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2000-LS-2-M2

FINAL REPORT (SECTION 1 OF 3)

Nitrate Leaching - Farm Scale

(2000- L S 2.3.1.1-M2)

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by

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DISCLAIMER

Nitrate Leaching – Farm Scale
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Summary

This farm-scale study, carried out at the Teagasc, Moorepark (Curtin's) farm, examined the effect of four managements (treatments) on nitrate-nitrogen (NO_3-N) leaching between 2001 and 2004. The soil on the grassland farm is a free-draining sandy loam overlying Karstic fissured limestone.

Leaching was measured using 24 ceramic cups at 1 m deep in each the four treatments - (T1) plots receiving dirty water and nitrogen (N) fertilizer which were grazed; (T2) two-cut silage and grazing plots receiving slurry and fertilizer N; (T3) grazed plots receiving fertiliser N and (T4) one-cut silage and grazing plots receiving slurry and fertiliser N. There were 33, 37 and 26 sampling dates in the 2001/2002, 2002/2003 and 2003/2004 drainage seasons, respectively. The NO_3-N and ammonium- N (NH_4-N) concentrations (mg/l) were determined in the water samples. The annual average and weekly concentration of these parameters was analysed using a repeated measures analysis. The aggregated data were not normally distributed. Effective rainfall (drainage) was different in each of the three drainage seasons.

The mean N direct inputs for the four treatments in 2001, 2002, 2003 were 311, 309, 326 kg/ha with mean stocking rates of 2.12, 2.47, 2.47 cows/ha, respectively. Fertiliser N constituted 72-90 % of the total N input to the dirty water plots and was 92 -94 % of the total input to the silage plots in those years.

The NO_3-N and NH_4-N concentrations recorded from the ceramic cups during the monitoring of an intensive dairy farm on a vulnerable soil give cause for concern. The level of concern will depend on the water quality targets required. However, the results must be put in the context of the soils which were selected on the basis of their high vulnerability in terms of leaching. Secondly, management options to reduce the pressure from the intensive dairy system monitored are evident. These can be implemented to reduce the N loading from the system without requiring changes in the production potential of the current management system. Their impact on water, however, remains to be evaluated.

Estimated annual losses, based on the weighted annual mean concentrations of NO_3-N and effective rainfall plus irrigated dirty water were 34.8, 22.6, 36.2 kg/ha N, for drainage years 1, 2 and 3, respectively. The mean losses were 11%, 7% and 11 % of applied N in years 1, 2, 3, respectively. Estimated annual N losses in leached NH_4-N were 1.6, 1.8, 1.1 kg/ha N, for drainage years 1, 2, and 3, respectively, based on the weighted annual mean concentrations of 0.345, 0.317, 0.275 mg/l NH_4-N and effective rainfall plus dirty water irrigation amounts. The amounts of NH_4-N leached were low i.e., 0.5, 0.6, 0.3 % of applied N in years 1, 2 and 3, respectively.

Significant differences ($p=0.05$) in NO_3-N concentrations were found between treatments in the first and second drainage years but not in the third year. In year 1, the grazed (4.9 mg/l) and 1 cut (1.9 mg/l) treatments had lower mean NO_3-N concentration than the dirty water (12.1mg/l) and 2 cut (11.8 mg/l) treatments. In the second drainage

year, the grazed (2.1 mg/l) and 1 cut (0.9 mg/l) again had lower mean NO_3-N concentration than the dirty water (8.1 mg/l) and 2 cut (5.3 mg/l) treatments. T4 (1 cut) had the lowest while T1 (dirty water) had the highest concentration in two of the three years. There were no significant treatment or year effects in the NH_4-N data in the first two years; means ranged 0.18 – 0.42 mg/l.

Weekly average concentrations were analysed separately for each year. For NO_3-N, in year 1 there was an interaction between treatment and week ($p<0.001$). The T4 treatment had the lowest concentration at most times during the year and was significantly lower than T1 in 29 of 33 weeks. T4 was significantly lower than T2 in 28 of 33 weeks but was only significantly lower than T3 for 14 of the 33 weeks. In year 2, there was an interaction between treatment and week ($p<0.001$). T4 had the lowest mean NO_3-N concentration in the majority of weeks. It was significantly lower than T1, T2 for 32 of the 37 weeks and significantly lower than T3 in 20 weeks or 54% of the time-a somewhat poorer relative performance for T3 than in year1. In year 3 there was no interaction between treatment and week and the trends observed in years 1, 2 were not repeated. T4 was very variable and there were no significant treatment effects.

With the NH_4-N data, there was an interaction between treatment and week in all years. In year 1, NH_4-N for T4 was lower than all other treatments at week 2 but was higher than all others at week 26. In year 2, T2 was higher than T4 at 10 of the 37 weeks. In year 3, T2 was higher than T3, T4 for 9, 8 weeks, respectively. Dirty water treatment had highest and 1-cut silage had lowest NO_3-N concentrations in 2 of the 3 years; concentrations in the grazed plots were low in 2 of the 3 years.

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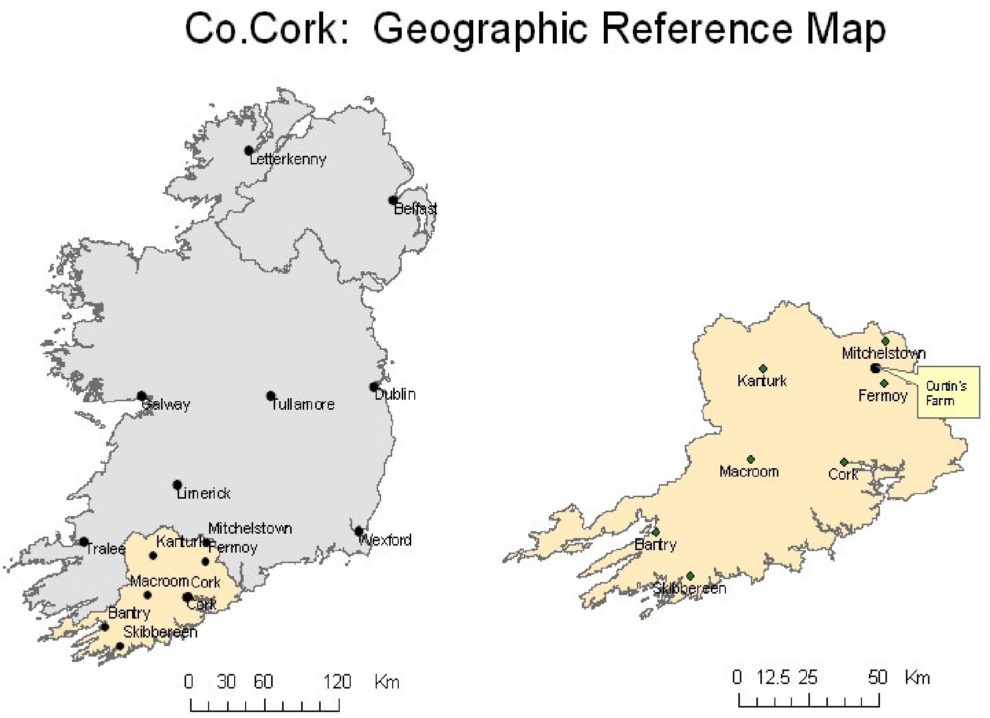
Appendicies

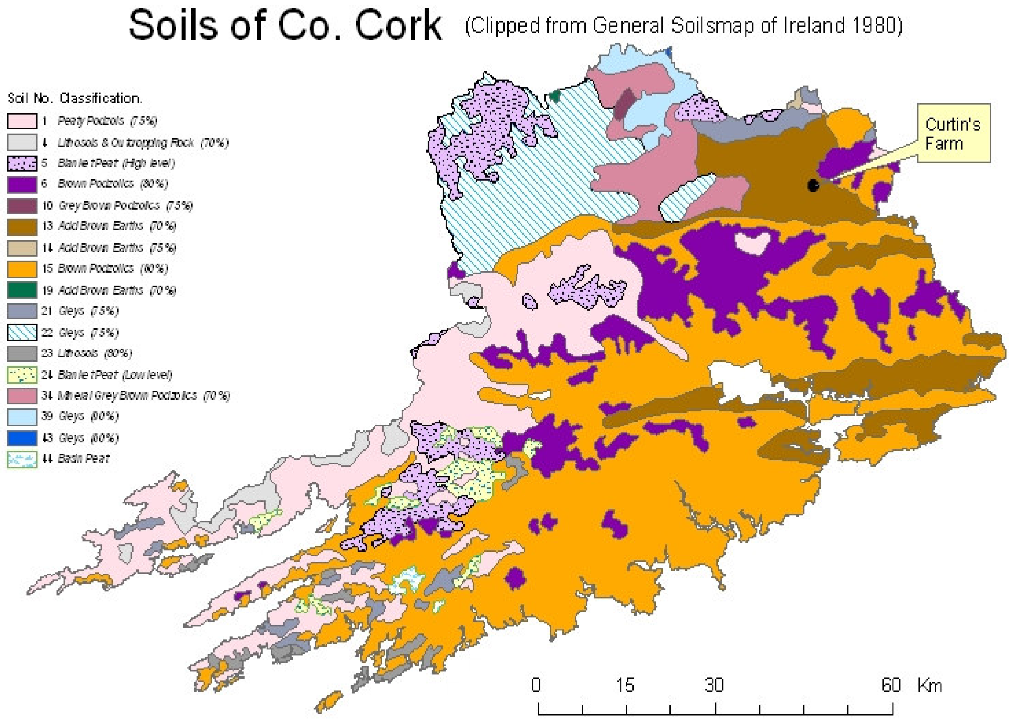
1. Introduction

Nitrate leaching from farmland to receiving waters poses a risk to water quality as well as representing a financial loss. These concerns are discussed in the two accompanying work packages of this study (Bartley and Johnston, 2006; Gibbons *et al.*, 2006) and were to the fore when this project was planned in 2000 and undertaken in 2001-2004.

1.1. Background

In 2000, knowledge regarding the scale, timing and distribution of nitrate leaching from Irish farmland was limited. Studies of nitrate leaching from grass had been carried out on selected grazed plots, cut plots and grass grown in lysimeters (Sherwood, 1990; Sherwood and Ryan, 1990; Ryan and Fanning, 1996, 1999). Until then there had not been an Irish study which measured, contemporaneously, on one farm, the effects of the common, dairy-farm grass managements, on leaching. Dairy farming was seen as the system most likely to pose risk of nitrate leaching since it was known to use the highest levels of nitrogen (N) fertiliser (Coulter and Murphy, 2001) while carrying the highest numbers of stock (stocking rate) per hectare (ha). Areas of the country had been identified as having soils which were considered as being vulnerable in terms of nitrate leaching. This study was undertaken to provide new data on the risks associated with intensive dairy farming on vulnerable soils. The study should provide proposals for remedial action which could be adjusted nationally for both vulnerable and lower risk areas. A vulnerable site (Map1), based on soil characteristics (Gardiner and Radford, 1980), was selected in the Teagasc Dairy Research Centre at Moorepark, near Fermoy, County Cork. This site, Curtin's Farm, has free-draining soils overlying a karstified-limestone bedrock aquifer with an average overburden of 2.5 m (Bartley and Johnston, 2005). Large-scale studies of leaching, such as the present one, are normally limited to just one site over a short number of years because of the costs involved. Clearly, information on leaching risk is required for a range of sites within Ireland and this suggested the use of models. A modelling team from the Institute of Grassland and Environmental Research (IGER) were contracted to develop an Irish-based version of NCYCLE. The model (Scholefield *et al.*, 1991) had shown success in predicting N loss to the environment in the UK and it was expected that, with the use of current and historical data from Irish experiments, the gap in knowledge of N loss to the environment, for a range of soils and sites, could be bridged.





Map 1: Geographic reference and soil map of Co. Cork.

The objectives of the project were:

1. To measure nitrate leaching from an intensively managed dairy farm on a free-draining soil, typical of a nitrate-vulnerable zone.
2. To modify and develop NCYCLE for application to typical Irish systems and sites.

