Effect on Nitrate Leaching of Plant N Uptake in the Perimeter of a Urine Patch

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Johanna Kate Margaret Smith

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Abstract

Intensification of New Zealand's grazed pasture systems over the past decade has brought focus upon the negative impacts of agriculture on the environment. The important issue of nitrate leaching losses is currently driving policy and regulation that will significantly influence the way agricultural practices are carried out in the future. Urine patches are the leading cause of nitrate leaching losses, as urinary N concentrations far exceed plant N uptake capacity. Previous studies have suggested that the effective area of a urine patch is larger than the directly wetted area. However, the effect of this on nitrate leaching has not been studied. Therefore, the aim of this research was to investigate the effect on nitrate leaching of plant N uptake in the perimeter of a urine patch.

A lysimeter study was conducted at Lincoln University using 28 lysimeters collected from a perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture on a Templeton silt loam soil. Of the lysimeters, 14 represented the wetted area of a urine patch (300 mm diameter) and 14 represented a urine patch and perimeter grass (500 mm diameter). Within these two groups 7 lysimeters had 0.8 L of cattle applied to their central 300 mm diameter area, equivalent to an N loading rate of 700 kg N/ha. The remaining 7 control lysimeters were treated with 0.8L water applied to the central 300 mm diameter area. Natural rainfall was supplemented with simulated rainfall applied, first at the 75th and then at the 90th percentile of historical average rainfall for the area. Drainage water was collected once to twice per week, or as required following a significant rainfall event and the leachate was analysed to measure the NO_3^- - N concentration.

Results showed a 45% reduction in leaching losses from urine patches when perimeter grass was included. However, plant N uptake, dry matter production and botanical composition results indicate that the primary cause of this reduction was not plant N uptake in the perimeter of the urine patch, but differences in soil moisture. Due to the design of the sprinklers used there was an error in irrigation application leading to higher application and drainage volumes from the 300 mm diameter lysimeters than the 500 mm diameter lysimeters. In order to account for this, results were presented on a NO_3^- - (kg/ha) loss per 100 mm of drainage basis. However, the unequal irrigation amounts had a profound effect on pasture growth, therefore it cannot be determined whether plant N uptake in the perimeter of the urine patch has an effect on nitrate leaching. It is recommended that this trial be repeated using a re-designed, lysimeter diameter-specific irrigation sprinkler system.

Keywords: lysimeter, nitrogen, concentration, effective area, periphery, New Zealand, Canterbury, grazed, pasture, growth, pastoral, dairy, farm systems, root foraging, Templeton silt loam, *Lollium perenne, Trifolium repens.*

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Reducing nitrate leaching losses from pastoral farming systems has been a leading research focus over the past two decades. Nitrate leached to groundwater can cause water quality issues as it has potential to be detrimental to both human health and aquatic life (Cameron, 1992; Cameron, Di, & Moir, 2013; Di & Cameron, 2002a, 2002b). Intensification of New Zealand's farm systems over the past decade has accelerated leaching losses and concern over this has led to the development of regulatory policies, which will increasingly govern the way in which farming practices are carried out. Therefore understanding of how best to manage and reduce N leaching is important for retaining farm and industry profitability. Nitrate leaching losses are undesirable both from a pasture production and environmental perspective, thus the goals of increasing pasture production and reducing N leaching are aligned.

Previous research has established that urine patches are the main contributor to N leaching losses, as they deposit a high concentration of N (700 – 1200 kg N/ha) over a very small area, which far exceeds plant uptake capacity 300-400 kg N/ha/ yr (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002a, 2002b; O'Connor & Gregg, 1971). During winter, rainfall is usually sufficient to cause drainage of the soil profile thus negatively charged NO_3^- ions not taken up by plants leach through the soil profile with drainage water.

The objective of this lysimeter study was to better understand urine patch dynamics by accounting for plant uptake in the perimeter of the urine patch. Previous lysimeter studies have typically applied urine treatments to the entire lysimeter area and in doing so may not have accounted for the total effective area of the urine patch. In a field situation, plants growing at the perimeter of the wetted area of the urine patch may also be able to harness N uptake benefits. This should be accounted for when determining the overall effect of a urine deposit on the environment. Quantification of the effective area of a urine patch and it's effect on N leaching could have applications in calibrating nutrient budgeting models to increase the accuracy of N loss predictions from whole-farm systems.

Chapter 2

Literature Review

2.1. Introduction

Nitrogen losses from soils are undesirable, both for soil fertility and plant growth and from an environmental perspective. Nitrogen is the most common limiting nutrient for plant growth worldwide (Andrews et al., 2013) and when available in soil is readily taken up by plants. A typical ryegrass (*Lollium perenne*) and white clover (*Trifolium repens*) pasture will utilise 300-400 kg N/ha/ yr (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002a, 2002b; O'Connor & Gregg, 1971). Urine deposited by grazing animals has a high N concentration (700-1200 kg N/ha) and therefore causes an increase in pasture growth rates, however the heterogeneous distribution of urine patches makes them a major environmental concern (Di & Cameron, 2002b; Haynes & Williams, 1993).

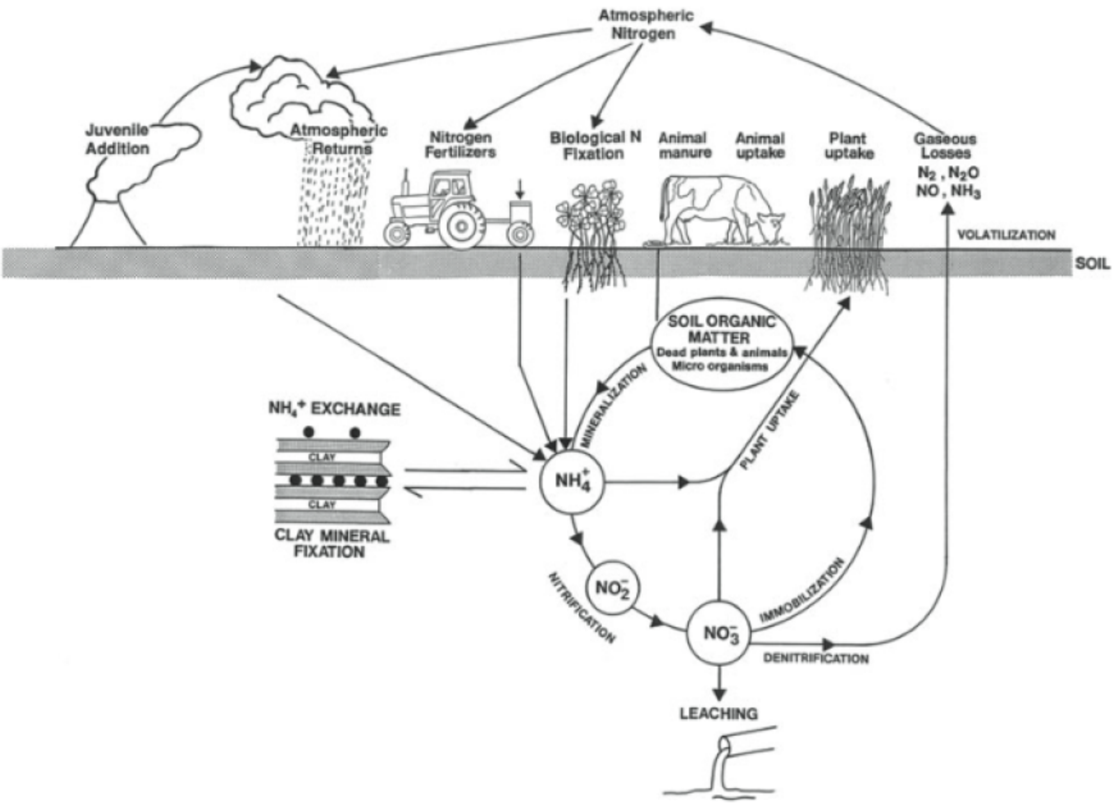
When nitrogen in soil is in excess of plant requirements or uptake capacity it can have adverse effects on the environment (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002a, 2002b). Nitrate is prone to leaching through the soil profile during drainage events caused by high rainfall (Cameron, 1992). This contributes to the nitrate concentration of groundwater and/or surface water that is used for human consumption and/or recreational purposes (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002b). Nitrate loss into waterways can cause eutrophication (algal blooms) making the water detrimental to the health and survival of aquatic species. Contamination of drinking water has also been linked to methaemoglobinanemia in babies, heart disease and cancer (Cameron et al., 2013).

The following report will review the sources of N input for a typical grazed pasture farm system, the nature of N transformations and movement in soil which lead to N leaching losses, factors affecting nitrate leaching and best management practice techniques for mitigating N loss from urine patches.

2.2. The nitrogen cycle in the soil/plant system

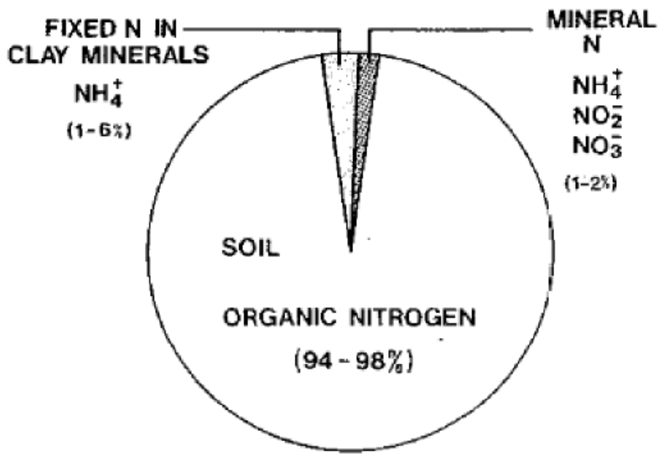
Nitrogen is abundant in both the earth's crust and atmosphere, which contain 18 x 10^{15} and 3.8 x 10^{15} tonnes of nitrogen respectively (McLaren & Cameron, 1996). This equates to 98% of the Earth's nitrogen, contained in the lithosphere (rock and mineral layers below soil). The remainder is found in the hydrosphere (water) and biosphere (within plants and animals). Nitrogen in soil represents only a very small proportion of total lithosphere N, and is the main source of N residing in living organisms (Cameron, 1992; Haynes, 1986)

In order to move between spheres N undergoes a number of transformations between organic and mineral forms in soil (Fig.2.1) (Cameron, 1992; Cameron et al., 2013).



