DRIP IRRIGATED SUGARCANE RESPONSE TO NITROGEN APPLIED IN DRY FORM AND BY FERTIGATION IN LATE AND EARLY SEASON CYCLES

WEIGEL A[1], MEYER JH[2], MOODLEY S[1], TONSING W[1], NIXON DJ[3] and VAN DEN BERG M[1]

[1]*South African Sugarcane Research Institute, Private Bag X02 Mount Edgecombe, 4300, South Africa*
[2]*Agricultural Consultant, jmeyer@netactive.co.za*
[3]*Booker Tate Limited, Masters Court, Church Road, Thame, Oxon, OX9 3FA, UK*
annett.weigel@sugar.org.za suran.moodley@sugar.org.za werner.tonsing@sugar.org.za
maurits.vandenberg@sugar.org.za david.nixon@booker-tate.co.uk

Abstract

Two identical subsurface drip irrigated experiments were established at the SASRI research farm in Mpumalanga province, on a shallow Shortlands form soil (30% clay), with a medium N mineralisation potential. The first trial was planted in October 2002 (late season cycle) and the second in May 2003 (early season cycle) The objectives were to measure the benefits of fertigation by comparing sugarcane yield responses to a range of nitrogen rates applied in standard dry form (solid) and by fertigation, to develop best management practice guidelines. N32 and grown on a 12-month cropping cycle receiving nil, 48, 96 and 144 kg N/ha (solid and by fertigation). All treatments were applied as two equal splits in the plant crop, and four equal splits at bi-monthly intervals in the ratoon crops. Yield and quality parameters, the N uptake of the above-ground parts of the crop were measured and used to determine nitrogen balances. The improved nitrogen saving through fertigation and better recovery of sucrose were more marked in the early than the late season cycle crops. The most likely reasons for the improved N use efficiency are discussed.

Keywords: sugarcane, fertigation, nutrition, nitrogen, nitrogen use efficiency, nitrogen balances

Introduction

Improved fertiliser management is not only an economic issue, but has been recognised as one of the major precautions for sustainable and ecologically sound agriculture. Fertiliser nitrogen (N) in particular, when not applied in a balanced way, is a potential source of air and groundwater pollution. To prevent losses from leaching, volatilisation or denitrification, the N application should as closely as possible be synchronised with the amount and time of crop demand.

The increasing popularity of drip irrigation in southern African sugar industries presents opportunities for improved fertiliser management. Drip irrigation is considered efficient as it facilitates more accurate and flexible application of soluble fertilisers through the irrigation system (fertigation), leading to greater N fertiliser efficiency compared with conventional solid fertiliser application. This has been demonstrated for sugarcane in Mauritius (Ng Kee Kwong *et al*., 1999) and Australia (Dart *et al*., 2000; Thorburn *et al*., 2003), where results indicated increases in N fertiliser use efficiency of up to 30%. Work was done by Butler *et al*. (2002) to compare different application schemes, i.e. growth curve and various split design applications. The results showed that splitting the nitrogen evenly over the first four months of crop development was the most efficient.

In 2002/03, a project was initiated at the South African Sugarcane Research Institute (SASRI) research farm at Komatipoort in the northern province of Mpumalanga, to measure the benefits of fertigation in terms of yield and nitrogen use. The purpose of the project was to develop best management practice guidelines for N application by fertigation for use in the northern irrigated areas of the sugar industry. Specific objectives included:

- Comparison of yield responses to N applied by fertigation and solid carriers.
- Comparison of responses to applied N in early and late season cycles,
- Estimation and comparison of N use efficiency between the two methods of application.

Material and Methods

Both the early (May 2003) and late (October 2002) season experiments were established as plant crops on a virgin site. Average annual rainfall at the site over the past seven years (2001-2007) was 596 mm, and mean annual temperature was 23.2°C. The soil at the site was identified as a shallow red blocky clay of the Shortlands form (±500 mm depth), and was classified by near-infrared (NIR) spectroscopy as a Category 2 N mineralisation potential soil, representing a medium rate of N release in the topsoil of ±60 kg/ha/year. This classification corresponds well with the analysed soil organic matter content of 4.0% and medium clay content of 30%. The standard SASRI Fertiliser Advisory Service (FAS) N recommendation for this Shortlands soil is 120 kg N/ha.