2. Methodologies

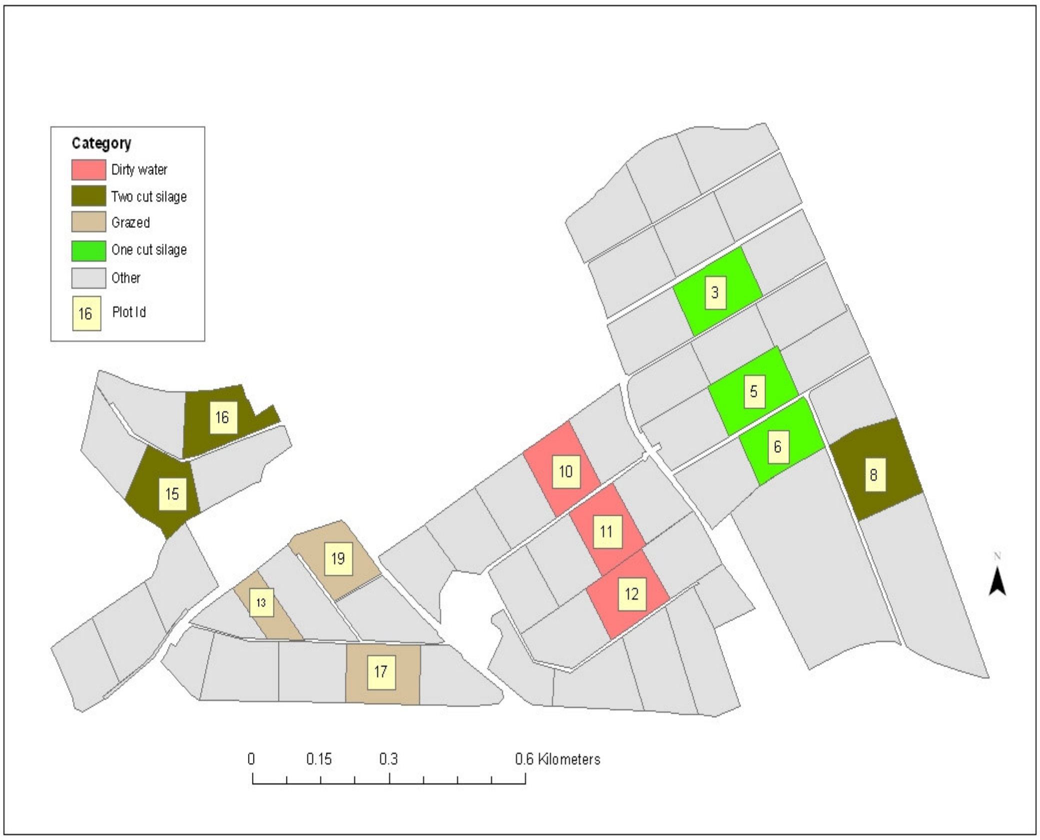
2.1 Four Grassland Managements

The study was a three-year project, 2001-2004, within which the effect of intensive grassland management practices on nitrate leaching at farm scale was investigated. Nitrate leaching to 1 m deep, from managements determined to be representative of the major variables on a dairy grassland farm, was measured using ceramic suction cups. Curtin`s farm, at the commencement of this project, was entirely in grass and dedicated to an animal breeding investigation titled “A comparison of three strains of Holstein Friesian cows managed under various pasture-based systems of milk production” (Horan *et al.*, 2004). There were three herds of cows in the investigation which were allocated to “red”, “yellow” and “blue” subplots within each of the plots on the farm. One third of the total cows grazing Curtin`s farm in each year were allocated to each of these herds and within each herd there were equal numbers of New Zealand, High Durability and High Merit strains. The “blue” plots were used for this farm-scale study and there were 108, 117,117 and 126 dairy cows allocated to these plots in 2001, 2002, 2003, and 2004, respectively.

The managements, from hereon called treatments, studied involved plots that were: (T1) Grazed, receiving dirty water and fertiliser N applications; (T2) Cut twice for silage, grazed, receiving slurry and fertiliser N applications; (T3) Grazed only, receiving fertiliser N applications; (T4) Cut once for silage, grazed, receiving slurry and fertiliser N applications. The managements had variable grazing pressures and N inputs within years but similar pressures and inputs across years.

2.2 Replication - number of plots and ceramic cups

Three replicate plots were chosen from the field plots to represent each of the treatments. These were unevenly distributed in the relevant blocks across the site, e.g. all the dirty water plots were contiguous while the other treatment plots were not (Map 2). Plot sizes ranged 0.775-0.865, 0.768-1.257, 0.45-0.919, 0.865-0.866 ha in the four treatments, from hereon designated, dirty water, 2–cut, grazed, 1-cut.



Map 2: Layout of treatment plots on Curtin's Farm

2.3 Drainage water samples

The objective of the study was to measure NO_3-N in drainage water moving below the root zone of each plot of each of the treatments described above. Ceramic suction cups were used to obtain samples of the soil solution. These were considered to be a reliable technique for collecting drainage water samples in free draining unstructured soils similar to those found on Curtin's farm (Goulding and Webster, 1992). The ceramic sampling cups were installed at 1 m deep and a total of 24 were used for each of the four treatments. Sampling during the autumn-spring drainage period was on a once weekly routine. This practice provided 33, 37 and 26 sampling dates in years 1, 2, 3 of the project, respectively.

2.4 Preparation of ceramic suction cups

Eight cups were installed in each grass plot giving 24 replicate cups per treatment and a total of 96 cups for the 12 plots. An equal number of 1 l pyrex (BS 1739) Buchner flasks, to collect drainage water under vacuum, were fitted with tight-fitting rubber bungs having one perforation to allow entry of tubing (6 mm o.d., 4 mm i.d.) that connected to a tight-fitting bung in the ceramic cups. The 96 sealed ceramic cup samplers were assembled in the laboratory at Johnstown Castle prior to installation in the field. Cups are round-bottomed, straight necked, 80 mm long having a 23 mm o.d., 14 mm i.d. To make the tube connections from the ceramic cups to the water-collecting flasks, a rubber seal (u ring), 14 mm o.d., 8 mm i.d., was introduced into the ceramic cup. Norgren tubing, 8 mm o.d., 5 mm i.d., was then put through this rubber seal in the ceramic cup. Finally, nylon tubing (7 mm o.d., 4 mm i.d.), which connects to the rubber bung in the water flasks, was inserted into the Norgren tube. The rubber seals were glued to the cup using Loctite Super glue and sealed on the outside using clear Silicone sealant.

Soil water was extracted from the soil using hand pumps supplying a vacuum of 50 k Pa. The ceramic cups (100 k Pa entry value) and hand- pumps were manufactured by Soil Moisture Equipment Corporation, Santa Barbara, California, USA.

2.5 Insertion of ceramic cups

Insertion of ceramic cups at 1 m depth was started on May 14th, 2001 using a soil coring screw auger which bored a 25 mm hole. Due to excessive soil smearing this proved unsuitable and was immediately abandoned in favour of the Giddings Deep Boring Machine which bored holes of the same diameter without smearing. Insertion of cups recommenced on May 28th, 2001 and was completed by August 2001. Delay in the completion of insertion was experienced due to experimental grazing requirements of plots and the need to minimise damage to herbage-on-offer by the drilling rig. The cores for insertion of the ceramic cups were drilled in an alternating pattern in each plot, i.e. if the first was 6 m from the edge of the plot the second was placed 8 m from the edge etc. Where hedges were present, the drilling took place 10 to 13 m from the hedge. The cups are generally linearly located 15 to 20 m apart. Soil retrieved from soil core drilling was laid out on the ground on plastic in the order of its removal from top to bottom. Prior to the insertion of the ceramic cups into the bored hole, they were surrounded with a slurry made up from the soil removed from the bottom of the core. The remaining soil was returned to the bored hole in the order of its removal in so far as was possible.

To avoid the risk of solution being channeled along the body of the tubing and sampler, a plug of expanding betonite clay was placed around the tubing at *ca* 150 mm below the ground surface at the time of insertion.

Once the ceramic cups were installed in a zig-zag pattern in the plots, the connecting tubing was led underground to the electric fence area of each plot where the water collecting flasks were located, overground. Electrified wires, carried on plastic posts, protected the flasks from interference by cows. Connection of tubing to water-collecting flasks and the protection of flasks was completed by September 26th, 2001.

2.6 Initial application of vacuum

Soil water was extracted from the cups using hand-pumps that applied a vacuum of 50 k Pa. From October 1st 2001 suction was applied to half the cups as a test for free drainage water in the soil. Only four cups delivered water after four days. Suction was applied on weekly basis during October 2001 with 67 water samples collected on

October 24th. Thereafter, suction was re-applied and water samples were collected weekly. All ceramic cups, with one exception, provided water samples by December 2001, which was indicative of very satisfactory installation and appropriate suction applied.

2.6.1. Annual sampling of soil water

In the first year, sampling of ceramic cup soil water commenced on October 24th, 2001 and continued weekly until June 5th, 2002. In the second and third years, the sampling periods were from October 30th, 2002 to July 9th, 2003 and November 19th 2003 to May 11th, 2004, respectively. The soil water samples collected were stored at 4° C over-night prior to 0.06 ml concentrated sulphuric acid being added next day. They were maintained at 4°C for one week at Curtin`s farm before being transported to the Johnstown Castle laboratory in a cool- box at 4°C. The soil water samples collected were analysed for NO_3-N and NH_4-N concentrations on a KONELAB auto-analyser. The accuracy of the auto-analyser was checked against standards on one occasion per five batches analysed. Quality checks were also performed in tandem where tolerances for high and low values had to be within 90 and 10%, respectively. The relationship between volume of drainage water and NO_3-N concentration was tested with samples and volumes collected from 47 cups replicated on three dates in November 2004.

2.7 N applications

Apart from a small annual input of atmospheric N, measured to be 9 kg/ha/yr in 2002-04, the main inputs of N to the 4 treatments were from fertiliser, slurry, dirty water and returns of dung and urine by grazing animals

2.7.1 Fertiliser

Fertiliser type was varied and included urea (46% N), sulfa-CAN (5% sulphur, 27%N) spread in spring with calcium ammonium nitrate (CAN) and the N, phosphorus (P), potassium compounds 10.10.20 and 27.2.5.5 applied during the remainder of the year. Rates and dates of fertiliser N application are shown in Section 2, Appendix 1.

2.7.2. Slurry

Slurry was applied prior to first and second cut silage (Section 2, Appendix 1). The timing, rates of application together with nutrient concentrations and the amounts of N added to plots in slurry are shown in Section 2, Appendix 2. The usable N value assigned to slurry was 0.25 total N for spring applications only. Even though slurry was applied for second cut silage, the N value was discounted to zero, as advised by Johnstown Castle laboratories (Coulter, 2004) and was not included in the total N inputs in Section 2, Appendix 1.

2.7.3. Dirty water

Dirty water irrigation was carried out using a self-propelled rotary sprinkler, trade name “Roto-rainer”. Initially, two plots were used but this was extended to a third plot in July – August, 2001. A new Roto-Rainer was purchased and set up for irrigation on November 7th, 2001. Monitoring showed that the rate of irrigation was 164,510 l/ha on plot 11 (0.775 ha) and 182,846 l/ha on plot 12 (0.865 ha), in the periods 6th to 27th

November and 28th November to December 7th, 2001, respectively. These equate to 16.5 and 18.3 mm, respectively. Annual rates applied to plots 10, 11, 12 in 2002 and 2003 were 26.3, 31.4; 19.7 and 35.9; 24.2, 32.8 mm, respectively (Table 1).

Table 1. Dates and rates (mm) of irrigation of dirty water on plots 2002- May 2004.

Plot	Date	Rate	Plot	Date	Rate	Plot	Date	Rate	Plot	Date	Rate
10	29/4-1/5/02	3.5	10	24/5-3/6/03	12.1	11	18/5-22/5/02	3.6	12	22/5-24/5/02	2.7
	1/6-5/6/02	5.7		23/7-4/8/3	7.0		17/6-24/6/02	4.5		12/8-14/8/02	5.8
	29/7-31/7/02	2.5		1/10-9/10/03	5.9		23/12-1/1/03	13.1		25/11-6/12/02	15.7
	9/9-16/9/02	4.8		31/12-10/1/04	5.4		24/2-17/3/03	24.1		30/1-24/2/03	20.5
	28/10-4/11/02	9.8		8/3-16/3/04	6.5		15/10-22/10/03	5.7		16/5-24/5/03	4.4
	28/4-5/5/03	6.4					15/12-23/12/03	4.6		14/6-19/6/03	2.7
							24/3-7/4/04	12.5		9/12-15/12/03	5.2
										13/2-25/2/04	6.8
										30/4-7/5/04	10.8

Apart from plots 11, 12 which each had > 20 mm applied once and had >10 mm applied in November 2002-January 2003 the dirty water irrigation rates were generally irrigated in-line with those recommended by Gibbons *et al.,* (2006)

Dirty water samples for laboratory analyses were collected from the end of the irrigation pipe when experimental plots were being irrigated. The volumes and concentrations of NH_4-N, NO_3-N, total N, (total P, where available) in the dirty water, as land-spread in 2002-2004, are shown in Appendix 3 of Section 2. The quantities of N applied from the dirty water irrigation in the experimental years are shown in Appendix 1, Section 2.

A value of 0.85 of the total N applied in the dirty water was used to calculate the dirty water N contribution to the total N budget. This was to allow for possible ammonia volatilization during spray irrigation and retardation of the organic N mineralisation. In contrast, Di *et al.* (1998), in a lysimeter study, where dairy shed effluent was applied as spray or flood irrigation at 400 kg/ha N, allowed the total N in the effluent without discount for possible losses, in calculating N applied.

Plots irrigated with dirty water receive mineral and organic carbon (C) and N additions on a regular basis. Soil samples were taken at three random locations within each of three replicate plots of the four management treatments in December 2003 and analysed for total N and organic C. Each of the 12 plots sampled was visually subdivided into three sub divisions and 15 soil cores, 100 mm deep, were randomly taken within each subdivision. The laboratory analysis was carried out on 0.5 g air-dried samples using a LECO CN 2000 analyser.

