

Nitrogen losses in artificial drainage and surface runoff from pasture following grazing by dairy cattle

David Houlbrooke, James Hanly, Dave Horne and Mike Hedley

Institute of Natural Resources, Massey University, Private Bag 11-222, Palmerston North, New Zealand. <http://inr.massey.ac.nz>
Email: D.J.Houlbrooke@massey.ac.nz, J.A.Hanly@massey.ac.nz, D.J.Horne@massey.ac.nz, M.Hedley@massey.ac.nz

Abstract

Dairy cattle are significant contributors to the nutrient enrichment of New Zealand's aquatic environment. However, there have been very few field studies that quantify the accelerated loss of nutrients that occurs when grazing coincides with or is immediately followed by drainage and/or surface runoff. More detailed information is required on the environmental risk associated with cows grazing at times when rainfall is likely to generate drainage and surface runoff. Nitrogen loss occurring in drainage and surface runoff immediately after grazing was quantified at a research site established on an artificially drained, fine-textured soil, at Massey University's No. 4 Dairy Farm in the Manawatu.

The direct effect of an early winter grazing, which was immediately followed by a drainage event, on total N concentrations of drainage water was evident only during the first ~3 mm of a single drainage event. During this drainage episode there was a large initial increase in total N concentration of drainage water (~ 20 mg N litre⁻¹), which quickly decreased to values comparable to drainage water from plots that had been grazed 7 days prior to the drainage occurring. The greater initial total N concentration from the freshly grazed plots was attributable to greater initial concentrations of both total organic-N and ammonium-N. Although the total quantity of N lost in this single drainage event was similar for both treatments, being ~ 4 kg N ha⁻¹, the forms of N lost differed. From the freshly grazed plots, the non-nitrate forms of N (total organic-N and ammonium-N) were ~ 0.5 kg N ha⁻¹ greater, and were likely to be associated with the direct drainage or preferential flow of cattle urine. This loss attributed to direct leaching of urine-N is relatively small compared to the total annual quantities of N typically lost from dairy pastures in drainage (25-30 kg N ha⁻¹ yr⁻¹).

Key Words

Nitrogen, cow urine, mole and pipe drainage, surface runoff, cattle grazing.

Introduction

The number of field studies quantifying the contribution of intensive dairy farming to increased nutrient and suspended solid loads in New Zealand surface waterways is relatively small (e.g. Sharpley & Syers 1979; Monaghan *et al.* 2002, Houlbrooke *et al.* 2003). These studies have established that grazing dairy cattle are a cause of nutrient enrichment of artificial drainage water. Artificial drainage, such as the mole-pipe systems commonly used in poorly drained soils in New Zealand, may exacerbate the risk of nutrient leaching. They can promote rapid macropore flow to the mole drain ensuring that the drainage water bypasses a great deal of the soil matrix (Kladivko *et al.* 1991, Kohler *et al.* 2001). However, there is still limited information on what happens to the forms and quantities of nutrients lost when grazing coincides with drainage and/or runoff.

Approximately 70% of the N consumed by grazing dairy cattle is returned to the soil surface as dung and urine. With N concentrations in urine ranging from 8000 to 15000 mg N litre⁻¹ (Haynes and Williams 1993), urine patches provide large quantities of highly soluble, neutral urea-N which is prone to leaching (Silva *et al.* 1999; Silva *et al.* 2000; Di and Cameron 2002). The quantity of N deposited in a urine patch (~ 0.4 m²; Williams and Haynes 1994) is equivalent to a rate of ~ 1000 kg N ha⁻¹ (Silva *et al.* 1999). Urine patches occur randomly across grazed paddocks and at a stocking rate of 3 cows ha⁻¹, may cover ~ 25% of the paddock area in one year (Silva *et al.* 1999).

