Using the soil as a buffer allows more sustainable management of nitrogen in sugarcane production

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Abstract
Nitrogen (N) fertiliser management is increasingly important in sugarcane as imperatives to reduce environmental impacts of N escalate. In this paper we report testing of a new concept for N management in sugarcane, the N Replacement system. This system relies on soil N reserves to buffer differences in crop N needs and N fertiliser supply in individual crops, and so aligns N applications with *actual* cane production rather than *potential* production. In five experiments conducted over four crops, total sugar yields in the N Replacement treatment were similar to those achieved with the farmers' conventional N management even though average N applications were 36% lower. N lost to the environment was estimated to be reduced by 62%. The results imply that N buffering was adequate in the soils which spanned a wide range of carbon (C) levels (0.8-2.1%). We conclude that the ecologically-based N Replacement system may deliver superior environmental outcomes without significantly reducing production for sugarcane, and other semi-perennial crops in the tropics and subtropics.

Key Words
Immobilisation, Mineralisation, Environmental impact, Organic matter, N Replacement.

Introduction

Controlling N losses from cropping systems is important because of the impacts of N on human health and ecosystems (predominantly as NO_3^-) and its role in contributing to climate change (through N_2O emissions). These are challenging issues for sugarcane, which requires high applications of N fertiliser for commercial production (Roy *et al.* 2006) and is increasingly used for biofuels (Macedo *et al.* 2008). It is possible that traditional N fertiliser recommendations for sugarcane will not meet these challenges. Recommendations in many countries are based on potential or expected crop yields (e.g. Schroeder *et al.* 2006) and so result in over-application of N is the common situation, as *actual* production is often less than potential.

Sugarcane is a deep rooting semi-perennial crop (i.e. it is allowed to ratoon a number of times after annual harvesting) grown in subtropical and tropical areas where soil N cycling is often rapid. This rapid N cycling allows large amounts of N to be immobilised and subsequently mineralised over the long term (Ng Kee Kwong *et al.* 1984; Meier *et al.* 2006), where it can be efficiently retrieved by the deep root system (Thorburn *et al.* 2003). In effect, the soil may be able to act as a good buffer for N – absorbing N fertiliser additions by immobilisation and subsequently making this N available through mineralisation. If so, sugarcane may be well suited to an ecologically-based approach to N management (Drinkwater and Snapp 2007), where N fertiliser applications are geared to maintaining soil N stores. These soil N stores can then provide the crop's N needs, rather than more directly 'feeding' the crop with fertiliser N.

Such an ecologically based N management system, known as N Replacement, was proposed for sugarcane by Thorburn *et al.* (2004). They linked N applications to crop N off-take in the previous crop. The assumption was that, if the yield of the coming crop was larger than that of the previous crop, additional N requirements would be supplied from soil N stores. Conversely, these N stores would be 'topped up' when a small crop followed a large one. They suggested a potential saving in N fertiliser up to 40% compared with common N fertiliser applications in Australia, and consequently N lost to the environment may be reduced by 90%. In this paper we report on five field experiments established to test this concept over four crops in the diverse soils and climates of the Australian sugarcane industry.

Methods

Experiments were established on commercial farms in 2003 or 2004 to compare the N Replacement (NR) system with the farmers' conventional N fertiliser management (NF) over four crops. Farms were located in the wet tropics around Cairns (~16°S - Mulgrave and Innisfail, Table 1), the dry tropics near Townsville (~19°S - Burdekin), and the sub-tropics at Bundaberg (~25°S to 28°S). Crops at sites BK-1, BK-2 and BU-1 were irrigated and the others rainfed. Crops at sites BK-1 and BK-2 were burnt at harvest. Others were harvested unburnt with all residues retained on the soil surface. The amount of N fertiliser (kg/ha) applied in the NR approach was targeted to be 1 kg N/t cane harvested in the previous crop where residues were retained and 1.3 kg N/t cane where the crop was burnt (Thorburn *et al.* 2004, 2010). This is less than current recommendations, either in Australia (Schroeder *et al.* 2006) or more generally (Roy *et al.* 2006).