Treatments in both the solid and fertigated experiments consisted of an untreated control, a low application rate of 48 kg N/ha, a medium rate of 96 kg N/ha and a high rate of 144 kg N/ha. In the plant crop, N was applied as urea in the solid treatments, and as dissolved urea in the fertigated treatments In the ratoon crops, N was applied in the form of lime ammonium nitrate (LAN), solid and in solution. The treatments were replicated six times in a randomised block design with a net plot size of 7 x 5.4 m. Variety N32 was grown on a 12-month cropping cycle. Phosphorus and potassium were applied annually in accordance with FAS recommendations.

In all treatments, N was applied in two (plant crop) or four (ratoon crops) equal splits at bi-monthly (plant crop) and monthly intervals (ratoon crops) after planting or harvesting. The plant crop application was delayed by four weeks to allow for germination. In the early season experiment, the nitrogen splits were applied in Jul/Sept for the plant crop, and in Jul/Aug/Sep/Oct for the ratoon crops. In the late season experiment, the application schedule was Dec/Mar and Nov/Dec/Jan/Feb for the plant and ratoon crops, respectively.

To allow for N application as fertigation, the main irrigation pipe was split with a manifold at the field edge, so that each plot had an in-line control valve and flow meter. The fertiliser was injected into the fertigation system using an injection pump. A pulsating device with a flow regulator ensured slow and even distribution of the fertiliser throughout each plot. This device was provided with a digital counter, which gave the exact amount of fertiliser flowing through.

Irrigation was scheduled according to the CANESIM model (Singels, 2007) in terms of evaporative demand and rainfall. Table 1 gives the amounts of irrigation applied and rainfall received for all cropping periods in the late and early season fertigation experiments. The irrigation rate for most ratoons varied from 1 000 to 1 300 mm/ha. However, due to water restrictions in 2005-2006, the 2nd ratoon of the early season cycle experiment received about 50% of the normal irrigation application.

Table 1. Recorded rainfall and irrigation amounts for the fertigation trials from 2002 to 2007.

Crop	Growing period	Irrigation (mm)	Rainfall (mm)	Total (mm)
Late season cycle				
Plant crop	08.10.02 to 08.10.03	1 323	518	1 841
1st ratoon	09.10.03 to 04.10.04	977	858	1 835
2nd ratoon	05.10.04 to 19.10.05	1 061	404	1 465
3rd ratoon	20.10.05 to 13.10.06	913	828	1 741
4th ratoon	14.10.06 to 16.10.07	1 115	612	1 727
Early season cycle				
Plant crop	01.04.03 to 11.05.04	1 178	836	2 014
1st ratoon	12.05.04 to 10.05.05	1 177	453	1 630
2nd ratoon	11.05.05 to 09.05.06	560	791	1 351
3rd ratoon	10.05.06 to 06.06.07	1 284	594	1 878

Fertility at the experiment sites was monitored by taking soil samples annually on a plot-by-plot basis for complete nutrient analysis by the FAS. Soil mineral N was assayed by taking samples at depths of 0-20, 20-40 and 40-60 cm before planting and after harvest in most of the years. Above-ground biomass measurements were carried out prior to the 2007 harvests. Seven plants per plot were partitioned into stalks, trash and various leaf stages. Samples from each of these components were analysed for their N contents in order to compute N uptake fluxes. At harvest the stalk yields and sucrose contents were measured.

N balances were calculated, which compared the measured N output, i.e. the N uptake from the crop via the harvested above-ground biomass, against all available N sources *viz*. N input from fertilisation, atmospheric N input, and N mineralised from the soil pool.

Results and Discussion

Yields

The estimated recoverable crystal (ERC) yields obtained for both early and late season cycle experiments are presented in Table 2.

Table 2. Comparison of ERC yields (t/ha) between solid and fertigated N treatments for plant and ratoon crops in late and early season cycle experiments.

