Effect of Agricultural Practices on Nitrate Leaching

END OF PROJECT REPORT

RMIS 4973

Authors

M.Ryan[1], K.McNamara[2], C.Brophy[3], J.Connolly[3], O.T.Carton[1] and K.Richards[1]

[1]Johnstown Castle Research Centre, Wexford
[2]Moorpark Research Centre, Fermoy, Co. Cork
[3]Department of Statistics and Actuarial Science, University College Dublin

Teagasc, Johnstown Castle Research Centre, Wexford

December 2005

ISBN No. 1 84170 448 2

Teagasc wishes to acknowledge with gratitude funding from the 2000-2006 EPA RTDI programme in financing this research project.

Teagasc

AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY

TABLE OF CONTENTS

SUMMARY

A farm-scale study, carried out at Teagasc, Moorepark (Curtin's farm), examined the effect of four managements (treatments) on nitrate-nitrogen (NO_3-N) leaching over the period 2001-`05. Leaching was measured in these treatments: (T1) plots receiving dirty water and N fertilizer which were grazed; (T2) 2-cut silage and grazing plots receiving slurry and fertilizer N; (T3) grazed plots receiving fertilizer N and (T4) 1-cut silage and grazing plots receiving slurry and fertilizer N. The soil is a free-draining sandy loam overlying Karstic fissured limestone.

The mean direct N inputs (kg/ha) for T1-T4 in 2001-`04 were 311, 309, 326, 331, respectively, with stocking rates (LU/ha) of 2.12 - ~2.47. Eight ceramic cups per plot, in 3 replicate plots of each treatment, were used to collect water, on a weekly basis, from 1.0 m deep using 50 kPa suction. There were 33, 37, 26 and 24 sampling dates in the 4 years, respectively.

The NO_3-N and NH_4-N concentrations (mg/l) were determined in the water samples. The annual average and weekly concentration of these parameters was statistically analysed for all years, using a repeated measures analysis. The aggregated data were not normally distributed. There was an interaction between treatment and year ($p<0.001$). Significant differences ($p=0.05$) in NO_3-N concentrations showed between the treatments in years 1, 2, 4 but not in year 3. For the NH_4-N data there was no interaction between treatment and year, $p=0.12$, or main effect of treatment, $p=0.54$ but there were differences between years, $p=0.01$. Mean weekly concentrations were analysed separately for each year. For NO_3-N, in years 1, 2 and 4 there was an interaction between treatment and week ($p<0.001$). With NH_4-N, there was an interaction between treatment and week in all 4 years. Dirty water was significantly higher than grazed and 1 cut silage in NO_3-N concentrations in year 1; in year 2, dirty water and 2 cut silage were significantly higher than the other treatments while in year 4, dirty water and grazed were significantly higher than the other two treatments. The overall four-year weighted mean NO_3-N and NH_4-N concentrations were 8.2 and 0.297 mg/l.

The NCYCLE (UK) model was adapted for Irish conditions as NCYCLE_IRL. The NCYCLE empirical approach proved to be suitable to predict N fluxes from Irish grassland systems in most situations. Experimental data appeared to agree quite well, in most cases, with the outputs from NCYCLE_IRL. The model was not capable of predicting data from some of the leaching experiments, which suggests that the observed leaching phenomena in these experiments could be governed by non-average conditions or other parameters not accounted for in NCYCLE_IRL. An approach that took into account denitrification, leaching and herbage yield would probably explain the differences found. NCYCLE_IRL proved to be a useful tool to analyse N leaching from grazed and cut grassland systems in Ireland.

INTRODUCTION

Groundwater is at risk from nitrate that leaches from the soil profile. Elevated concentrations are an unwanted consequence of increased population pressure and more intensive industrial-agricultural production methods. The EU nitrates Directive (December 1991) was adopted by all Member states in order to contain and reverse such degradation in water quality. The Directive required that areas at risk be identified and national action programmes be set up to counter nitrate pollution. At that time data was lacking in Ireland on the effects of intensive farming on nitrate leaching, therefore a research project to study nitrate leaching to 1, 3 and 28 m below ground level, as affected by N inputs and management, was undertaken. Teagasc and the Irish Environmental Protection Agency (EPA) jointly funded the project.

MATERIALS AND METHODS

Site Description

In one of three work packages, nitrate leaching to 1 m deep was measured at the Teagasc Dairy Production Centre, Fermoy, County Cork (52° 07` N, 08° 16` W) on grass plots over four winters. The area has a mild moist oceanic climate; annual rainfall (1971-2000) averages 1007 mm (Met Eireann);mean and max-min air temperatures (1992-2003) average 10.1 and 13.9-6.2 C (Teagasc Meteorological database). Average actual evapotranspiration, as % annual precipitation, 1961-1990, equals 46% (Mills, 2000); the 30-year average annual recharge is 570 mm (Bartley and Johnston, 2005). The freely drained soil, derived from mixed sandstone-limestone glacial till, overlies a karstified limestone bedrock aquifer; texture is sandy loam and depth ranges 0-450 cm with rock commonly occurring at 2-3 m below ground surface (Gibbons *et al.*, 2005).

Treatments

Treatment plots were; (T1) Grazed, receiving dirty water and fertilizer N; (T2) Cut twice for silage, grazed, receiving slurry and fertilizer N; (T3) Grazed only, receiving fertilizer N; (T4) Cut once for silage, grazed, receiving slurry and fertilizer N. Three replicate plots of each treatment were instrumented with eight, randomly distributed, ceramic cups, inserted at 1 m deep and having a bentonite seal on the connecting tube at 150 mm deep.

Grazing management

The farm was intensively managed with paddocks rotationally grazed year-round except during December and January.

Annual water sampling

Soil water samples were collected, using 50 kPa suction, on dates shown in Appendix D. The samples were stored overnight at 4 °C, acidified with 0.06 ml concentrated sulphuric acid (H_2SO_4) and transported at 4 °C for analysis, usually within 7 days.

Groundwater monitoring started by Bartley and Johnston, (2005) was continued from 12/12/03 to 05/10/05. Depth to the water table was measured and duplicate groundwater samples were taken monthly from 9 boreholes on the farm. Prior to sampling, each borehole had 3 well volumes purged using a Grundfoss submersible pump. Samples were stored at 4 °C and analysed within 24 hours of sampling.

All water samples were analysed for total oxidized nitrogen (TON), nitrite-N (NO_2-N), nitrate-N (NO_3-N) and ammonium-N (NH_4-N) on a KONELAB discrete auto-analyser using standard procedures.

N inputs

Mean fertiliser, dirty water and slurry N inputs to the treatments are shown in Table 1.

Table 1: Fertiliser, dirty water (D), slurry (S) N inputs in 2001, 2002, 2003, 2004.