A.1 1 Nitrogen cycling in the soil/plant system (Cameron, 1992).

N additions to soil occur naturally from juvenile addition and biological fixation but are also manipulated and increased via fertiliser applications and animal transfer (Fig.2.1). Within soil, N is present in many different forms. However only a small proportion of this N is available to plants. The majority (95%) exists in soil organic matter (Fig.2.2) and must undergo microbial processes such as mineralisation and nitrification to ammonia (NH_4^+) or nitrate (NO_3^-) in order to become plant available (Fig.2.1) (Cameron, 1992).



A.1 2: Distribution of soil nitrogen (McLaren & Cameron, 1996).

When soil N concentration exceeds plant N uptake capacity, excess N is lost via leaching, ammonia volatilization and denitrification (Cameron 1992). These losses from agricultural systems have negative consequences for our natural environment. (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002a, 2002b).

2.3. Forms of N addition to agricultural soils

2.3.1. Fertiliser

Nitrogen fertilisers are commonly broadcast onto agricultural soils, increasing pasture production by 5-20 kg DM/ kg N applied and thus improving animal performance (Cameron, 1992). Urea (CO (NH_2)) containing 46% N is the most commonly applied fertiliser throughout the world (Andrews et al., 2013). Like most fertilisers, urea is ammonium based, formed through the Haber-Bosch (Fig 2.3) process which combines nitrogen and hydrogen under heat and pressure (Cameron, 1992).

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

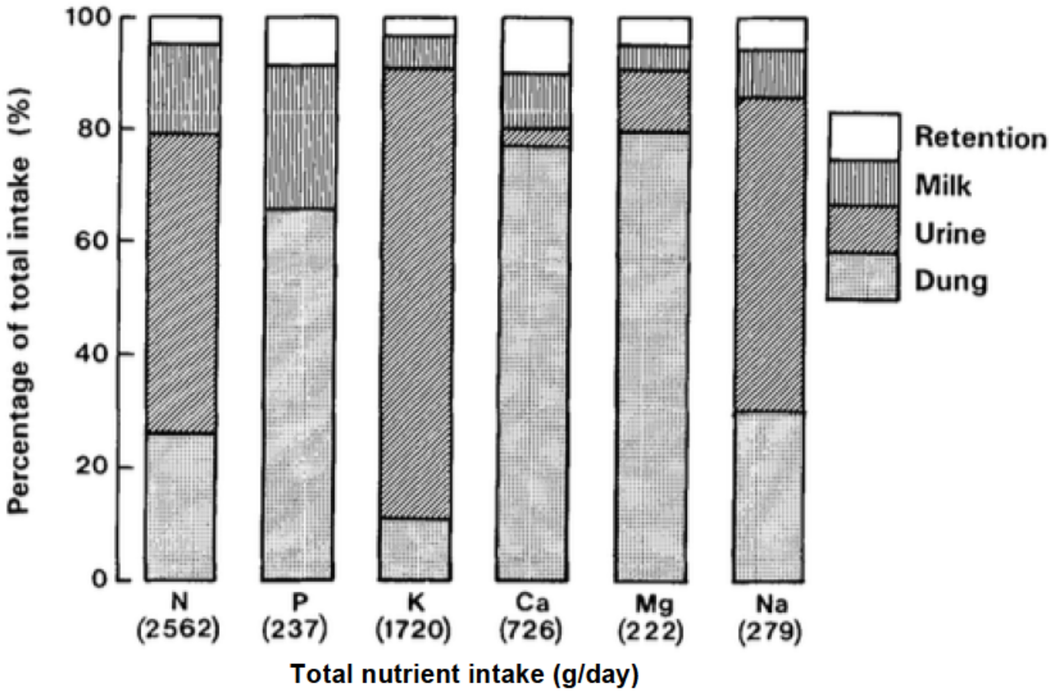
A.1 3 Chemical equation for the Haber-Bosch process used to manufacture ammonium fertilisers.

Most farm systems will apply less than 200 kg N/ha, although in some instances large applications up to 400 kg N/ha may be applied (Di & Cameron, 2002b). Pasture will usually utilise 300-400 kg N/ha/ yr (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002a, 2002b; O'Connor & Gregg, 1971). This suggests that farmers will usually apply N less than plant uptake capacity, and that leaching losses should not occur. However, due to the timing of application and coinciding climate factors, which cannot be managed, plants will not utilise all N applied. High application rates applied in autumn can increase leaching losses, as autumn applied N is used less efficiently than spring applied N (Cameron et al., 2013). There may be a large amount of N left in soil in autumn as plant growth and N uptake declines with cooling temperatures. This is likely to be leached during winter as high rainfall causes soil drainage. Splitting fertiliser into two or more applications will reduce wastage, providing the greatest plant response as well as reducing the risk of leaching loss. Care must be taken in regard to weather forecasts, applications followed by a subsequent rainfall event or excessive irrigation, may result in leaching losses.

According to (Haynes, 1986) crop recovery on applied N is in the range of 30-70%. In accordance with this, Goulding et al. (2008) reported that plants recover on average 51% of fertilizer applied to cereal crops, and even less (25-30%) is recovered in meat and milk products in grazing systems. This low utilisation suggests there are no production gains to be made from applying fertiliser above the rate of plant uptake and that excessive fertiliser rates will only lead to increased wastage and leaching losses. Thus, matching fertiliser application rates to plant growth requirements is an important factor for reducing nitrate leaching. It is rare that farmers should wish to apply N fertiliser at rates above that which a pasture is capable of utilizing for growth, therefore the goals of achieving increased plant growth and minimal N losses from fertiliser are aligned.

2.3.2. Urinary N input

Nitrogen returned in stock urine increases the risk of leaching and denitrification losses (Bristow et al., 1992; Ryden et al., 1984). When stock graze pasture, only a small proportion of N from consumed feed is retained by the animal or evident in milk produced (Haynes & Williams, 1993). The majority is excreted in dung and urine (Cameron et al., 2013; Fraser et al., 1994; Haynes & Williams, 1993). Hutton et al. (1967) reported proportioning of N consumed to be 71% to urine, 23% in milk and 6% retained (Fig.2.4). Jarvis et al. (1995) stated similar findings for N excretion in both urine and dung at 60-90% of N consumed. Cameron et al. (2013) later estimated this to be higher at 85-90% of N ingested. A majority of animal transfer N is in the form of urine rather than dung, with 70-90% of urine N as urea ($CO\ (NH_2)$).



A.1 4: Percentage excretion and retention of nutrient in lactating dairy cows. Nutrient element intake totals (grams per day) are shown in parentheses (Haynes & Williams, 1993).

The nitrogen content of urine increases with the protein content of feed (Colmenero & Broderick, 2006). Colmenero and Broderick (2006) determined that the optimum level of crude protein in dairy cow feed in order to maximise milk protein and minimise N excretion was 16.5%. In New Zealand's typical grazed pasture systems, stock consume pasture with a high crude protein level (average 18.5%) (Edwards et al., 2007). Therefore the inefficiency of protein metabolism by ruminants is an environmental concern, especially in New Zealand where the economy relies heavily on agricultural grazing systems.

For grazed pasture, stock urine contributes between 125-300 kg N/ha/yr (Bristow et al., 1992; Whitehead, 1986) This was found to be true whether the pasture is reliant on either biological fixation or 250-350 kg N/ha fertiliser for nitrogen supply. Urine patches occur heterogeneously across the grazing area (Whitehead, 1986). Thus, only a proportion of the pasture can benefit through increased N uptake, and fertiliser is usually applied to increase growth across the entire pasture area. In a typical New Zealand dairy farm system with a stocking rate of 3.5 cows/ha it is estimated that urine patches make up 25% of the grazing area (Di & Cameron, 2002a; Haynes & Williams, 1993).

Urine N addition is in a very concentrated form, compared with typical fertiliser application rates. N loading of a cow urine patch was reported by Cameron (1992) to be equivalent to 500-1000 kg N/ha. Around the same time Haynes and Williams (1993) reported this to be slightly higher at 700-1200 kg

N/ha (Di & Cameron, 2002b; Haynes & Williams, 1993). This exceeds optimal pasture N requirements of 350-400 kg N/ha/yr. Consequently urine patches are major source of N losses from soil (Cameron et al., 2013; Di & Cameron, 2002a, 2002b; Haynes & Williams, 1993; O'Connor & Gregg, 1971).

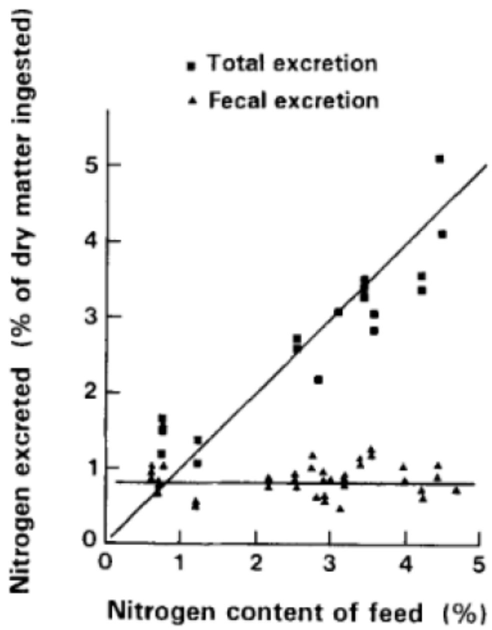
In a leaching loss study on a shallow, stony Canterbury dairy farm soil, with a 3.5 cow/ha stocking rate, effluent irrigation and urea fertiliser application only marginally increased NO_3^- losses above the level from urine patches (Di & Cameron, 2002a). This suggests that animal transfer, rather than fertiliser applications are the major source of N addition affecting groundwater quality. Based on these findings, research aimed at increasing the 'effective area' of a urine patch by manipulating where, how and what concentration of urine is deposited on soil is important for reducing total N loss to groundwater.

