A STOCKTAKE OF THE LEVELS AND SOURCES OF NITRATE IN GROUNDWATERS ASSOCIATED WITH SUGARCANE AREAS

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FINAL REPORT

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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. Previous studies have found elevated nitrate concentrations in groundwaters underlying sugar-growing areas, particularly the Bundaberg and Burdekin areas, and that in Bundaberg the problem was escalating. Nitrate pollution of groundwaters of the sugar industry is of particular concern because of the proximity of the industry to environmentally sensitive areas and the large number of people (in cities and rural areas) relying on groundwaters for drinking water.

However, apart from recent studies in Bundaberg, data on nitrate in groundwater has generally come from inconsistent studies. These studies examining either a limited number of groundwater bores, or large databases of groundwater chemistry where sampling and analytical methods have been variable and, in some cases, inappropriate. So a reliable, consistent, industry-wide definition of the problem does not exist.

This project determined the extent of nitrate contamination in groundwater underneath sugar-growing regions of eastern Australia, and examined the likely source of the nitrate. In bores where nitrate concentrations were elevated, and therefore likely to be a result of human activities, concentrations were monitored to provide an assessment of trends in nitrate concentrations. This information was used to promote "best management practices" through relevant extension, industry and regulatory groups, to restrict leaching of nitrate to groundwater.

Findings/outcomes of the project are:

- Overall, groundwater beneath sugarcane growing areas on the eastern coast of Australia is relatively free from **excessive** nitrate contamination, with nitrate concentrations in only 3 % of bores above the drinking water guideline. However, a further 11 % have elevated nitrate concentrations likely to be a result of human activities. These percentages are similar to those found in many other intensive agricultural areas.
- Nitrate in approximately half of these bores was likely to have come from fertiliser. Nitrate in very few bores is likely to have come from organic sources, such as sewage, septic or feedlot overflows. (Nitrate in the remaining bores could not be attributed to a particular source.) Thus, improvement of nitrogen fertiliser management practices is a key activity in managing groundwater nitrate concentrations.
- Widespread **nitrate pollution occurs** in the Burdekin, Bundaberg and Mackay regions, where 14-21 % of bores are affected.
- In the Burdekin and Mackay regions, there was no general trend in groundwater nitrate concentrations over 2 years of monitoring. However, there was considerable variability within bores between sampling times. In Bundaberg, nitrate concentrations in 40 % of bores significantly declined over 6 years (1993-1999) of regular monitoring. This decrease is consistent with reduced inputs of nitrate into the groundwater. However, rainfall was below average during this time, which could affect results.
- Awareness of the "nitrate situation" was raised during this project amongst growers and industry groups, particularly in the Burdekin and Mackay regions. (Extension activities were conducted in Bundaberg in a previous project.) Best management practices, which concentrate on limiting nitrogen fertiliser inputs to recommended levels and regularly monitoring nitrate concentrations in drinking and irrigation water, were communicated to these groups.

- Extension activities/outcomes included:
  - In the affected areas around Mackay and Proserpine, growers commenced monitoring nitrate in their own bores using nitrate test strips initially distributed during shed meetings conducted by project staff.
  - In a parallel activity, test strips were shown to accurately discriminate between nitrate concentration ranges in practical, on-farm use (as opposed to laboratory conditions).
  - New initiatives were undertaken by BSES and CANEGROWERS following communication of results of the groundwater survey. These activities included further communication of the need to reduce nitrogen inputs to crops, monitoring of local bore water and soil nitrate concentrations, and demonstration of appropriate nitrogen fertiliser applications rates.

The sugar industry is now in a unique position, having defined the severity and extent of nitrate pollution in groundwaters of the industry in eastern Australia – similar information is not available for any other agri-industry in Australia. No other study has covered a similar area distributed as widely; included such a large number of bores sampled consistently; nor coupled broadscale sampling with as intensive monitoring through time.

However, there are still unresolved issues regarding the problem:

- 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. Understanding these processes is likely to result in "smart" ways to manage nitrogen that will be more appealing than "blanket recommendations".
- 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.

BACKGROUND

Nitrate is a common chemical pollutant of groundwater in agricultural areas. High concentrations of nitrate in groundwater are of concern due to the potential impact on both human health and the environment. In Australia, The National Health and Medical Research Council (NHMRC) has stated that, for infants <3 months, nitrate concentration in drinking water should not exceed 50 mg NO3/L. For adults, and children over 3 months of age, the standard is 100 mg NO3/L (NHMRC, 1996). When nitrate is reduced to nitrite in the stomach, the nitrite interferes with the ability of haemoglobin to transport oxygen. In very young children, haemoglobin has a greater affinity for nitrite than is usual because children's stomachs lack the necessary acid to inhibit the conversion of nitrate to nitrite. Although the condition can be fatal, it is now very rare.