	Mean **Inputs of Nitrogen (kg/ha) to Plots (16.92 ha Jan-Nov `01; 16.87 ha from Nov `01)											
	2001(36 cows)			**2002(39 cows)**			**2003(39 cows)**			**2004 (42 cows)**		
	Fert	**D/S**	**Total**	**Fert**	**D/S**	**Total**	**Fert**	**D/S**	**Total**	**Fert**	**D/S**	**Total**
Dirty Water	207	36	243	278	31	309	248	95	343	254	106	360
2 cut silage	364	28	392	333	27	360	314	22	336	287	41	328
Grazed	239	0	239	265	0	265	294	0	294	298	0	298
1 cut silage	323	22	345	266	22	288	298	22	320	298	36	334
Weighted Mean			311			309			326			331
Mean LU/ha			2.12			2.47*			2.47*			> 2.47

All means weighted on basis of plot size. D/S = applied as dirty water or slurry
*All second cut silage exported from farm; **Exclusive of 9 kg/ha/yr estimated atmospheric N wet deposition (9.2 kg/ha 1/5/2-30/4/3, 8.7 kg/ha 1/5/3-30/4/4).
0.85, 0.25 of total N allowed for N input from dirty water and slurry, respectively

Grazed, recycled N

Estimates of N recycled during grazing (Ryan *et al.*, 2005), are shown in Table 2.

Table 2: Recycled N (kg/ha) (cows 36 in`01, 39 in`02, `03, 42 in `04) @108 kg/cow/yr				
	Year 1 2001	**Year 2 2002**	**Year 3 2003**	**Year 4 2004**
Dirty water	206	226	248	233
2-cut silage	56	85	96	108
Grazed	241	228	222	204
1-cut silage	138	136	165	178
Weighted mean	153	163	178	177

Rainfall

Rainfall recorded at Moorepark Research Centre in 2001-`05 is shown in Table 3.

Table 3: Monthly rainfall (mm) 2001-`05 and 42-year mean, at Moorepark, Co. Cork.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Mean*	116	93	78	65	67	60	54	79	80	105	99	109	1005
2001	76	91	107	73	29	48	47	98	74	120	30	62	855
2002	176	105	54	85	126	78	49	58	21	165	178	107	1202
2003	64	71	61	101	101	105	87	4	41	32	125	91	883
2004	103	57	112	65	43	89	47	171	79	170	27	69	1032
2005	120	35	79	83	75	82	67	-	-	-	-	-	-

*Long-term mean monthly rainfall (1961-2002)

Ceramic cup Data

The raw data for each year consisted of NO_3-N and NH_4-N concentrations in the leachate of 96 individual cups, measured weekly, for 33, 37, 26 consecutive weeks in years 1-3 and for 24 weeks in year 4. Frequently there was not enough leachate to carry out laboratory analyses and concentrations often varied widely between cup samples in a plot.

Data Analysis

The NO_3-N and NH_4-N concentrations should be analysed and presented on the original scale of measurement, as this is the scale on which they affect the environment. The analyses consisted of:

1. *Analysis of annual average N concentrations in plot drainage water:* The annual average concentration of the two types of N was analysed using a repeated measures analysis over the four years. The data consisted of 48 values for each N type (4 treatments x 3 replicates x 4 years). These aggregated data were not normally distributed. A generalized linear mixed model was fitted that assumed a Gamma (positively skewed) distribution and incorporated a log link and allowed for the repeated measures nature of the data. (More detail on this model fitting is available in Ryan *et al.*, 2005). Three types of correlation structure (Ryan *et al.*, 2005) were examined to describe the relationship among the repeated values across years using the GLIMMIX macro in the statistical software package SAS.
2. *Analysis of weekly average N concentrations in plot drainage water:* Within each year a repeated measures analysis on the average concentration (over 8 cups) per plot per week was performed. These data were not normally distributed. Within each year a generalized linear mixed model was fitted that assumed a Gamma (positively skewed) distribution and incorporated a log link and allowed for the repeated measures nature of the data. Three types of structure (Ryan *et al.*, 2005) were tested to describe the correlation between the repeated measurements for each plot.

Means predicted from models with a log link are back-transformed to give means for presentation on the scale of measurement. To compare these means a Least Significant Ratio (LSR) is used rather than a Least Significant Difference (LSD), (See Appendix A, Ryan *et al.*, 2005). If the ratio of the larger mean to the smaller one is greater than the LSR, the two means differ significantly at the 5% level.

Additional analyses were performed. The relationship between rainfall, leachate volume and average N concentrations was examined; as was the relationship between leachate volume and treatment. The annual number of cow-grazing days/ha and N applied/ha were calculated for each plot. These were included as covariates in the analysis of annual average N concentrations in plots.

Model Development

The NCYCLE model, developed in the UK, was adapted for Irish conditions as NCYCLE_IRL. Scientists submitted a compact disk, including explanatory text and usable model, to the EPA, *per* contract with the Institute of Grassland and Environmental Research (del Prado *et al.*, 2005). The model is empirical and predicts N fluxes from Irish grassland systems and provides outputs of leached, denitrified, volatilized, mineralized and milk N. NCYCLE (IRL) allows the whole complexity of the N cycle to be encompassed and can be used as a tool to explore the effect of different climatic, soil and management options on N fluxes in Ireland.

RESULTS AND DISCUSSION

Rainfall

Rainfall in November, December 2001 was exceptionally low while October, November 2002 were very wet (Table 3). October to January, 2001-`02 and 2002-`03, had 45 and 43% of the 2001, 2002 annual total. The years 2001, 2003 had 15 and 12% lower than average rainfall whereas 2002 had 20% greater than normal rainfall. Rainfall was a little above average in 2004.

Analysis of annual average N concentrations

In the following, all effects mentioned were significant at the 5% level or less unless otherwise stated. There was an interaction between treatment and year ($p<0.001$). In year 1, T3 and T4 had lower mean NO_3-N concentrations than T1 or T2 and T4 was lower than T3, (Figure 1). In year 2, T3 and T4 were lower than both T1 and T2, whereas in year 3, there were no significant differences between treatments. In year 4, T2 was lower than both T1 and T3. The dirty water treatment (T1) was consistently high in all years. The grazed treatment (T3) gave low NO_3-N in years 1 and 2 but increased in year 3 and by year 4 it had the highest concentration, which was not significantly different to T1 however. For the NH_4-N data, there was no interaction between treatment and year, $p=0.12$, or main effect of treatment, $p=0.54$, but there were differences between the years, $p=0.01$ (Figure 2). Tables of means used to construct Figures 1 and 2 are in Appendix A. For both the analysis of the NO_3-N and NH_4-N data, compound symmetry, CS, was found to be the most appropriate way to describe the correlation between the repeated measurements, (Appendix, B).

Analysis of weekly average N concentration

NO_3-N.

In year 1, there was an interaction between treatment and week ($p<0.001$), (Figure 3; means in Appendix D). T4 had the lowest NO_3-N concentration at most times during the year and was significantly lower than T1 in 29 of the 33 weeks. T4 was significantly lower than T2 in 28 weeks but was only significantly lower than T3 in 14 weeks. This analysis from year 1 indicated that the one-cut silage treatment (T4) was that which gave the lowest NO_3-N concentration followed closely by the grazing-only treatment (T3).