LATE SEASON CYCLE			
Treatment (kg N/ha)	**Solid ERC (t/ha)**	**Fertigation ERC (t/ha)**	**Difference fertig/solid (%)**
Plant crop ERC yields (08-10-02 to 08-10-03)			
0 N	20.0		
48 N	19.7	20.2	+2.5
96 N	19.3	19.8	+2.6
144 N	18.8	20.3	+8.0
LSD (p=0.05)	1.82		
1st Ratoon ERC yield (08-10-03 to 04-10-04)			
0 N	17.3		
48 N	18.8	19.5	+3.7
96 N	19.9	20.8	+4.5
144 N	21.5*	21.3	-0.9
LSD (p=0.05)	4.04		
2nd Ratoon ERC yield (04-10-04 to 19-10-05)			
0 N	13.7		
48 N	15.8	16.5*	+4.4
96 N	15.9	18.0*	+13.2
144 N	15.5	16.9*	+9.0
LSD (p=0.05)	2.55		
3rd Ratoon ERC yield (19-10-05 to 13-10-06)			
0 N	9.8		
48 N	11.6*	11.3	-2.6
96 N	13.9**	10.8	-22.3
144 N	17.3**	14.3**	-17.1
LSD (p=0.05)	1.65		
4th Ratoon ERC yield (13-10-06 to 16-10-07)			
0 N	10.1		
48 N	13.5*	15.4*	+14.1
96 N	15.1*	14.5*	-4.0
144 N	16.5**	13.3*	-19.4
LSD (p=0.05)	2.73		

EARLY SEASON CYCLE			
Treatment (kg N/ha)	**Solid ERC (t/ha)**	**Fertigation ERC (t/ha)**	**Difference fertig/solid (%)**
Plant crop (cut back) ERC yields (01-04-03 to 11-05-04)			
0 N	15.4		
48 N	15.4	17.1	+11.0
96 N	15.6	18.0	+15.4
144 N	17.0	18.4*	+8.2
LSD (p=0.05)	2.75		
1st Ratoon ERC yield (11-05-04 to 10-05-05)			
0 N	8.4		
48 N	11.8*	15.0*	+27.1
96 N	15.7**	18.5**	+17.8
144 N	16.4**	16.8**	+2.4
LSD (p=0.05)	2.15		
2nd Ratoon ERC yield (10-05-05 to 09-05-06)			
0 N	3.9		
48 N	5.8*	6.2*	+6.9
96 N	7.5**	8.5**	+13.3
144 N	9.0**	8.0**	-10.1
LSD (p=0.05)	1.21		
3rd Ratoon ERC yield (09-05-06 to 06-06-07)			
0 N	6.2		
48 N	9.1*	12.6*	+38.5
96 N	11.7**	11.3*	-3.4
144 N	9.4*	10.2*	+8.5
LSD (p=0.05)	1.68		

*significant to the control, **significant compared to other levels

Late season cycle

In the plant crop of the late season trial there was no response to N for both the solid and the fertigated treatments, due to the high N release from mineralisation of soil N following cultivation of this virgin Shortlands soil. The N release effect from soil remained evident in the 1st ratoon. The solid N treatments yielded better at the high 144kg N/ha level, while fertigation showed a small advantage at the medium 96 kg N/ha level. In the 2nd ratoon crop the yield of the control plot was lower than in the years before, a sign that the available soil mineral N reserves had started to deplete. As a consequence there was a significant yield response to applied N. Both fertigated and solid treatments peaked at 96 kg N/ha, although the response of the solid treatment to applied N was smaller and non-significant. In the 3rd ratoon, with the exception of the low 48 kg N/ha level, the solid N treatments outperformed the fertigated treatments. The solid treatments showed distinct yield responses up to the highest N level, which were highly significant for 96 and 144 kg N/ha. The results for the 4th ratoon were similar to those of the 3rd ratoon. While the solid treatments showed significant responses up to the highest N level, the yields of the fertigated treatments declined linearly up to the 144 kg N/ha level. However, the low 48 kg N/ha fertigated treatment yielded 2 t/ha ERC higher than the low solid treatment.