A few studies have measured the forms of N in leachate under patches of cattle urine. Park (1996) found that total organic nitrogen (TON) and ammonium-N (NH₄⁺-N) were the dominant forms of N in leachate. The collected TON was likely to be predominantly derived from cow urine suggesting the likelihood of

preferential flow of the urine applied. High concentrations of NH_4^+ -N are to be expected as urea has an estimated half-life of only 3-4 hours (Haynes and Williams 1993) and is rapidly hydrolysed to the ammonium form once applied to the soil surface. Silva *et al.* (2000) demonstrated that in water saturated soil, applied cattle urine leached through the soil in the form of unhydrolysed urea. Condon *et al.* (2004) partitioned the forms of N in soil, at a range of depths, following the application of a urea solution to simulate cow urine. On the day of the application, urea was the dominant form of N recovered. Between 1 and 16 days after the application, NH_4^+ -N was the dominant form recovered, whilst between day 16 and day 32, NO_3^- -N was the dominant form recovered. Consequently, the form of N in drainage under urine patches will depend on how soon drainage occurs after grazing. If drainage occurs within 24 hours of grazing, then the form of urine N lost in drainage is expected to be predominately urea. However, when drainage occurs > 10 days after grazing then the form of urine derived N lost in drainage will mostly be as NO_3^- -N (Sharpley and Syers 1979; Houlbrooke *et al.* 2003). Although, NH_4^+ -N is expected to be the dominant form of urine derived N in the soil between 1 and 10 days after a grazing, this form of N is less susceptible to leaching in drainage compared to both the urea and NO_3^- forms of N.

While there has been no work on runoff of urine-N, the form of N lost in surface runoff tends to be dominated by TON and NH_4^+ -N rather than NO_3^- -N. Smith and Monaghan (2003) found that losses of NH_4^+ -N in surface runoff were greater in the spring period which was attributable to increased grazing pressure creating soil treading damage during moist soil conditions. The increased volumes of surface runoff water that are induced by rainfall occurring after grazing by cattle have been attributed to compaction caused by cattle treading during grazing (Nguyen *et al.* 1998; Tian *et al.* 1998; Drewry & Paton 2000).

The major aim of this research was to determine changes in the forms and concentrations of nitrogen in drainage and surface runoff when drainage occurs immediately following grazing of pasture with dairy cattle.

Materials and Methods

Site and soil

The site was established on a mole-pipe drained soil in the Manawatu region of New Zealand (NZMS 260, T24, 312867) to investigate nutrient leaching losses from grazed dairy pasture. The site was located on a Tokomaru silt loam soil on Massey University's No. 4 Dairy Farm. The soil was classified as an Argillic-fragic Perch-gley Pallic Soil (Hewitt 1998) or a Typic Fragiaqualf (Soil Survey Staff 1998), and was derived from loess blown from adjacent river sediments to be deposited on a deeply dissected uplifted marine terrace (Molloy 1991). The Tokomaru silt loam soil consists of a weak to moderately developed, brown, silt loam A-Horizon (~ 0 - 250 mm soil depth); a weakly developed, grey, strongly mottled, clay loam B-Horizon (~ 250 - 800 mm soil depth); and a highly compacted, weakly-developed, pale-grey, silt loam fragipan C-Horizon. This fragipan acts as a natural barrier to drainage (Scotter *et al.* 1979a). The site is located in a flat to easy rolling landscape (~ 3% slope), which receives an average annual rainfall of ~ 1000 mm. The site supports a mixed pasture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*).

The research area consisted of 8 plots (each 40 m x 40 m). Each plot had an individual mole-pipe drain network. Mole drains were installed at a depth of 45 cm and at 2 metre intervals. Drainage from the mole network on each plot was intercepted by a perpendicular collecting pipe drain at a depth of 60 cm at one edge of the plot. At the corner of each plot a pit was excavated and a V-notch weir placed at the exit of the pipe drain to continuously monitor drainage flow rates with data loggers. Drainage water was sampled manually from the pipe outlet for determination of N concentrations. Isolated sub-plots (each 5 m x 10 m) were installed in four of the research plots for the measurement of surface runoff. Surface runoff water collected from each sub-plot passed through a tipping bucket instrument to measure flow volume and to provide a flow proportioned and mixed sample for water quality analysis.