In year 2, there was an interaction between treatment and week ($p < 0.001$). Again, T4 (one silage cut) had the lowest mean NO_3-N concentration in most weeks, (Figure 3; means in Appendix D). It was significantly lower than both T1 and T2 in 32 of the 37 weeks and was significantly lower than T3 in 20 weeks, or 54% of the time. Following on from year 1, T4 continued to emerge as the treatment with the lowest NO_3-N concentration. In year 3, there was no interaction between treatment and week (p=0.086). The trends observed in years 1 and 2 were not repeated, T4 was very variable and there were no significant treatment effects. In year 4, there was an interaction between week and treatment, (p<0.001). T3 was very high at the beginning of the year and was significantly higher than T1, T2 and T4 for 4, 12 and 6 weeks, respectively, of the first 12 weeks (Figure 3d). During the second 12 weeks, T3 reduced to become on par with the other treatments and T1 emerged as the highest treatment, with T2 the lowest. T2 was lower than T1 at 8 of the last 12 weeks.

The AR (1) correlation structure (Appendix C) was the most appropriate for the relationship among repeated measurements for years 1 to 4.

NH_4-N.

While no trends were observed in the first analysis on the data with NH_4-N as the response variable, each year was still analysed separately. In all years there was an interaction between treatment and week, (p=0.002, <0.001, 0.004, 0.004). In year 1 the interaction between treatment and week was caused by a small number of weeks, (Figure 4a; means in Appendix D). There were treatment effects at 6 weeks during the year but these effects were not consistent; e.g. NH_4-N concentration for T4 was lower than all other treatments at week 2 but was higher than all other treatments at week 26. In year 2, the only trend observed was that NH_4-N concentration for T2 was higher than for T4 at 10 of the 37 weeks, (Figure 4b). In year 3, T2 was higher than T3 and T4 for 9 and 8 weeks, respectively, of the 26 weeks, (Figure 4c). In year 4, no trends were observed, (Figure 4d). The correlation structure CS was appropriate to describe the relationship between the repeated measurements in years 1, 3 and 4 and AR (1) was appropriate in year 2, (Appendix C). Many of the NH_4-N concentrations, when considered in the context of the water quality required for freshwater fish e.g., Irish Salmonid Standards, Statutory Instrument No 293, 1988 and EC Directive 78/659/EEC, were high. The former provides for a Salmonid water quality standard of 0.778 mg/l NH_4-N but this is considered too lenient by some experts (M. Neill, pers com) who consider the EC guide levels of 0.156 and 0.031 mg/l NH_4-N for Cyprinid and Salmonid water quality standards, more appropriate. It must be remembered that concentrations measured at 1 m deep may not exactly reflect those in surface or ground waters due to transformations.

Figure 1: Mean NO_3-N concentration (mg/l) for each year x treatment combination. Differences between treatment means within a year can be assessed using the least significant ratio (LSR). If the ratio of the larger mean to the smaller one is greater than the LSR, the two means differ significantly at the 5% level. (See Appendix A, Ryan *et al.*, 2005 for more detail on the LSR.)

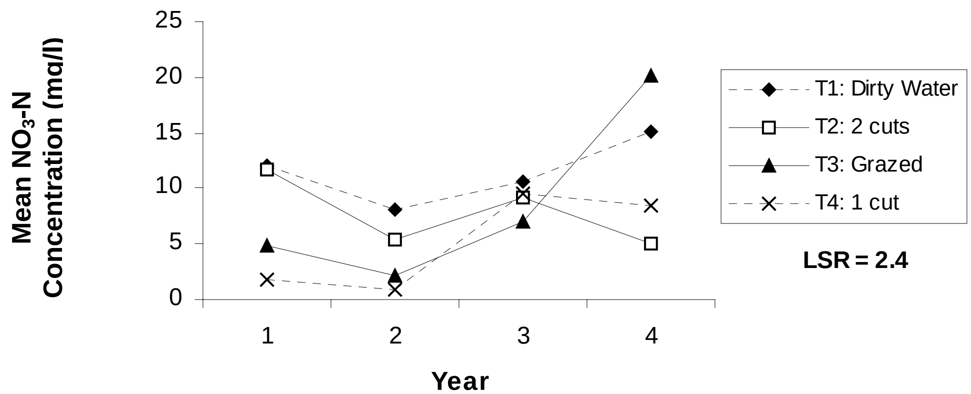


Figure 2: Mean NH_4-N concentration (mg/l) for each year x treatment combination.

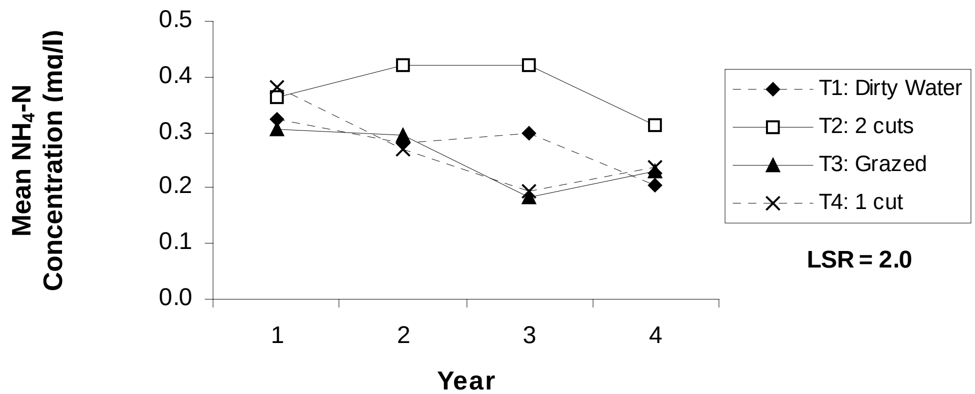


Figure 3: Mean NO_3-N concentration (mg/l) by week for each year.

