from plant crops. However, during ratoon crops, there was a noticeable reduction in tonnage at the lower fertilizer rates, although CCS was higher. In the majority of cases, N-fertilizer rates of between 160-200 kg/ha produced the greatest profits for ratoon crops.

In order to ascertain the actual N-fertiliser rates used by growers, a Grower Fertilizer Survey was conducted in 1996 and again in 2000. On both occasions interviews were conducted with all growers in the Herbert region and representative samples of growers from other districts.
The surveys showed that in 1996 60% of growers were using in excess of 200 kg/ha N on plant crops. By 2000, this figure had halved to approximately 30% of growers. A similar trend was reported for ratoon crops, with 18% of growers using N-fertiliser rates in excess of 200 kg/ha in 1996, reducing to 9% in 2000. It was concluded that the reduction in the rate of N-fertilizer used during this period was, in part, due to the downturn in economic circumstances and the necessity for growers to minimize production costs.

The above findings were considered in the context of maintaining soil fertility and a short course was developed on this theme. The course was presented in the Innisfail, Tully, Ingham and Burdekin regions during 2001 and the focus groups included growers, researchers, resellers and the community. The aims of the course were to: (a) encourage responsible nutrient management in the sugar industry, (b) inform growers that better nutrient management has the potential to increase profitability, reduce production costs and prevent long-term environmental problems, and (c) encourage the industry to act responsibly in order to avoid the imposition of external environmental legislation. In general, it was considered that growers had a good understanding of fertiliser requirements and were keen to know more. It was considered that the trial work conducted in this project provided growers with

some reassurance that a reduction in N-fertilizer rates would not disadvantage them in terms of profitability per unit area of production.

Reports/publications

Reducing nitrogen applications using subsurface trickle irrigation

S. Stacey
Bundaberg Sugar

Summary

The large losses of N to the environment during sugarcane production has prompted many questions regarding current fertiliser practices. In particular, the efficacy of applying a single annual application has attracted much debated. It has been hypothesised that more efficient use of N-fertilizer could be gained through the delivery of smaller and more frequent applications using methods such as fertigation and subsurface trickle irrigation. However, little is known about the response of sugarcane yield to fertigation. This experiment was designed to determine the optimal rate of N required to maximise sugar yield under subsurface trickle irrigation.
The experiment started in 1996 on a site containing three soil types: a Red Kandosol, a Red Dermosol and a Redoxic Hydrosol. The experiment was a randomised complete block design with 3 replicate blocks. Average plot size was 0.2 ha. Variety Q124 was planted throughout the site at a depth of 15cm above the trickle tape. The experiment contained 6 N treatments: no N applied (N0) and five treatments with plant and ratoon application rates of 60 and 80 kg/ha (N80), 90 and 120 kg/ha (N120), 120 and 160 kg/ha (N160), 180 and 240 kg/ha (N240), and 120 and 160 kg/ha (Nstd), respectively. Treatments N80, N120, N160 and N240 had N applied in four equal applications in the form of prilled urea via subsurface fertigation between November and February. Treatment Nstd was included in the experiment to represent current industry standard, with N being applied as a side dressing.

Samples of soil mineral N (SMN) to a depth of 2 m showed 203 kg/ha of SMN at the site prior to planting. This reduced to 159 kg/ha by the time of the plant crop harvest and further reduced to 32 kg/ha by the first ratoon crop harvest in treatments N0, N160 and N240.

There was no yield response in the plant crop to the rate of N applied. However, in ratoon crops there was a trend for increasing yield up to 80 kg/ha N. Beyond this rate, there was no further response to increased rates of N. This would suggest that:

(a) the presence of SMN was sufficient to supply the plant crop without causing a discernible reduction in yield,
(b) 80 kg/ha N fertiliser was sufficient for optimum production of sugarcane in ratoon crops, however, this rate may result in N deficiency in the longer-term,
(c) N applications can be substantially reduced from current industry trends of applications above 160kg/ha when it is applied through trickle tape.

In addition, higher rates of N did not depress CCS.

Whilst this experiment has provided some insight into the potential contribution of fertigation to improving N efficiency, further questions need to be addressed. For example, will 80 kg/ha sustain optimum cane growth in the longer term, and what will be the yield response to even smaller and more frequent applications of N?