Table 1. Details of soils at the experimental sites and the average N fertiliser applied and N lost to the environment (both kg/ha/crop) in different treatments (NR-N Replacement; NF-N Farm).

Site code	Region	Soil texture 0-0.6 m	Soil C 0-0.3 m (%)	Soil C/N 0-0.3 m	N applied		Environmental losses of N	
					NR	NF	NR	NF
BK-1	Burdekin	sandy clay loam	0.77	14.2	159 [a]	318 [a]	2	194
BK-2	Burdekin	sandy clay loam	0.84	15.3	217 [a]	326 [a]	107	231
BU-1	Bundaberg	sandy loam to sandy light clay	0.75	14.8	95	140	45	93
IN-3	Innisfail	light clay	2.16	16.6	117	144	74	87
ML-1	Mulgrave	sandy clay	1.17	16.9	135	180	69	123

[a] N applications include substantial N applied through nitrate contained in irrigation water.

The sites had been managed using the farmers' normal practice prior to the experiments, except at BU-1, where the experiment was established in the first ratoon crop of a pre-existing N rate experiment (Thorburn *et al.* 2003). In this experiment the NR treatment was applied to plots that had received **no** N fertiliser in the preceding plant crop (yielding 83 t/ha). The experiments were managed by the farmers using their normal practice so that yields were representative of commercial production, not research station experiments.

The experimental layout at each farm was decided jointly with collaborating farmer groups. Three experiments (BK-1, BK-2 and BU-1) were established as randomised designs with treatments replicated, while the other two were non-replicated demonstration experiments. Plots were large enough to allow harvested cane yield, cane sugar content and, hence, sugar yield to be determined from commercial harvesting and milling operations. The amount of N lost to the environment over the whole experiment was estimated for each treatment as the difference between N applied and that (1) lost through crop harvest and, where applicable, residue burning, and (2) change in soil mineral N (assuming no change in organic N). The amount of N in the crop and trash was determined from mass and N concentration in the harvested cane and residue measured at harvest. Soil N was measured (to 2 m) at the start of the experiments and after harvest. In 2007, soils (0-0.3 m) were also analysed for total C and 'labile C' (i.e. C oxidised by 3.33 mM $KMnO_4$).

Results

Across the five sites, sugar yields were lower in the NR treatment than the NF in the first and second crops, but higher in the third and fourth crops (Figure 1). However, yields increased in the NR treatment relative to NF in subsequent crops so that cumulative sugar yields were similar in the two treatments over the four crops (Figure 2), and with an average improvement across all sites of 0.16 t/ha in the NR treatment. Yields in the NR treatment were achieved at substantially lower N inputs (an average of 80 kg/ha/crop; Table 1) than the NF treatment and so the N use efficiency in the NR treatment (i.e. slopes of the lines in Figure 2) was higher.

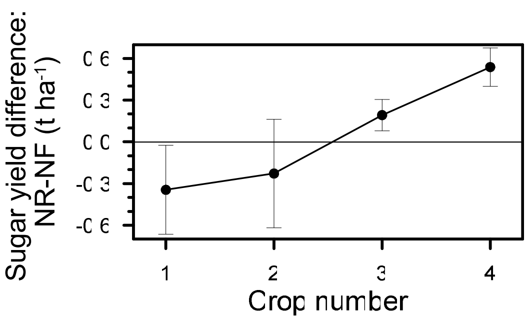

Figure 1. Difference in sugar yield between the NR and NF treatments for each crop harvested averaged across the five experiments. Error bars indicate ± 1 standard error.

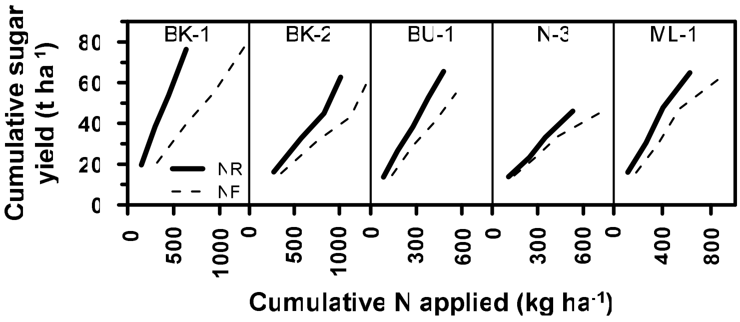

Figure 2. Cumulative sugar yields as a function of cumulative N fertiliser applications for the NR and NF treatments at each experiment.