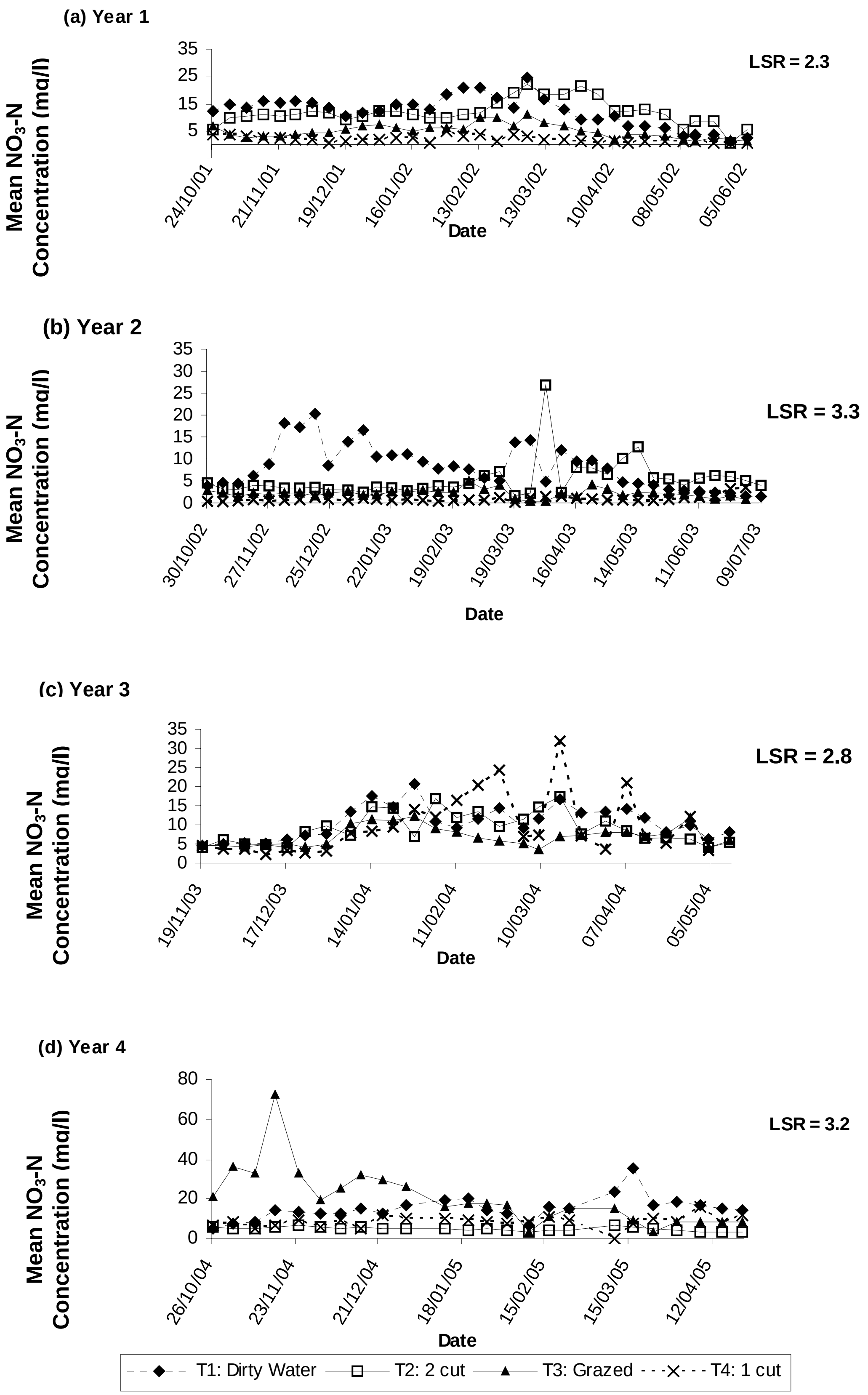
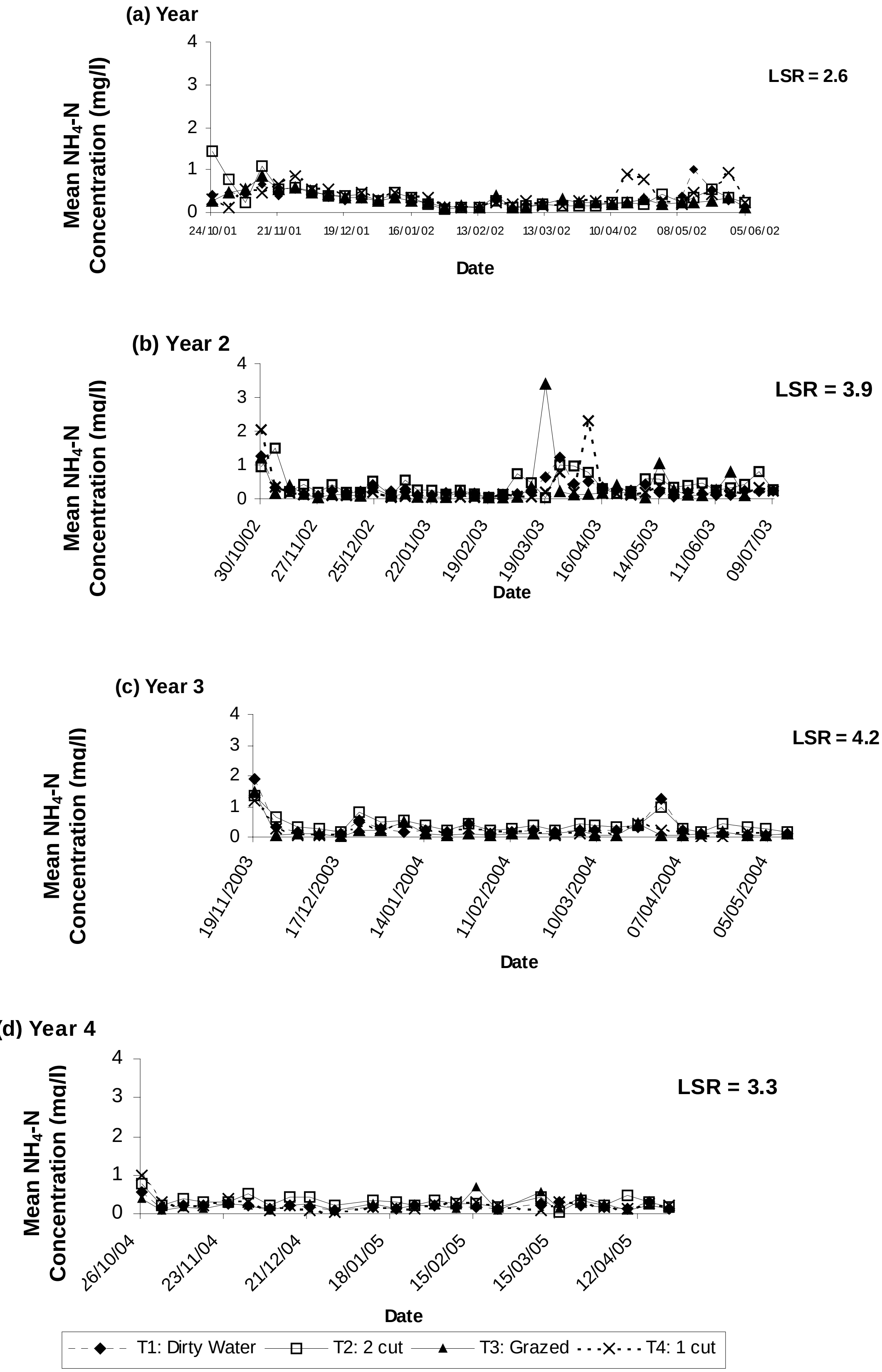


Figure 4: Mean NH_4- N concentration (mg/l) by week for each year.



No relationship was found between N concentrations and weekly rainfall, cow grazing days or total N applied within each treatment. N concentration and leachate volume in the cups were negatively related over time but not within plots or across plots. There was no effect of treatment on the leachate volume in the cups (Ryan *et al.*, 2005).

Groundwater nitrate and nitrite concentrations

The average groundwater total oxidized nitrogen (TON) and median NH_4-N concentrations for 2003-2005, are shown in Figure 5.