2.7.4. N inputs

Mean fertiliser, dirty water and slurry N inputs to the treatments for 2001, 2002, 2003 and 2004 are shown in Table 2.

Table 2. Fertiliser, dirty water (D), slurry (S) nitrogen inputs in 2001, 2002, 2003, 2004.

Mean[1]Inputs of Nitrogen (kg/ha) to Curtin`s - Farm-Scale Plots												
(16.92 ha Jan-Nov 01; 16.87 ha from Nov 01-Nov 03)												
	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	n/a	239	265	n/a	265	294	n/a	294	298	n/a	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 2nd cut silage exported from farm; [1]9 kg/ha/yr N from atmosphere not included.
0.85, 0.25 of total N allowed for N input from dirty water and slurry, respectively

2.7.5. Grazed, recycled N

The estimates of the N recycled at grazing for 2001, 2002, 2003 and 2004 are shown in Table 3. The number of cows grazing each plot(s) and the number of grazings, i.e. AM (daytime) or PM (night time) in each of the four years, 2001 to 2004, are shown in Appendix 4 – Section 2. Cow grazing days is the number of grazing days (total number of grazings per plot divided by two) multiplied by the number of cows grazing. For example, plot 12 Blue in 2001 (Appendix 4 – Section 2) had 48 grazings made up of AM and PM grazing events. This equates to 24 grazing days which when multiplied by the number of cows, 36, gives 864 cow grazing days on plot 12. This is equivalent to 999 cow grazing days per ha as the area of the plot 12 is 0.8649 ha. Recycled N (kg/ha) was calculated by multiplying the number of cow grazing days by 0.3 kg/day N. This is the estimated daily N excretion rate for the cows on Curtin's farm (P. Dillon, pers comm.) Herbage-on-offer, dry matter (DM), N yields and crude protein concentrations for the grass at grazing in 2001, 2002 and 2003 are given in Appendix 5 - Section 2.

Table 3. Recycled N (kg/ha) (cows 36 in`01, 39 in`02, `03, 42 in `04) @108 kg /cow/yr

	Year 1	Year 2	Year 3	Year 4
	2001	2002	2003	2004*
Dirty water	206	226	248	58
2-cut silage	56	85	96	39
Grazed	241	228	222	72
1-cut silage	138	136	165	40
Weighted mean	153	163	178	51

*To May

2.8. Rainfall

The rainfall data for the drainage years, 2001 to 2003 and up to May 2004, are presented in Table 4. Annual effective rainfall for the same periods is shown in Appendices 7 to 9 – Section 2.

Table 4. Monthly rainfall (mm) for 2001, 2002, 2003 and up to May 04 and 42-year mean at Teagasc, 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								

*Long term mean monthly rainfall (1961-2002)

November and December 2001 were exceptionally low rainfall months – 30 and 62 mm, respectively, compared with 42 year means of 99 and 109 mm, respectively. October and November 2002 were very wet months – 165 and 178 mm, respectively compared with the 42 year means for both months of 105 and 99 mm, respectively. Rainfall amounts for the periods October to January (i.e., the period when most leaching is expected) were approximately 44% of the annual average. The years 2001 and 2003 had 15% and 12% lower than average rainfall, respectively, whereas 2002 had 20% higher than the long-term annual mean rainfall.

3. Results

The NO_3-N and NH_4-N concentrations for each cup for each treatment on each date in each year together with weekly drainage are presented in Appendices 7, 8 and 9 in Section 2. The weekly drainage was calculated using the FAO Penman-Monteith method (Allen *et al.*, 1998) for evapotranspiration and the Aslyng scale to modify potentially overestimated evapotranspiration data (Aslyng, 1965). Where no water sample was obtained, the abbreviation "ns" is used; for readers interested in considering the large amount of data presented in relation to a quality target, values > EU maximum admissible concentration for drinking water are printed in red, i.e., 11.3 and 0.23 mg/l for NO_3-N and NH_4-N, respectively (S.I. No.81 of 1988).

The data for each year consisted of NO_3-N and NH_4-N concentrations in the leachate in 96 individual cups measured weekly for 33 consecutive weeks in the first year and for 37 and 26 weeks in the second and third years, respectively. Frequently there was not enough leachate in a cup to carry out a laboratory analysis. Sometimes concentrations varied widely between cups in a plot.

The NO_3-N and NH_4-N concentrations were 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 N types was analysed using a repeated measures analysis over the three years. The data consisted of 36 values for each N type (4 treatments x 3 replicates x 3 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. (See Appendix A for more detail on this model fitting). Three types of correlation structure (Appendix B) were examined to describe the relationship among the repeated values across years. The GLIMMIX macro in the statistical software package SAS was used.
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 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) (Appendix A). 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.

The relationship between rainfall and average N concentrations was examined. A number of additional analyses were performed. During the experiment: the number of cow-grazing-days /ha and the N applied (kg/ha) for each year were calculated for each plot. Annual N per plot was the total N from fertiliser, slurry and dirty water. The number of cow-grazing-days and the N applied were included as covariates in the analysis of annual average N concentrations in plots. The relationship between N concentration and cup leachate volume was checked using the leachate volume data from some cups that was recorded on three dates in November 2004. The relationship between the leachate volume and N concentrations for each cup measured was investigated on each of the dates using both the raw data for each cup and the averaged data for each plot. An additional analysis was carried out using this data to determine if the leachate volume in the cups was affected by the treatment applied to it.

3.1. Analysis of annual average N concentrations

In the following, all effects noted were significant at the 5% level or less unless otherwise stated. There was an interaction between treatment and year (p=0.0072). In drainage year 1 (October 24th 2001 to June 5th 2002 – 33 weeks), T3 (grazed) and T4 (1 cut) had lower mean NO_3-N concentration than T1 (dirty water) or T2 (2 cuts)(Figure 1). The T4 or 1 cut treatment was also lower than grazed treatment (T3) (Figure 1). In year 2 (October 30th 2002 to July 9th 2003 – 37 weeks), T3 (grazed) and T4 (1 cut) were lower than both T1 (dirty water) and T2 (2 cut). In year 3 (November 19th 2003 to May 11th 2004 – 26 weeks), there were no significant differences between treatments. This analysis indicated that the treatment with one cut (T4) caused the lowest NO_3-N concentration, while the dirty water treatment (T1) caused the highest. However, while these conclusions were supported in year 1 and 2, they were not in year 3.

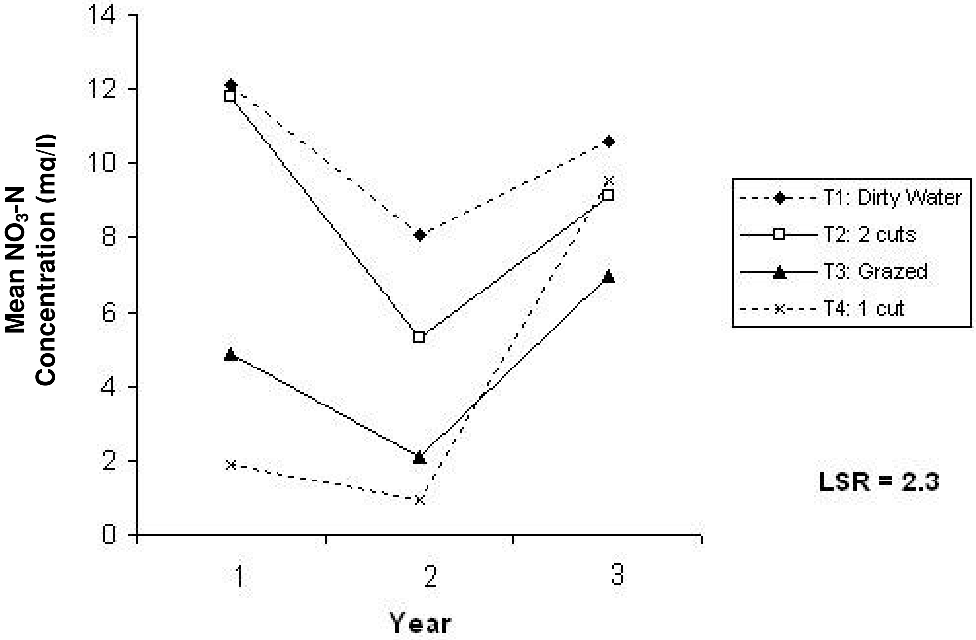


Figure 1: Mean NO_3-N concentration (mg/l) for each year by treatment combination.

Note: **1** Year 1 = October 24th 2001 to June 5th 2002; Year 2 = October 30th 2002 to July 9th 2003 and Year 3 = November 19th 2003 to May 11th 2004.

Note 2. 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 for more detail on the LSR.)

There were no significant treatment effects for the NH_4-N data in years 1 and 2. However, there was a significant effect of treatment in year 3 when T3 (grazed) and T4 (1 cut) were significantly lower than T2 (2 cuts) (Figure 2).

Weighting concentration by effective rainfall in forming an annual concentration did not appear to have much effect. Tables of means used to construct Figures 1 and 2 are presented in Appendix C. For the analysis for the NO_3-N data, compound symmetry (CS) was found to be the most appropriate way to describe the correlation between the repeated measurements, (Appendix D).

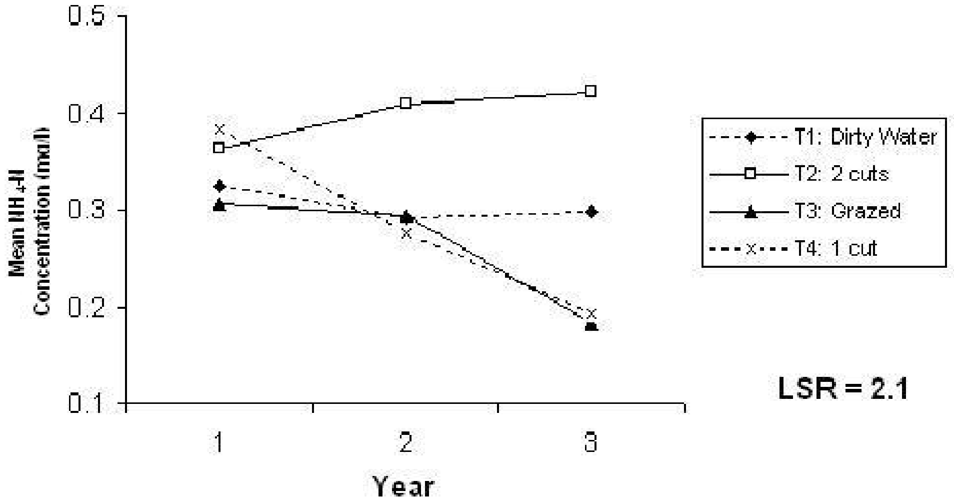


Figure 2: Mean NH_4-N concentration (mg/l) for each year by treatment combination.

Note: **1** Year 1 = October 24th 2001 to June 5th 2002; Year 2 = October 30th 2002 to July 9th 2003 and Year 3 = November 19th 2003 to May 11th 2004.

Note 2. 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 for more detail on the LSR.)

3.2. Analysis of weekly average ceramic cup water nitrogen concentrations

3.2.1. Nitrate nitrogen (NO_3-N). This analysis was carried out separately for each year. In year 1, there was an interaction between treatment and week ($p<0.001$) (Figure 3a; means in Appendix F). T4 (1 cut) had the lowest NO_3-N concentration at most times during the year and was significantly lower than T1 (dirty water) for 29 of the 33 weeks. The T4 (1 cut) treatment was significantly lower than T2 (2 cuts) for 28 of the 33 weeks but was only significantly lower than T3 (grazed) for 14 of the 33 weeks. This analysis indicated that the T4 treatment (1 cut) gave the lowest NO_3-N concentration while the T3 treatment (grazed) gave a close second lowest in the first drainage year.

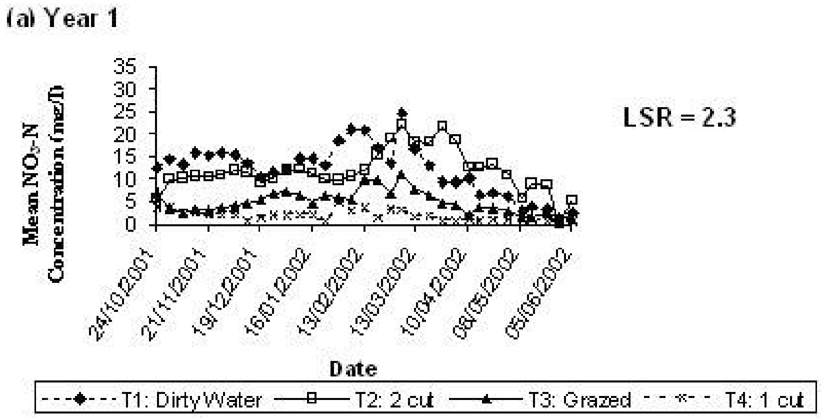


Figure 3a. Trends in mean NO_3-N concentration (mg/l) for each treatment by week for drainage year 1 (October 24th 2001 to June 5th 2002).