The poor performance of the medium and high fertigated treatments over the last two years is difficult to explain. Weather conditions were markedly different over the two years. In spring/summer 2005-2006 (3rd ratoon) almost double the amount of rainfall was recorded than over the same period in 2006-2007. These wet soil conditions could have been the reason for higher N losses through leaching or denitrification; however, the regularly taken leaf samples did not show a nitrogen deficiency. In contrast, in January to March 2007 (4th ratoon) a very dry period occurred. In times of low river flow, an increase in salinity in the irrigation water could have resulted in greater N losses through volatilisation due to an increased pH. Accordingly, measured pH at this time showed an increase to 7.5 compared to the starting value of 6.4 in 2002. In 2005-2006 and 2006-2007 there was an increase in mosaic and smut in the experiment plots, but the results did not show a clear interaction between fertigation and disease infection.

Early season cycle

The plant crop of the early season experiment was also influenced by the high soil N mineralisation rate following the conversion of the virgin soil, as reflected by the high yield of the control plot. In the 1st ratoon there was a clearly significant response to increased N in both the solid and the fertigated treatments. While the yields at the high N level were almost the same, the fertigated treatment showed better yields at the low and medium application rates (+27% at 48 kg N/ha and +17.8% at 96 kg N/ha), indicating a markedly increased fertiliser N use efficiency.

Yields in the 2nd ratoon were markedly down, which could have been caused by moisture stress following water restrictions in 2005-2006. Despite this limitation, and unlike the late season cycle, there were significant yield responses to all three fertigated N applications, peaking at the medium 96 kg N/ha rate. The solid N treatment yields peaked at the high 144 kg N/ha rate and the responses to all three treatments were significant. In general, the fertigated low and medium treatments were superior to the solid treatments.

In the 3rd ratoon **of the fertigated treatment** the low 48 kg N/ha rate yielded the highest, and there was no further response to N treatment. The solid N treatment yield peaked at 96 kg N/ha and the responses to applied N was significant. The yield of the fertigated 48 kg N/ha treatment was markedly (38%) higher than the solid treatment at this rate, while at the 96 and 144 kg N/ha levels there were no significant differences.

The average ERC yields for early and late season cycles are presented in Figure 1. The average response curves over five crops in the late season cycle showed almost no differences between the solid and the fertigated treatments. The solid treatment appeared to be slightly better than fertigation at the high N rate, whereas fertigation at the low N rate appeared better than solid placement. These results could be explained primarily by the reduced performance of fertigation in the 2nd and 3rd ratoons, due to the reasons already mentioned above.

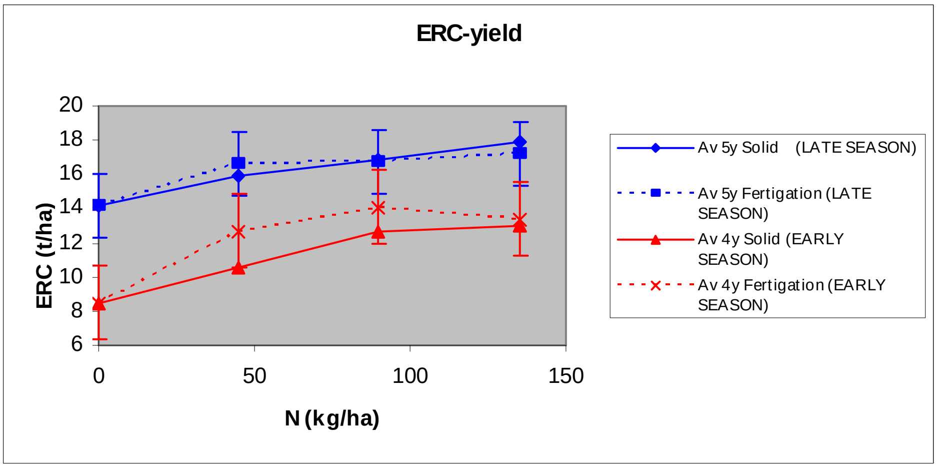

Figure 1. Estimated recoverable crystal (ERC) yields with increasing nitrogen (N) application as solid and fertigated treatments (late season cycle average for 2003-2007; early season cycle average for 2004-2007).