Reports/publications

A stocktake of the levels and sources of nitrate in groundwaters associated with sugarcane areas

P.J. Thorburn, J.S. Biggs and K.L. Weier
CSIRO Sustainable Ecosystems

Summary

Water containing high concentrations of nitrate is unfit for human consumption and, if discharging to freshwater or marine habitats, can contribute to algal blooms and eutrophication. Nitrate pollution of groundwaters in coastal northeastern Australia is of particular concern because of its proximity to environmentally sensitive areas (eg, the Great Barrier Reef) and the large number of people (in cities and rural areas) relying on groundwaters for drinking water. This study determined the extent of nitrate contamination in groundwater in this region based on information from 1,454 wells, and examined the likely source of the nitrate by comparing $\delta^{15}N$ values of groundwaters to those of possible industrial or organic nitrogen contaminants. In wells where nitrate concentrations were elevated, and therefore likely to be a result of human activities, concentrations were subsequently monitored to provide an assessment of temporal trends in nitrate concentrations. Overall, groundwaters were relatively free from excessive nitrate contamination, with nitrate concentrations in only 3 % of wells above the maximum permissible limit for drinking water (50 mg/L). However, a further 11 % had elevated nitrate concentrations ($\geq$ 20 mg/L) with the greatest occurrence (14-21 % of wells affected) of elevated nitrate concentrations in the Burdekin, Mackay and Bundaberg areas. These percentages are similar to those found in many other intensive agricultural areas. Nitrate in approximately half of these wells was likely to have come directly from fertiliser. Nitrate in only eight wells was likely to have come from organic sources, such as sewage, septic or feedlot overflows. Nitrate in the remaining wells could not be attributed to a particular source. Thus, improvement of nitrogen fertiliser management practices is a key activity in managing groundwater nitrate concentrations. In the Burdekin and Mackay areas, there was no general trend in groundwater nitrate concentrations over 2 years of monitoring of wells with initial nitrate concentrations > 20 mg/L. However, there was considerable variability within wells between sampling times and further monitoring is required. In Bundaberg, nitrate concentrations in 40 % of wells significantly declined over 6 years (1993-1999) of regular monitoring. The results for this area suggest that nitrogen fertiliser inputs during the monitoring period were not excessive relative to the local aquifer's nitrogen balance. While this project has made considerable progress in characterising the groundwater nitrate situation in sugar producing areas, there still remains considerable knowledge gaps. Notably, the nature of nitrate leaching from sugarcane crops is still poorly understood. The link between fertiliser inputs and leaching is known in a broad sense (i.e., long-term averages). But, there is evidence that it may be more important to manage specific parts of the cropping cycle (e.g., fallow or plant crops). The role of mill by-products, particularly mill mud, in supplementing nitrogen fertiliser and impacting on nitrate leaching is also poorly understood. Likewise, the dynamics of nitrogen in groundwater aquifers is unknown in the Burdekin and Mackay areas. Thus we do not know (1) the time lag between changes in on-farm management and consequent changes in groundwater nitrate concentrations, (2) the "catchment area" for nitrate in the affected areas, or (3) the interaction between nitrate-rich groundwater and freshwater or marine environments. Future work will be required to address these important issues, and devise

high quality "best management" practices for minimising the impact of sugar production on groundwater nitrate, and the human and natural environment.

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Modelling the impact of sugarcane trash management on soil nitrogen management

P.J. Thorburn, J.S. Biggs and H.L. Horan
CSIRO Sustainable Ecosystems

Summary

Sugarcane crop residues (known as trash blankets) contain considerable quantities of dry matter, nitrogen (N) and other nutrients (13, 1, 3). When sugarcane is burnt either pre- and/or post-harvest, 70–95 % of the dry matter and N are lost from the system (3). Thus harvesting cane green and retaining the trash blanket has a considerable effect on organic matter conservation N fertility of the soil, and also enhances infiltration and suppresses evaporation of water. It has been suggested that N fertiliser application rates could be reduced following the adoption of trash blanketing (13, 5).

Field experiments comparing trash blanketed and burnt treatments generally show that increases in soil organic matter and total N in trash blanketed treatments occur with trash retention, but these effects are small and confined to the surface soil (8, 12). However, microbial activity is clearly stimulated by trash blanketing (6, 2, 5) and crop uptake of N from a trash blanket in the season following trash deposition is negligible due to the immobilisation of N in the soil organic matter (4). From these results it is difficult to predict the impact of trash blanketing on cane production and N fertiliser management.

The APSIM-Sugarcane cropping systems can simulate yields and soil organic C in response to trash management (9, 11) and different rates of N fertiliser application (7). Thus, it has potential to provide insights into the long-term fate of N contained in trash and the N fertiliser management implications of trash retention. In this paper we use the model to examine how trash retention influences the amount of N fertiliser required for maximum yield in Australian sugarcane systems and the time scales over which N cycling (and N fertiliser requirements) come into equilibrium.

Simulations were preformed of different rates of applied N fertiliser to each of two trash management systems (trash burnt and trash retained at harvest) at sites in three districts on the Queensland coast (Bundaberg, Mackay and Ingham). The APSIM model was configured and parameterised as done by Thorburn et al (9, 10, 11). Soil model parameters were based on measurements of N, C and soil water made at sites in Bundaberg (10), Mackay (11) and Ingham (9). Parameter values for the variety Q124 were used in the sugarcane model. After harvest of each crop, trash weights were reduced by 95 % (3) in the burnt treatment to represent pre- and post-harvest trash burning.