From an environmental viewpoint, groundwater rich in nitrogen (N) that discharges into freshwater lakes, wetlands, streams and marine environments disturbs the natural ecological balance resulting in the formation of algal blooms. Following the death of the blooms, the resultant bacteria not only consume the bloom but also consume any available oxygen in the water. This has an immediate effect on fish and other organisms in the water resulting in their death. This process of eutrophication can occur naturally, but it can be greatly accelerated by human activities.

Although nitrate formation is a natural process in soils, the process can be exacerbated by agronomic practices. When soil is cultivated, crops planted and nitrogen fertiliser applied, the processes of mineralisation and nitrification supply a source of nitrate that can leach to underlying groundwater aquifers. In Europe, nitrate concentrations above 50 mg/L have been found in groundwater under 22 % of cultivated land. Similar high concentrations have been found in USA and China (Laegreid *et al*., 1999). Increasing nitrate contamination has caused European countries to enact legislation to reduce the problem, such as compulsory nitrogen balance sheets for individual farms, regulated fallow management and *Nitrate Protection Areas* around individual bores (Canter, 1997; Iversen *et al.;* 1998, Eichler *et al*., 1998).

In Australia, significant nitrate contamination has been identified in all states and territories across differing land uses (Bauld, 1994; Bolger and Stevens, 1999). Agricultural areas with incidences of nitrate contamination of groundwater include the irrigated areas of northern Victoria, horticultural areas over lying the coastal aquifers near Perth and under the irrigated and dryland pastures and vineyards of the South East region of South Australia. In Queensland, Keating *et al*. (1996) found high percentages of bores with nitrate concentrations above 50 mg/L in the eastern Darling Downs and Callide Valley regions.

Elevated groundwater nitrate concentrations have also been found in areas of the sugar industry, notably the Bundaberg and Burdekin regions (Sunners, 1993; Bauld, 1994; Keating *et al.*, 1996). Nitrate pollution of groundwaters of the sugar industry is of particular concern because of (1) the intensive use of nitrogen fertilisers in the sugar and commonly associated horticultural industries, (2) the proximity of the industry to environmentally sensitive areas and (3) the large number of people (in cities and rural areas) relying on groundwaters for drinking water.

The knowledge base on nitrate in groundwater has been built on many 'one-off' studies and very little work has been done to systematically record temporal trends over extended periods of time in these same areas. Monitoring of a bore network in Bundaberg since 1993 has proved that a regular monitoring program provides a much enhanced understanding of nitrate contamination in a regions groundwater system (Biggs *et al.*, 2000). This project has provided the Australian sugar industry with a unique and thorough investigation of the problem of nitrate contamination (spatially and temporally) on an industry-wide scale.

OBJECTIVES

The aim of this project was to determine on an industry-wide scale the extent of and source of nitrate contamination in groundwater underneath sugar cane growing regions. This information together with medium term monitoring of groundwater with elevated concentrations of nitrate would be used to promote "best management practices" through relevant extension; industry and regulatory groups so that leaching of nitrate to groundwater may be restricted.

RESEARCH METHODOLOGY

This project was conducted in three stages, as described below. (Note; details of methods are given in the *Materials and Methods* sections of Appendices 1.2, 1.3 and 2.1.)

Industry-wide survey of groundwater nitrate ("Snapshot" study)

Nitrate concentrations were measured in bores through out the industry. After consultation with Department of Natural Resources (DNR) Queensland and Department of Land and Water Conservation (DLWR) New South Wales, 1188 investigation bores were selected in cane growing regions from northern NSW to Mossman. Two regions were excluded from this study; the Moreton region in south-east Queensland, due to a lack of a suitable investigation bore network, and Bundaberg, where a similar study had been conducted in 1993 (Sunners, 1993). In each region, bores were selected to form a network that covered the maximum area of land assigned to sugarcane farms (Appendix 2.1: maps 1-13). Most (64 %) bores were located in the Mackay, Proserpine and Burdekin regions (Table 1). Northern NSW was the only other area with a large number (7 %) of bores.

Table 1. Number of bores visited and tested for nitrate and in each range of nitrate concentration described as high (≥ 50mg/L), medium (≥ 20mg/L and < 50mg/L), and low (< 20mg/L).