Unlike the late season cycle, the early season cycle 4-year average response curve showed distinct differences between solid and fertigated N treatments. The response curves for both the fertigated and solid treatments peaked at 96 kg N/ha, with the fertigated N response curve initially being steeper. The highest ERC yield difference (fertigated minus solid) was 2.2 t/ha (20%) at the lowest N level, slightly under the LSD of 2.24 at $p<0.05$. This difference decreased to 1.5 t/ha (11%) for the treatment with 96 kg N/ha, and to 1.1 t/ha (8%) for the treatment with 144 kg N/ha.

It may be inferred from the results that for most of the years the 96 kg N/ha fertigated treatment yielded similarly to the 144 kg N/ha solid fertiliser application, suggesting a more than 30% improvement in fertiliser N use efficiency. This was more distinct for the early season cycle than for the late season cycle.

The most likely reason for the better performance of fertigation in the early season cycle is that the demand for N by a young crop growing during an early season cycle with lower temperatures and evaporation rates, is more closely synchronised with N supply than a young crop growing in a favourable late season cycle with higher temperatures and evaporation rates. Results from Pongola lysimeter experiments (Thompson, 1991; Schumann, 2000) show that, after four months' growth in an early season crop only 12-15% of applied N is taken up, compared to over 60% for a late season crop. This means that there is a much higher risk of applied N loss in an early season cycle, particularly where N is applied in the solid state.

With fertigation, the N demand by the crop is more closely matched by the multiple split N amounts.

Another important factor to consider is that the average daily temperature of the top 200 mm of the soil is a lot lower during the early season cycle than during the late season cycle. For example, the average soil temperature in July is 17.7ºC and in February is 28.7ºC (Thompson, 1991). This large difference in temperature will have a marked effect on the potential for N to be mineralised from the soil. A lower release of N from the soil implies a greater response to applied fertiliser N, particularly where applied more evenly and efficiently through fertigation. A greater potential for N release during the late season will also help explain why the zero N treatments generally yielded better, with a lower response to applied N during the late season compared with the early season, particularly for the plant and early ratoon crops.

N use efficiency

External N use efficiency, being the amount of cane yield produced per applied kg N for the late and early season crops averaged out over all experiment years, is presented in Table 3. The N requirement in South Africa for rainfed cane is on average 1.25 kg N/ton cane (Meyer *et al.*, 2007). This corresponds to 0.8 tons cane/kg N applied, which equates to the N use efficiency at the high 144 kg N/ha rate. Comparing the two application systems, the fertigated treatments showed an improved external N use efficiency in the early season cycle only, and only at the low and medium N levels.

Table 3. External nitrogen (N) use efficiency of fertigated and solid treatments (average of five years for the late season cycle, average of four years for the early season cycle).

Fertiliser level	Late season cycle		Early season cycle	
	Solid	Fertigated	Solid	Fertigated
	t cane/kg N	t cane/kg N	t cane/kg N	t cane/kg N
48 kg N/ha	2.34	2.36	1.90	2.20
96 kg N/ha	1.24	1.22	1.13	1.23
144 kg N/ha	0.86	0.82	0.75	0.78

N balances

Calculation of N balances can be used to control the environmental impact of nitrogen application. The N balances of the late season cycle (4th ratoon) and the early season cycle (3rd ratoon) are presented in Table 4, in which N uptake by the crop is balanced against all available N sources such as fertiliser, atmospheric N input, N in irrigation water and N mineralised from the soil.

The shallow Shortlands form soil at the experiment site was evaluated as a Category 2 soil, which corresponds to an approximated N release of about 60 kg N/ha/year in the topsoil. In 2007, the N_{min} values for the early season cycle corresponded well with the Category 2 rating, whereas the late season cycle showed a very low mineralised N content of only ±30 kg N/ha.