Experimental procedure

During the 2003 winter drainage season, two drainage events that occurred immediately following grazing events were monitored (Experiment 1 & Experiment 2). In Experiment 1, a natural rainfall event (36 mm) occurred on the 6th of June (beginning of the drainage season) which caused drainage to start 2

hours after cows had grazed four of the experimental plots (grazing intensity of 90 cows ha⁻¹ for 12 hours). The other four adjacent plots were not grazed at this time, but had been grazed 7 days prior to rainfall and subsequent drainage, so were used as a comparison for the freshly grazed plots. Experiment 2 was conducted on two plots at the end of the drainage season, and involved two drainage events (Experiment 2a & 2b) generated using a rainfall simulator (with a coverage of 150 m²), which reduced the effective drainage plot area to 150 m². Surface runoff also occurred at each of these drainage events. The drainage events occurred 2-4 hours following grazing (Experiment 2a; 7th of October), and two days after grazing (Experiment 2b; 9th of October). The pasture was grazed with 130 cows ha⁻¹ for 12 hours. The quantity of rainfall required to cause drainage was estimated using a soil water balance model developed by Scotter *et al.* (1979b).

Laboratory analyses

Drainage and surface runoff water samples were analysed with a Technicon Auto Analyser II using the following methods: Kamphake *et al.* (1967) for nitrate-N (NO₃⁻-N); Searle (1975) for ammonium-N (NH₄⁺-N) and McKenzie & Wallace (1954) for Kjeldahl N. Total N (TN) was calculated by adding NO₃⁻-N concentrations to both the Kjeldahl N concentration and the dissolved Kjeldahl N concentrations. Total organic N (TON) concentration was calculated by subtracting NH₄⁺-N from Kjeldahl N. All measures of dissolved nutrients were determined on samples passed through a 1.2 µm glass filter. The variability in nutrient concentrations is quantified using the standard error of means (SEM) from 4 replicates (Experiment 1) or 2 replicates (Experiment 2).

Results and Discussion

Losses and forms of nitrogen in surface runoff and artificial drainage

The 36 mm rainfall event occurring in Experiment 1 resulted in an average of 13.5 mm of drainage and no surface runoff. The TN concentration of water draining near the beginning of the event (~ 0.3 mm of accumulated drainage) from freshly grazed pasture was 50 mg N litre⁻¹ compared with 26 mg N litre⁻¹ from plots that had been grazed 7 days earlier (Fig 1a & 1b). Total N concentrations in drainage from the freshly grazed plots steadily decreased to about 25 mg N litre⁻¹ during the first ~3 mm of drainage, and remained at 25-30 mg N litre⁻¹ for the duration of the drainage event (Figure 1a). The large decrease in TN concentration during the first ~3 mm of drainage from the grazed plots was due primarily to the marked decrease in TON and NH₄⁺-N concentrations. Total organic N and NH₄⁺-N made up the majority (about 60%) of TN at the start of the drainage event, but provided less than 30% of TN after the initial 3 mm of drainage. After 3 mm of drainage, the concentrations of all forms of N, except for NH₄⁺-N, in drainage water were similar for both grazing treatments, with NO₃⁻-N being the dominant form of N in drainage water. These relatively high levels of NO₃⁻-N are consistent with other studies which show that the levels of NO₃⁻-N in drainage tend to be high (typically 15-30 mg N litre⁻¹) early in the winter drainage season (Houlbrooke *et al.* 2003) (Fig 4). The flushing pattern evident in the first 3 mm when drainage immediately follows grazing may not be evident when grazing and drainage events are simultaneous.

The total N drainage loss was similar for both grazing treatments being ~ 4 kg N ha⁻¹ (Table 1). However the treatments differed in the forms of N lost. The combined TON and NH₄⁺-N drainage loss was ~ 0.5 kg N ha⁻¹ higher from the freshly grazed plots compared with plots grazed 7 days before drainage occurred. This greater loss of TON and NH₄⁺-N from the freshly grazed treatment suggests that these losses were associated with the direct loss of urine-N. This loss is relatively small compared to the total annual quantities of N typically lost from dairy pastures in drainage (25-30 kg N ha⁻¹ yr⁻¹; Houlbrooke *et al.* 2003). On the plots grazed 7 days prior to the drainage event, NO₃⁻-N loss represented a larger proportion of total N drainage loss. This apparent increased loss of NO₃⁻-N may be due to the occurrence of nitrification during the 7 days between grazing and drainage.