Region	Nº (and % of total) of bores sampled	Nº (and % of region) of bores in each nitrate concentration range			
		Low	Medium	High	Medium + high*
Atherton	13 (1)	13 (100)	0	0	0 (0)
Babinda	16 (1)	16 (100)	0	0	0 (0)
Burdekin	397 (38)	341 (86)	36 (9)	20 (5)	56 (14)
Gordonvale	26 (2)	17 (65)	8 (31)	1 (4)	9 (34)
Ingham	57 (5)	53 (93)	2 (3.5)	2 (3.5)	4 (7)
Innisfail	55 (5)	52 (95)	3 (5)	0	3 (5)
Mackay	165 (16)	131 (79)	25 (15)	9 (6)	34 (21)
Mareeba	41 (3)	39 (95)	2 (5)	0	2 (5)
Maryborough	24 (2)	24 (100)	0	0	0 (0)
Mossman	47 (4)	47 (100)	0	0	0 (0)
Northern nsw	73 (7)	72 (99)	1 (1)	0	1 (1)
Proserpine	106 (10)	99 (93)	6 (6)	1 (1)	7 (7)
Tully	11 (1)	10 (91)	1 (9)	0	1 (9)
Total	**1031**	**914 (89)**	**84 (8)**	**33 (3)**	**117 (11)**
Bundaberg (sunners, 93)	423	334 (79)	74 (17)	15 (4)	89 (21)

* Number of bores sampled in the monitoring study.

Samples were collected from only 1031 of the bores due to various reasons, such as bores having small diameter casings, being dry and/or damaged. Groundwater samples in Queensland were collected between June 1997 and December 1997, while northern NSW bores were sampled in March 1998.

The naturally-occurring nitrogen isotopic ratio was also measured on groundwater samples with nitrate concentrations > 20 mg/L. This ratio can be indicative of the source of the nitrate in the groundwater (details are given in Appendix 2.1).

Along with taking a sample for nitrate analysis, temperature, pH, electrical conductivity (EC), redox potential (Eh) and dissolved oxygen (DO) and soluble carbon were also measured.

All nitrate concentrations reported here are expressed in mg/L as nitrate (NO_3^-). The nitrate concentrations have been grouped into one of three classes – 'low' (<20 mg/L), 'medium' (≥20 and <50 mg/L) or 'high' (≥50 mg/L). The high class of nitrate concentrations was selected to represent the NHMRC drinking water guideline for infants (<3 mths) of 50mg/L (NHMRC, 1996). The 'medium' class was selected to represent the bores where nitrate concentrations were high enough to indicate the influence of human activities (Spalding and Exner, 1993). The 'low' class represents the bores with a low probability of exceeding the health limit.

Temporal trends in nitrate concentrations

Following the snapshot study, groundwater nitrate concentrations were monitored in bores that had nitrate concentrations ≥20 mg/L (i.e., medium or high) in that study. The bores sampled were mainly those in the Mackay, Proserpine and Burdekin regions (totalling 97 bores). Water samples were obtained from most bores eight times, from October 1998 until June 2000. A small number of bores in each region could not be monitored due to inaccessibility after floods and/or damage to the bore. A small number of bores (19 bores) were re-sampled in north Queensland (generally by local DNR personnel) from February 1998 until April 1999. Details of the methods are given in Appendices 1.3 and 2.2.

As well as the bores sampled in the snapshot study, data collected from 6 years of bore monitoring in the Bundaberg region was analysed as part of this project. These bores were a network of 49 domestic and production bores, and included all bores found to have high (>50 mg/L) nitrate concentrations in a wider survey undertaken in 1993, and a selection of bores around three experimental sites where nitrate movement in the soil profile was studied. The bores were sampled 16 times between 1994 and 1999 (details given in Appendix 1.2). Results from the Bundaberg monitoring presented here differ from that reported by Biggs *et al.* (2000) due to the data being reanalysed using the technique described in the following paragraph.

To summarise the results at each sampling time, nitrate concentrations in each bore were classified into three ranges used in the snapshot study; high (≥ 50 mg/L), medium (≥ 20 mg/L and < 50 mg/L) and low (< 20 mg/L). Also the temporal trend in nitrate concentrations in each bore was determined using regression analysis. Nitrate concentration trends were classified as 'positive' if the slope of the regression relationship between concentration and time was significantly greater than zero. Similarly, trends were classified as 'falling' if slopes were significantly less than zero. Where slopes were not significantly different from zero, trends in nitrate concentration were classified as having either "steady" or "varying" nitrate concentrations, depending on the standard deviation of the nitrate concentrations over all sampling times. Bores with low standard deviations were classified as "steady" and bores with high standard deviations were classified as "varying". Details of these classification procedures are given in Appendix 1.3.

TECHNOLOGY TRANSFER

Following the snapshot study and throughout the monitoring stage of the project, various communications were under taken through local reference panel meetings, workshops, 'shed' meetings and a number of industry publications. All of these raised awareness of the existing or potential problems in the relevant regions.