In year 2, there was an interaction between treatment and week ($p < 0.001$). Again, T4 (1 cut) had the lowest mean NO_3-N concentration in most weeks (Figure 3b). It was significantly lower than both T1 (dirty water) and T2 (2 cut) for 32 of the 37 weeks. It was significantly lower than T3 at 20 of the 37 weeks, or 54% of the time. Similar to the trend in year 1, T4 continued to emerge as the treatment with the lowest NO_3-N concentration.

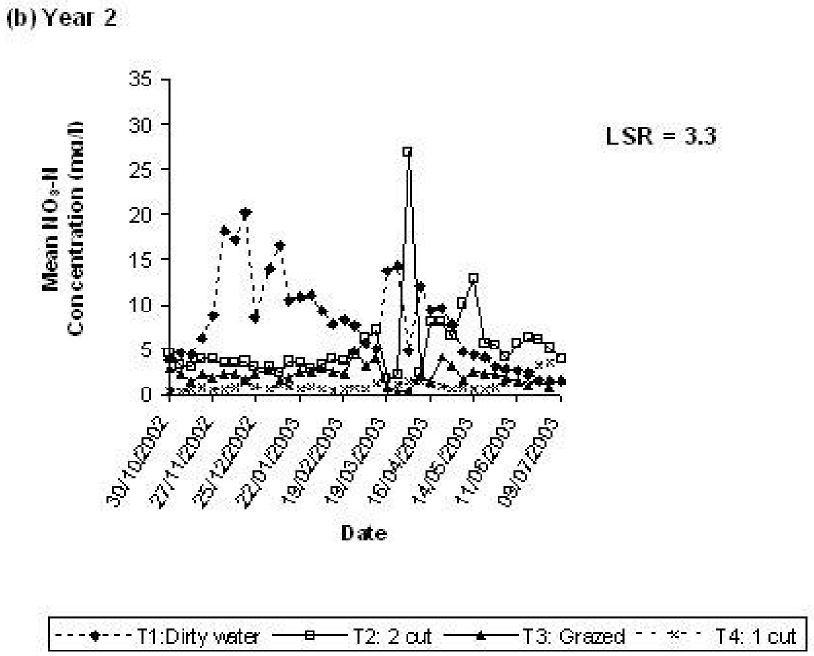


Figure 3b. Trends in mean NO_3-N concentration (mg/l) for the four treatments by week during drainage year 2 (October 30th 2002 to July 9th 2003).

In year 3, there was no interaction between treatment and week (p=0.086). The trends observed in the first two drainage years were not repeated. The NO_3-N concentrations for the T4 (1 cut) were very variable. There were no significant treatment effects. (Figure 3c). The AR (1) correlation structure was the most appropriate for the relationship among repeated measurements for each year, (Appendix E).

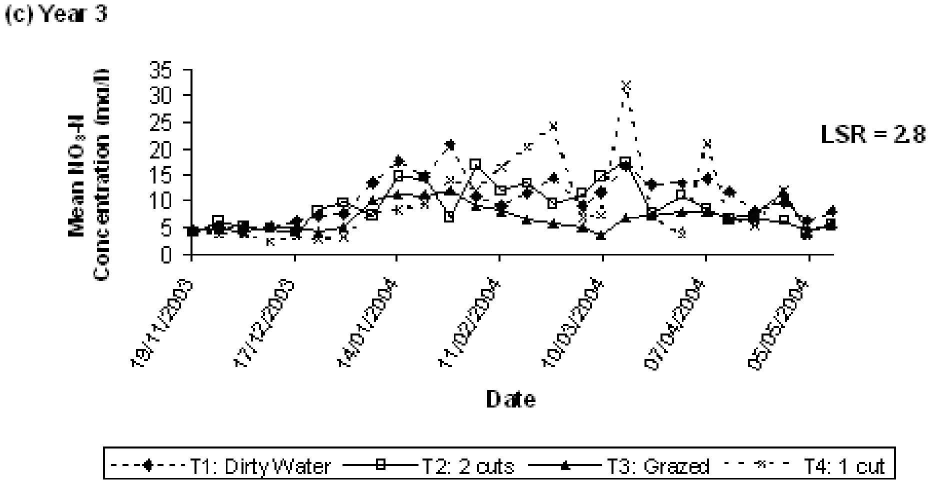
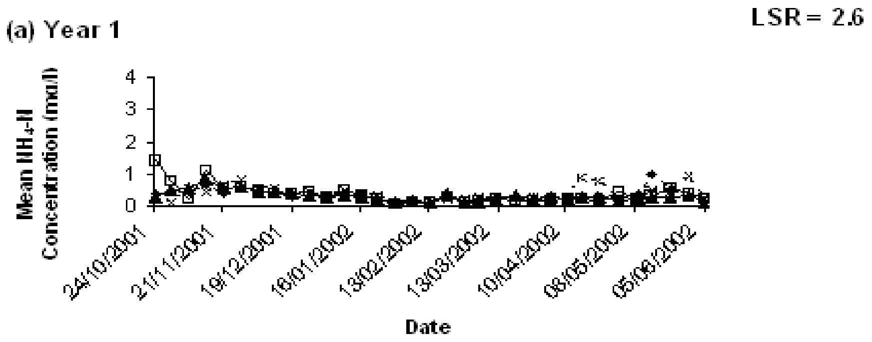
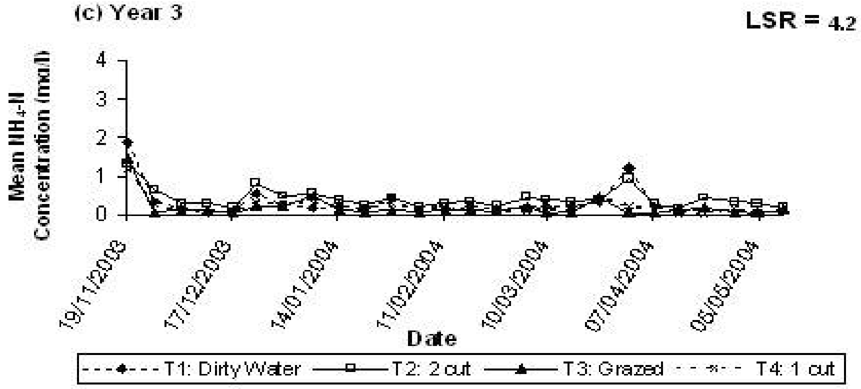


Figure 3c: Trends in mean NO_3-N concentration (mg/l) for each treatment by week for drainage year 3 (November 19th 2003 to May 11th 2004).

3.2.2. Ammonium-nitrogen (NH_4-N). While no trends were observed in years 1 and 2 in the first analysis of the data with NH_4-N as the response variable, each year was also analysed separately. In all years there was an interaction between treatment and week, (p=0.002, <0.001, =0.004). In year 1 the interaction between treatment and week was caused by a small number of weeks, (Figure 4a; means in Appendix F). There were treatment effects for six weeks during the year but these effects were not consistent, e.g., the NH_4-N concentration for T4 (1 cut) 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 (2 cuts) was higher than for T4 (1 cut) for 10 of the 37 weeks (Figure 4b). In year 3, T2 (2 cuts) was higher than T3 (grazed) and T4 (1 cut) for nine and eight weeks, respectively, of the 26 weeks, (Figure 4c). The correlation structure CS was appropriate to describe the relationship between the repeated measurements in years 1 and 3 and AR (1) was appropriate in year 2, (Appendix E).





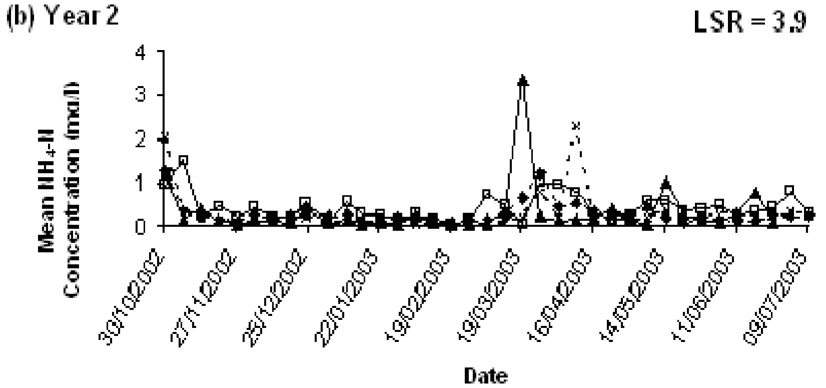


Figure 4a, b and c: Trends in mean NH_4- N concentration (mg/l) for each treatment in each of the three drainage years. Year 1 = October 24th 2001 to June 5th 2002; Year 2 = October 30th 2002 to July 9th 2003 and Year 3 = November 19th 2003 to May 11th 2004.

3.2.3. Rainfall and N concentration.

Rainfall was recorded for each week of the experiment. Weekly effective rainfall measurements and NO_3-N and NH_4-N concentrations were plotted for the first year of the experiment (Figures 5 and 6). No obvious trends emerged which may not be surprising. The ceramic cups were buried at 1 m. Therefore, there will be a lag time between the occurrence of the effective rainfall and the time it reaches the ceramic cup. The lag time will depend on many factors, including the amount of effective rainfall, the moisture content in the soil and soil structure. The time taken can vary from a week or two to many months.

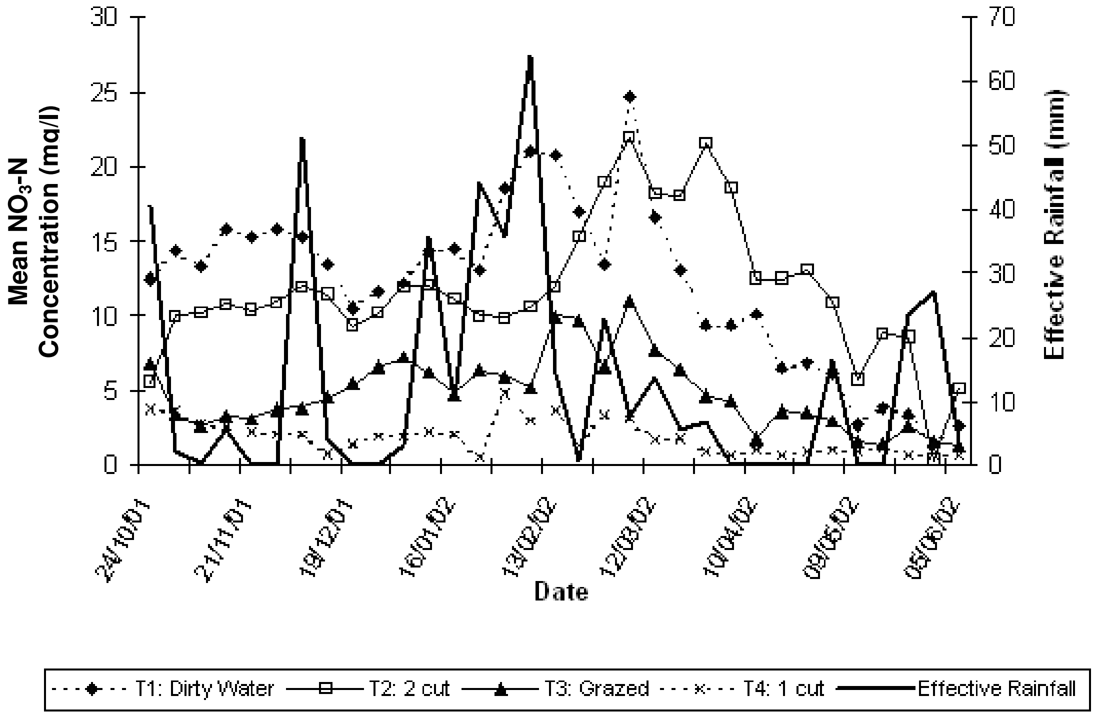


Figure 5. Trends in mean NO_3-N concentration (mg/l) and effective rainfall (mm) for each week in year one.

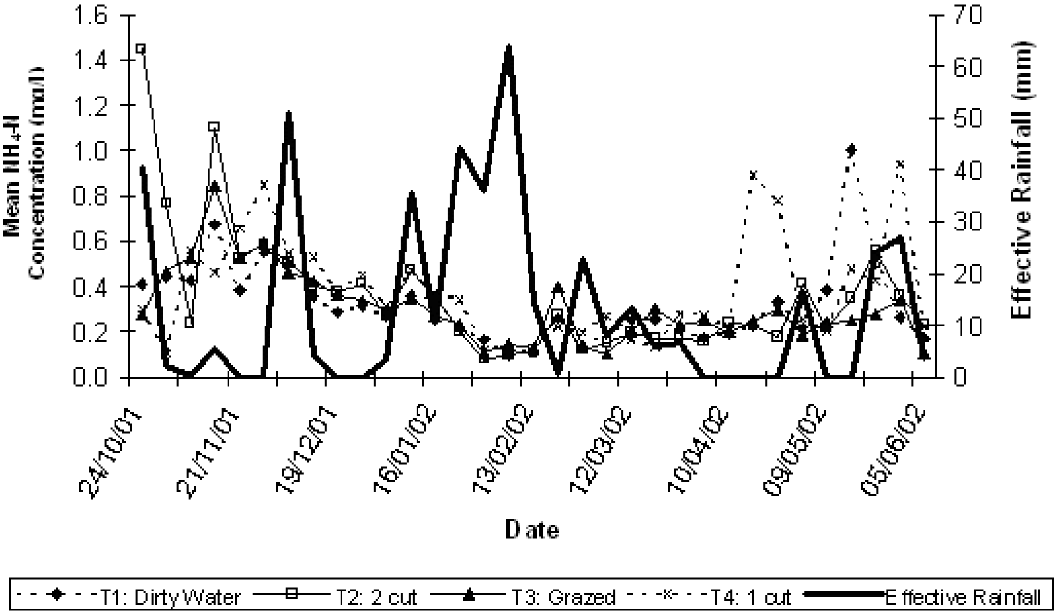


Figure 6. Trends in mean NH_4-N concentration (mg/l) and effective rainfall (mm) for each week in year one.