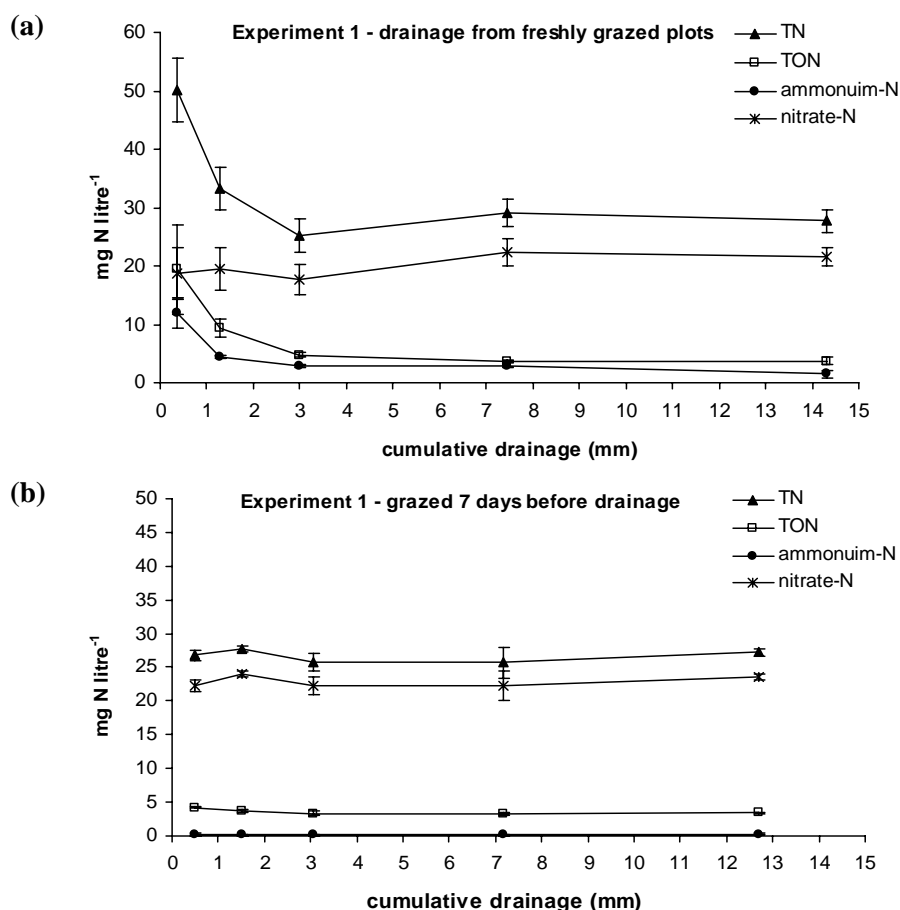


Figure 1. The change in concentrations of different forms of N with cumulative drainage from a natural rainfall event (Experiment 1) on 06/06/03 for (a) freshly grazed plots and (b) plots that had been grazed 7 days before. Bars represent one SEM.

Table 1. Mean concentrations and losses of different forms of N in drainage on 06/06/03 (Experiment 1) from plots that had been freshly grazed compared with plots that had been grazed 7 days before the drainage event. Standard errors of means (SEM) are presented in brackets. TN = total N, TON = total organic N.

Nitrogen form	Concentration (mg litre ⁻¹)		Nitrogen Loss (kg ha ⁻¹)	
	Freshly grazed	Grazed 7 days before	Freshly grazed	Grazed 7 days before
TN	28.8 (2.0)	26.5 (0.9)	4.1 (0.1)	4.0 (0.7)
NO ₃ ⁻ -N	21.6 (1.8)	22.8 (1.0)	3.1 (0.1)	3.5 (0.6)
NH ₄ ⁺ -N	2.34 (0.41)	0.18 (0.09)	0.3 (0.04)	0.02 (0.004)
TON	4.79 (0.25)	3.43 (0.04)	0.7 (0.06)	0.5 (0.09)