RESULTS AND DISCUSSION

Results

"Snapshot" study

Nitrate

The region with the highest number of bores sampled (397) was the Burdekin, followed by Mackay with 165 bores (Table 1). Atherton, Babinda, Maryborough and Tully each had fewer than 30 bores.

Of the 1031 bores sampled, nitrate concentrations were high in 3 % of bores and medium in another 8 % (Table 1). Groundwater with high nitrate concentrations occurred in only five regions, the Burdekin, Gordonvale, Ingham, Mackay and Proserpine (Table 1). Of these regions, only Burdekin and Mackay had more than two bores with high nitrate concentrations. Notably both regions also had large numbers (36 and 25 respectively) of bores with medium concentrations. Atherton, Babinda, Maryborough and Mossman had no groundwater nitrate concentrations above 20 mg/L. The low groundwater nitrate concentrations in these regions may be due to the diluting effect of the high rainfall in these areas, or because the groundwater in many of the regions exhibited the conditions necessary for biological denitrification (see section 5.1.3) which can reduce the extent of nitrate contamination of the groundwater.

Bores with medium and high nitrate concentrations in the Burdekin and Mackay regions occurred in "pockets" (Appendix 2.1: maps 1, 2). In the Burdekin, two pockets were identified within five kilometres of the Burdekin River, around the Home Hill and Clare townships. Mackay had a pocket located within five kilometres south of the Pioneer River and extending east to Walkerston and west to Mirani. (For more detail see Appendix 1.1 and 2.1.)

Groundwaters with medium and high nitrate concentrations are also frequent in the Bundaberg region. Bundaberg groundwaters were investigated for nitrate contamination by sampling 423 bores in 1993 (Sunners, 1993). At that time, 4 % of bores had high concentrations of nitrate and another 17 % had medium concentrations (Table 1). A pocket of medium and high levels of nitrate was identified in the Gooburrum/Oakwood area north of the Burnett River, which was in a known groundwater recharge zone.

EC and pH

The Maryborough, Mareeba, Burdekin and Proserpine regions had >40 % of bores with EC values above the drinking water guideline value (1.6 dS/m, Table 2). In Maryborough, 83 % of bores exceeded this limit. Atherton, Babinda and Tully were the only regions that did not have any bores above the EC limit.

The average pH in all bores sampled was generally slightly acidic (pH 5.00 to 7.00). However some individual bores had extreme values of 3.37 and 11.61 (Table 3). In Gordonvale, Innisfail and Mossman, average pH was less than 6.00.

Table 2. Proportion of bores exceeding the drinking water health guideline for electrical conductivity (1.6 dS/m) and the maximum electrical conductivity (EC) measured in each region.

Region	% of Bores ≥ 1.6 ds/m	Maximum EC (dS/m)
Atherton	0	0.4
Babinda	0	0.2
Burdekin	50	144.8
Gordonvale	4	21.8
Ingham	26	5.6
Innisfail	2	8.2
Mackay	27	39.3
Mareeba	59	23.9
Maryborough	83	35.6
Mossman	13	41.3
Northern nsw	18	13.5
Proserpine	43	33.8
Tully	0	0.3

Table 3. Basic statistics for pH values in each region.

Region	pH			
	Mean	S.D.	Maximum	Minimum
Atherton	6.57	0.66	8.27	5.77
Babinda	6.18	0.50	6.93	5.34
Burdekin	6.68	0.51	11.61	5.52
Gordonvale	5.58	0.78	7.77	4.62
Ingham	6.14	0.39	6.86	5.02
Innisfail	5.73	0.95	7.72	4.23
Mackay	6.63	0.46	7.97	5.36
Mareeba	6.81	0.53	8.10	5.50
Maryborough	6.27	0.83	7.68	3.37
Mossman	5.47	0.88	7.60	3.95
Northern nsw	6.09	0.90	8.68	3.77
Proserpine	6.54	0.68	8.66	3.64
Tully	6.56	0.34	7.34	6.30

Biological denitrification within groundwater

Favourable conditions for denitrification existed in 50.3% of all bores sampled, with at least 16% of bores having these conditions in each region. However, there was no significant difference between the average nitrate concentration in bores with (5 mg/L, s.d. 13) and without (10 mg/L s.d. 19) favourable conditions for denitrification. These results suggest that denitrification was not an overriding factor influencing the nitrate concentrations of the bores sampled. However, the nitrate concentrations in the bores may not be a true indication of the amount of nitrate flowing to the aquifers, as some may have been lost by denitrification once in the aquifer.

Source of nitrate contamination

Nitrogen isotope ratios were determined on water samples from 117 bores (those that had nitrate concentrations ≥20 mg/L as nitrate). In 44 % of bores, the ratios indicated that nitrate was most likely to have come from an inorganic source (i.e., fertiliser). In only one bore in Gordonvale was the nitrate contamination most likely to have come from an organic source (e.g. septic systems). The source of nitrate in the rest of the bores could not be resolved, but may have been due to a mixing of inorganic and organic sources or due to organic nitrogen being immobilised and then later mineralised before being leached into the groundwater.