A single cattle urination event has an average volume of 1.262 - 2.2 L and an average N concentration of 6.8- 21.6 g N/L (Table.2.1) (Bristow et al., 1992; Buckthought, 2013; Cameron et al., 1992). Bovine urination frequency has been reported in the range of 8-12 times per day (Buckthought, 2013; Cameron, 1992; Cameron et al., 1992; Haynes & Sherlock, 1986). Based on 10 urinations per day, wetting a 0.26 m^2 area the annual area affected by the urine deposition of a single cow would equate to 0.95 ha/yr. The area directly wetted by a urination event has been reported to range from 0.16-0.49m^2 (Buckthought, 2013). The 'effective area' of the urine patch includes the area directly outside the wetted area where plants can benefit from access to urinary N (Buckthought, 2013; Lantinga et al., 1987; Lotero et al., 1966; Nye & Tinker, 1977). However, many lysimeter studies on N leaching losses account for only the wetted area of the urine patch. Relatively little work has been done in quantifying the effective area of a urine patch, however it has been estimated in the range of 0.03-1.3m^2 (Buckthought, 2013; Lotero et al., 1966; Moir et al., 2011). Little is known about plant N uptake in the perimeter of urine patches and the potential effect this could have on nitrate leaching losses.

Table 2.3.1 Examples of frequency, volume and surface area covered by dairy cattle urinations in grazed pasture systems. From (Buckthought, 2013).

Study	Frequency of urinations per day	Volume of single urination (L)	Wetted area covered by single urination (m^2)
(Ledgard *et al.*, 1982)	9.8	-	-
(Lovell and Jarvis, 1996a)	10.1	-	-
(Williams *et al.*, 1999)	11.0	-	-
(Williams *et al.*, 2000)	-	1.6	-
(Haynes and Williams, 1999)	9.4	-	-
(Petersen *et al.*, 1956)	8.0	-	0.28
(Grayston *et al.*, 2001)	10	2.2	0.19
(Haynes and Sherlock, 1986)	12.1	-	-
(Prins and Neeteson, 1982)	-	-	0.18
(Safley *et al.*, 1984)	11.0	1.9	-
(Cameron *et al.*, 1992)	10.0	2.0	-
(Richards and Wolton, 1976)	-	-	0.49
(Patra *et al.*, 2005)	-	-	0.16

Cattle urine is approximately 65-90% urea (Bristow et al., 1992; Buckthought, 2013). The N content of urine increases with the N content of feed eaten, while the N content in dung remains relatively constant (Fig 2.5) (Haynes & Williams, 1993). Urine N concentration can also be influenced by a number of other factors including the time of day, hydration level, type of feed eaten and climatic conditions (Buckthought, 2013; Haynes & Williams, 1993).



A.1 5: Relationship between feed N content and N excreted by grazing animals. (Haynes & Williams, 1993)

2.3.3. Biological fixation

Inert atmospheric N_2 gas can be introduced to soil as ammonia via biological fixation (Cameron, 1992; McLaren & Cameron, 1996). Biological fixation is carried out either by free-living soil bacteria, or symbiotic bacteria (*Rhizobium*) living in association with plant roots. In the past, this process was relied on to provide all pasture N (100-350 kg/ha/yr) however as farm systems have become more intensified, fertiliser application has become commonplace (Di & Cameron, 2002b).

Legume plants commonly form associations with rhizobia species, offering an advantage in low N soils over other species that may suffer nitrogen stresses (Andrews et al., 2009). The rhizobia bacteria form nodules on plant roots, where N fixation activity takes place (Andrews et al., 2013; McLaren & Cameron, 1996; Tan et al., 2015). These symbiotic bacteria are able to reduce N_2 to NH_3, (Fig 2.6) a reaction catalysed by the enzyme nitrogenase (Cameron, 1992; McLaren & Cameron, 1996)

$$N_2 + 6e^- + 6H^+ \xrightarrow{\text{Nitrogenase enzyme}} 2NH_3$$

A.1 6: Equation for the reduction of N_2 to NH_3 by rhizobia.

Some free living soil bacteria are able to fix atmospheric N without forming a symbiotic relationship with plant roots (Cameron, 1992; McLaren & Cameron, 1996). The contribution of these bacteria to pasture based farming is less (<25 kg N/ha) than that of symbiotic bacteria (Cameron, 1992).

Plants grown in association with legumes can also benefit from fixed N. Nodules sloughed off in soil as legume roots decay, have potential to release mineral nitrogen. The break-up of clover root systems when pastures are ploughed also increases potential for mineralisation of organic matter (Cameron, 1992; McLaren & Cameron, 1996) The dynamics of biological fixation explain why the combination of perennial ryegrass (*Lollium perenne*) and white clover (*Trifolium repens*) is the most commonly grown pasture mix in New Zealand farm systems. Since the white clover legume is able to increase soil N fixation and provide N to support the ryegrass component, this combination persists without N fertiliser addition. Still, pasture dry matter production is increased through N fertiliser application (Cameron, 1992). There appears to be some disadvantages of using fertiliser as opposed to relying on biologically fixed N. Ryegrass tends to be a stronger competitor for fertiliser N, perhaps because it cannot fix its own (Jacobs & Strieker, 1976). This often results in high yielding ryegrass, which suppresses clover yield and thus reduces the pastures capacity for biological fixation. Harris and Clark (1996) also found that clover N fixation was higher ($P<0.05$) under no fertiliser than when

400kg N/ha applied. This indicates that the efficiency of biological fixation is reduced when there is a high concentration of mineral N available as a result of fertiliser use.

2.3.4. Atmospheric addition

Nitrogen gasses and suspended particles such as ammonia (NH_3), nitrous oxide (N_2O) and nitric oxide (NO) in the atmosphere can be deposited onto soil or plant surfaces, and incorporated into the soil system via transformation processes (Cameron, 1992). These additions can be categorized into wet and dry deposition (Cameron, 1992; Haynes, 1986). Wet deposition being additions from particles suspended in rain and precipitation hitting the soil surface, and dry deposition being gaseous and air suspended N particles. In agricultural systems, the main form deposited is NH_3, as atmospheric concentrations are high due to the presence of animal excreta (Cameron, 1992).

2.4. N transformations in soil

2.4.1. Nitrification

The term nitrification describes the transformation of NH_4^+ into NO_3^-, a process governed by soil bacteria (Cameron, 1992; Cameron et al., 2013; Haynes, 1986). During nitrification, ammonia-oxidising bacteria (AOB) oxidise NH_4^+ to NO_2^-. This part of the process is mainly carried out by nitrosomonas (McLaren & Cameron, 1996). Another group of bacteria (nitrobacter) then oxidise NO_2^- to NO_3^-.

Because NH_4^+ is rapidly converted to NO_3^- most soils have very low levels of NH_4^+ present (Di & Cameron, 2002b). Both NH_4^+ and NO_3^- are plant available, however NO_3^- is the most common form of N taken up by plants (Andrews et al., 2013). NO_3^- ions and soil colloids are both negatively charged. Thus NO_3^- is not well retained by soil. If not taken up by plants, NO_3^- is lost from soil via volatilisation, denitrification or leaching (Cameron et al., 2013; Di & Cameron, 2002b, 2002c).

The nitrification process is affected by soil moisture content and temperature. Optimum rates occur when soils are close to field capacity, and in the optimum temperature range of 25 - 30°C (McLaren & Cameron, 1996). Nitrification rates are also higher within the pH range 4.5 -7.5 as Ca and Mg deficiency or Al toxicity in acid soils can limit the bacteria involved.

Haynes and Sherlock (1986) noted that inhibiting nitrification and conserving N as NH_4+ in soil could reduce denitrification and leaching losses. This has been further examined and proven successful by

(Di & Cameron, 2005) who used dicyandiamide to inhibit nitrification and deceased leaching from 134 to 43 kg N/ha/yr. As a result, a nitrification-inhibiting product was developed for use on New Zealand farms (Eco-N). However, this was removed from the market in 2013 due to political reasons. Until this is remedied, further research into this area in search of another nitrification inhibitor could be beneficial.

2.4.2. Mineralisation/immobilisation

Mineralisation

Mineralization is the conversion of organic N in soil into mineral (plant available) form (Cameron, 1992). A majority (>95%) of the N that exists in soil is in organic forms (McLaren & Cameron, 1996). When microbes decompose soil organic matter such as crop residue, the carbon to nitrogen ratio of the material governs whether N mineralization can occur (Cameron, 1992). The microbes responsible for breaking down carbon in crop residue require some N for energy in order to carry out the process (Cameron, 1992; McLaren & Cameron, 1996). If organic material has high nitrogen content, the C: N ratio will be low (<25:1). In this case there is excess nitrogen above that required by the decomposing bacteria. Thus mineralization will occur, releasing mineral N for use by the current crop or pasture.

During mineralization proteins found in organic material are split up into amino acids. Amino acids are then converted to NH_3 by soil organisms, a process termed ammonification. This provides the energy used by microbes in the process (Cameron, 1992; Haynes, 1986; McLaren & Cameron, 1996).

Immobilisation

Immobilization is the opposite process to mineralization, converting mineral N into organic forms (Cameron et al., 1992; McLaren & Cameron, 1996). This is where the soil microbes take up their required proportion of mineral N and incorporate it into their structure to use for their own functions. It is estimated that globally, immobilisation processes re-cycle half of gross annual N released via mineralisation (Haynes & Williams, 1993).

Immobilisation and mineralization processes occur simultaneously in soil. The C: N ratio of organic matter in soil governs whether the net effect of this is mineralization or immobilization. A C: N ratio >25:1 will give net immobilisation, <25:1 will give net mineralization. This explains why pasture yields are often low in the first year following a cereal crop. Since the C: N ratio of crop residues such as wheat straw (80:1) can be very high, (McLaren & Cameron, 1996). Microorganisms require a great amount of energy to break down this carbon, and use all of the N produced, for energy to carry out the process. Thus net immobilisation occurs. While the residue is being broken down there is no excess N for release. As a result the following pasture may suffer N stress and low yields in the first year. To avoid this, farmers often apply an extra 25 kg N/ha of nitrogen fertiliser at pasture establishment.