3.2.4. Additional variables recorded.

No relationship was found between the N concentration and either cow grazing days or total N applied (kg/ha) within each treatment. The 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. Details of these analyses are given in Appendices G, H and I, respectively.

4. Deliberation on the data

4.1. Nitrate-N

Estimated annual losses, based on the weighted annual mean concentrations of NO_3-N and effective rainfall plus irrigated dirty water were 34.8, 22.6, 36.2 kg/ha N, for years 1, 2 and 3, respectively. The mean losses were 11%, 7% and 11 % of applied N in years 1, 2, 3, respectively.

It is suggested that denitrification may have been responsible for the lower mean loss figure (7%) recorded in second year compared with year 1 and 3. In the three months, October-December 2002, rainfall was 450 mm compared with 212 and 248 mm for the same periods in 2001 and 2003, respectively (Table 4). There were 15 days with rainfall amounts >10 mm in those months of the second year compared with only six days in the other two years. This additional wetting of the relatively warm soil in 2002

(11.3, 9.3, 7.2°C mean maximum at 0.3 m deep in October, November, December with maximum daily air temperatures of 9.7-19.5 °C in October, 8.2-16.7 °C in November, 4.1-12.8, °C in December (Met Eireann, 2002)) could have induced relatively high denitrification rates in the soils well supplied with N. A soil temperature of >5°C is usually required for significant denitrification rates to occur (Aulakh *et al*, 1983) although Firestone (1982) states that the minimum temperature required may range from 2.7-10°C. It is expected that highest rates would have occurred in the dirty water plots.

In year 1 the N leached from T1 (dirty water), T2 (2 cut), T3 (grazed) and T4 (1 cut), based on effective rainfall and irrigated dirty water, was 55, 52, 21, 8 kg/ha, respectively. This was equivalent to 23%, 13%, 9%, 2 % of the N applied to each of the four treatments (T1 – T4), respectively. In the second year, the N leached was 46, 29, 11, 5 kg/ha (or 15%, 8%, 4%, 2 % of the N applied) for T1, T2, T3 and T4, respectively. In the third year, the N leached was 44, 36, 28, 38 kg/ha (or 13%, 11%, 10%, 12 % of the N applied) for T1, T2, T3 and T4, respectively. These N leaching losses are generally lower than expected losses (14%), as quoted by Sherwood and Tunney (1991). The losses from the grazed-only plots (T3), at 7.6%, are lower than the mean of 8 years, 13%, reported by Watson *et al.* (1998) for grazed plots in Northern Ireland.

Weighted mean NO_3-N concentrations appeared to be inversely related, on an annual basis, to annual effective rainfall e.g., 398, 440, 539 mm effective rainfall were associated with mean NO_3-N concentrations of 9.1, 7.9 and 4.2 mg/l in years 3, 1, 2, respectively. This result is similar to one recorded by Bartley and Johnston (2005) for year 2 compared with year 1 in their study. A regression of NO_3-N concentration (y = mean values for treatments in each year), on effective rainfall (x) showed a low R^2 value. The statistically non-significant relationship was: $y = - 0.0352x + 23.12$, $R^2 = 0.3091$ ($p>0.05$). Due to the small number of years represented in the data, this can only be regarded as a hint as to what might occur with varying effective rainfall. It is a repeated measures observational point and would require low and high rainfall treatments for further elucidation.

Statistically significant effects of treatment on NO_3-N concentrations were shown in two of the three years (Appendix C, Table C1). However, an important feature of the data is the variability in the NO_3-N concentrations recorded for each of the 24 cups in any of the four treatments across the totality of weeks in each of the three measurement years. The full extent of this variability is evident from Appendix F, Table F1, Figures 3 and 4 and Appendices 7-9 in Section 2. Some examples of this variability are highlighted below.

Weekly mean NO_3-N concentrations in year 1 (Appendix F, Table F1), for T1 (dirty water), T2 (2 cut), T3 (grazed) and T4 (1 cut) ranged 1.36-24.71, 0.36-22.0, 1.31-11.07 and 0.64–4.84 mg/l, respectively. The larger range for T1, T2, compared with T3, T4 is notable. In cup 16 of T1 (dirty water), a maximum of 131.10 mg/l was recorded on November 14th 2001 which was in the third week of a run of 16 weeks with elevated values starting with 19.19 mg/l on October 31st 2001 and ending with 15.76 mg/l on February 13th 2002. The effective rainfall ranged 0.0-63.88 mm in that period. A nearby cup, number 15, had elevated values for 21 weeks starting on November 28th 2001 with 11.36 mg/l, a maximum of 86.24 mg/l on March 5th 2002 (15th week), and ending on April 16th 2002 at 21.92 mg/l. The effective rainfall was identical to that of cup 16.

Cup 29 of the T2 treatment (2-cut) had elevated NO_3-N concentrations starting with 61.71 mg/l on October 31st 2001, declining to 33.80 mg/l after 19 weeks followed by two `no sample` weeks and then a maximum 99.69 mg/l March 27th 2002. The effective rainfall associated with the elevated values, 61.71-80.75 mg/l was generally low initially, i.e., 0.0-5.66 mm/week with one exception of 51.14 mm. Higher effective rainfall of 0.51-63.88 mm/week was associated with somewhat lower concentrations, 33.80-66.08 mg/l NO_3-N from January 9th to March 20th 2002. The overall relationship of concentrations with effective rainfall was poor, as described above.

Cup 48 (T2 – 2 cut) had five weeks with sample values ranging 16.03–28.67 mg/l from March 5th to April 3rd 2002 while cup 46 had four weeks with values 19.58-48.08 mg/l in the period February13th to March 5th 2002. This was followed by two weeks with no sample and then four more weeks of high concentrations 17.33-35.35 mg/l.

Grazed plots (T3) had a maximum 92.99 mg/l on March 5th 2002 which was midway in a run of high concentrations for cup 67 that started with 82.92 mg/l on February 13th 2002 and finished with 23.02 mg/l on April 3rd 2002. The treatment had an example (cup 50) of a high concentration on a single date (15.79 mg/l – March 5th 2002) which was not preceded (previous five samples ranged from 6.51-8.57 mg/l) nor followed by a similar concentration (subsequent three samples ranged from 5.42-9.68 mg/l).

There was considerable variation over time in the NO_3-N concentrations recorded for cup 95 in the T4 (1-cut) treatment. On December 26th 2001 the value was 15.35 mg/l and remained high over four weeks, reaching 31.84 mg/l on January 16th 2002. The concentration then declined to 0.01 mg/l for one week before rising to a maximum value of 51.16 mg/l on January 30th 2002. Subsequently, there were no samples for six weeks but the concentration was still high, 17.99 mg/l, when the next sample was collected on March 20th 2002. This may not be too surprising as there was no apparent drainage during this period. In the following two weeks concentrations declined to 5.26, 8.84 mg/l before increasing again to 15.94 mg/l on April 10th 2002 and declining to 2.37 mg/l on April 16th 2002.

The second year data of mean NO_3-N concentrations (Appendix F, Table F1) showed the ranges for T1-T4 inclusive, to be 1.50-20.28, 1.63-26.87, 0.85-4.13 and 0.31-3.51 mg/l, respectively. The largest range was for T1 (dirty water) and T2 (2 cut) treatments which was similar to the first year. High concentrations persisted for nine weeks in cup 5 of the T1 treatment, commencing with 160.59 mg/l on December 4th 2002 increasing to a maximum 172.99 mg/l two weeks later before declining to 16.37 mg/l by February 12th 2003. Nitrate nitrogen concentrations of 17.54-23.30 mg/l occurred between April

9th and the 30th 2003. Cup 22, also from the T1 treatment, had values ranging 15.70-31.26 mg/l over the 14 week period from December 4th 2002 to March 5th 2003 with the highest value, 75.61 mg/l, recorded in the 5th week. Concentrations for T2 (2 cut) were noticeably lower than T1 (dirty water) which in general, contrasted with year 1. Cup 35, in T2 was notable in that, it had high NO_3-N concentrations for the 14 weeks between April 2nd and July 2nd 2003 with two exceptions. The values ranged from 51.3 mg/l initially down to 12.6 mg/l with a maximum of 66.2 mg/l April 30th 2003. Low numbers of samples were recovered from March 19th to April 30th 2003 in all treatments.

There were only five dates (four for cup 70 and one for cup 71) with high concentrations for the T3 (grazed) treatment in year 2. The maximum value recorded for this treatment was 20.20 mg/l (cup 70) on March 12th 2003 having increased from11.30 mg/l on February 26th 2003. Similarly T4 (1 cut) had only three dates with elevated concentrations in one cup (93). The NO_3-N concentrations in this cup increased progressively from 3.31 mg/l on June 18th 2003 to 44.13 mg/l on July 9th 2003.

In the third drainage year, with cup 7 in T1 (dirty water), NO_3-N concentrations started at 16.06 mg/l on December 10th 2003 and increased to a maximum of 95.06 mg/l six weeks later. Concentrations remained high until March 23rd 2004 and there were four dates with no water sample. Cup 28 in the 2 cut silage treatment (T2) also started with a high NO_3-N concentration of 58.77 mg/l on December 23rd 2003 to 74.64 mg/l on March 16th 2004 with a maximum value of 219.79 mg/l recorded on January 21st 2004. There were 13 weeks of high to exceptionally high concentrations with one anomaly 1.2 mg/l on January 28th 2004 and one date with no sample. On cup (70) in the grazed treatment (T3) started eight weeks of high NO_3-N concentrations on December 17th 2003 going from 23.80 mg/l to 104.18 mg/l on January 28th 2004 with 2 weeks of no water sample included. The 1 cut treatment (T4) had one cup (87) with 18.65 mg/l NO_3-N on January 14th 2004 followed by 13 weeks of high values with a maximum value of 178.83 mg/l on April 7th 2004. This run included five dates with no water sample.

The timing during the drainage season of the maximum NO_3-N concentration for individual cups in treatments was variable. Dirty water, (T1) in drainage years 1, 2 and 3 had maximum values on November 14th 2001, December 18th 2002, and January 14th 2004, respectively. For the T2 (2 cut) treatment the respective maxima for the three drainage years were recorded on March 27th 2002, April 30th 2003 and January 21st 2004. The grazed plots (T3) had their respective maxima on March 5th 2002, March 12th 2003, and January 28th 2004. Finally, the T4 (1 cut) treatment recorded the maximum NO_3-N concentration on January 30th 2002, July 9th 2003 and April 7th 2004. The range for the occurrence of maxima was from November to July. Grazing, residual N and mineralisation effects may have contributed to the occurrence of the autumn-winter maximum values. The spring-summer peaks are probably related to those plus N applications with recharge and effective rainfall being the overall primary mover of NO_3-N from the surface to the 1 m depth.

The accumulated effective rainfall to maximum concentration was calculated for all treatments in all years. There was no absolute consistency although two years had reasonably close data. Accumulated effective rainfall (mm) to maximum concentration for T1, T2, T3 and T4 in year1 was 48.8, 369.1, 342.9, 233.3; it was 229.8, 472.9, 454.9, 538.8 in year 2 and in year 3 was 197.5, 209.7, 229.7, 371.0.

4.2. Ammonium-N

Estimated annual N losses in leached NH_4-N were 1.5, 1.8, 1.1 kg/ha N, for years 1, 2, and 3, respectively, based on the weighted annual mean concentrations of 0.345, 0.317, 0.275 mg/l NH_4-N and effective rainfall plus dirty water irrigation amounts. The amounts leached were low i.e., 0.5, 0.6, 0.3 % of applied N in years 1, 2 and 3, respectively. The N leached in year 1 from the four treatments, T1 (dirty water), T2 (2 cut), T3 (grazed) and T4 (1 cut) was 1.5, 1.6, 1.4, 1.7 kg/ha, respectively. This was equivalent to between 0.5% of the applied N. In second and third drainage years the N loss through leaching of NH_4-N was 1.6, 2.3, 1.6, 1.5 kg/ha 1.3, 1.7, 0.7, 0.8 kg/ha, respectively. These losses were equivalent to between 0.2 and 0.7% of applied N.