Atmospheric N deposition is caused mainly by environmental pollution from road traffic and industry, and to a certain extent also by volatilisation and denitrification of N fertiliser sources. For South Africa, values of 8-19 kg N/ha/year were reported by Galy-Lacaux *et al.* (2003). For the Komatipoort site, a conservative amount of 10 kg N/ha/year atmospheric N deposition was included in the N balances, given the distance of the site from industrial activities. For N in irrigation water there was no recent measurement available. However, previous measurements of water quality in the Crocodile River, the source of irrigation water at the experiment site, showed a value of 0.4 mg N/litre (Meyer and van Antwerpen, 1995). This equates to about 5 kg N/ha input from irrigation water. In future work, analysis of irrigation water quality should be included, as the N status of rivers and dams is increasing, especially in irrigated areas (Gaerdenaes *et al.*, 2005).

Table 4. Nitrogen (N) balances of fertigated and solid treatments (2007 late and early season cycles).

Treatment	Total N uptake (kg/ha)	Fertiliser (kg/ha)	Soil N_{min} 0-60 cm (kg/ha)	Atmospheric/ irrigation N input (kg/ha)	Output minus input (kg/ha)	kg/ha	%
2007 Late season	**OUTPUT**	**INPUT**			**Balance***	**Losses**	**Losses**
Nil N	80	0	38	10+5	**27****		
Solid N1	87	48	31	10+5	-7	-34	28
Solid N2	99	96	31	10+5	-43	-70	41
Solid N3	129	144	35	10+5	-65	-92	42
Fertigated N1	116	48	33	10+5	20	-7	6
Fertigated N2	108	96	27	10+5	-30	-57	35
Fertigated N3	81	144	30	10+5	-108	-135	63
2007 Early season	**OUTPUT**	**INPUT**			**Balance**	**Losses**	**Losses**
Nil N	127	0	66	10+5	**46****		
Solid N1	112	48	55	10+5	-6	-52	32
Solid N2	132	96	62	10+5	-41	-87	40
Solid N3	163	144	52	10+5	-48	-94	37
Fertigated N1	153	48	62	10+5	27	-18	11
Fertigated N2	138	96	65	10+5	-38	-84	38
Fertigated N3	140	144	70	10+5	-90	-136	49

*Balance = output minus input

**Positive balance for the Nil N plot = additional N sources have been used. Because it is assumed that this additional N is available for all plots, it is added to the losses.

Despite all mentioned approximations and uncertainties, this N balance provides a first attempt to quantify the magnitude of N loss. A positive figure for the nil N plots indicated that more N had been used than assumed for the input side of the balance, and suggested that available mineral N, N from atmospheric deposition, N from irrigation water, and mineralised soil N had either been underestimated, or additional sources (biological N fixation) had been used. This additional **N** was assumed to be available for all plots, and was added to the input side of the balance for all N treatments for calculation of the N losses (Thorburn *et al.*, 2000).

In the fertigated treatments, % N loss increased rapidly up to the high 144 kg N/ha rate, indicating substantial N loss to the environment. At the medium 96 kg N/ha rate, the loss was ±80 kg N or about 40% of total available N, and at the high 144 kg N/ha rate was ±130 kg N or about 50%.

Comparing fertigated and solid application treatments, highly favourable balances of 6% and 11% losses for the late and early season cycles, respectively, were associated with the low 48 kg N/ha rate in the fertigated treatments. At the medium 96 kg N/ha rate, the N losses with fertigation and solid application were similar, with the balance for the fertigated late season cycle being slightly better. In contrast, N losses at the high 144 kg N/ha rate in the fertigated treatments in 2007 were higher than in the solid treatments, for both the late and early season cycles. This may be partly a consequence of the reduced performance of fertigation in 2007. However, the yield results have shown that, in most of the years, the solid treatment responded linearly to N up to the high 144 kg N/ha rate, whereas the response curve for fertigation appeared to peak much earlier, with no further N uptake.

These results showed that fertigation is not a tool to increase yields over a certain level, but a tool for saving N without reducing yield. This corroborates the findings of Thorburn *et al.* (2003) in Australia. In the Australian experiments, at a medium application rate of 80 kg N/ha, the N loss with fertigation was about half that of the solid N application. However, the solid N was administered as a single application. Splitting the solid applied fertiliser in the Komatipoort experiment appears to have reduced losses at the medium 96 kg N/ha rate.