2.4.3. Cation exchange adsorption

Nitrogen in the form of ammonium (NH_4^+ cations) can be retained in soil by cation exchange sites on clay and organic matter surfaces (Cameron et al., 2013; McLaren & Cameron, 1996). Clay minerals and organic matter have negatively charged surfaces, which hold onto the cations via electrostatic attraction (Haynes, 1986; McLaren & Cameron, 1996).This mechanism reduces the amount NH_4^+ in soil solution and offers some protection from leaching, although NH_4^+ in solution is rapidly converted to NO_3^- via nitrification (McLaren & Cameron, 1996). When nitrification occurs, NH_4^+ removed from soil solution is replaced by adsorption site NH_4^+ in as the two are in equilibrium. Considering this, and the fact that NH_4^+ in soil solution is plant available it would appear that leaching losses could be reduced without sacrificing plant production, if the nitrification process did not occur, and large amounts of NH_4^+ were present in soil. This was the foundation for extensive research by Di and Cameron (2002c) and others into applying a nitrification inhibitor to pasture, as discussed in section 2.4.1, Nitrification.

2.5. N movement in soils via solute transport mechanisms

The nature of N movement in soil can be described by three key transport mechanisms: convection, diffusion and dispersion (Cameron et al., 2013).

2.5.1. Convective transport

Convective transport is movement of solutes through soil via the mass flow of water (McLaren & Cameron, 1996). While this is predominantly vertical transport down the soil profile, horizontal convection can also occur. Darcy's law (Fig 2.7) allows us to understand the rate of water flow through a porous medium. In the case of nitrate leaching losses, we can use a modified version of this to calculate the rate of convective solution flow through soil in order to calculate its nitrate leaching potential.

Darcy's Law

$$J_c = q\ c = -\ c\ [k\ dH/dx]$$

A.1 7: Darcy's law

Key factors for this calculation are hydraulic conductivity (K), hydraulic gradient (dH/dx), water flux (q), and solute concentration (c), used to calculate convective solute flux (J_D).

Hydraulic conductivity refers to the vertical pull of water down through the soil profile. This is largely affected by pore size. For example, sandy soils with many large macro pores with have a much higher hydraulic conductivity than clay soils, which have very small pore spaces. As a result, a faster rate of vertical convection is observed in sandy soils, while more horizontal convection occurs in clay soils. The hydraulic conductivity is governed by the hydraulic gradient. This refers to the slope gradient towards the water table, when slope measured between two points in the soil. As the hydraulic gradient increases, the hydraulic head (pressure) increases. The increase in pressure causes faster vertical convection resulting in rapid drainage.

2.5.2. Diffusive transport

Diffusive transport occurs when there is an uneven distribution of solutes in soil solution (McLaren & Cameron, 1996). This causes solutes to move from areas of high to low concentration in the soil, equalizing solute distribution. This process occurs at a slower rate in soil solution compared to water because solute flow paths are torturous. This process can be described by Fick's Law, (Fig 2.8) where D_s represents the diffusion coefficient of a particular solute in soil, dependent on θ (volumetric water content). The D_s for solute in soil solution will be slower than for the same solute in water as solute moving through soil solution has to follow the path around soil particles.

Fick's Law

$$J_d = -D_s\ (\theta)\ dc/dx.$$

A.1 8: Fick's Law

2.5.3. Hydrodynamic dispersion

The term hydrodynamic dispersion is used to describe the mixing effect that occurs when soil solution flows rapidly through soil. The mechanical action of solution flow also contributes to equalizing solute distribution, sometimes overriding the effects of diffusion. The 'mixing effect' is a result of the following three effects:

The velocity of solute movement through pores is variable. This can be understood via Poiseuille's Law, (Fig 2.9) which uses density (ρ), acceleration due to gravity (g), viscosity (η) and soil pore radius (r) to describe the flow rate of solution (Q).

Poiseuille's Law

$$Q = (\pi \rho g / 8\eta)\ r^4$$

A.1 9: Poiseuille's Law

The effect of pore friction on flow rate is much like that observed in a riverbed, where water flowing in the middle of the channel will flow faster than water at the bottom of the channel or riverbank edges. Likewise, solution moving in the centre of a soil pore will flow faster than solution that is in direct contact with pore walls and is being slowed by drag.

Because of the large variety in pore sizes, soil pore water velocity varies greatly. Solution taking a pathway through large soil macropores can flow at 10,000 times the rate of solution entering the soil at the same time, following a micropore pathway (Cameron, 1992; Nye & Tinker, 1977)

The torturous distribution of pores results in a range of flow path lengths (McLaren & Cameron, 1996). Solute moves faster along certain pathways and slower along others, as it must travel around soil particles. This results in a more even distribution of solute throughout the soil.

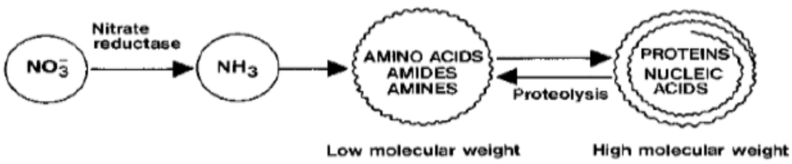
2.5.4. Preferential flow

Preferential or bypass flow occurs when large 'macro' pores in soil allow water to drain through the profile much faster than the rate of solute movement through the rest of the soil pore matrix (Nye & Tinker, 1977). When a large volume of water from rainfall or irrigation is applied to soil immediately following N deposition, preferential flow can cause much larger NO_3^- leaching losses than usual, which occur at a much quicker rate than usual (McLaren & Cameron, 1996). Thus, NO_3^- breakthrough curves resulting from preferential flow occurring are asymmetrical when compared with breakthrough curves resulting from hydrodynamic dispersion alone as they peak abruptly and then drop towards zero more slowly (Nye & Tinker, 1977).

2.6. N removal from soil

2.6.1. Plant uptake

Nitrogen is an essential element for plant development as it is an integral part of many plant metabolites including DNA, RNA, plant proteins, chlorophyll, auxin and cytokinins (Andrews et al., 2013). It is required at all stages of plant development from seed germination through to seed production. Nitrogen is the most limiting plant nutrient globally and hence urea (46% nitrogen) is the most widely used fertiliser throughout the world. A typical dairy farm pasture will usually take up 300-400 kg N/ha/ yr (Cameron, 1992; Cameron et al., 2013; Di & Cameron, 2002a, 2002b; O'Connor & Gregg, 1971). Within the plant N can be translocated and used as nitrate or is reduced to ammonia (NH_3) in the roots (Fig 2.10) (McLaren & Cameron, 1996). Ammonia is converted to amino acids, amines or amides to be translocated through the plant and used to produce proteins and nucleic acids. This process also operates in reverse in order to mobilise N from old to young leaves. Young leaves are then supplied with sufficient N while the old leaves undergo senescence.



A.1 10: Nitrogen metabolism in plants (McLaren & Cameron, 1996).

It is important that N inputs to agricultural systems are matched as closely as possible to plant N uptake demands in order to reduce and/or prevent other N loss mechanisms such as gaseous losses and leaching which are harmful to the environment.

2.6.2. Gaseous losses

A study by Allison (1955) found a puzzling disappearance of applied nitrogen fertiliser, giving rise to a paper titled "The enigma of soil nitrogen balance sheets". It was later discovered that this 10-30%

disappearance was due to gaseous losses via ammonia volatilization and denitrification (Haynes & Sherlock, 1986).

Volatilisation

Ammonia volatilization increases when free NH_3 is present at the soil surface (Haynes, 1986; Ledgard et al., 1998; McLaren & Cameron, 1996). Such conditions usually occur after nitrogen fertiliser application or animal urine deposition (McLaren & Cameron 2012). Unless rain or irrigation occurs immediately afterwards and washes the application down into the soil, NH_3 gas is volatilized, from soil and lost into the atmosphere. Gaseous losses for entire grazed pastures have been reported in the range of 20 – 120 kg/ha/yr (Ryden, 1986).

(Ledgard et al., 1998) reported results from a Hamilton pasture with no N fertiliser applied, which lost an average of 15 kg N/ha/yr. Adding fertiliser increased this loss to 41 kg at 200 kg N/ha applied, and 65 kg at 400 kg N/ha applied. This indicated that although animal excreta is the biggest problem source for leaching loss, this is not the case for volatilization losses, which are greater due to fertiliser application.

Denitrification

Denitrification is the transformation and loss of NO_3^- in soil solution to gaseous forms in the atmosphere (Fig.2.1). Denitrification occurs when soils are poorly aerated causing anaerobic conditions (Cameron, 1992; Cameron et al., 2013; McLaren & Cameron, 1996). It can be facilitated by bacteria (biological denitrification) or by reactions in soil (chemo-denitrification) (Cameron, 1992).

Denitrification is a major source of N loss in agricultural systems. A Canterbury study by Fraser et al. (1994) reported that 28% fertiliser N applied was lost to atmosphere under flood irrigation due to wet, anaerobic soil conditions. In waterlogged soils, the lack of oxygen available favours anaerobic bacteria, which are able to use NO_3^- for respiration instead of oxygen (Cameron et al., 2013; Haynes, 1986). During anaerobic respiration NO_3^- is reduced, producing nitrite (NO_2), nitric oxide (NO), nitrous oxide (N_2O) and di-nitrogen (N_2) as by-products (Cameron et al., 2013).

Factors affecting denitrification

Soil acidity

The rate of denitrification decreases with soil acidity, and is lower in soils with a pH <5 (Cameron, 1992; Cameron et al., 2013; Haynes, 1986). Most farmers aim to keep agricultural soils in the range of pH 5.8-6, however in more acidic soils liming may help reduce gaseous N losses (Cameron et al., 2013).

Soil moisture

When soil moisture is greater than field capacity, the potential for denitrification increases significantly (Cameron et al., 2013). As a result, denitrification rates are greater during autumn, winter and early spring when soil moisture content tends to be highest. Heavy clay soils become easily waterlogged due to their small pore spaces and are more prone denitrification compared with free draining soils. Taking these factors into account, it appears that the rather expensive installation of soil moisture monitoring technology, precision irrigation software and soil drainage systems could offer tangible benefits in terms of pasture yield as a result of reducing N loss to denitrification.

Temperature

Temperature is positively correlated with denitrification rate, with denitrification losses reported to increase ten times between 10 and 20 degrees Celsius (Cameron et al., 2013). Although irrigation increases soil moisture status, which favours denitrification, consistent irrigation could lead to lower soil temperatures, thus reducing the rate of denitrification. It has already been reported that the effect of temperature is less in irrigated soils (Cameron et al., 2013). Perhaps this is because the temperature does not increase quickly or stay high for long enough in frequently irrigated soils for denitrifying bacteria activity. This further suggests that investment in irrigation technology may help retain more N in the soil – plant system.