There were no significant effects of treatment on mean concentrations (Appendix C, Table C1) in years 1 and 2. However, there were significant effects in third drainage year. Mean concentrations across weeks (Appendix F, Table F1) in year 1 for the four treatments, T1 to T4, ranged from 0.102-1.003; 0.078-1.449; 0.104-0.844; 0.105-0.941 mg/l, respectively. The T2 (2 cut) had the largest range. In the second drainage year, the range was 0.055-1.264; 0.033-1.500; 0.016-3.390; 0.017-2.308 mg/l for the T1, T2, T3 and T4 treatments, respectively. The concentration range was largest for the T3 (grazed) treatment and the ranges in the second year were larger than those for year 1. The NH_4-N concentration ranges for the four treatments, T1 to T4, were 0.049-1.865; 0.157-1.336; 0.043-1.437; 0.020-1.189 mg/l, respectively, within the three years.

Many of the foregoing 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, will be seen to be high. The former provides for a Salmonid water quality standard of 0.778 mg/l NH_4-N but this is considered too high 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.

The weekly concentrations shown in Appendix F, Table F1, indicate that in year 1, the concentrations for all treatments in all weeks were greater than the Salmonid guide value; only 2, 3, 6 and 5 of the values for T1,T2, T3 and T4 treatements, respectively, were less than the Cyprinid guide. In year 2, only four values in the T3 (grazed) and two values in the T4 (1 cut) treatments were less than the Salmonid guide. There were 13, 7, 20, 19 concentrations in the T1 to T4 treatments, respectively, less than the Cyprinid guide. In year 3 there was only one value of the T3 (grazed) and two values of the T4 treatment less than the Salmonid guide but there were 11, 19 and 16 values less than the Cyprinid guide in the T1, T3, T4 treatments, respectively. It must be remembered that concentrations measured at 1 m deep may not exactly reflect those in surface or ground waters due to transformations.

4.3. Factors affecting outcome

The experiment, as conducted, was a monitoring exercise rather than a regular randomised block, response experiment where incremental amounts of fertiliser, water or herbicide are applied and direct comparisons of the effects of the increments are measured. In grassland experiments, e.g., those concerned with responses to N fertiliser versus white clover, plots are sometimes attuned to the requirements of the study for one or two years to allow decay of any residual effects of previous management that might affect the outcome. This also allows time for stabilisation of grass and clover ground-cover and growth before measurements commence. Moloney and Murphy, (1963) allowed 18 months from establishing swards to applying fertiliser on their experiment measuring N responses at Johnstown Castle. Such did not apply to the study being reported here and the data are a record of leaching from plots previously laid down to specified managements in an established experiment. It is thought that, in their past history, high inputs of N occurred on of some of the dirty water, silage and grazed plots.

4.3.1. Dirty water

A major part of the area dedicated to dirty water irrigation (T1) had been receiving the effluent for more than 30 years prior to the start of the current study i.e., plot 11 and half of plot 12 (Map 2). A sprinkler system was introduced in 1990-1991, prior to which, effluent was piped to plots and distributed in a less even fashion than currently. High total N and organic C, phosphorus and potassium concentrations have built up in the soils as a result (Appendix 6 – Section 2). The drainage water from the plots reflects the history to a degree.

Drainage-water from plots 12 and 11, had mean NO_3-N concentrations in the first drainage year of 13.71 and 16.19 mg/l, respectively, compared with 6.47 mg/l for plot 10 (the third dirty water plot) which was introduced as a dirty water irrigation plot in July – August 2001. In the second and third drainage years the mean NO_3-N concentrations were 12.47, 3.53, 7.35 mg/l and 12.03, 10.74, 9.05 mg/l for plots 12, 11 and 10, respectively. The overall three year mean NO_3-N concentrations were 12.7, 10.1 and 7.7 mg/l for plots 12, 11 and 10, respectively. Maximum NO_3-N concentrations recorded in the dirty water plots 12, 11 and 10 were 84.94, 131.10, 115.43 mg/l in drainage year 1; 172.99, 9.95, 75.61 mg/l in drainage year 2 and 95.06, 39.18, 41.13 mg/l in drainage year 3, respectively.

The dirty water 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 other three treatments (Appendix 6 – Section 2). The mean organic C and total N concentrations (%) for the dirty water, 2-cut, grazed and 1-cut treatments (T1 to T4) were 5.78, 3.27, 3.72, 2.97 and 0.51, 0.34, 0.38, 0.31, respectively. The corresponding C:N ratios were 11.4, 9.7, 9.7 and 9.7. Comparable C and N concentrations (%) and C:N ratios in the well-drained Clonroche soil of County Wexford (Gardiner and Ryan, 1964) and Elton soil of County Limerick (Finch and Ryan, 1966) are 4.38, 0.36 and 12.2 and 3.1, 0.34 and 9.0, respectively. Even though mineralisation rates were not measured, the higher N concentration in the T1 (dirty water) soils together with the C:N ratio of 11.4 would be expected to favour higher release rates of soil organic N. Drying and wetting of soil, which occurs with dirty water irrigation, is an important process in soil organic matter decomposition and nutrient cycling (Mikha *et al.,* 2005). This should also increase mineralisation of soil organic N. Dirty water (T1) did not appear to cause increased N concentrations in the herbage (Appendix 5 – Section 2). Mean herbage N concentrations (%) for 2001 and 2003 in T1, T2, T3 and T4 were 2.7, 2.7, 2.7, 2.4 and 2.9, 2.9, 2.8, 2.9, respectively. Sampling dates and numbers of samples taken varied within and between treatments.

Increased mineralisation of soil N in the T1 plots together with the extra hydraulic load may have contributed to the higher leaching from those plots. There is evidence for this. Zaman *et al.* (1999 a, b) have shown that under field conditions, the application of dairy shed effluent (DSE)- a mixture of solid organic materials from the faeces with urine and water- significantly increased the soil microbial biomass, extra cellular enzyme activities and gross N mineralisation rates above a control. They reasoned that this was probably because a significant proportion of the organic N in the freshly added DSE was readily mineralisable and could be released within a short period of time. The gross mineralisation rates decreased markedly after 30 days, probably due to resistance to mineralisation by the remaining organic substrates. The gross mineralisation rate was shown to be best explained by microbial biomass C and N and this was different from the findings in a laboratory incubation study where protease was the variable most frequently included in the equation to account for the variation of gross N mineralisation.

More recent work by Hawke and Summers (2003) has shown how six years of farm dairy effluent (FDE) irrigation has improved soil fertility with small but significant increases in plant-essential nutrients. The application of FDE had the most significant effect on the top 0.1 m of the soil profile. At the recommended rate,150 kg/ha N, the application of effluent significantly increased the cation exchange capacity in the upper profile (0.1 m), probably due to the increase in total C. The authors considered that the increase in plant-available exchangeable cations, due to effluent application, would benefit long-term soil fertility and pasture production. Six years of effluent application led to significant increases in the concentrations of total N, C, Olsen P and plant-available nutrients in the upper part of the soil profile. In addition, the organic matter content of the soil has increased by about 30%. "The net effect of effluent application will probably increase soil fertility and future pasture productivity". It was considered likely that effluent application had resulted in increases in microbial biomass C and N which consequently increased gross N mineralisation rates. While readily mobile N, NO_3^-, NH_4^+, may be rapidly leached or taken up by plants, this organic form may accumulate and explains the significant increases in total N, total C confined to the top of the soil profile (0.1 m depth).

The additional liquid load (Table 1) from irrigation of dirty water would have made a contribution towards increased leaching on the T1 plots. Plot 10 received 26.3, 31.9, 11.4 mm in 2002, 2003 and 2004, respectively, as well as an unknown total amount in 2001. Similarly for plots 11 and 12, the loads were 19.9, 35.7, 12.5 mm and 24.2, 32.8, 17.6 mm for 2002, 2003 and 2004, respectively with unknown amounts applied in 2001.

4.3.2. Slurry

In general, slurry application tends to increase activities of enzymes involved in N cycling to a greater extent than enzymes involved in the C cycle (Bol *et al.*, 2003). This has implications for N release for grass growth from organic matter. An increase in urease activity following slurry and farm-waste applications to soil has been reported in the literature. Slurry treatment provides, not only an input of substrate for soil micro-organisms, but also urease itself, i.e., slurry application is equivalent to an application of urealytic micro-organisms. This might be the reason why urease activity reacts much faster than all of the other enzymes measured and leads to loss of ammonia when urea is applied (Bol *et al.*, 2003).

The elevated mean NO_3-N concentrations in the 2-cut silage (T2) drainage water in year 1 (Figure 3 a) may have been caused by high applications of slurry to one of the three treatment plots (plot 16) in previous years (F. Flynn pers. com.). The mean NO_3-N concentration in plot 16 in year 1 was 19.98 mg/l compared with the values recorded in the other two T2 plots of 7.72 and 7.70 mg/l. The concentrations for the three, T2, plots in the second and third drainage years were 4.03, 9.66, 2.25 and 14.74, 4.34, 5.91, with overall 3-year mean values of 12.92, 7.24 and 5.29 mg/l, respectively.

4.3.3. Fertiliser N

If , as is assumed, high N fertiliser inputs occurred on Curtin's farm in the past, this would have consequences in terms of significant residual effects for a number of years. Watson and Mills (1998) studied gross N transformation in a grassland soil which had been grazed and received annual fertiliser N inputs of 100, 200, 300, 400, and 500 kg/ha for the previous seven years. They reported that cumulative gross nitrification after 21 days was equivalent to 44.0, 84.2, 106.8, 165.7 and 181.7 kg N /ha for the soils with the annual N fertiliser inputs of 100, 200, 300, 400 and 500 kg/ha, respectively. Similarly, 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. Soil from an undrained plot, that had received 200 kg N/ha for the previous 10 years but none in the current year, had a total net annual mineralisation of 292 kg N/ha which was only 25 kg/ha less than a comparable soil which received 200 kg N/ha in the current year.

4.3.4. Reducing nitrate leaching

In the present study the N fertiliser input to the grazed plots was 33 kg/ha in excess in 2001 and 46, 17 kg/ha less than the recommended rate in 2002 and 2003 (Coulter, 2004). The recommended amount of slurry N to use for silage was 30 kg/ha; the actual amount applied to the silage plots was less, i.e. 22-28 kg/ha in those years.

To ensure a valid comparison of the cow breed strains involved in the Curtin`s farm experiment it was desirable that animal dry matter intake at grazing would not be limiting. This was achieved by not being parsimonious, on occasion, with the N inputs. Considering silage was exported from the farm in two of the three study years it suggests that there is room to reduce N fertiliser while maintaining the productivity of the system. This reduction in fertiliser inputs should occur in the dirty water (T1) plots and in the silage-cutting area (T2 and T4). Such a strategy 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 mineralisation of soil organic matter under permanent grassland to meet the requirements for grass growth during the autumn, winter and early spring.

Interestingly, Di and Cameron (2002) report that by treating pasture soil, including urine patches, with the nitrification inhibitor, dicyandiamide (DCD), the amount of nitrate leaching was decreased by 42-76 %. Research is currently being conducted to investigate options for on-farm application of DCD. A preliminary economic analysis has shown that the cost associated with the application of DCD can be well offset by the agronomic benefits derived from the application of DCD, with the actual returns depending on the method of application. This does not take into account the potential environmental benefits following on from DCD application (Di and Cameron, 2004). These possibilities need further elaboration through research.

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, less than 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.

The relevance of the farm-scale results to Ireland`s “whole territory” approach to the Nitrates Directive must be considered in conjunction with the results emanating from the two other work packages. Soil water samples, collected using ceramic cups inserted at 1 m deep, while indicative, are not sufficiently representative of the status of the water bodies of concern to be used in isolation for policy-making on a national scale.

5. Conclusions and Recommendations

5.1 Introduction

The objective of the study was to measure nitrate leaching from an intensively managed dairy farm on a free-draining soil which is typical of a nitrate vulnerable zone. The soil in the experimental site area is No.13 on the General Soil Map of Ireland (Gardiner and Radford, 1980) and extends to 1.69% of the area of the Republic of Ireland. However, it is considered that between 5- 8% of the land area has comparable soils. These are described as loam to 0.8 m, loam with clay loam inclusions from 0.81 to 1.50 m and clay loam from 1.51 to 2.30 m with plentiful rooting only to 0.35 m and no roots below 0.80 m, ranging in depth from 0-4.5 m with an average depth of 2.5 m and overlying cavernous limestone (Bartley and Johnston, 2006; Gibbons *et al.*, 2006). This estimate requires more accurate determination.

The study involved the monitoring of N inputs to four grass management systems (treatments), typical of those used on dairy farms. Three replicate plots of each treatment were instrumented with ceramic suction cups at 1 m deep to collect drainage water which was analysed for NO_3-N and NH_4-N concentrations over three winters.

5.2. Main conclusions and recommendations from the farm-scale study

1. The NO_3-N and NH_4-N concentrations recorded from the ceramic cups during the monitoring of an intensive dairy farm on a vulnerable soil give cause for concern. The level of concern will depend on the water quality targets required. However, the results must be put in the context of a "worst case scenario" for Irish agriculture in that the soils were selected on the basis of their high vulnerability. Secondly, management options to reduce the pressure from the intensive dairy system monitored are evident. These can be implemented to reduce the N loading from the system without requiring changes in the production potential of the current management system. Their impact on water, however, remains to be evaluated.