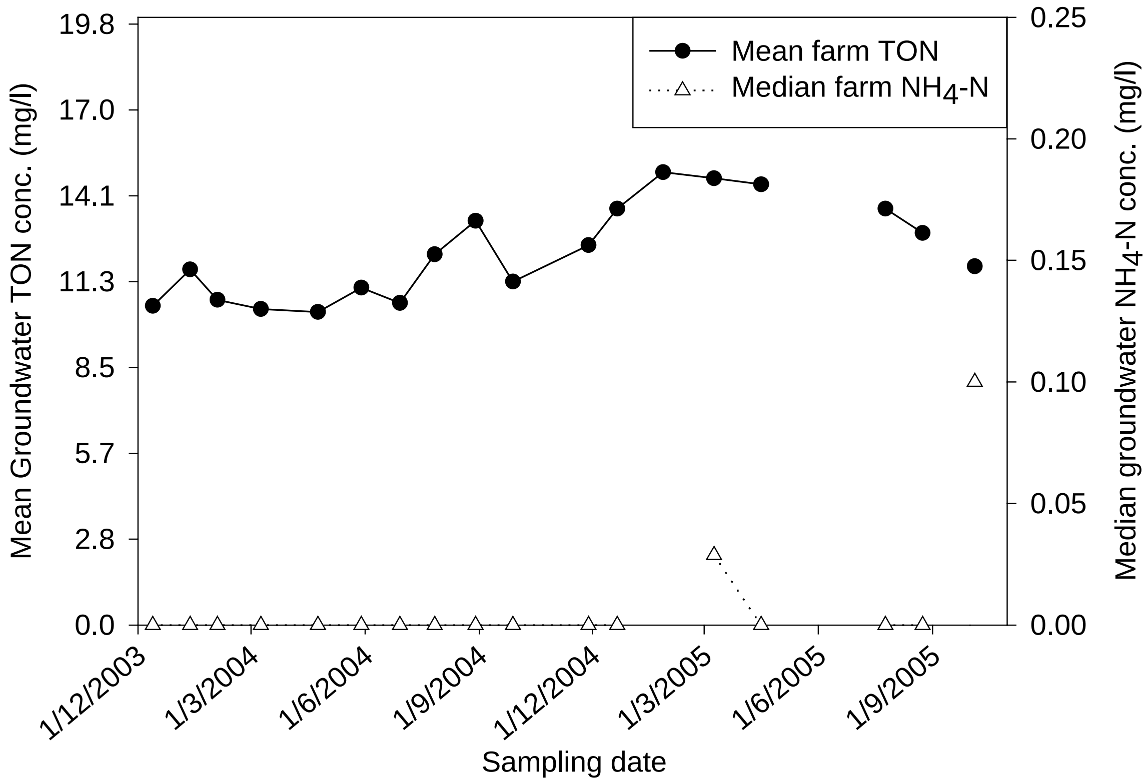


Figure 5: Mean farm groundwater TON and median NH_4-N concentrations (mg/l) from 13/12/2003 to 5/10/2005.

The mean farm groundwater TON concentrations ranged from 8.3 mg/l on 12/03/04 to 14.9 mg/l on 27/01/05 (Figure 5). The overall farm average groundwater TON concentration during the monitoring period (12/12/03 to 05/10/05) was 12.3 mg/l (n=18). The annual mean farm TON concentration for 2004 was 11.6 mg/l. A temporal trend is apparent within groundwater TON data. Groundwater TON concentrations increased gradually from 10.6 mg/l on 29/06/04 and peaked at 14.9 mg/l on 27/01/05 after which they decreased to 11.8 mg/l on 05/10/05.

Median groundwater NH_4-N concentrations are presented during the monitoring period (Figure 5). Median is used rather than mean as on many of the sampling dates there were a large number of boreholes that had NH_4-N concentrations less than the method detection limit (MDL) of 0.01 mg/l. Borehole 4, close to the farm yard, consistently had elevated NH_4-N concentrations; the mean was 1.5 mg/l (range 0 to 3.9 mg/l). On certain sampling dates NH_4-N was detected e.g., once in boreholes 8 and 9, three times in boreholes 2 and 7 and four times in borehole 5. The two sampling dates with median NH_4-N concentrations greater than MDL were 0.03 mg/l on 09/03/05 and 0.10 mg/l on 05/10/05.

NCYCLE_IRL

The model predicts N fluxes in Irish grasslands and within Ireland regional grass growth patterns were studied and 6 agro-climatic zones for grass were identified and modeled into NCYCLE_IRL. Other parameters that proved important in controlling N fluxes were soil type and drainage status; experimental data were used in order to build these differences into the model. NCYCLE_IRL parameters proved sensitive enough to management changes and different soil and climatic conditions and the predicted results agreed reasonably well with most of the Irish data. The model is expected to predict N fluxes for average situations and hence, possible discrepancies with some data are expected to occur. However, enough flexibility is built into the model to solve these issues. Not only should this enable the user to account for these deviations but it also can be used to explore hypothetical situations and possible abatement actions. NCYCLE_IRL has also proved to be useful as a starting point to develop tools which can predict at larger or finer scales. NCYCLE_IRL proved useful in analysing N leaching from grazed and cut grassland systems. However it was not able to predict data accurately for some of the leaching experiments, which suggests that observed leaching in these experiments could be governed by non-average conditions not accounted for in NCYCLE_IRL.

Factors affecting outcome

Statistically significant effects of treatment on concentrations were shown in 3 of the 4 years (Table A1, Appendix A). The highly varied nature of the data from week to week is revealed in Appendix D; high concentrations may be recorded for several weeks or just one week. Concentrations > the EU maximum admissible concentration for drinking water (MAC) were recorded in all treatments. High N fertiliser inputs in the past would have significant residual effects for a number of years. Gill *et al.* (1995) showed that the extent of mineralisation depends more on the previous management and a build-up of readily mineralisable materials than on current fertiliser input.

High inputs of N occurred, in the past, on of some of the dirty water, silage and grazed plots e.g., a major part of the dirty water (T1) area had received the effluent for >30 years. This treatment had a highly significant effect ($p<0.001$) on the % organic C and % total N concentrations in the soils of the irrigated plots compared with the soils from the plots of the remaining treatments (Ryan *et al.*, 2005). Higher N concentration in T1 soils together with a C/N ratio of 11.4 would be expected to favour higher release rates of soil organic N. High NO_3-N concentrations in the

2-cut silage (T2) drainage water in year 1 may have been caused by high applications of slurry to one plot over previous years. The mean NO_3-N concentration (mg/l) in that plot in year 1 was 19.98 compared with only 7.72, 7.70 in the other plots. Overall 3-year mean values were 12.92, 7.24 and 5.29 mg/l, respectively

Reducing nitrate leaching

Considering that silage was exported from the farm in 3 of the 4 study years it would appear that there is room for a reduction in N inputs while still carrying 2.47 LU/ha. This should occur in the dirty water (T1) plots and in the silage-cutting area and could reduce potential losses directly, due to a lower N load on the plots and indirectly perhaps through reduced N concentrations in the herbage. There may be scope to improve the amount of fertiliser N captured in output by matching the timing and quantity of N application to soil supply and sward requirements and so reduce potential losses. Improved N-use efficiency can be achieved by the strategic application of fertiliser N which takes account of N supply of net mineralised soil organic matter-N and avoids excessive applications which can lead to unnecessary losses (O`Connell, *et al.*, 2004). Humphreys *et al.*, (2003), in emphasising N-use efficiency in grassland, urged making use of N released by net mineralization of soil organic matter under permanent grassland to meet the requirements for grass growth during the autumn, winter and early spring

Autumn deposition of urine from consumed herbage is an important contributing factor to nitrate leaching (Sherwood, 1986; Cuttle and Bourne, 1993). Results quoted by these authors show that, of the mineral N remaining in the soil in the autumn, < 20% was deposited in spring/early summer and 80% was deposited from late summer onwards. Ways of reducing the impact of autumn-deposited N, e.g., lowering N concentration in herbage and extension of land area grazed, require consideration and possibly research.