Despite the lower N inputs and similar sugar production in the NR treatments, there was no evidence of soil organic matter rundown. Total C and labile C (expressed either per mass of soil or as a fraction of total C) were similar in both treatments (Table 2). Similarly, there was generally no evidence that soil mineral N (SMN) was rundown (to 2 m soil depth) through time (e.g. Site BU-1, Figure 3), except at site IN-3 (Figure 3). There, SMN decreased by 18.3 kg/ha/crop (i.e. the slope of the line in Figure 3) during the experiment in the NR treatment compared with an average increase of 0.5 kg/ha/crop in the NF treatment. Hence there was a relative reduction in SMN of 18.8 kg/ha/crop in the NR treatment relative to NF. At the other sites, SMN decreased in the NR treatment relative to NF by 2.1 and 2.5 kg/ha/crop at the BU-1 and ML-1 sites, respectively, and increased by up to 44 kg/ha/crop at sites BK-1 and BK-2.

Table 2. Average total C (TC), labile C (LC) and LC as a proportion of TC (LC/TC) in soils sampled from sites at harvest in 2007 for the NR and NF treatments. Standard errors are shown in parenthesis.

	Total C (%)	Labile C (%)	LC/TC
NR	1.4 (0.2)	0.11 (0.01)	0.073 (0.004)
NF	1.2 (0.1)	0.08 (0.01)	0.071 (0.004)

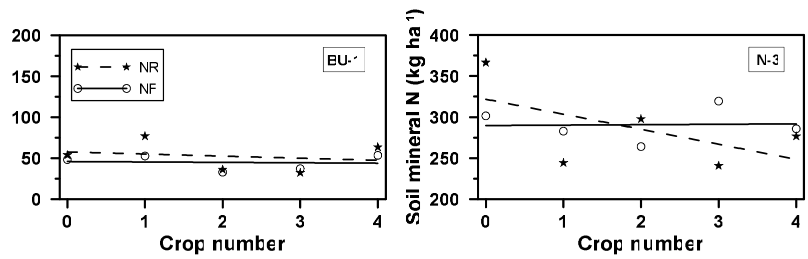

Figure 3. Soil mineral N (0.2 m depth) sampled at the start of the experiment (crop number = 0) and at harvest of the four successive crops. The legend applies to both panels.

N lost to the environment was between 87 and 231 (mean 146) kg/ha/crop in the NF treatment, but was reduced to between 2 and 107 (mean 59) kg/ha/crop in the NR treatment (Table 1). The highest losses occurred at sites BK-1 and BK-2 where substantial N was applied to the plots in irrigation water.

Discussion

Our results confirm that the N replacement concept has promise for meeting the productivity needs of N fertiliser management in sugarcane, while reducing potential environmental losses of N, as proposed by Thorburn *et al.* (2004). Total sugar production during the experiments was maintained (Figure 2) at substantially (36%) reduced N fertiliser inputs (Table 1). This result would increase farm profitability (through lowering input costs) and maintain sugar mill region profitability (which relies on total sugar production). The trend for yields to increase in the NR relative to the NF treatment over successive crops (Figure 1), which may be due to lower N applications enhancing root activity (Thorburn *et al.* 2003), suggest there is potential for the NR system to further enhance profitability of the sugar industry through time. The lower fertiliser inputs resulted in a >50 % decrease in the amount of N lost to the environment (Table 1). This decrease was not as great as that predicted by Thorburn *et al.* (2004) because N contained in sugarcane in the experiments was lower than predicted (Thorburn *et al.* 2010), allowing more N to be lost to the environment. While we have not assessed the relative magnitude of the different N loss pathways to the environment (e.g., denitrification, leaching or runoff), a 50 % reduction in losses for any or all pathways would greatly enhance the sustainability of sugarcane production.