2. The highest leaching occurred in the dirty water plots which not only had the highest direct N input in one year but which had, with the grazed plots, the highest recycled dung and urine N

3. The dirty water and 2-cut treatments had significantly higher mean NO_3-N concentrations than the grazed and 1-cut treatments in the first and second years. In the first drainage year, the 1-cut treatment was significantly lower than the grazed treatment. In those two years, dirty water had the highest while 1-cut had the lowest mean concentration. The weighted mean NO_3-N concentrations for all treatments were 7.85, 4.15 and 9.10 mg/l in years 1, 2 and 3, respectively. The 3-year NO_3-N mean concentration for all treatments was 7.03 mg/l.

4. The mean annual NH_4-N concentrations were significantly different from one another, based on treatment, in the third year only. The weighted mean concentrations for all treatments were 0.336, 0.322 and 0.281 mg/l in years 1, 2 and 3, respectively. The 3-year mean NH_4-N concentration for all treatments was 0.313 mg/l.

5. Without the use of the tracer ^{15}N it is not possible to decipher the origin of leached N. It is probable that in the context of this study, autumn-winter leached N is primarily derived from deposited grazed N, mineralised soil organic N including plant residues and irrigated dirty water N; spring-summer leaching is more than likely associated with these with a somewhat greater probability of leached fertiliser N.

6. Reducing N fertiliser applications to the dirty water and silage plots should be investigated in the next phase of the work, 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. More emphasis on the latter is necessary. Nitrification inhibitors could also contribute to this effort of improving efficiency.

7. Improvement in washing routines, increased land-spreading area and any other procedures which give a reduction in the dirty water hydraulic load to be irrigated should be investigated as a means of reducing winter land spreading and leaching.

8. Direction as to tolerable N concentrations at the 1 m level, when provided, will allow for new studies to carry out the research required to relate admissible concentrations to appropriate N inputs and stocking rates for this type of vulnerable soil.

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Appendix A: Statistical models and presentation of results.

When results are required on the scale of measurement but it appears that a logarithmic transformation is appropriate for description of the means, a simple analysis on the log scale with back-transformation of the means can be badly biased. A simple example will illustrate this. Suppose NO_3-N concentrations of 0.1, 1 and 10. Their average is 11.1/3 = 3.7. These values are –1, 0 and 1 respectively on the $\log_{10}$ scale with an average of 0, which back-transforms to an average of 1 on the measurement scale. This grossly underestimates the true average computed on the scale of measurement. To allow for this in analyses in which the logarithmic scale is appropriate for describing the population means, an approach based on a Generalized Linear Model or, where there is a complex error structure, a Generalized Linear mixed Model is more appropriate and gives appropriate treatment means on the measurement scale. This is the approach implemented throughout this report. This appendix details these models and how to present results from them on the scale of measurement.

Simple case – One variable analysed (analysis at each week individually).
Case (a) - cup values averaged and the averages analysed.
Case (b) - cup values not averaged.

Case (a): The data consists of the averages of up to eight cups for each of three replicates of four treatments. Assume that the model is a GLM with log link and Gamma distribution.

$E(y) = \mu$
$\eta = \log(\mu) = X\beta$
and y has a gamma distribution

Predict means for treatments on the original scale as, where $\mu_i = e^{L_i'\beta}$ is the mean for the i^th^ treat, for some vector L_i.

$$\hat{\mu}_i = e^{L_i'\hat{\beta}}$$

For inference on individual means, compute a CI on the linear predictor scale and back transform. For inference on pairs of means μ_i-$\mu_{i'}$, compute the ratio of predicted means as

$$\frac{\hat{\mu}_i}{\hat{\mu}_{i'}} = e^{(L_i - L_{i'})'\hat{\beta}}$$

On the log scale this gives

$$\ln\left(\frac{\hat{\mu}_i}{\hat{\mu}_{i'}}\right) = (L_i - L_{i'})'\hat{\beta}$$

with variance

$$(X_i - X_{i'})'V(\hat{\beta})(X_i - X_{i'})$$

Using this to compute a CI for the log of the ratio and back-transform to give a CI on the ratio scale for the means being compared. Compute a least significant ratio (LSR) to present with the means. If LSD is the least significant difference on the log of the ratio scale then LSR = e^{LSD}.

Case (b) cup values not averaged: The data consists of up to eight cups for each of three replicates of four treatments. Assume that the model is a GLMM with log link and Gamma distribution and with a random N(0,σ^2) for plot on the linear predictor.

E(y|ε) = μ

η = log(μ) = Xβ+ε

and y has a gamma distribution

Predicted means for treatments on the original scale are, conditional on the random effect ε,

$$\hat{\mu}_i = e^{L_i'\hat{\beta}+\varepsilon}$$

To obtain the unconditional estimate of the mean (the marginal mean) integrate over the normal random variable ε. $\int \hat{\mu}_i f(\varepsilon)d\varepsilon = e^{L_i'\hat{\beta}} \int e^{\varepsilon} e^{-\frac{\varepsilon^2}{2\sigma^2}} d\varepsilon / \sqrt{2\pi\sigma^2}$

Completing the square in the exponent within the integral gives the integral as

$$\int e^{-\frac{(\varepsilon^2-2\varepsilon\sigma^2+\sigma^4)-\sigma^4}{2\sigma^2}} d\varepsilon = \int e^{-\frac{(\varepsilon-\sigma^2)^2-\sigma^4}{2\sigma^2}} d\varepsilon = e^{\frac{\sigma^2}{2}} \sqrt{2\pi\sigma^2}$$

Thus the unconditional estimate of the mean is

$$\hat{\mu}_i = e^{L_i'\hat{\beta}+\hat{\sigma}^2/2}$$

For inference on individual means compute a CI on the linear predictor scale as follows and back transform.

$$\ln(\hat{\mu}_i) = L_i'\hat{\beta} + \hat{\sigma}^2/2$$

with variance

$$L_i'V(\hat{\beta})L_i + V(\hat{\sigma}^2)/4 + \operatorname{cov}(\hat{\sigma}^2, L_i'\hat{\beta})$$

estimated by replacing variance terms by their estimates. **(However, the covariance in the above is problematic.)** Compute the SE of $\ln(\hat{\mu})$ as the square root of this estimate of variance. Construct a 95% CI using the normal approximation (±1.96SE). Back transform (exponentiate) this CI to give a CI for the estimated marginal mean.

For inference on pairs of means μ_i-$\mu_{i'}$, compute the log of the ratio of estimated marginal means (the scaling factors exp(σ^2) cancel) as

$$\ln(\hat{\mu}_i - \hat{\mu}_{i'}) = (L_i - L_{i'})'\hat{\beta}$$

with variance

$$(L_i - L_{i'})'V(\hat{\beta})(L_i - L_{i'})$$

Using this compute a CI for the log of the ratio and back-transform to give a CI on the ratio scale for the means being compared. Compute a least significant ratio (LSR) to present with the means. If LSD (= $t_{0.05}$ x SED) is the least significant difference on the log of the ratio scale then LSR = e^{LSD}.

Complex case – One variable analysed with repeated measures at t times

Case (a) - cup values averaged and the averages analysed.

Case (b) - cup values not averaged.

Case (a): The data consists of the averages of up to eight cups for each of three replicates of four treatments at t times. Assume that the model is a GLMM with log link and Gamma distribution with time a repeated measure within plot. Let y_{ijk} be the response from treatment i, time j and replicate k.

$$E(y_{ijk} | \text{plot ik and time j}) = \mu_{ij}$$

$$\eta_{ijk} = log(\mu_{ij}) = X_{ij}\beta + u_{ik(j)}$$

where y has a gamma distribution conditional on $u_{ik(j)}$, which has a variance covariance matrix R within each plot. R can take various forms including compound symmetry, AR(1), unstructured (UN), Toeplitz etc. Assume that the variance of $u_{ik(j)}$ is constant for all j and is σ^2.

Then, conditional on the random effect $u_{ik(j)}$, and where L_{ij} is a vector such that $\mu_{ij} = e^{L'_{ij}\beta + u_{ik(j)}}$

$$\hat{\mu}_{ij} = e^{L'_{ij}\hat{\beta} + u_{ik(j)}}$$

To obtain the unconditional mean, integrate over the normal random variable.

$$\int \hat{\mu}_{ij} f(u_{ik(j)}) du_{ik(j)}$$

which is the same form as before and so this gives the unconditional estimate

$$\hat{\mu}^M{}_{ij} = e^{L'_{ij}\hat{\beta} + \sigma^2/2}$$

For inference on individual means compute a CI on the linear predictor scale as before and back transform.

For inference on pairs of means, μ_{ij} and $\mu_{i'j'}$, compute the log of the ratio of estimated marginal means as

$$\ln(\hat{\mu}^M{}_{ij} - \hat{\mu}^M{}_{i'j'}) = (L_{ij} - L_{i'j'})'\hat{\beta}$$

The variance of treatment difference on the linear predictor scale is

$$(L_{ij} - L_{i'j'})'V(\hat{\beta})(L_{ij} - L_{i'j'})$$

Using this compute a CI for the log of the ratio and back-transform to give a CI on the ratio scale for the means being compared. Compute a least significant ratio (LSR) to present with the means. If LSD (= $t_{0.05}$ x SED) is the least significant difference on the log of the ratio scale then LSR = e^{LSD}.

Case (b): The data consists of the individual cup values for each of three replicates of four treatments at t times. Assume that the model is a GLMM with log link and Gamma distribution with plot random and time a repeated measure within plot. Let y_{ijkl} be the response from treatment i, time j, replicate k and cup l.

E(y_{ijkl}|plot ik and time j) = μ_{ij}

$\eta_{ijk} = log(\mu_{ij}\, X_{ij}\beta + \varepsilon_{ik} + u_{ik(j)})$

where y has a gamma distribution ε_{ik} has variance σ^2_p and $u_{ik(j)}$ has a variance covariance matrix R within each plot. R can take various forms including compound symmetry, AR(1), unstructured (UN), Toeplitz etc. Assume that the variance of $u_{ik(j)}$ is constant for all j and is σ^2.

Predicted means for treatments on the original scale are, conditional on the random effects $\boldsymbol{\varepsilon}_{\mathbf{ik}}$ and $u_{ik(j)}$,

$$\hat{\mu}_{ij} = e^{L'_{ij}\hat{\beta}+\varepsilon_{ik}+u_{ik(j)}}$$

To obtain the unconditional mean integrate over the independent normal random variables ε_{ik} and $u_{ik(j)}$,

$$\hat{\mu}^M_{ij} = \iint \hat{\mu}_{ij}\, f(u_{ik(j)})\, f(\varepsilon_{ik})\, du_{ik(j)}\, d\varepsilon_{ik}$$

which, gives the unconditional estimate

$$\hat{\mu}^M{}_{ij} = e^{L'_{ij}\hat{\beta}+(\sigma^2_p+\sigma^2)/2}$$

For inference on individual means compute a CI on the linear predictor scale as before and back transform.

For inference on pairs of means, μ_{ij} and $\mu_{i'j'}$, compute the log of the ratio of estimated marginal means as

$$\ln(\hat{\mu}^M{}_{ij} - \hat{\mu}^M{}_{i'j'}) = (L_{ij} - L_{i'j'})'\,\hat{\beta}$$

The variance of treatment difference on the linear predictor scale is

$$(L_{ij} - L_{i'j'})'V(\hat{\beta})(L_{ij} - L_{i'j'})$$

Using this compute a CI for the log of the ratio and back-transform to give a CI on the ratio scale for the means being compared. Compute a least significant ratio (LSR) to present with the means. If LSD (= $t_{0.05}$ x SED) is the least significant difference on the log of the ratio scale then LSR = e^{LSD}.

Appendix B: Correlation structures used to describe the relationships between observations in a repeated measures series

Compound Symmetry (CS): This type of structure assumes that the correlation between any two measurements in a given series is the same regardless of how far apart they are in the series. Two parameters are estimated, a correlation coefficient and the variance.

Autoregressive (1) (AR(1)): This type of structure assumes that the correlation between any two measurements in a given series depends on how far apart they are in the series. The placement of the two observations does not affect the correlation, (i.e. the correlation between observation 2 and 4 is the same as that between observation 6 and 8). Two parameters are estimated, a correlation coefficient and the variance.

Unstructured (UN): An individual correlation is calculated for every pair of observations in the series. A large number of parameters are estimated depending on the number of observations in the series.

Appendix C: Average annual NO_3-N and NH_4-N concentrations (mg/l) for four treatments

NO_3-N			
	Year		
Treatment	1	2	3
T1: Dirty Water	12.12	8.09	10.61
T2: 2 cuts	11.78	5.31	9.10
T3: Grazed	4.86	2.09	7.00
T4: 1 cut	1.88	0.94	9.52
LSR to compare treatment means **within a year**: 2.3			
NH_4-N			
	Year		
Treatment	1	2	3
T1: Dirty Water	0.325	0.281	0.299
T2: 2 cuts	0.363	0.420	0.421
T3: Grazed	0.307	0.295	0.184
T4: 1 cut	0.383	0.271	0.194
LSR to compare treatment means **within a year**: 2.1			

Appendix D: AIC values for various correlations structures 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 D1: AIC values for various correlation structures for the analysis of annual average N concentrations.