In Experiment 2, 12 mm of artificial rainfall was applied at a rate of 1.3 mm min⁻¹ to two drainage plots on 7 October (Experiment 2a) and again on 9 October 2003 (Experiment 2b). At the first artificial rainfall event, the predicted soil moisture deficit was 5.5 mm, and 2.7 mm of drainage and 3.9 mm of surface runoff were measured. At the second rainfall simulation, the predicted soil moisture deficit was 2.9 mm, and 5.8 mm of drainage and 3.7 mm of runoff were recorded. The N composition of drainage from the freshly grazed plots in this experiment (Figure 2a) suggested a similar trend to that measured for drainage from the freshly grazed plots in Experiment 1. In both of these experiments, TON, NH₄⁺-N, and TN concentrations decreased steadily over the initial stage of the drainage event (<3 mm). As with Experiment 1, the NO₃⁻-N concentrations in Experiment 2 remained relatively constant throughout the duration of the drainage event. Figure 2b shows the concentrations of N in drainage following artificial rainfall applied two days after grazing. The main differences, compared with the freshly grazed scenario, were reductions in TN and TON concentrations.

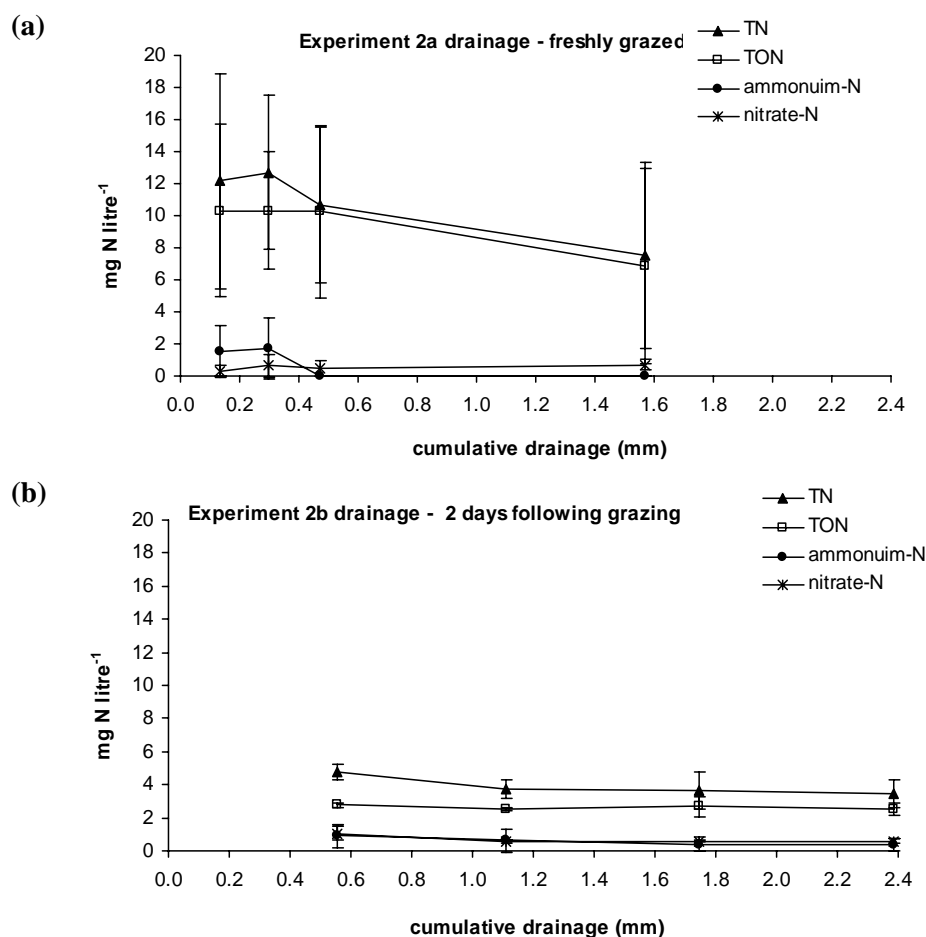


Figure 2. The change in concentrations of different forms of N with cumulative drainage from two artificial rainfall events (Experiment 2) on (a) 07/10/03 for freshly grazed plots and (b) 09/10/03 for the same plots two days following grazing. Bars represent one SEM.