The results of these experiments also suggest that the philosophy of drawing on N reserves in the soil to buffer some of the short term differences between crop N needs and N supply from fertiliser is applicable in sugarcane production. This is a more complete view of soil N processes than used in some other recommendation systems, which focus only on N mineralisation (Schroeder *et al.* 2006). Buffering of N inputs to, and outputs from soils may be greater in soils with higher organic matter, so having greater capacity to immobilise and mineralise N. However, there was no difference in the relative performance of the NR treatment at sites with soils of low organic matter (e.g. BU-1) and those with substantially higher organic matter (IN-3), suggesting that high organic matter levels are not necessary to provide sufficient buffering for the NR system to be successful. In fact, the low organic matter soil at BU-1 was able to overcome the deliberate rundown of N in the NR plots prior to the experiment, resulting in similar total production in both N treatments.

There are several possible drivers for over-application of N to sugarcane. One is the concept of aligning fertiliser applications to potential yields (e.g. Meyer and Wood 1994; Schroeder *et al.* 2006). This clearly wastes fertiliser when actual yields do not realise their potential. It also overlooks the potential for stores of N in the soil to provide additional N to the crop over the short-term (e.g. a single crop). Yields in a crop can be 20-30% greater than those expected without being limited by N supply (Thorburn *et al.* 2010). Another driver of high N applications in sugarcane is the perception of high losses of N to the environment caused by high rainfall or irrigation. Our results in the wet tropics (Site IN-3, average rainfall of 3,600 mm/yr) and fully irrigated crops in the Burdekin show that while losses of N can be substantial (Table 1), they can be lowered considerably by reducing N rates. Hence high losses are more due to the high amounts of N applied in farmers' conventional practices than the environment itself. Thus a more ecologically-based approach to N management, focussing more on having fertiliser applications maintaining soil N stores (Drinkwater and Snapp 2007), may be the basis for sustainable management of N fertiliser in tropical and subtropical perennial and semi-perennial crops such as sugarcane. Further work to define the amount of N that needs to be replaced after each crop in the NR system would be valuable.

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References
Drinkwater LE, Snapp SS (2007) Nutrients in agroecosystems-Rethinking the management paradigm. *Advances in Agronomy* **92**, 163-186.
Macedo IC, Seabra JEA, Silva JEAR (2008) Greenhouse gas emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/06 averages. *Biomass and Bioenergy* **32**, 582-595.
Meier EA, Thorburn PJ, Wegener MK, Basford KE (2006) The availability of nitrogen from sugarcane trash on soils in the wet tropics of North Queensland. *Nutrient Cycling in Agroecosystems* **75**, 101-114.
Meyer JH, Wood RA (1994) Nitrogen management of sugar cane in South Africa. *Proceedings of the Australian Society of Sugar Cane Technologists* **15**, 93-104
Ng Kee Kwong KF, Deville J, Cavalot PC, Riviere V (1986) Biological immobilization of fertilizer nitrogen in humid tropical soils of Mauritius. *Soil Science* **141**, 195-199.
Roy RN, Finck A, Blair GJ, Tandon HLS (2006) 'Plant nutrition for food security: A guide for integrated nutrient management'. FAO Fertilizer and Plant Nutrition Bulletin 16 (FAO, Rome).
Schroeder BL, Wood AW, Moody PW, Panitz JH, Sluggett RJ, Salter B (2006) Delivering nutrient management guidelines to growers in the central region of the Australian sugar industry. *Proceedings of the Australian Society of Sugar Cane Technologists* **28,** 142-154.
Thorburn PJ, Horan HL, Biggs IM, Park SE (2004) Which is the most important crop when assessing nitrogen applications – the next or the last? *Proceedings of the South African Sugar Technologists Association* **78**, 383–391.
Thorburn PJ, Dart IK, Biggs IM, Baillie CP, Smith MA, Keating BA (2003) The fate of nitrogen applied to sugarcane by trickle irrigation. *Irrigation Science* **22**, 201-209.
Thorburn PJ, Webster AJ, Biggs JS, Biggs IM (2010) A new way to determine nitrogen fertiliser requirements of sugarcane crops to meet global environmental challenges. *Plant and Soil*, in press.