	Correlation structure			
	AR(1)	CS	UN	**Choice:**
NO_3-N	50.6	49.3	52.5	**CS**
NH_4-N	30.5	31.4	36.1	**AR(1)**

Appendix E: AIC values for various correlations 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)**

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**

Appendix F: NO_3-N and NH_4-N concentrations for each week in Years 1, 2 and 3. 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			

Table F1 Continued

		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	.	0.197
22	26/03/03	14.30	2.22	.	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	.	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			

Table F1 Continued

		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			

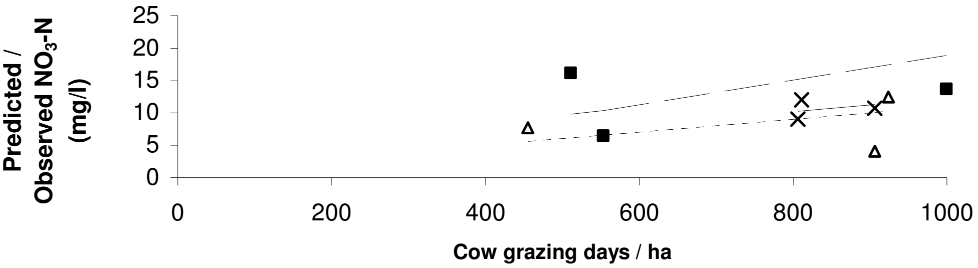
Appendix G: Statistical analyses and results from investigation of relationship between the number of cow grazing-days and the NO_3-N and NH_4-N concentrations.

The covariate 'Number of cow-grazing-days per hectare' (CGD) was included in the analysis of annual average N concentrations in plots for both the NO_3-N and the NH_4-N data. Using this covariate has the difficulty that, although grazing intensity was not a factor in this experiment, CGD varied widely with treatment and so its effect is confounded with treatment effect. The CGD effect, measured when treatment is in the model and CGD is a covariate, is based on the within treatment relationship between N concentration and CGD. As the CGD variation within treatment is small (the three plots for any treatment are rather similar in CGD) the tests of the relationship will not be very powerful.

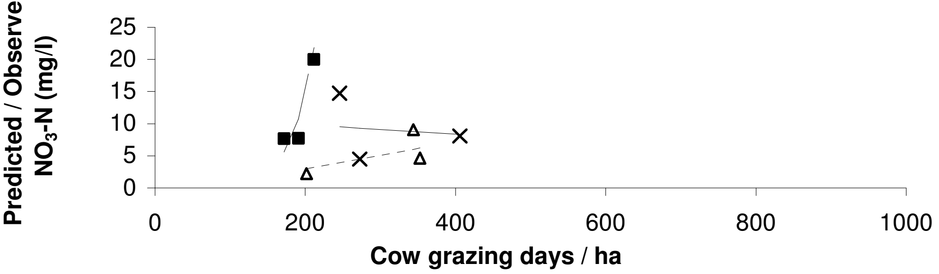
For NO_3-N the three factor interaction between treatment, year and CGD was borderline significant, $p=0.0679$. This indicates that the effect of CGD within treatment was not consistent across treatments or years (Figure G1). For example, for T2, the effect of CGD in year one was strongly positive while in year three it was weakly negative, (Figure G1b).

For NH_4-N CGD did not have a significant effect nor were its interactions with treatment and year significant.

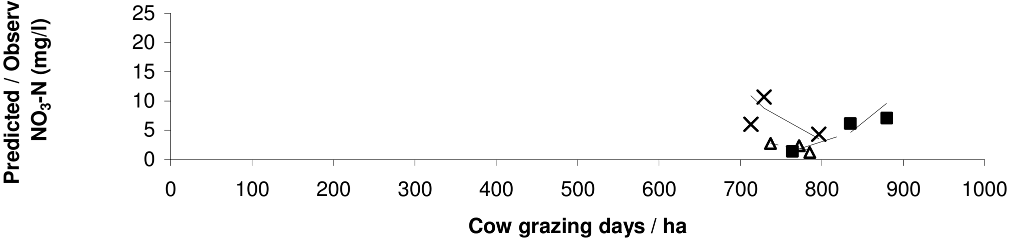
(a) Treatment 1



(b) Treatment 2



(c) Treatment 3



(d) Treatment 4

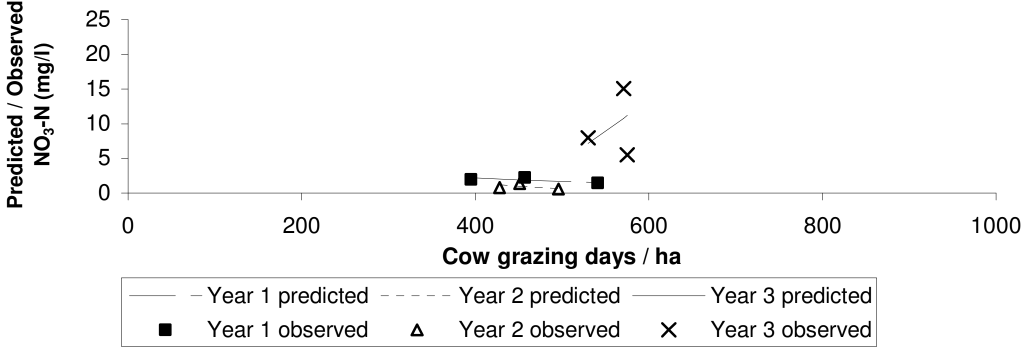


Figure G1: Predicted NO$_3$-N concentrations (lines) and observed NO$_3$-N concentrations (dots) versus CGD days for each treatment*year combination.

Appendix H: Statistical analyses and results from investigation of relationship between the N applied to the plots and the NO_3-N and NH_4-N concentrations.

The covariate 'Total Nitrogen applied to plots (kg/ha)', (Nitrogen) was included in the analysis of annual average N concentrations in plots for both the NO_3-N and the NH_4-N data. This variable included any N added to the plots through fertiliser, slurry and dirty water. The comments on the use of CGD as a covariate apply here also in respect of N, as within treatment the variation in N is very small compared with the variation between treatments. Having removed the effect of treatment, there were no significant effects of N or N interactions with treatment or year for either N type.

Appendix I: Statistical analyses and results from investigation of relationship between the NO_3-N concentrations and leachate volume and between leachate volume and treatment

On three dates (November 2nd, 9th and 16th, 2004) the NO_3-N concentration and the leachate volume (ml) was measured for some cups from each plot. On the first sampling date, the volume of leachate in the first four cups with non-zero values in each plot was recorded. As one plot had only three cups with non-zero volume, 47 measurements were recorded on this date. Measurements were taken from the same four cups on the following two dates, with a missing value recorded for those cups with zero leachate volume. On the second and third dates, 37 and 40 measurements were recorded, respectively. One plot (11) was irrigated with 123,818 l/ha dirty water in the period 28 October- 8 November, 2004.

NO_3-N concentration vs leachate volume

Three analyses were carried out: Analysis of data was on the logarithmic scale for analyses 1 and 2 due to heteroscedasticity in the NO_3-N data.

1. *NO_3-N concentration vs leachate volume – analysis over time for each cup:* The analysis examined the relationship between N concentration and time for cups. A model was fitted to the log(NO_3-N+0.1) concentrations with leachate volume and cup (53 different cups) as explanatory variables.
2. *NO_3-N concentration vs leachate volume – within plot at each of 3 times:* At each of the three times the relationship between log(NO_3-N+0.1) concentrations and leachate volume was examined.
3. *NO_3-N concentration vs leachate volume – correlation between average plot values at each time*: Pearson's correlation coefficient was used to describe the relationship between the average NO_3-N concentrations and average leachate volume for each plot on each date.

Analysis 1. *NO_3-N concentration vs leachate volume - within cup over time analysis:*
There was no evidence of a cup x leachate volume interaction. There were significant variations among cups and a negative relationship with leachate volume (slope = -0.00182, p=0.021).

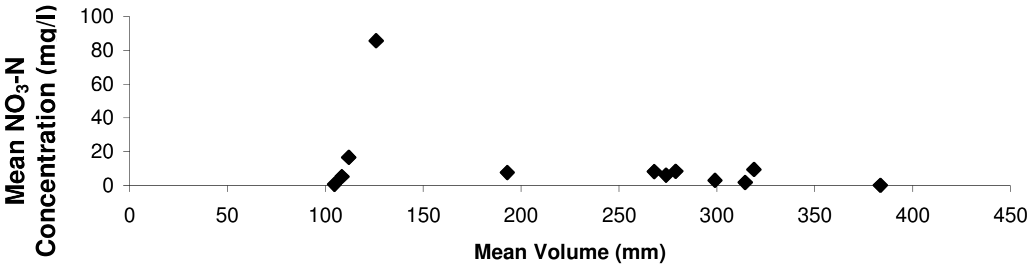
Analysis 2. NO_3-N concentration vs leachate volume – within plot at each of 3 times: At each time the relationship between log(NO_3-N+0.1) concentrations and leachate volume was examined using a model that included the effect of plot and leachate volume. There was no evidence for an effect of leachate volume. There was no evidence of a plot effect on this relationship or a plot x leachate volume interaction.

Analysis 3. *NO_3-N concentration vs leachate volume – correlation between average plot values at each time*: Average NO_3-N and average leachate volume were calculated for each plot at each time, averaged over the cups within each plot. Observed Pearson correlation coefficients were small and non-significant at each time (Table I1). Figure I1 shows graphs of average NO_3-N per plot versus average leachate volume per plot for each date.

Table I1: Correlation coefficient (R) between leachate volume and NO_3-N concentrations with corresponding significance levels at each of the three sampling dates. These are not significant even when the outlier (Figure I1) is omitted.

	Nov 2nd	9th	16th	(2004)
R	-0.394	0.061	-0.105	
P-value	0.205	0.85	0.746	

(a) Nov 2nd



(b) Nov 9th

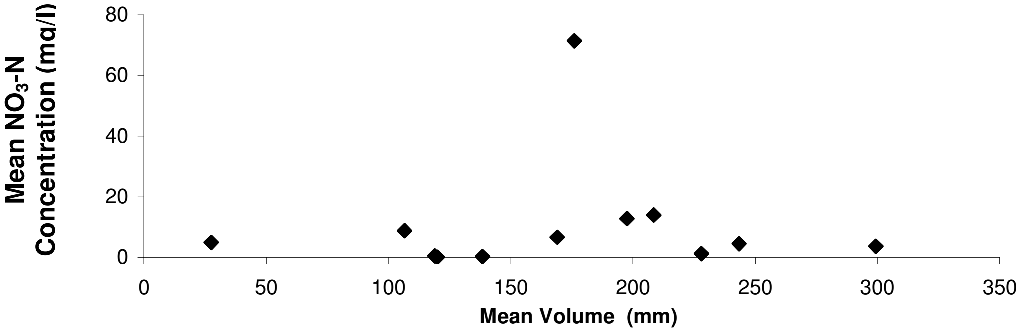


Figure I1 contd

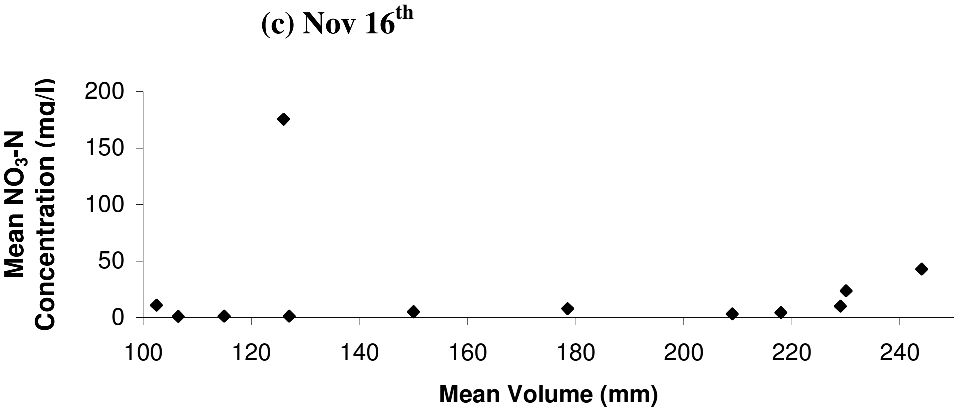


Figure I1: Mean NO_3-N concentration versus mean leachate volume for each plot on the three sampling dates November 2nd, 9th and 16th, 2004.

In summary, based on these three dates, there was no evidence of a relationship between the NO_3-N concentrations and the leachate volume within a plot or on average between plots. However, there was some evidence of a negative relationship over time within cups (as leachate volume increased NO_3-N concentrations decreased).

Effect of treatment on leachate volume in cups.

To investigate if treatment had an effect on leachate volume, a linear mixed model was fitted with the leachate volume in cups as the response, treatment as a factor and date as a repeated measurement. The effect of treatment was non-significant. Based on these three sampling dates, there were no significant effects of treatment on leachate volume in the cups, Table I2.

Table I2: Mean leachate volume (ml) for each treatment based on the three sampling dates November 2nd, 9th and 16th 2004.

T1	T2	T3	T4		s.e.d.
167.7	192.3	210.0	191.1		37.3