During Experiment 2, surface runoff occurred with both artificial rainfall events. TN concentrations in runoff from the freshly grazed plots were predominantly in the form of TON. Also, both TN and TON concentrations decreased over the first ~3 mm of runoff (Figure 3a). Figure 3b shows that when artificial rainfall caused surface runoff two days after grazing, TN was lower as a result of lower TON concentrations. However, because no samples were collected at the very beginning of these two surface runoff events, it was not possible to determine what N levels were like in the initial runoff. Concentrations and forms of N in surface runoff from freshly grazed plots were very similar to those in drainage water with the exception of NO_3^- -N which was either very low or not detectable (Figure 2a & 3a).

In Experiment 2, the concentrations of TON from the freshly grazed plots were considerably lower than those in initial drainage in Experiment 1, even though samples were collected for the first 0.1 mm of drainage. One possible explanation for the lower TON levels in Experiment 2 was the small plot size. In Experiment 1, the size of each of the plots was 1600 m² which was considerably larger than the 150 m² plot area used in Experiment 2 (i.e. under the rainfall simulator). As only a small area (< 5%) of a paddock is likely to receive urine at any one grazing, it is conceivable that by chance the smaller plots did not receive urine at rates comparable to the rest of the paddock.

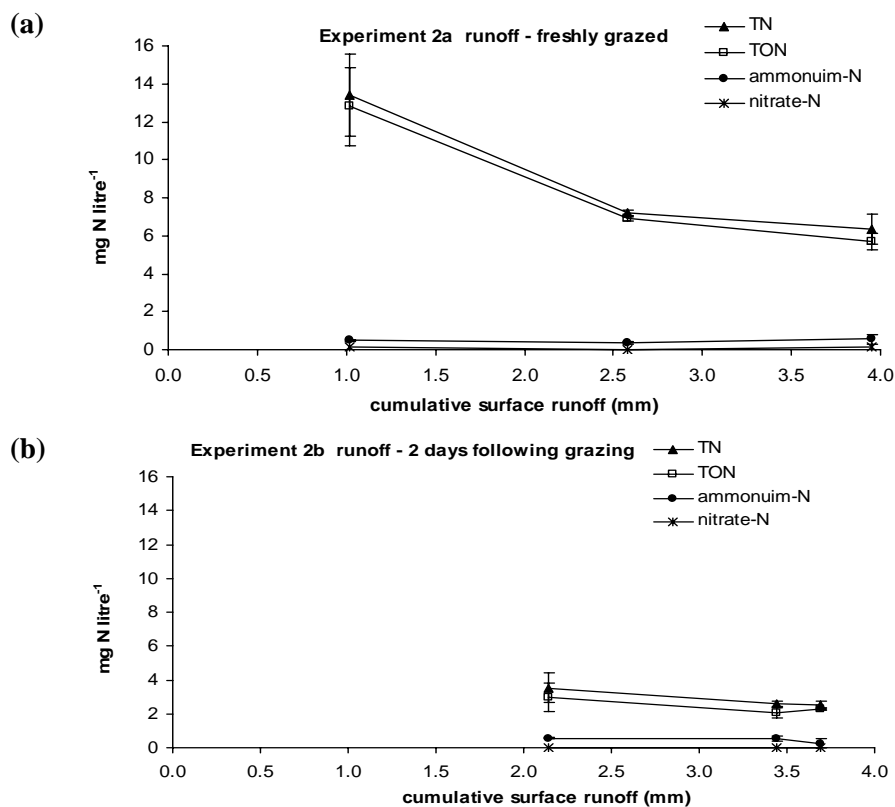


Figure 3. The change in concentrations of forms of N with cumulative runoff from two artificial rainfall events (Experiment 2) on (a) 07/10/03 for freshly grazed plots and (b) 09/10/03 for the same plots two days following grazing. Bars represent one SEM.