Monitoring nitrate concentrations

In Bundaberg, nitrate concentrations in 40 % of bores were significantly falling during the period 1994 to 1999 (Table 4). Only 6 % had increasing nitrate concentrations. Of the bores with high nitrate in the 1993 survey, nitrate concentrations in 56 % had fallen below 50 mg/L by 1999. (For more detail see Appendix 1.2.)

Table 4. Proportion (%) of bores in each region grouped according to their temporal trend (rising, falling, steady or varying).

Region (Nº of Bores)	Trend Category (% of bores)			
	Rising	Falling	Steady	Varying
Bundaberg (49)	6	40	44	10
Burdekin (52)	4	6	30	60
Mackay (33)	12	15	46	27
Proserpine (6)*	0	2 bores	1 bore	3 bores

* Proserpine results presented as number of bores due to the small number investigated.

In the Burdekin, 90 % of bores did not demonstrate any significant temporal trends during the period 1998-2000, with 6 % (3 bores) having decreasing nitrate concentrations and 4 % (2 bores) with rising concentrations (Table 4). The majority of bores (60 %) were varying over time. This large percentage of varying bores was due to the isolated increase in nitrate concentration in November 1999. If this increase did not occur, the majority of these varying bores would have had steady trends in nitrate concentration. (For more detail see Appendix 1.3.)

In Mackay, nitrate concentrations in 15 % of bores fell while nitrate concentrations in 12 % rose (Table 4). The majority of bores were classified as steady despite highly variable rainfall during the study period. (For more detail see Appendix 1.3.)

In Proserpine, no bores had a significant rising trends and two had falling concentrations (Table 4).

In the areas from Ingham to Mossman (including the Tablelands) where bores were resampled, nitrate concentrations did not increase through time (with one exception in Ingham). For more details see Appendix 2.2.

Technology transfer activities

A summary of communication activities conducted is presented in Table 5.

Table 5. Technology transfer activities conducted during the project.

Method	Date	Place	Attendance (approximate)
Initial Workshops	17 Aug 1998	Mackay, Ayr and Innisfail	20, 15 and 15 respectively
Industry Representatives Meeting (BSES – CANEGROWERS)	6 May 1999	Burdekin	
Reference Panel Meetings	24 May 1999	Mackay, Ayr and Innisfail	15, 10 and 10 respectively
Shed Meeting (BSES-CANEGROWERS)	26 May 1999	Leibrechdt Rd., Burdekin	
Shed Meeting	19-20 July 1999	Mackay and Proserpine	30 and 20 respectively
Shed Meeting	April 2000	Mackay (Walkerston and Marian)	
Radio Interview	May 2000	ABC Radio	N/A
Magazine Article	April-May 2000	Australian Sugarcane	N/A
Final Workshops	November 2000	Burdekin and Mackay	25 and 15 respectively

After the snapshot study was completed, workshops were conducted in Mackay, Ayr and Innisfail. The snapshot results were presented and discussed, with booklets produced (Appendix 3.1, 3.2 and 3.3) and distributed to workshop attendants. Best management practices were promoted at these workshops and possible avenues for achieving these were outlined. Project reference panels for Burdekin, Mackay-Proserpine and Innisfail, were also established at these workshops.

The three reference panels met (separately) in May 1999 to review the initial stages of the "monitoring" phase of the project. At all three meetings it was suggested that extension activities should be conducted in the "pockets" identified with high and medium concentrations of nitrate. In May, extension activities in the Burdekin, where results of this project were presented, were conducted jointly by BSES and CANEGROWERS. Extension activities were also conducted in Mackay and Proserpine in July 1999 and again in April 2000, in collaboration with BSES. Discussion time at all these meetings was productive and positive suggestions for achieving best management practices raised. Also, the concept of growers using nitrate test strips to monitor groundwater nitrate concentrations was raised and test strips were supplied to all interested growers. Discussions at meetings in April 2000 indicated that local growers with groundwater nitrate problems were actively using the test strips.

Awareness of nitrate contamination of groundwater under sugarcane was raised through a paper on the temporal changes in nitrate contamination in the Bundaberg region presented at ASSCT 2000 (see Appendix 1.2). From this paper, radio interviews and magazine articles were produced.

The final workshops were held in Mackay and Burdekin in November 2000 to present all the project's results including both the "snapshot" and "monitoring" phases, as well as preliminary findings from the modelling of nitrate leaching under different trash management schemes. The presentations to this final workshop are given in Appendix 3.4.