Conclusion

The results of this study clearly confirm that fertigation can reduce the use of N fertilisers by about 30% without reducing yield. This is especially important given the sharp escalation in the price of N fertilisers over the past year.

The N saving effect (higher N use efficiency) in the experiment was more distinct and significant for the early season cycle. The fertigated treatments peaked at the medium 96 kg N/ha rate, showing a yield increase of 12% compared to the solid treatment at the same application rate, and an increase of 8% compared to the solid treatment at 144 kg N/ha, suggesting an overall improvement in fertiliser N use efficiency of about 30%.

The results suggest that splitting the fertiliser applications and applying N via the irrigation system is of special advantage in early season cycles. This is attributed to the lengthy demand for N in early season crops being better matched by the split doses. Given that the standard FAS recommendation for this Shortlands form soil is 120 kg N/ha, savings of at least 30 kg N/ha can be made using fertigation in an early season crop.

The medium application rate of 96 kg N/ha will be relevant in agricultural practice using fertigation, because the achieved yield was comparable to the yield obtained from the high 144 kg N/ha rate using solid N application. However, although the highest N use efficiency with the lowest impact on the environment was achieved at the low 48 kg N/ha rate, the yield was compromised and was ±10% lower than the highest yield at the medium application rate of 96 kg N/ha.

The results of the study also strongly suggest that the present N recommendations for plant cane growing on a virgin soil are too high and can be reduced by almost 50%.

REFERENCES

Butler DW, Meyer JH and Schumann AW (2002). Assessing nitrogen fertigation strategies for drip irrigated sugarcane in southern Africa. *Proc S Afr Sug Technol Ass* 76: 162-172.

Dart IK, Baillie CP and Thorburn PJ (2000). Assessing nitrogen application rates for subsurface trickle irrigated cane at Bundaberg. *Proc Aust Soc Sug Cane Technol* 22: 230-235.

Gaerdenaes AI, Hopmans JW, Hanson BR and Simunek J (2005). Two dimensional modelling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural Water management* 74: 219-242.

Galy-Lacaux C, Ourabi AH, Lacaux JP, Gardrat J, Mpepya K and Pienaar K (2003). Dry and wet atmospheric nitrogen deposition in Africa. *Geophysical Research Abstracts* 5: 09644.

Meyer JH and van Antwerpen R (1995). Trends in water quality of selected rivers in the South African sugar industry. Proc S Afr Sug Technol Ass 69: 60-67.

Meyer JH, Schumann AW, Wood RA, Nixon D and van den Berg M (2007). Recent advances to improve nitrogen use efficiency of sugar cane in the South African sugar industry. *Proc Int Soc Sug Cane Technol* 26: 238-246.

Ng Kee Kwong KF, Paul JP and Deville J (1999). Drip-fertigation – a means for reducing fertilizer nitrogen to sugarcane. *Experimental Agriculture* 35: 31-37.

Schumann AW (2000). Fertigation for sugarcane. Paper presented at the Fertiliser Society of South Africa Fertigation Symposium held on 25 August 2000 at Lynnwood Ridge, 0040, South Africa.

Singels A (2007). A new approach to implementing computer-based decision support for sugarcane farmers and extension staff. The case of My Canesim. *Proc Int Soc Sug Cane Technol* 26: 211-219.

Thompson GD (1991). The growth of sugarcane variety N14 at Pongola. Mount Edgecombe Research Report No. 7. Published by the South African Sugar Association Experiment Station, Mount Edgecombe, South Africa.

Thorburn PJ, Dart IK and Baillie CP (2000). Nitrogen balances in trickle irrigated sugarcane. Paper presented at the 6th International Micro-irrigation Congress, Cape Town, South Africa, October 2000.

Thorburn PJ, Dart IK, Biggs IM, Baillie CP, Smith MA and Keating BA (2003). The fate of nitrogen applied to sugarcane by trickle irrigation. *Irrigation Science* 22: 201-209.