Availability of mineral N

Increasing the availability of NH_4 and NO_3^- increases the potential for denitrification (Cameron et al., 2013). The availability of these mineral N forms increases greatly after fertilizer application and in areas where animals excrete dung and urine (Cameron, 1992; Cameron et al., 2013). Gaseous losses for fertiliser and animal manure have been reported to be in the ranges of 0.1-2% and 0 to 5% respectively (Cameron et al., 2013). Fertiliser increasing mineral N presence is inevitable. However it appears that by considering these factors and avoiding fertiliser application when other conditions favour denitrification, greenhouse gas production could be reduced. For example, fertiliser application should be avoided in waterlogged areas of soil. This is a further incentive for investing in technology such as variable rate irrigation.

2.7. Leaching losses

Nitrate is commonly leached through the soil profile during drainage events caused by high rainfall. This process can increase the nitrate concentration of groundwater and/or surface water that is commonly used for human consumption and/or recreational purposes (Cameron, 1992; Cameron et al., 2013).

Nitrate loss into rivers can cause eutrophication (algal blooms) making the water undesirable for recreational use, and detrimental to the health and survival of aquatic species (Cameron, 1992; Cameron et al., 2013). Eutrophication is defined as conditions where the N concentration in water reaches between 0.4 and 0.6 mg L (Di & Cameron, 2002a). Nitrate contamination of drinking water also poses human health risks such as methaemoglobinanemia in babies and has also been linked to heart disease and cancer (Cameron et al., 2013).

Retaining NO_3^- in soil is difficult, as these negatively charged anions are repelled by the negative charges on clay mineral and organic matter surfaces (McLaren & Cameron, 1996). Nitrate leaching losses are primarily caused by mineral N supply in excess of plant N requirements and uptake capacity coupled with soil moisture content that exceeds plant and evapotranspiration demands (Cameron et al., 2013). Leaching loss requires a drainage event to occur, high mineral N concentration alone will not result in leaching, and thus the timing of management practices is extremely important in reducing leaching losses.

2.7.1. Factors affecting nitrate leaching

Fertiliser application on urine patches

When high rates of N fertiliser are applied to already concentrated urine patches the risk of nitrate leaching is increased, (Cameron, 1992; Cameron et al., 2013) thus the placement of fertiliser is important. Buckthought (2013) found that fertiliser at a rate of 400 kg N/ha caused an increase in NO_3^- leaching losses when applied over top of a urine patch. However, when applied at 200 kg N/ha over a urine patch, fertiliser addition did not increase N loss. Many modern commercial fertiliser-spreading operations now have trucks equipped with GPS fertiliser placement technology, which can help avoid spreading fertiliser in undesirable areas such as wet or unproductive zones. Similar technology can also be used in planes for aerial spreading and soil testing by aerial photography is an emerging technology which will soon allow the same insight into soil fertility on hill country as is currently possible on flat farmland. This will allow farmers to make better-informed decisions around fertiliser use and placement, making the process more economic and sustainable.

Climate

As outlined in section 2.2.1, conditions promoting leaching loss are usually present in late autumn, winter and early spring in temperate regions. This is due to mineralisation occurring into autumn despite decline in plant uptake, as growth becomes temperature limited (Cameron *et al.* 2013). High rainfall during the subsequent winter causes drainage and thus leaching losses.

While summer leaching losses are less common in temperate regions, there are certain circumstances where leaching can occur. Fertiliser applications throughout summer are commonplace on most New Zealand dairy farms. If pastures are over-irrigated or irrigation to field capacity is followed by a rainfall event, drainage can occur resulting in loss of fertiliser applied N (Cameron et al., 2013; Haynes, 1986). Pasture growth can also become limited in summer where evapotranspiration rates exceed water supply. In response, plants will reduce growth and thus N uptake. This leaves a high mineral N concentration in soil, prone to leaching loss when drainage begins to occur the following winter.

Soil texture

Soil texture and structural properties are also factors of nitrate leaching potential. For example, a poorly structured sandy soil will have greater leaching potential than a clay soil, due to its lower particle density allowing water to drain quickly through its macropore matrix (Cameron et al., 2013). Clay soils are less free draining due to greater particle density and can easily become waterlogged. This increases the potential for denitrification (Cameron et al., 2013; McLaren & Cameron, 1996), thus there is less nitrate N available for leaching. When the soil is drained, mineralization is increased, and the soil is aerated, reducing denitrification (Cameron et al., 2013). The distance that water must travel through the soil profile can also be reduced. As a result, drainage systems can contribute to increasing nitrate leaching losses.

2.7.2. Measuring leaching losses

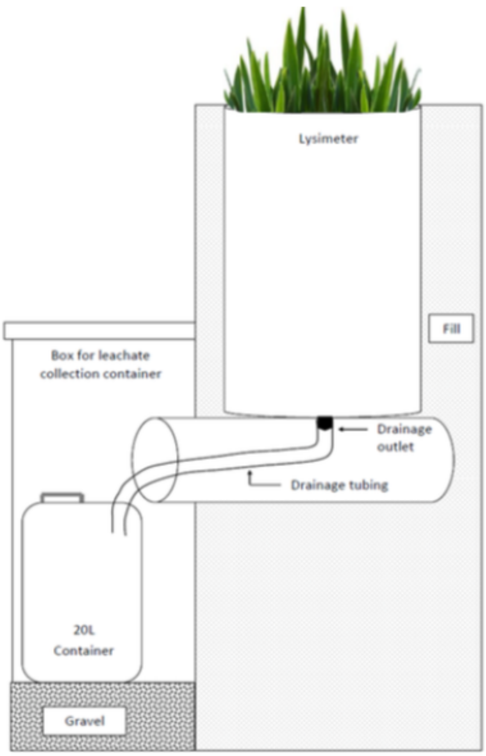
Ceramic suction cups

Ceramic suction cups are an easy and affordable way to gather information on soil N leaching potential (Wang et al., 2012) although they have a number of limitations and uncertainties, such as their influence of normal soil water dynamics. Thus suction cups are often regarded as a flawed method despite their widespread use (Wang et al., 2012; Webster et al., 1993). The cups are installed at a certain depth in soil and attached to a glass bottle which can be placed under suction, allowing a soil water sample to pass through a porous medium into the collection cup (Webster et al., 1993). This provides a measure of the concentration of nitrate in soil solution at a certain point in the soil profile, however the amount of drainage occurring must be estimated in order to calculate total leaching losses potentially entering groundwater (Webster et al., 1993).

Wang et al. (2012), compared measurements from ceramic suction cups and lysimeters and concluded that the suction cups are more appropriate for measuring leaching loss in sandy soils, as they can fail to accurately measure losses from soils with a non-uniform pore matrix. Because the cups take a localised measurement in soil, and only hold a small drainage volume it is possible for them to miss preferential macropore flow occurring in soil and give a false low reading. Placement of the cups can also cause them to directly intercept macropore flow giving a false high reading.

Lysimeters

Lysimeters provide a simulation of real soil water dynamics by using an undisturbed soil monolith. This allows measurement and analysis of the entire drainage output from an area of soil (Fig 2.11).



A.1 11: A soil monolith lysimeter (Buckthought, 2013).

A lysimeter measurement accounts for variation in soil pore size throughout the soil (Wang et al., 2012) , as they are guaranteed to capture any preferential macropore flow drainage which may be missed by a localised measuring apparatus such as the ceramic suction cup. Upon comparison of nitrate leaching losses measured by ceramic suction cups, lysimeters and soil core extracts, Webster et al. (1993) found that the results recorded from the soil cores were highly variable in relation to the two aforementioned methods for which results were similar. Therefore lysimeters and suction cups are two of the more commonly accepted and credible methods for measuring nitrate leaching losses.

Historically the main limitation of lysimeter measurements was the potential for preferential edge-flow to occur where drainage was able to 'fast-track' down the side of the lysimeter walls between the soil and the metal lysimeter edge. However, the accepted solution for minimising edge-flow potential is to line the walls of the lysimeter with petroleum jelly (Cameron et al., 1992). This method was designed by Cameron et al. (1992) who introduced a 10 mm angled cutting ring to the bottom edge of the lysimeter casing which creates a small gap between the soil monolith and lysimeter casing as the lysimeter is being prepared. Once lysimeters are in place, the gap is filled with melted petrolatum and creates a watertight seal around the monolith.

2.7.3. Mitigation of leaching losses

While fertiliser N inputs can be fully controlled, it is difficult to manage the concentration and placement of urine N. Thus, the understanding and awareness of N movements within the whole farm system and commitment to best practice by farmers is key to reducing potential N losses from soil.

Fertiliser application practice

The most important principle for reducing N losses from pasture is matching the supply of N inputs to the pasture uptake demand (Di & Cameron, 2002b). When N is supplied in conditions where plants are actively growing and at the rate at which plants are able to take N up, and soil moisture is below saturation point, there is no significant risk of N leaching to groundwater. Maintaining sufficient levels of other essential plant nutrients such as potassium and sulphur is also important. Plants can only grow at the rate at which the most limiting nutrient will allow. For example, if a potassium deficiency were to limit plant growth, the plant's ability to take up N would also be reduced. This could cause an abundance of NO_3^- N in soil, increasing the potential for NO_3^- to be leached to groundwater.

Split applications of N fertiliser can reduce N losses, as the amount of N applied at each application is better matched to the rate of plant N uptake, reducing the amount of N loss that could occur if an unexpected rainfall event was to occur immediately after application. Di et al. (1998) showed that when N was applied in four rather than two applications, leaching losses were reduced from 13-49 to 6-17 kg N/ha. Leaching losses from fertiliser can be higher when applied in autumn (15-19%) than in spring (8-11%) (Cameron et al., 2013). This is because there is often higher rainfall, and hence more drainage events in winter following autumn application. Applying fertiliser in spring when soil temperatures are becoming warmer and before or during a light rainfall event, when there is sufficient soil moisture but little risk of soil saturation, will ensure that the fertiliser is dissolved in soil solution and taken up by plants as quickly as possible. Thus, best practice fertiliser application helps to reduce both gaseous emissions and N leaching potential.