The simulations were conducted over 50 years (1950-2000) with 50, 100, 150, 200 and 300 kg/ha of N fertiliser applied to ratoon crops, with plant crops receiving 75 % of that applied to the ratoon crops. In all there were eight cropping cycles simulated with each cropping cycle composed of a 15-month plant crop (planted in May) followed by four 13 month ratoon crops.

The simulated response of cane yield to N fertiliser application varied markedly between each crop in each of the three regions (data not shown) in response to climatic differences over the different growing seasons. However, the general response was for maximum yields

to be greater under trash retention, and these yields to be achieved at similar or greater rates of N fertiliser application to those in the burnt system (Figure 1). Similar responses have been found in more detailed simulation studies in South Africa (7).

The time to equilibrium between the supply of N from the decomposing trash blanket and the fertiliser N requirement of the crop is difficult to ascertain because of the large variation in yields between crops in response to climatic variation. However at all sites, yields tended to be suppressed by trash retention under low rates (e.g. 50 and 100 kg/ha) of N fertiliser for approximately the first 10-20 crops. This suppression is due to the immobilisation of N by the decomposing trash blankets (4), which are generally of high C:N ratio (e.g., > 80; 13, 5). In later crops the response to trash retention at these low N rates was generally positive, but the overall response was not great (Figure 1). With an application of at least 150 kg/ha of N, there was a positive yield response to trash retention in the majority of crops for Ingham and Mackay, with very little evidence of yield suppression in early crops. A similar situation did not occur for Bundaberg until application of at least 200 kg/ha of N.

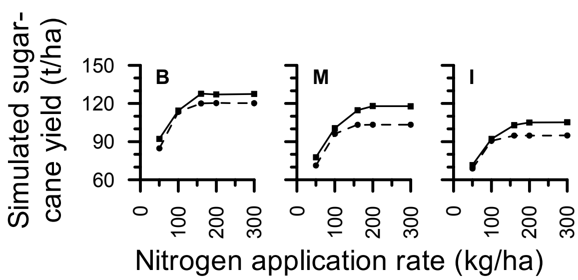

Figure 1. Mean simulated response of sugarcane yields to different rates of applied N where crop residue is retained (squares, solid lines) or removed (circles, dashed lines) at three sites: Bundaberg (B), Mackay (M) and Ingham (I). Note; the data are means for the period 1970-2000. Earlier data were excluded to avoid bias from pre-equilibrium conditions.

It has been assumed that because N is "recycled" through trash blanketing that N fertiliser application rates can be decreased following the adoption of trash blanketing (13, 5). The results of simulations conducted in this study indicate that this may not be the case. The N "recycled" in a trash blanket system may be required for crops to reach higher potential yields in that system, with these increased potential yields a result of improved moisture conservation. Thus, the N fertiliser applications appropriate for a burnt system should be maintained following the adoption of trash blanketing for maximum sugarcane production (Figure 1). Reductions in N application rates, particularly at or soon after the adoption of trash blanketing, are likely to have deleterious effects on sugarcane production due to the immobilisation "demand" of the trash blanket.

Obviously the moisture conservation benefits of trash retention would be minimal in a fully irrigated environment, and fully irrigated trash retained systems may require lower applications of N (and irrigation water) when an N-cycling equilibrium has been reached. Further investigations are required into these systems. Another factor that has not been considered in this study are the comparative losses of N to the environment in trash-burnt or –retained systems. Further work is also required to understand the interactions between trash retention, soil N and water cycling, and N losses.

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Economics of non point source pollution and nutrient management

E. Qureshi

Summary

There is a growing community concern about water quality as a result of harmful consequences of agricultural production. Fertiliser, in particular nitrogen and phosphorous not used by the crop, attach to sediments and can pollute groundwater and surface water. While this incurs unnecessary costs to landholders, the cost of environmental damage is borne by the wider community. Economics provides a method of analysis that helps choose among alternatives by allocating scarce resources among competing alternatives. Economics can play an important role in identifying strategies that can internalise the costs borne by the society, and ensure that appropriate environmental standards are achieved at least cost. It can also help resource managers and policy makers in implementing appropriate policy options by examining their environmental, social and economic impacts.

This work develops the basic economic concepts that are essential for deriving optimal allocation of resources including marginal cost and marginal benefits of production as we as the difference between maximum yield and maximum profit. The concept of externalities is introduced to distinguish marginal private costs and marginal social costs and a distinction is made between private and social optimal level of production and pollution. An example of profit and leaching losses due to nitrogen application is used to demonstrate the tradeoffs between profit and contamination. It is argued that pollution occurs at inefficiently high levels of production because the growers do not consider pollution costs (imposed on others, i.e. society) in their decision making process. Choice of an instrument and economic instruments available to change the growers' behaviour (or to internalise the externalities) are discussed along with the role of these instruments in irrigation technology adoption behaviour.

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