The contributions of NO_3^- -N towards TN concentration in Experiments 1 and 2 were very different (TN ~ 85% for Experiment 1 and ~ 20% for Experiment 2). These differences can be largely explained by the seasonal variation in NO_3^- -N leaching (Figure 4). At the time of Experiment 1 in early June, only approximately 20 mm of cumulative drainage had occurred and the average NO_3^- -N concentration in drainage was ~ 18 mg N litre⁻¹. Experiment 2 was conducted in early October after approximately 200 mm of cumulative drainage had occurred over winter and the average NO_3^- -N concentration of drainage water was only ~ 3 mg N litre⁻¹. The relative contributions of TON to TN in drainage associated with grazing events are higher later in the winter-spring season when NO_3^- -N concentrations are lower.

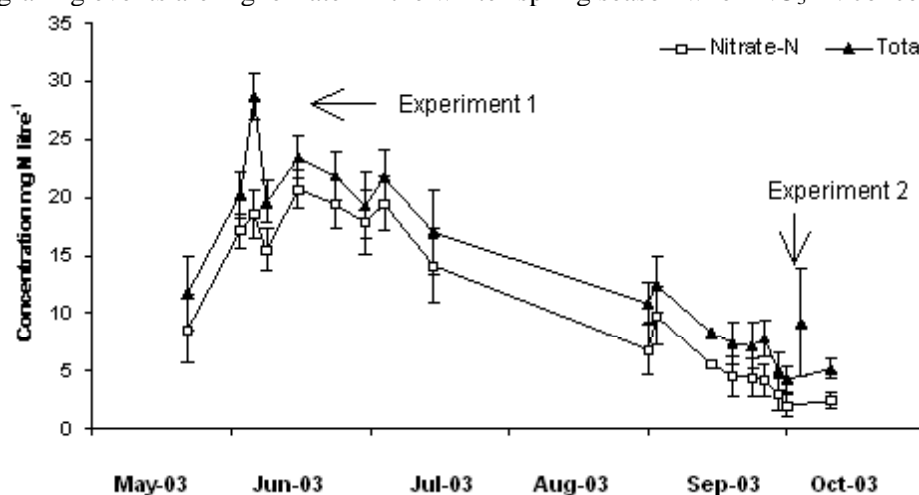


Figure 4. The change in concentrations of total-N and nitrate-N (averaged for each drainage event) throughout the 2003 winter-spring drainage season. Arrows indicate when Experiments 1 & 2 occurred in relation to the winter-spring drainage period. The average total-N concentration of drainage from freshly grazed plots in Experiment 2 is indicated by an isolated solid triangle, as it involved an artificial rainfall event. Bars represent one SEM.

Summary and conclusions

When subsurface drainage occurs immediately following grazing, drainage water may initially have higher total N concentrations due to the contribution of TON and NH_4^+ -N from direct drainage or preferential flow of cattle urine. However, these elevated concentrations are short-lived and disappear following ~3 mm of cumulative drainage. Although the total quantity of N lost in a single drainage event was similar whether drainage occurred either immediately or 7 days following grazing (~ 4 kg N ha⁻¹), the forms of N lost differed. The non-nitrate forms of N (total organic-N and ammonium-N) were ~ 0.5 kg N ha⁻¹ greater from the freshly grazed plots. This loss, which was attributed to direct leaching of urine-N, is relatively small compared to the total annual quantities of N typically lost from dairy pastures in drainage (25-30 kg N ha⁻¹ yr⁻¹).

Acknowledgements

The authors are grateful for financial assistance from Dairy InSight, the C. Alma Baker Trust, Marley NZ Ltd, Spitfire Irrigators Ltd and Horizons Regional Council. The support of staff from Massey University's Institute of Natural Resources, No. 4 Dairy Farm and Drainage Extension Service is also gratefully acknowledged.