Groundwater

The 2004 mean annual farm groundwater TON concentration at 11.6 mg/l was similar to the previous year 2 and year 3 mean concentrations of 12.6 and 10.8 mg/l, reported by Bartley and Johnston (2005). On 11 of the 18 sampling dates, mean farm TON concentrations were greater than MAC. A temporal trend in groundwater mean TON concentrations was evident within the data. In order to separate the influences of meteorology and agricultural practices on groundwater TON levels, it is recommended that monthly groundwater sampling be continued. Consideration should be given to implementation of measures to reduce the TON losses occurring from the farm in order to improve farm nutrient efficiency and to meet agreed groundwater quality targets.

CONCLUSIONS

The soil in the experimental site is No.13, General Soil Map of Ireland (Gardiner and Radford, 1980) and extends to 1.69% of the area of the Republic of Ireland. It is believed that areas with equivalent, comparable soils, comprise 5-8 % of the land area. Management options to reduce the pressure from the intensive dairy system monitored are evident. These can be implemented to reduce N loading from the system without requiring changes in production potential. Their impact on water, however, remains to be evaluated. Reducing N fertiliser applications to the dirty water and silage plots should be investigated in the next phase, as a means of improving N-use efficiency. Improved N efficiency, if achieved, by reducing inputs and maximising the benefit of soil organic N will reduce leaching. Improvement in washing routines, increased land-spreading area and any other procedures which give a reduction in the dirty water load to be irrigated should be investigated to reduce winter land-spreading and leaching. Groundwater monitoring should be continued on Curtin`s farm until long-term, stable data are obtained. NCYCLE_IRL is a useful model which requires more development.

ACKNOWLEDGEMENTS

Gratitude is expressed to K. O`Farrell, S. Crosse, P. Dillon, J. Humphreys and B. Horan, Moorepark and Curtin`s farm staff. Thanks are due to a Steering Committee and M. Rodgers, J. Mulqueen, P. Gibbons, P. Johnston, P. Bartley for beneficial discussions and to field/laboratory technical staff at Johnstown Castle, in particular D.Noonan, J. Scott, F. Codd, J. Cullen, P. Sills. Dr B. Hyde provided invaluable assistance in assembling data. Dr P. Bartley provided assistance in compiling effective rainfall.

REFERENCES

Bartley, P. and Johnston, P. (2005). Nitrate Responses in Groundwater to Dairy Farming Agriculture. *Summary Report M1- 2.3.1.3 to EPA*, Wexford, Ireland.

Cuttle, S. P. and Bourne, P. C. (1993). Uptake and leaching of nitrogen from artificial urine applied to grassland on different dates during the growing season. *Plant and Soil.*150: 77-86.

del Prado, A., Scholefield, D., Brown, L., Ryan, M., and Carton, O. T. (2005). Welcome to NCYCLE_IRL, A model to predict N fluxes in Irish grasslands**.** *Environmental Protection Agency*, Johnstown Castle, Co.Wexford, Ireland

Gardiner, M. J. and Radford, T. (1980). Soil Associations of Ireland and their land use potential. *Explanatory Bulletin to Soil Map of Ireland*. An Foras Taluntais, Dublin.

Gibbons, P., Rodgers, M. and Mulqueen, J. (2005). Eutrophication from Agricultural Sources. Nitrate leaching: Soil investigation package LS 2.3.1.2. *Report to EPA*, Wexford, Ireland.

Gill, K., Jarvis, S.C. and Hatch, D. J. (1995). Mineralization of nitrogen in long-term pasture soils:effects of management. *Plant and Soil.* 172: 153-162

Humphreys, J., O`Connell, K. and Watson, C. J. (2003). Effect of nitrate legislation on fertilizer nitrogen management for grassland. *Proceedings 517, The International Fertiliser Society*. IFS, PO Box 4, York, UK.

Mills, G. (2000). Modelling the water budget of Ireland-evapotranspiration and soil moisture. *Irish Geography*: 33, 99-116.

O`Connell, K, Humphreys, J. and Watson, C. J. (2004). Quantification of Nitrogen Sources for Grassland. *Publication No. 40, Winter Scientific Meeting.* The Fertiliser Association of Ireland.

Ryan, M., Mc Namara, K., Carton, O.T., Brophy, C., Connolly, J. and Houtsma, E. (2005). Eutrophication from Agricultural Sources. Nitrate leaching, Farm Scale Package. (2000-LS 2.3.1.1 M2) *Final Report*, *EPA*, Wexford, Ireland.

Sherwood, M. (1986). Nitrate leaching following application of slurry and urine to field plots. *In:* Dam Kofoed, A., Williams, J. H. and L`Hermite, P. (eds) *Efficient land use of sludge and manure.* Elsevier Press, London, pp. 150-157.

APPENDICES

Appendix A: Tables of overall means for each treatment for each year for the NO_3-N and NH_4-N data from the analysis of annual average N concentrations (mg/l) in plots.

Table A1: Average annual NO_3-N and NH_4-N concentrations (mg/l) for four treatments.

NO_3-N	**Year**			
Treatment	1	2	3	4
T1: Dirty Water	12.12	8.09	10.61	15.10
T2: 2 cuts	11.78	5.31	9.10	4.96
T3: Grazed	4.86	2.09	7.00	20.18
T4: 1 cut	1.88	0.94	9.52	8.52

LSR to compare treatment means **within a year:** 2.4

NH_4-N	**Year**			
Treatment	1	2	3	4
T1: Dirty Water	0.325	0.281	0.299	0.203
T2: 2 cuts	0.363	0.420	0.421	0.313
T3: Grazed	0.307	0.295	0.184	0.229
T4: 1 cut	0.383	0.271	0.194	0.237

LSR to compare treatment means **within a year:** 2.0

Appendix B: Table of AIC Statistics to help decide correlation structure for the analysis of annual average N concentrations.

A model that explains the data well and has a small number of parameters is desirable. This concept is called parsimony. The AIC (Akaike Information Criterion) statistic is a tool used in model selection that uses this concept; i.e. it measures how well the model fits the data but also takes account of the number of parameters in the model. The model with the smallest AIC is assumed to be the best. The AIC supplements the usual tests of significance for inclusion of terms in a model. In most of the models used in this report the inclusion or exclusion of terms is based on likelihood ratio tests, a generalisation of the usual F tests used in multiple regression modelling. These are not appropriate for comparing models in which the unknowns to be estimated are not a subset in one model of those in another. In such cases, the comparison of likelihoods is modified by inclusion of a penalty factor favouring the model with fewer parameters to give the AIC. In the same spirit, the AIC is used for comparing models where the number of parameters is the same in both models but where the parameters are different (e.g. models with CS vs AR (1) correlation structure).