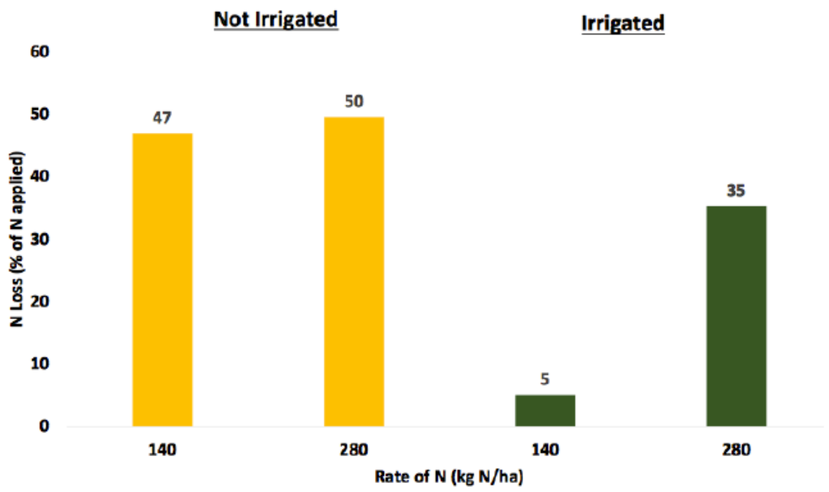
Soil cultivation

Ploughing pasture causes a spike in mineralization, potentially releasing >100 kg N/ha/yr (Cameron et al., 2013). Ploughing during autumn can increase leaching potential, as there is a high mineral N release, little plant uptake occurring, and drainage occurring over the subsequent winter months. Pasture renewal is an agricultural practice commonly carried out in autumn, although good pasture establishment can also be achieved in spring. Considering the above, there is stronger support for renewing pastures in spring as it poses less risk of nitrate leaching.

Irrigation management

Sensible irrigation application should aim to keep soil moisture slightly below field capacity. This allows sufficient water so as not to limit plant growth, but also allows for unexpected rainfall events to occur without bringing the soil to saturation point. If the soil is not saturated, drainage events are unlikely to occur and there is little potential for nitrate to be leached to groundwater. This can be achieved through soil moisture monitoring and precision irrigation technology, which can adjust irrigation rates accordingly. Irrigation placement can also be controlled with variable rate irrigation systems, which allow irrigation to be turned off for certain areas of the farm such as stock tracks and wet areas. This avoids saturation of areas where urine deposits are high and plant growth is not required and areas where drainage is likely occur. Delaying irrigation by a few days after livestock have grazed a paddock may also reduce nitrate leaching (Di & Cameron, 2002b). Monitoring of soil temperature along with moisture is also important. Irrigation is likely to reduce soil temperatures and if these are already low they may be reduced to a point where plant growth will stall. A reduction in active plant growth causes a reduction in N uptake and thus an increase in nitrate leaching potential.

An American study, by Hahne et al. (1977) reported a decrease in leaching losses from corn crops when proper irrigation was applied as opposed to no irrigation (Fig.2.12). This experiment was conducted using 3 different soil types, undergoing continuous corm cropping for 5 years. The reduction in leaching losses from crops under irrigation was more pronounced at 140 kg N/ha applied, than when 280 kg/ha was applied, and also in sandy soils with higher drainage rates. Termed "environmental irrigation", this concept is a result of increased plant growth under irrigation, which allows plants to utilise more of the available N in soil (Cameron & Di, 2015; Hahne et al., 1977). Leaching losses can be reduced using irrigation, provided that the irrigation applications are carefully monitored so as not to exceed plant uptake capacity.



A.1 12: Irrigation to reduce nitrate leaching loss from continuous corn cropping. Adapted from (Hahne et al., 1977). From (Cameron & Di, 2015).

In some areas where the summer dry period is short, such as in the Waikato region in the upper North Island of New Zealand, irrigation is not typically applied. In some instances this may increase potential for N leaching where plants stop actively growing due to low soil moisture. Any fertiliser N or animal urine deposited during this time are then left sitting in soil. It is also common for farmers to feed out supplementary feed onto dry paddocks during this period of pasture shortage, which also increases the area of pasture receiving high concentration nutrient deposits. These N deposits will be prone to leaching when rainfall arrives during the subsequent winter. In these instances, irrigation during the short dry period could reduce N leaching loss by encouraging plant growth for a longer period and reducing the N concentration in soil during winter when drainage is likely to occur (Cameron & Di, 2015; Hahne et al., 1977). In order to provide further evidence for the environmental irrigation effect, it would be useful to conduct a similar experiment using pasture, and measuring denitrification as well as leaching losses. Using the environmental irrigation strategy in autumn during the late part of the irrigation season could help reduce the amount of available N in soil at the beginning of winter. Thus reducing nitrate leaching losses during the winter period.

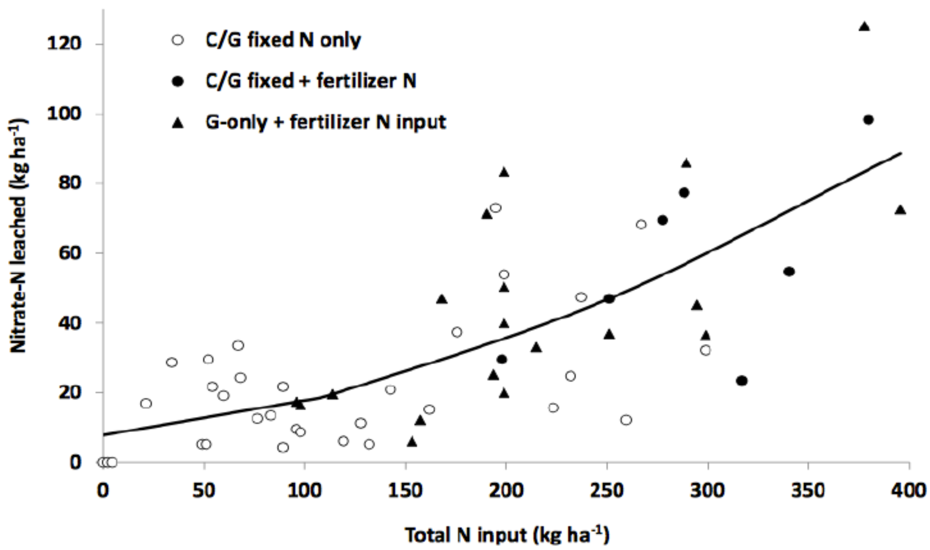
Livestock management

Best practice livestock management can help reduces N losses by removing stock from pasture as critical times, such as during a significant rainfall event, which is likely to cause soil saturation and thus drainage to groundwater. Use of a feed pad during these high-risk conditions will reduce potential for urinary N to be lost in drainage and also reduce pugging damage to paddocks, saving valuable stock feed.

Careful placement of supplementary feed and feed stations such as palm kernel bins and hay feeders may also help reduce losses. Because livestock continually visit these areas to consume feed, high urinary N concentrations occur. Placing feed in different areas each time will encourage a more even spread of N inputs across the paddock. Increased plant uptake during winter by species such as Italian ryegrass can reduce nitrate leaching compared to perennial ryegrass which slows its growth during winter (Malcolm et al., 2015). Therefore when feeding out supplements such as silage on to pasture, choosing an Italian ryegrass paddock rather than perennial ryegrass would be recommended best practice (Cameron & Di, 2015).

Lower input systems

An increase in total N inputs into the farm system will increase the amount of nitrate-N leached (Fig.2.13) (Cameron & Di, 2015). Total N inputs into the system can be decreased by lowering the stocking rate, which reduces animal transfer and the need to import supplementary feeds or by reducing fertiliser inputs. Finding ways to get the same or better crop/pasture production from our soils, using less N inputs more efficiently will reduce the potential for N additions to end up as leaching losses. A current 5-year research project at Lincoln University called the 'Pastoral 21' trial is investigating the potential to reduce N loss through lower input systems while retaining profitability. Perhaps research into biological solutions and/or nitrification inhibitors other than DCD will also help to achieve this.



A.1 13: Relationship between total N inputs (kg ha^{-1}) and nitrate-N leached (kg ha^{-1}) compiled from both NZ and UK data (Cameron & Di, 2015).

2.8. Summary and areas for future research

- Nitrogen added as fertiliser is used in most New Zealand farm systems to increase pasture production. However it can also increase N losses if not managed carefully with regard to application rates and timing.

- Urinary N is the most highly concentrated N input to pasture, and therefore has the greatest potential to increase leaching losses.

- Transformation of NH_4^+ to NO_3^- via nitrification favours plant uptake, as there is a preference for the NO_3^- form, however this does not favour the environment as the negatively charged NO_3^- ions are more prone to leaching than NH_4^+.

- When applied appropriately, irrigation can be used to increase plant uptake in late summer/ autumn, thus reducing nitrate leaching losses over the subsequent winter.

- Less N input into the system decreases the potential for N losses. Methods of increasing N use efficiency are an important area for future research. This could enable us to be more conservative with N inputs, thus protecting the environment without reducing the productive potential of our farm systems.

- Important research areas include new methods of inhibiting nitrification in soil, as DCD is no longer commercially available in New Zealand, and research aimed at increasing the 'effective area' of a urine patch by manipulating the placement, volume and concentration of urine that is deposited on soil.

Previous reports have mentioned that the effective area of a urine patch is larger than the directly wetted area due to plant uptake in the perimeter of the urine patch (Buckthought, 2013; Lantinga et al., 1987; Lotero et al., 1966; Nye & Tinker, 1977). However there is little research that quantitatively reports the distance from the urine patch to which plants can benefit from increased N uptake. The effects of this phenomenon on nitrate leaching losses is also yet to be quantified, thus this is an important area for future research in determining the impact of urinary N deposits on the environment.