References

- Condon JR, Black AS, Conyers MK (2004) The role of N transformations in the formation of acidic subsurface layers in stock urine patches. *Australian Journal of Soil Research* **42**, 221-230.
- Di HJ, Cameron KC (2002) Nitrate Leaching and Pasture Production from Different Nitrogen Sources on a Shallow Stony Soil under Flood-Irrigated Dairy Pasture. *Australian Journal of Soil Research* **40**, 317-334.
- Drewry JJ, Paton RJ (2000) Effects of cattle treading and natural amelioration on soil physical properties and pasture under dairy farming in Southland New Zealand. *New Zealand Journal of Agricultural Research* **43**, 377-386.
- Haynes RJ, Williams PH (1993) Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* **46**, 119-199.
- Hewitt AE (1998) *New Zealand soil classification 2nd ed.* Manaaki Whenua - Landcare Research New Zealand Ltd Press, Lincoln, New Zealand.
- Houlbrooke D J, Horne DJ, Hedley MJ, Hanly JA, Snow VO, (2003) The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. *Proceedings of the New Zealand Grassland Association* **65**, 179-184.
- Kamphake LJ, Hannah SA, Cohen JM (1967) Automated analysis for nitrate by hydrazine reduction. *Water Research* **1**, 205-216.
- Kladivko EJ, Vanscoyoc GE, Monke EJ, Oates KM, Pask W (1991) Pesticide and Nutrient Movement Into Subsurface Tile Drains on a Silt Loam Soil in Indiana. *Journal of Environmental Quality* **20**, 264-270.
- Kohler A, Abbaspour KC, Fritsch M, Van Genuchten MT, Schulin R (2001) Simulating Unsaturated Flow and Transport in a Macroporous Soil to Tile Drains Subject to an Entrance Head: Model Development and Preliminary Evaluation. *Journal of Hydrology* **254**, 67-81.
- McKenzie HA, Wallace HS (1954) The Kjeldahl determination of nitrogen - A critical study of digestion conditions-temperature, catalyst and oxidising agent. *Australian Journal of Chemistry* **7**, 55-77.
- Molloy L (1998) *Soils in the New Zealand Landscape: the living mantle 2nd ed.* New Zealand Society of Soil Science, Lincoln, New Zealand.
- Monaghan RM, Paton RJ, Drewry JJ (2002) Nitrogen and phosphorus losses in mole and tile drainage from a cattle grazed pasture in eastern Southland. *New Zealand Journal of Agricultural Research* **41**, 279-290.
- Nguyen ML, Sheath GW, Smith CM, Cooper AB (1998) Impact of cattle treading on hill land. 2. Soil physical properties and contaminant runoff. *New Zealand Journal of Agricultural Research* **45**, 197-205.

- Park S (1996) The fate of urine nitrogen on two Waikato soils. Unpublished M.Sc thesis, University of Waikato, Hamilton, New Zealand.
- Scotter DR, Clothier BE, Corker RB (1979a) Soil water in a Fragiaqualf. *Australian Journal of Soil Research* **17**, 443-453.
- Scotter DR, Clothier BE, Turner MA (1979b) The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research* **17**, 455-465
- Searle PL. (1975) Automated colormetric determination of ammonium ions in soil extracts with 'Technicon Autoanalyser II equipment'. *New Zealand Journal of Agriculture Research* **18**,183-187.
- Sharpley AN, Syers JK (1979) Loss of nitrogen and phosphorus in tile drainage as influenced by urea application and grazing animals. *New Zealand Journal of Agricultural Research* **22**, 127-131
- Silva RG, Cameron KC, Di HJ, Hendry T (1999) A Lysimeter Study of the Impact of Cow Urine, Dairy Shed Effluent, and Nitrogen Fertiliser on Nitrate Leaching. *Australian Journal of Soil Research* **37**, 357-369.
- Silva RG, Cameron KC, Di, HJ, Smith NP, Buchan GD (2000) Effect of Macropore Flow on the Transport of Surface-Applied Cow Urine through a Soil Profile. *Australian Journal of Soil Research* **38**, 13-23.
- Smith LC, Monaghan RM (2003) Nitrogen and phosphorus losses in overland flow from a cattle grazed pasture in Southland. *New Zealand Journal of Agricultural Research* **46**, 225-237
- Soil Survey Staff. (1998) *Keys to soil taxonomy 8th ed.* United States Department of Agriculture, Washington D.C.
- Tian Y, Singleton PL, Sheath GW, McCall DG, Carlson WT (1998) Modelling animal treading impacts on infiltration rate. *Proceedings of the New Zealand Grassland Association* **60**,149-152.
- Williams PH, Haynes RJ (1994). Comparison of initial wetting pattern, nutrient concentrations in soil solution and the fate of ¹⁵N-labelled urine in sheep and cattle urine patch areas of pasture soil. *Plant and Soil* **162**, 49-59.