DISCUSSION

In general, groundwater beneath sugarcane growing areas on the eastern coast of Australia is relatively free from excessive nitrate contamination, with nitrate concentrations in only 3 % of bores above the drinking water guideline (50 mg/L). This percentage is the same as that found in an assessment of nitrate in groundwater in the whole of Queensland (Keating *et al*., 1996) and lower than that found in broad surveys of groundwater quality in USA (Spalding and Exner, 1993), Europe (Fried, 1991; Chilton *et al*., 1991) and China (Zhang, 1996).

While the industry-wide situation may not be acute, it is clear that significant areas of nitrate pollution do exist within the sugar industry. Between 14 and 21 % of bores in the Bundaberg (Sunners, 1993), Mackay and Burdekin regions had elevated (≥ 20 mg/L) nitrate concentrations, with approximately 5 % of bores above the drinking water guideline (50 mg/L). The number of bores in these three regions is 68 % of the combined number sampled in this project and by Sunners (1993), this concentration in numbers being due to the intensive development of groundwater resources that has occurred in these regions.

The degree of groundwater nitrate pollution is these areas can be compared with studies done previously in these areas, and other parts of the country. Previous studies found that 68 % and 25 % of bores in the Bundaberg (Stickley, 1980) and Burdekin (Bauld, 1994; Keating *et al*., 1996) regions had nitrate concentrations greater than 13.5 mg/L. Keating *et al*. (1996) found high percentages of bores with nitrate concentrations above 50 mg/L in the eastern Darling Downs and Callide Valley regions. Similar, or higher percentages of bores with nitrate concentrations above 50 mg/L occur in the irrigated areas of northern Victoria (Bauld, 1994; Bolger and Stevens, 1999), horticultural areas over lying the coastal aquifers near Perth (Pionke *et al*., 1990) and under the irrigated and dryland pastures and vineyards of the South East region of South Australia (Bauld, 1994; Bolger and Stevens, 1999; Dillon *et al.*, 1999). While these comparisons are not definitive because of differences in sampling and data analyses, they do indicate that the situations in the Burdekin, Mackay and Bundaberg regions are not atypical for intensive agricultural areas in Australia.

Ongoing monitoring of groundwater nitrate concentrations has shown there has been little change in the situation over the last two years. This result confirms that the findings of the "snapshot" study were not an aberration, and that the problem in the Mackay and Burdekin regions is ongoing. This is particularly important information for the Mackay region, where detailed analyses of groundwater nitrate have not been conducted previously. In both the Mackay and Burdekin regions, the length of time over which bores were monitored was too short to gain any major insights into the trends in nitrate concentrations, with few bore having any significant trend during the monitoring period. In Bundaberg, where monitoring was conducted for 6 years, there was a trend for small decreases in nitrate concentrations in 44 % of bores. The optimistic interpretation of the monitoring results for Bundaberg is that N fertiliser inputs to the region over the 6-year monitoring period have not been excessive and, as a consequence, nitrate concentrations in the aquifers have started to decline.

In this project, nitrogen-isotope "finger printing" indicated that nitrate in approximately half the bores with elevated concentrations was likely to have originated from fertiliser. This result suggests that leaching of N from agricultural fields should be minimised in an effort to restrict nitrate pollution of groundwater. Verburg *et al*. (1998) studied leaching of nitrogen in two soils of the Bundaberg area. They showed that leaching increased rapidly with increasing N fertiliser application rates when cane yields "plateaued". In these two soils, yield plateaux occurred at N applications of approximately 160 kg/ha (the industry standard recommendation; Calcino, 1994). Surveys undertaken by Cane Protection and Productivity Boards in the Bundaberg (T. Wilcox, pers. comm.) and Mackay (A. Royal, pers. comm) regions show that approximately 40 % of growers are applying greater amounts of nitrogen fertiliser. Thus it is likely that there is potential for reducing nitrate accessions to groundwater through improved nitrogen management.

Technology transfer activities in this project raised awareness of groundwater nitrate concentrations and the linkage between nitrogen fertilise applications and nitrate leaching. Nitrate test strips were supplied to farmers in the Mackay and Proserpine areas, allowing them to monitor water from their own bores. Accuracy of nitrate test strips under "field" conditions was assessed and they were shown to accurately differentiate between different ranges of nitrate concentrations. Use of test strips provided a powerful "action learning" tool for growers to investigate their own problem and were adopted enthusiastically by farmers in areas with high groundwater nitrate concentrations (i.e., Walkerston and Marion). Test strips were subsequently incorporated into local extension programs conducted by BSES Mackay (T. Wilcox, pers. comm.).