Table B1: AIC values for various correlation structures for the analysis of annual average N concentrations.				
		Correlation structure		
	AR(1)	**CS**	**UN**	**Choice:**
NO_3-N	68.9	68.3	77.6	**CS**
NH_4-N	37.7	37.5	46.3	**CS**

Appendix C: Table of AIC Statistics to help decide correlation structure for the analysis of weekly average NO_3-N and NH_4-N concentrations.

Table C1: AIC values for various correlation structures for the analysis of annual average NO_3-N and NH_4-N concentrations.				
NO_3-N				
	AR(1)	CS	UN	**Choice:**
Year 1	600.4	653.7	NA	**AR(1)**
Year 2	675.9	741.2	NA	**AR(1)**
Year 3	455.9	484.6	NA	**AR(1)**
Year 4	416.0	438.6	NA	**AR(1)**
NH_4-N				
	AR(1)	CS	UN	**Choice:**
Year 1	559.2	558.6	NA	**CS**
Year 2	828.1	846.6	NA	**AR(1)**
Year 3	625.5	608.1	NA	**CS**
Year 4	523.6	483.3	NA	**CS**

Appendix D: *Mean NO_3-N and NH_4-N concentrations (mg/l) for each week in years 1, 2, 3 and 4.* The *LSR's for each set of means are for comparisons within a week only.*

		Year 1							
		NO_3-N Concentrations				NH_4-N Concentrations			
Week	Date	T1	T2	T3	T4	T1	T2	T3	T4
1	24/10/01	12.51	5.59	6.91	3.82	0.410	1.449	0.278	0.300
2	31/10/01	14.39	9.97	3.43	3.66	0.448	0.767	0.467	0.107
3	07/11/01	13.32	10.25	2.59	2.69	0.426	0.237	0.533	0.558
4	14/11/01	15.78	10.73	3.24	2.62	0.674	1.102	0.844	0.464
5	21/11/01	15.27	10.41	3.14	2.23	0.383	0.529	0.525	0.656
6	28/11/01	15.88	10.89	3.73	2.08	0.550	0.582	0.592	0.849
7	05/12/01	15.33	11.94	3.93	2.05	0.500	0.511	0.460	0.549
8	12/12/01	13.49	11.45	4.52	0.77	0.359	0.402	0.426	0.528
9	19/12/01	10.48	9.39	5.47	1.43	0.285	0.376	0.363	0.380
10	26/12/01	11.74	10.25	6.63	1.90	0.313	0.414	0.340	0.450
11	02/01/02	12.15	11.95	7.25	2.00	0.268	0.275	0.289	0.316
12	09/01/02	14.47	12.11	6.30	2.17	0.364	0.473	0.345	0.470
13	16/01/02	14.49	11.22	4.76	2.09	0.341	0.353	0.271	0.364
14	23/01/02	13.07	9.97	6.32	0.52	0.222	0.203	0.229	0.343
15	30/01/02	18.61	9.85	5.96	4.84	0.167	0.078	0.109	0.118
16	06/02/02	21.00	10.70	5.23	2.95	0.102	0.099	0.145	0.122
17	13/02/02	20.81	11.89	9.96	3.58	0.115	0.117	0.127	0.105
18	20/02/02	17.07	15.37	9.71	1.29	0.259	0.277	0.401	0.220
19	27/02/02	13.45	18.93	6.63	3.34	0.133	0.120	0.132	0.199
20	05/03/02	24.71	22.00	11.07	3.13	0.192	0.154	0.104	0.268
21	12/03/02	16.59	18.15	7.78	1.68	0.252	0.198	0.202	0.165
22	20/03/02	13.07	18.08	6.40	1.81	0.257	0.168	0.303	0.136
23	27/03/02	9.32	21.59	4.73	0.86	0.207	0.173	0.233	0.278
24	03/04/02	9.37	18.57	4.22	0.70	0.175	0.158	0.251	0.275
25	10/04/02	10.15	12.43	1.82	1.09	0.195	0.238	0.199	0.220
26	16/04/02	6.52	12.46	3.62	0.62	0.229	0.226	0.252	0.891
27	23/04/02	6.91	13.10	3.55	0.89	0.333	0.179	0.294	0.778
28	01/05/02	6.15	10.89	3.00	1.05	0.219	0.413	0.189	0.259
29	09/05/02	2.73	5.72	1.51	0.91	0.385	0.216	0.243	0.201
30	14/05/02	3.84	8.84	1.45	1.20	1.003	0.351	0.251	0.481
31	22/05/02	3.33	8.53	2.54	0.70	0.530	0.557	0.277	0.422
32	29/05/02	1.36	0.36	1.59	0.73	0.264	0.359	0.339	0.941
33	05/06/02	2.56	5.19	1.31	0.64	0.174	0.232	0.108	0.223
		LSR: 2.3				LSR: 2.6			

		Year 2							
		NO_3-N Concentrations				NH_4-N Concentrations			
Week	Date	T1	T2	T3	T4	T1	T2	T3	T4
1	30/10/02	3.88	4.53	2.81	0.52	1.264	0.948	1.208	2.041
2	06/11/02	4.60	3.19	2.25	0.35	0.331	1.500	0.160	0.347
3	13/11/02	4.44	3.07	1.45	0.31	0.249	0.213	0.387	0.177
4	20/11/02	6.19	3.99	2.18	0.52	0.138	0.423	0.130	0.119
5	27/11/02	8.81	3.84	1.91	0.73	0.088	0.190	0.029	0.019
6	04/12/02	18.16	3.35	2.19	0.50	0.232	0.417	0.125	0.093
7	11/12/02	17.20	3.39	2.28	0.58	0.173	0.190	0.119	0.093
8	18/12/02	20.28	3.56	1.59	0.74	0.210	0.192	0.080	0.087
9	24/12/02	8.54	2.98	2.29	1.31	0.413	0.519	0.331	0.186
10	02/01/03	13.93	2.93	2.66	0.80	0.219	0.092	0.081	0.039
11	09/01/03	16.54	2.47	1.70	0.63	0.280	0.552	0.143	0.072
12	15/01/03	10.57	3.60	1.85	1.01	0.100	0.257	0.044	0.050
13	22/01/03	10.83	3.41	2.48	0.84	0.102	0.251	0.057	0.036
14	29/01/03	11.08	2.77	2.49	0.62	0.175	0.135	0.042	0.048
15	05/02/03	9.35	3.31	2.85	0.82	0.132	0.255	0.219	0.046
16	12/02/03	7.78	3.87	2.47	0.60	0.155	0.141	0.080	0.039
17	19/02/03	8.32	3.63	2.35	0.38	0.055	0.043	0.016	0.017
18	26/02/03	7.66	4.41	4.98	0.56	0.123	0.122	0.018	0.139
19	05/03/03	5.68	6.26	3.08	0.67	0.144	0.742	0.047	0.074
20	12/03/03	5.03	7.10	4.07	0.65	0.252	0.469	0.338	0.054
21	19/03/03	13.80	1.63	0.85	1.23	0.640	0.033	0.0	0.197
22	26/03/03	14.30	2.22	0.0	0.13	1.220	0.997	3.390	0.778
23	02/04/03	4.83	26.87	0.38	1.15	0.443	0.966	0.215	0.193
24	09/04/03	12.04	2.39	0.37	1.44	0.510	0.778	0.0	2.308
25	16/04/03	9.44	8.01	2.04	1.48	0.335	0.302	0.120	0.160
26	23/04/03	9.66	7.99	1.40	1.04	0.275	0.155	0.133	0.150
27	30/04/03	7.82	6.51	4.13	0.92	0.243	0.216	0.171	0.109
28	07/05/03	4.70	10.10	3.12	0.65	0.425	0.592	0.395	0.187
29	14/05/03	4.39	12.73	1.64	0.69	0.186	0.581	0.166	0.370
30	21/05/03	4.07	5.73	2.42	0.55	0.064	0.341	0.022	0.169
31	28/05/03	3.08	5.45	2.24	0.54	0.186	0.392	1.037	0.184
32	04/06/03	2.78	4.04	2.22	0.79	0.147	0.465	0.262	0.256
33	11/06/03	2.64	5.61	1.86	1.26	0.110	0.251	0.106	0.258
34	18/06/03	2.42	6.28	1.47	1.27	0.107	0.324	0.096	0.218
35	25/06/03	1.57	6.03	0.88	1.67	0.236	0.422	0.254	0.142
36	02/07/03	1.52	5.11	1.62	3.27	0.217	0.801	0.788	0.330
37	09/07/03	1.50	4.01	0.72	3.51	0.232	0.266	0.097	0.229
		LSR: 3.3				LSR: 3.9			