Chapter 3

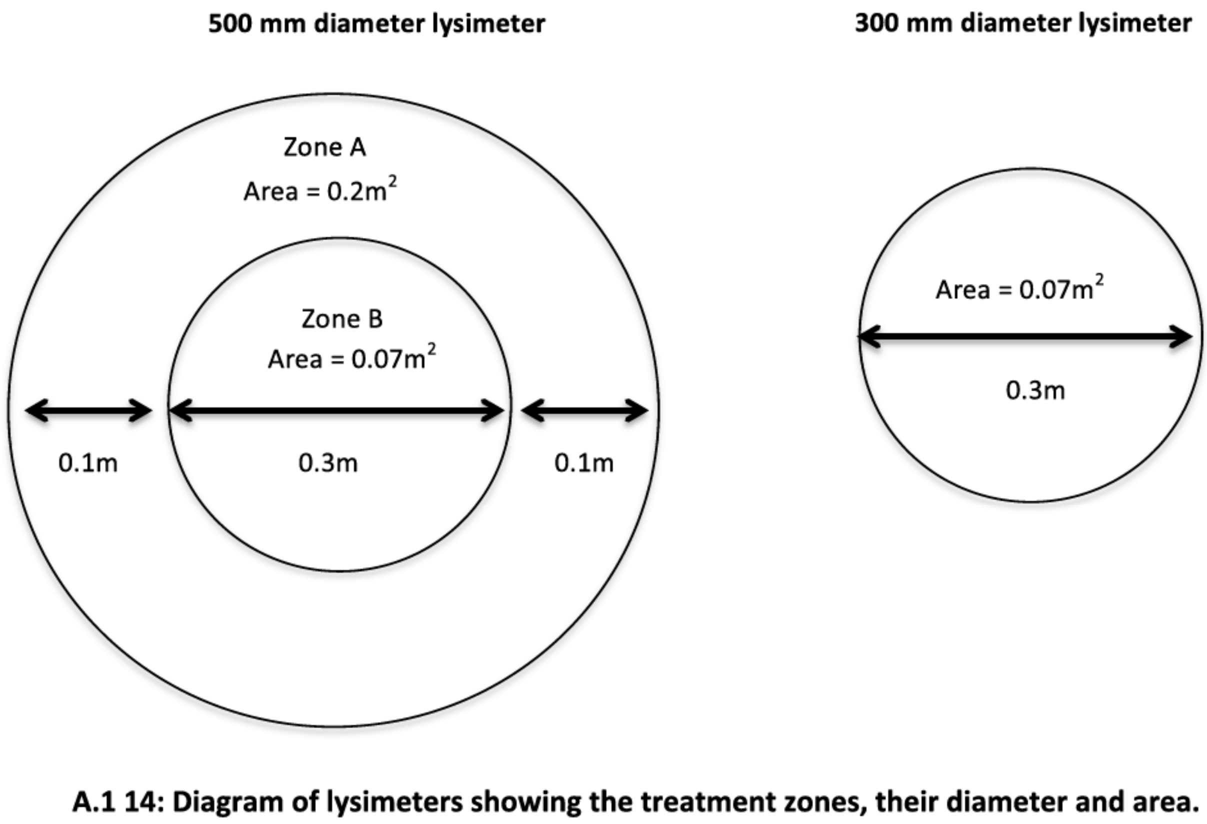
Materials and Methods

3.1 Experimental design and treatments

The experimental design was a completely randomized design. The design consisted of two treatments, (Fig 3.1) (i) Urine patch lysimeters (500 mm diameter) with perimeter grass in zone A and a urine patch in zone B, (ii) urine patch lysimeters (300 mm diameter). There were control lysimeters for each treatment giving four different treatment combinations. There were 7 replicates in each treatment group, giving a total of 28 lysimeters.

- (1) Urine - 500 mm diameter lysimeter
- (2) Control - 500 mm diameter lysimeter
- (3) Urine - 300 mm diameter lysimeter
- (4) Control - 300 mm diameter lysimeter

The four treatments were:



A.1 14: Diagram of lysimeters showing the treatment zones, their diameter and area.

A single synthetic bovine urine application of 0.8 L at a concentration equivalent to 700 kg N/ha was applied in a 0.07 m^2 area in the centre of all urine treatment lysimeters on the 6^{th} of April 2016. At the same time, all control lysimeters received 0.8 L of tap water, applied to their central 0.07 m^2 area.

In treatment (1) (urine 500 mm), urine was applied only to zone B on the 500 mm diameter lysimeters. In treatment (3) (urine 300 mm), urine was applied to the whole area of the 300 mm lysimeters. Zone A for the urine treated 500 mm diameter lysimeters represents the 'perimeter grass' directly surrounding a bovine urine patch. Seven replicates of each treatment were established in a randomized design.

3.2 Lysimeter origin and collection

Lysimeters used were a Templeton silt loam soil, originating from the Lincoln University Research Dairy Farm. For each lysimeter, a metal cylinder was placed over an area of soil with a wooden board over top. Using a sledgehammer first, the board was carefully hit so that the cylinder cut into the soil evenly. Once the cylinder was approximately 20 cm into the soil, the board was stood on top of and hit gently with a weighted pole so as to push the cylinder further into the ground evenly, and remaining upright. As the cylinder was pushed further into soil, the soil outside the cylinder was cut away. Once the top of the cylinders met with the undisturbed pasture (Fig 3.2) round metal plates were leveraged underneath the soil columns and bolts were inserted to attach the cylinders to the plates. Melted petroleum jelly was then poured down the insides of the lysimeter between the soil and metal sides, to prevent edge-flow, which could cause drainage water to 'fast-track' down the lysimeter. Once set, the lysimeters were then carefully lifted by tractor and transported to Lincoln University where they were placed in a trial pit (Fig 3.3).

A.1 15: Lysimeters ready to be sealed and lifted

A.1 16: Lysimeters arranged in the trial pit.

3.3 Simulated grazing

On the 1st of April 2016, prior to treatment application, all lysimeters were cut to 1500 kg DM/ha residual using a Heineger electric hand piece, to simulate a normal dairy cow grazing event.

3.4 Synthetic urine recipe

A synthetic urine mixture (Table 3.1) containing urea, glycine, potassium bi-carbonate ($KHCO_3$), potassium chloride (KCl), potassium bromide (KBr) and potassium sulphate (K_2SO_4) was made up to a concentration of 7.0 g N/L (Table 3.1). This was applied in a 0.8 L volume to the fourteen 0.07 m^2 areas (Zone B or 300 mm diameter lysimeters) requiring treatment, to give an N application rate equivalent to 700 kg N/ha.

Each ingredient was weighed out into separate plastic zip lock bags (Fig 3.4) in the laboratory using an enclosed Mettler Toledo NewClassic ML balance. The ingredients were then dissolved (Fig.3.5) in a 50 L container with water to a concentration of 7.0 g N/L.

Table 3.4.1: Synthetic urine recipe

Substance	Weight (g N/L)
Urea	13.6
Glycine	3.39
$KHCO_3$	16.31
KCl	2.94
K_2SO_4	1.61

A.1 17: Separate components of the synthetic bovine urine recipe after being weighed out.

A.1 18: Dissolving synthetic urine ingredients in water.

3.5 Treatment application

Coloured flags, red for treatments and blue for controls, were placed at the respective lysimeters prior to treatment application (Fig 3.6).

A.1 19 Blue flag placed next to a control lysimeter prior to application.

Following treatment application of an individual lysimeter, the flag was removed, to avoid applying treatments to the same lysimeter twice.

0.8 L of the urine mixture was measured into a 10 L plastic jug (Fig 3.7) and then poured evenly onto the seven randomly selected urine 300 mm diameter lysimeters by hand (Fig 3.8). The remaining seven control 300 mm lysimeters received 0.8 L of water, applied using the same method.

A.1 20: Synthetic urine being measured into application jugs.

A.1 21 Treatment being applied to a 300 mm lysimeter.

A 300 mm diameter plastic ring was placed in the centre of each of the 500 mm diameter lysimeters and pushed 1 cm into the soil by placing a board over the lysimeter and gently hammering the corners of the board with a mallet (Fig 3.9).

A.1 22 Plastic 300 mm ring being pushed into soil.

0.8 L of the urine mixture was applied within the plastic ring (zone B) of the seven urine 500 mm diameter lysimeters (Fig 3.10). The remaining seven control 500 mm lysimeters received a 0.8 L water application, applied using the same method.

A.1 23 Treatment being applied to zone B of a 500 mm lysimeter.

3.6 Irrigation

Individual sprinklers were installed over each lysimeter. These were of the same design used in previous lysimeter studies at Lincoln University using 500 mm diameter lysimeters. Prior to the start of the trial on the 6th of April 2016, lysimeters were under an irrigation regime to simulate what would occur under a normal Canterbury dairy farm system. Under the irrigation regime, 12 mm of water was applied every three days. This continued up until the 1st of May 2016. Thereafter, natural water inputs were supplemented with rainfall simulated by the irrigation system using the Risk 3000 programme to calculate application volume and timing. Simulated rainfall was set to the 75th percentile of historical average Lincoln rainfall for the trial period. The beginning of the 2016 winter season was abnormally dry. Low drainage volumes (<1 mm) in late June and July indicated that soil moistures were lower than usual and did not reflect those of a typical Canterbury winter. In order to remedy this, rain simulation was increased to the 90th percentile for the remainder of the trial. Following this change, drainage volumes indicated that soil moistures were closer to the expected level in Canterbury during winter.

3.7 Pasture cuts and processing

Pasture cuts (Fig 3.11) were taken when the average pasture herbage mass was approximately 3000 kg DM/ha by visual assessment, a typical pre-grazing residual for a Canterbury dairy farm. Cuts were taken to a typical post grazing residual of 1500 kg/ha. Separate cuts were taken for lysimeter zones A and B and the 300 mm diameter lysimeters (section 3.1), resulting in 42 samples (14 from zone A, 14 from zone B and 14 from the 300 mm diameter lysimeters). In order to cut pasture from zone A, a plastic ring was placed over the centre of the 500 mm lysimeters (Fig 3.11) to avoid cutting zone B. The ring was then cut around using an electric hand-piece. Cut pasture from zone A was placed into a paper bag before the plastic ring was removed to allow cuts to be taken from zone B. Zone B and the 300 mm diameter lysimeters were cut using the same method, without use of a plastic ring.

A.1 24 Taking a pasture cut from zone A (perimeter grass)

Each fresh sample was then weighed using a Mettler Toledo PB1502 balance, and the fresh weight recorded. Harvest 1 samples (Table 3.2) were separated for botanical composition analysis (section 3.7.1) after the fresh weights were taken.