In the Burdekin, early project results led to BSES activities in sampling irrigation water and promoting "best practice" nitrogen management through a shed meeting and some nitrogen-rate strip trials (R Coco, pers. comm.). CANEGROWERS also developed a communication plan for health and environmental issues associated with nitrogen in Burdekin groundwater in collaboration with CSIRO and BSES, and urged (by letter) their members to adopt "best practice" nitrogen management.

IMPLICATIONS AND RECOMMENDATIONS

The sugar industry is now in a unique position, having defined the extent of nitrate pollution in groundwaters of the industry in eastern Australia – similar information is not available for any other agri-industry in Australia. No other study has covered a similar area distributed as widely; included such a large number of bores sampled consistently; nor coupled broadscale sampling with as intensive monitoring through time.

Despite progress made in this project, several issues still remain unanswered. While it is clear that excess N fertiliser applications should be avoided, the factors upon which farmers base N fertiliser rate decisions are complex and often not related to environmental considerations (Keating *et al.*, 1997). Thus minimising excessive N applications is still a challenge for the industry, which may be aided by development of new approaches to block specific N monitoring and farmer feedback (SRDC project CTA029; Keating *et al.*, 1999).

However, blanket N fertiliser recommendations, even if block specific, may still not answer the problem. In other farming systems, nitrate leaching is well related to the length of fallows and how they are managed, with the result that fallow management is regulated (Iversen *et al.*, 1998). In the Australian sugar industry, little is known about the relationships between nitrate leaching and fallow length, fallow management, or the management of plant crops. The role of mill by-products, particularly mill mud, in supplementing nitrogen fertiliser and impacting on nitrate leaching is also poorly understood. Understanding these processes is likely to yield some "smart" ways to manage N so to minimise N leaching, that may be more "socially acceptable" to farmers than blanket recommendations. For example, preliminary analyses in the Mackay area suggest that N fertiliser management is most important in plant crops for reducing nitrate leaching (PJ Thorburn, unpublished data), and most farmers may not need to alter fertiliser management in ratoon crops provided plant crops are well managed. Concepts like these, if generally applicable, immediately highlight priorities for extension efforts and will have a higher probability of being adopted by growers.

Another factor that has not been considered by the sugar industry is the dynamics of nitrogen in groundwater aquifers. It is generally known that it can take considerable times (years to decades) for nitrate to enter groundwater in aquifers, flows through the aquifers, and enter streams and rivers. However, the time scales of these flows and the associated nitrate fluxes need to be quantified to properly define the impacts of nitrate-rich groundwater on the environment. Also, this knowledge would assist in determining the time lag between changes in on-farm management and consequent changes in groundwater nitrate concentrations, and the "catchment area" for nitrate in the affected areas. These last two points are necessary to develop effective best management practices.

DESCRIPTION OF INTELLECTUAL PROPERTY

The information in this project should be freely available to the Australian sugar industry and overseas industries. There are no intellectual property considerations that require attention.

TECHNICAL SUMMARY

Using test strips to measure groundwater nitrate concentrations on farms

Within the technology transfer activities, it became apparent that there was a priority need for an on-farm method of monitoring groundwater nitrate concentrations, to be used by growers. Best practice management requires that groundwater nitrate concentrations be monitored regularly. Nitrate test strips (Merkoquant Nitrat-Test strips) are one means for growers to monitor their bores. The strips are cheap and give an “instant” measurement of nitrate concentrations, and so are ideal for use by growers. But, growers are unlikely to use them under the controlled conditions in which they have been tested and calibrated, and the strips’ accuracy may suffer as a result.

To determine the accuracy of test strips for **in-field** use, we measured nitrate concentrations of ~ 1,200 groundwaters by test strips in the field, and subsequently in the laboratory (by standard colorimeteric methods). In the field, test strips were immersed in the water and colour development noted after approximately 1 minute. The concentration was then determined by comparing the colour of the test strip with that provided by the manufacturer (on the side of the container), and the concentration range (Figure 1) within which the test strip fell noted. We did not attempt to determine the exact concentration from matching the colours.

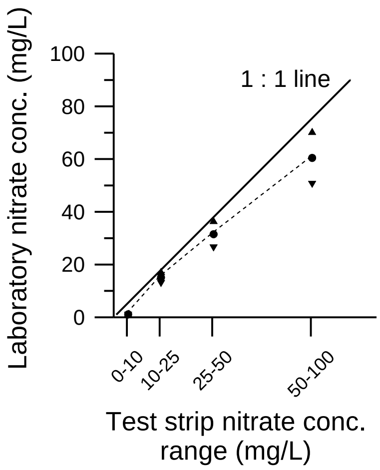

Figure 1. Mean (circle) and 99 % confidence intervals (triangles) of nitrate concentrations measured with nitrate test strips.