		Year 3							
		NO_3-N Concentrations				NH_4-N Concentrations			
Week	**Date**	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
1	19/11/03	4.57	4.09	4.64	4.57	1.865	1.336	1.437	1.189
2	26/11/03	5.02	6.10	4.56	3.67	0.338	0.656	0.066	0.282
3	03/12/03	5.24	4.99	4.20	3.64	0.162	0.307	0.110	0.050
4	10/12/03	5.12	4.77	4.89	2.25	0.049	0.280	0.121	0.045
5	17/12/03	6.20	4.07	5.09	3.29	0.112	0.171	0.018	0.065
6	23/12/03	7.26	8.27	4.15	2.71	0.547	0.811	0.226	0.300
7	30/12/03	7.63	9.71	4.92	3.20	0.247	0.490	0.230	0.279
8	07/01/04	13.47	7.25	10.29	7.86	0.170	0.548	0.491	0.302
9	14/01/04	17.56	14.70	11.36	8.34	0.219	0.376	0.135	0.232
10	21/01/04	14.68	14.38	11.12	9.43	0.152	0.239	0.063	0.124
11	28/01/04	20.72	6.93	12.15	14.00	0.418	0.444	0.095	0.297
12	04/02/04	10.85	16.80	9.00	12.06	0.101	0.205	0.075	0.137
13	11/02/04	9.23	11.93	8.11	16.37	0.142	0.292	0.117	0.181
14	18/02/04	11.54	13.45	6.58	20.34	0.235	0.356	0.124	0.094
15	25/02/04	14.38	9.55	5.76	24.29	0.147	0.227	0.088	0.057
16	04/03/04	9.17	11.46	5.10	6.97	0.203	0.453	0.198	0.095
17	09/03/04	11.61	14.68	3.52	7.34	0.223	0.394	0.048	0.151
18	16/03/04	16.67	17.43	6.92	31.88	0.229	0.346	0.056	0.080
19	23/03/04	13.14	7.63	7.24	7.09	0.337	0.389	0.456	0.448
20	31/03/04	13.44	11.00	8.01	3.63	1.217	0.948	0.050	0.224
21	07/04/04	14.18	8.44	8.02	20.98	0.202	0.278	0.046	0.120
22	13/04/04	11.84	6.48	6.96	6.65	0.106	0.157	0.132	0.026
23	20/04/04	8.13	6.63	7.58	5.23	0.131	0.436	0.171	0.020
24	28/04/04	9.83	6.30	11.78	12.16	0.052	0.336	0.059	0.154
25	04/05/04	6.29	4.12	4.11	3.29	0.065	0.286	0.043	0.077
26	11/05/04	8.07	5.43	5.87	6.22	0.096	0.176	0.123	0.032
		LSR: 2.8				LSR: 4.2			

		Year 4							
		NO_3-N Concentrations				NH_4-N Concentrations			
Week	Date	T1	T2	T3	T4	T1	T2	T3	T4
1	26/10/04	4.95	5.95	20.81	6.76	0.574	0.779	0.394	0.976
2	02/11/04	7.69	5.22	35.93	8.63	0.109	0.206	0.084	0.291
3	09/11/04	8.77	5.12	32.46	4.80	0.211	0.384	0.161	0.169
4	16/11/04	14.28	6.24	72.22	6.37	0.233	0.280	0.114	0.207
5	24/11/04	13.34	7.08	32.62	9.15	0.241	0.312	0.278	0.382
6	01/12/04	12.63	6.05	19.48	5.91	0.201	0.522	0.215	0.289
7	08/12/04	12.39	5.47	25.48	9.32	0.116	0.195	0.066	0.075
8	15/12/04	14.75	5.59	31.60	5.36	0.230	0.442	0.225	0.234
9	22/12/04	12.87	4.76	29.28	11.97	0.167	0.444	0.263	0.092
10	30/12/04	16.58	4.73	25.77	9.98	0.074	0.202	0.066	0.031
11	12/01/05	19.39	4.89	16.10	10.03	0.156	0.350	0.277	0.151
12	20/01/05	19.80	4.38	17.88	8.92	0.129	0.290	0.124	0.189
13	26/01/05	14.19	5.09	17.39	8.76	0.225	0.218	0.231	0.129
14	02/02/05	12.71	4.62	16.95	7.69	0.205	0.344	0.234	0.268
15	09/02/05	7.12	3.09	3.25	8.74	0.185	0.244	0.143	0.296
16	16/02/05	15.97	4.02	10.78	10.62	0.173	0.241	0.690	0.299
17	23/02/05	14.76	4.60	14.96	9.54	0.137	0.154	0.107	0.204
18	10/03/05	23.46	6.42	14.84	0.19	0.273	0.413	0.580	0.086
19	16/03/05	35.18	6.06	9.60	7.30	0.286	0.045	0.141	0.281
20	23/03/05	16.43	4.68	3.51	10.30	0.231	0.325	0.425	0.293
21	31/03/05	18.40	4.16	8.07	8.46	0.180	0.194	0.253	0.171
22	08/04/05	17.15	3.53	8.53	16.03	0.133	0.481	0.093	0.128
23	15/04/05	14.95	3.66	8.52	7.62	0.296	0.294	0.212	0.243
24	22/04/05	14.66	3.74	8.25	11.98	0.115	0.163	0.115	0.216
		LSR: 3.2				LSR: 3.3			