The way test strips were used in this study is similar to the way they would be used by growers – in the field, under different conditions (e.g., times of the day, temperatures, sunlight intensities), without precise control of time for colour development in the strip. Under these conditions, differences between nitrate concentration ranges (e.g., 10-25 *v.* 25-50) were highly significant ($P < 0.001$, using parametric and non-parametric AOV). Also, the nitrate concentration of the water sample is likely to be lower than that implied by the mid-value of the concentration range (Figure 1). For example, the mid-point of the 50-100 range is 75 mg/L but the mean concentration was 61 mg/L.

Thus, growers can use test strips in the field with confidence to differentiate between the concentration ranges indicated on the side of the container and results will tend to be conservative. However, if accurate measurements are required, formal laboratory analyses will be needed.

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PUBLICATIONS RESULTING FROM THE PROJECT

1. WEIER, K.L., BIGGS, J.S., McNEIL, A. and McEWAN, C.W. (1999). Source and nitrate concentration in groundwater beneath sugarcane growing regions. *Proceedings Australian Society Sugar Cane Technologists* **21**: 497.
2. WEIER, K.L. (1999). The quality of groundwater beneath Australian sugarcane fields. *Australian Sugarcane* **3(2)**: 26-27.
3. BIGGS, J.S., KEATING, B.A. and THORBURN, P.J. (2000). Time trends of nitrate in groundwaters under intensive agriculture in the Bundaberg region. *Proceedings Australian Society Sugar Cane Technologists* **22**: 296-301.
4. BIGGS, J.S., THORBURN, P.J., WEIER, K.L. and HOPP, M.L. (2001). Nitrate in groundwaters in Mackay and Burdekin regions, Queensland. *Proceedings Australian Society Sugar Cane Technologists* **23**: submitted.
5. THORBURN, P.J. and BIGGS, J.S. (2001). Using test strips to measure groundwater nitrate concentrations on farms. *Proceedings Australian Society Sugar Cane Technologists* **23**: submitted.

APPENDIX 1. SELECTED PUBLICATIONS

Appendix 1.1. WEIER, K.L., BIGGS, J.S., McNEIL, A. and McEWAN, C.W. (1999). Source and nitrate concentration in groundwater beneath sugarcane growing regions. *Proceedings Australian Society Sugar Cane Technologists* **21**: 497.

Appendix 1.2. BIGGS, J.S., KEATING, B.A., and THORBURN, P.J. (2000). Time trends of nitrate in groundwaters under intensive agriculture in the Bundaberg region. *Proceedings Australian Society Sugar Cane Technologists* **22**: 296-301.

Appendix 1.3. BIGGS, J.S., THORBURN, P.J., WEIER, K.L. and HOPP, M.L. (2001). Nitrate in groundwaters in Mackay and Burdekin regions, Queensland. *Proceedings Australian Society Sugar Cane Technologists* **23**: submitted.

Appendix 1.4. WEIER, K.L. (1999). The quality of groundwater beneath Australian sugarcane fields. *Australian Sugarcane*, June-July 1999, pp.26-27.

Appendix 1.5. BIGGS, J.S. and THORBURN, P.J. (2000). Take care with nitrogen fertilisers. *Australian Sugarcane*, April-May 2000, p. 25.

APPENDIX 2. UNPUBLISHED REPORTS

Appendix 2.1. BIGGS, J.S., WEIER, K.L., THORBURN, P.J. and HOPP, M.L. (2000). A 'Snapshot' of nitrate in groundwaters under sugar-cane growing regions. CSIRO Sustainable Ecosystems, Coastal Cropping Systems.

Appendix 2.2. BIGGS, J.S., THORBURN, P.J. and HOPP, M.L. (2000). Nitrate in groundwaters of northern Queensland. CSIRO Sustainable Ecosystems, Coastal Cropping Systems.

APPENDIX 3. TECHNOLOGY TRANSFER REPORTS

Appendix 3.1. WEIER, K.L. (1998). CSIRO/DNR Workshop Report: Mackay-Proserpine Groundwater Study, 17 August 1998. CSIRO Tropical Agriculture.

Appendix 3.2. WEIER, K.L. (1998). CSIRO/DNR Workshop Report: Burdekin Groundwater Study, 19 August 1998. CSIRO Tropical Agriculture.

Appendix 3.3. WEIER, K.L. (1998). CSIRO/DNR Workshop Report: Groundwater Study in the Ingham, Tully, Innisfail, Grodonvale, Atherton, Mareeba and Mossman Regions, 21 August 1998. CSIRO Tropical Agriculture

Appendix 3.4. THORBURN, P.J. (2000). Final Groundwater Workshop Presentations (Mackay and Burdekin), 13-14 November 2000. CSIRO Sustainable Ecosystems, Coastal Cropping Systems.