Table 3.7.1 Pasture harvest dates

Date	Harvest No.
5th May	1
3rd June	2
9th September	3

All samples were placed inside drying ovens for 3+ days at 60 degrees Celsius. Once dried, samples were removed from the ovens and weighed again on the Mettler Toledo PB1502 balance. Plant dry weights were recorded. The dried sampled were processed through a Retcsh grinder. Ground samples were weighed out into vials. Each vial contained 0.1930 – 0.2001 g of ground plant material. The samples were then analysed for total nitrogen content (mg/L) by rapid maximum N analysis

3.8 Botanical composition

Botanical composition analysis was carried out on the first batch of pasture cuts. Each of the 42 samples was separated into three different sub samples (Fig 3.13) according to the three main plant components (ryegrass, clover and weeds) giving 126 samples in total. Following this, the samples were placed in the drying ovens and processed as outlined in section 3.7.

A.1 25: Harvest 1 sample (bottom) being sorted into botanical components: Weeds, (left), ryegrass (top) and clover (right).

3.9 Leachate collection and analysis

Drainage was collected from lysimeters on a weekly basis or as required after a significant rainfall event. To measure leaching losses, drainage from an individual lysimeter was poured from the 15 L collection container into a 10 L plastic jug. As the leachate was poured, a sample (in a 50 mL plastic vial) was taken from the stream of leachate before it entered the 10 L jug, so as to avoid cross-contamination of samples. The total volume of leachate from the lysimeter was measured in the 10 L jug and recorded. 50 mL samples were analysed by flow injection analysis to determine the NO_3^- and NH_4^+ concentration of the drainage. The final leachate samples were collected on 9 August 2016 when the data obtained indicated that the NO_3^- concentrations in drainage water has passed their peak and declined again until the concentrations measured were almost zero.

3.10 Statistical analysis

All data sets were statistically analysed using Genstat 14. For each data set, an analysis of variance (ANOVA) was run to test for treatment effects and a 5% LSD test was conducted to determine which differences were significant.

Chapter 4

Results

4.1 Water inputs, drainage outputs and temperature

The 5-day period 29 May – 2 June 2016 produced a significant amount of rainfall (84 mm) with 49 mm occurring on June 1 alone (Fig 4.1). Following this, the 2016 early winter period was abnormally dry with little or no rainfall (<20 mm) occurring until the first week of August. Figure 4.2 shows the total water inputs beginning on the 6th of April 2016 at the time of treatment application and ending on the 9th of September when the final pasture cut was taken. Water inputs over this period were equivalent to 417 mm comprising of 202 mm rainfall and 215 mm irrigation/ simulated rainfall.

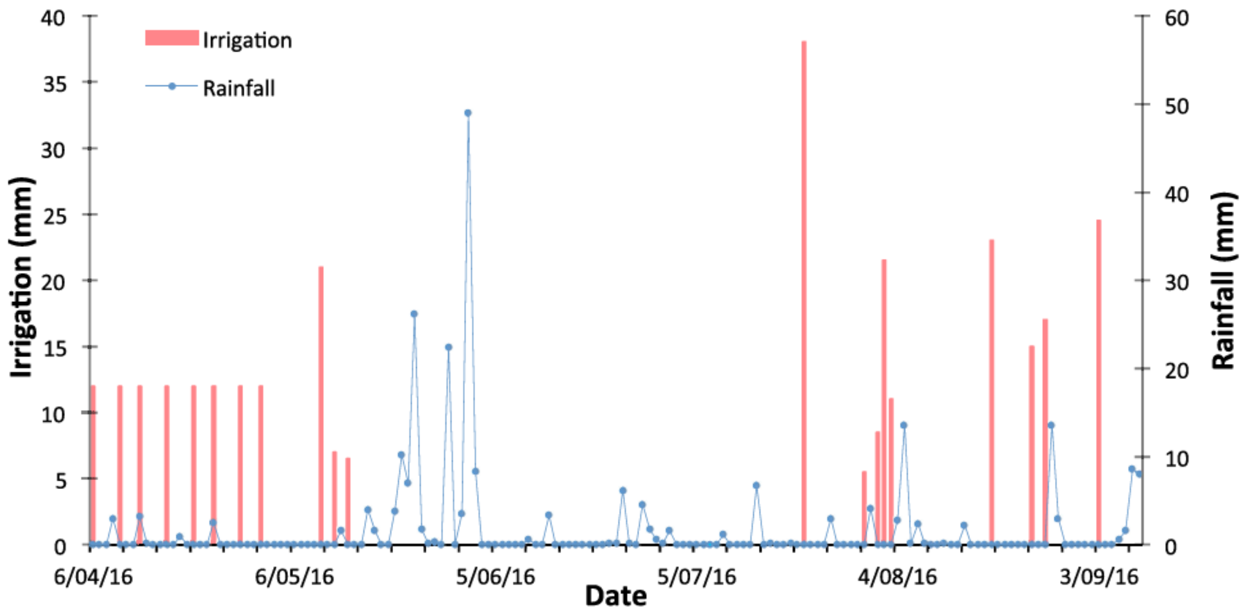


Table 4.1.1: Daily rainfall, and irrigation or simulated rainfall inputs (mm) over the duration of the trial period.

Total cumulative drainage for the control lysimeters was equivalent to 351 mm (Fig 4.2). There was a rapid increase in drainage due to the high amount of rainfall that occurred over the 5 day period 29 May – 2 June. During the long dry period following this (1 June - 5 August), very little drainage occurred. When simulated rainfall was increased to the 90th percentile in late July, drainage volumes continued to increase. The final drainage collection was done on the 9th of August and a combination (Fig 4.1) of actual and simulated rainfall continued to add water to the lysimeters until the final pasture cut was taken on the 9th of September 2016.

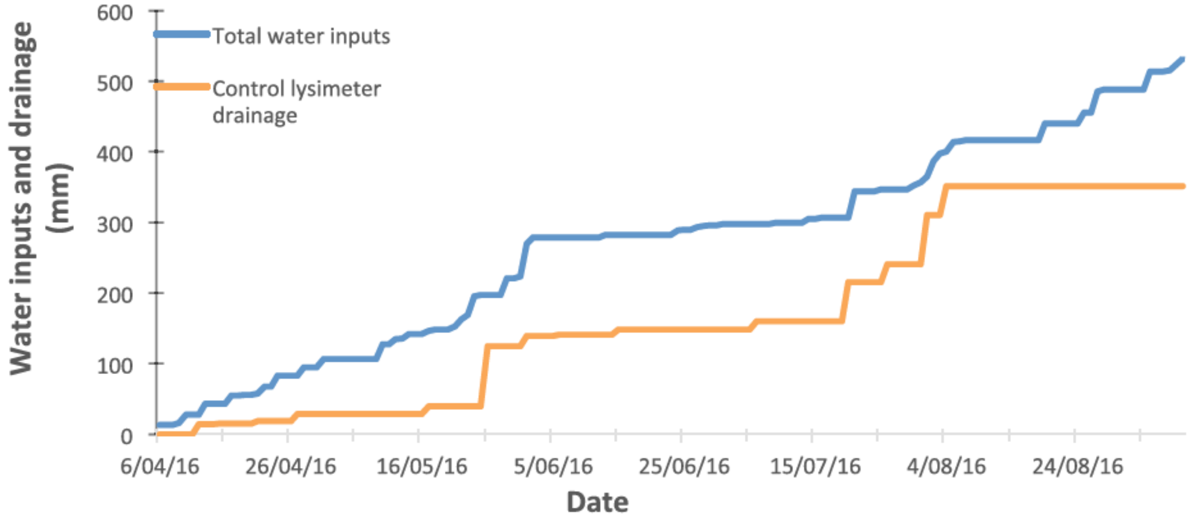


Table 4.1.2: Cumulative water inputs (rainfall + simulated rainfall) and drainage (mm) from control lysimeters over the duration of the trial period.

Average drainage volumes (Fig 4.3) for the 300 mm diameter lysimeters (233 and 295 mm for treatments and controls respectively) were higher (P<0.001) than for 500 mm diameter lysimeters, which drained 117 and 150 mm for treatments and controls respectively. For the 300 mm lysimeters drainage volumes were also higher (P=0.048) from control lysimeters, draining 295 mm compared to urine treated lysimeters, which drained 233 mm. The 500 mm diameter lysimeters showed no significant difference in drainage volumes between urine treated and control lysimeters.

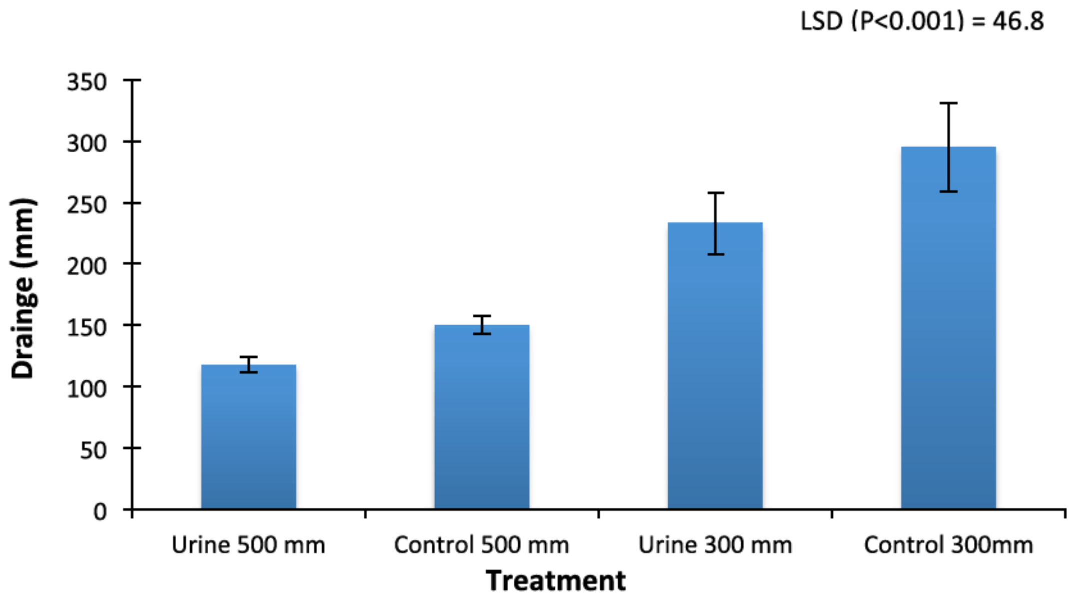
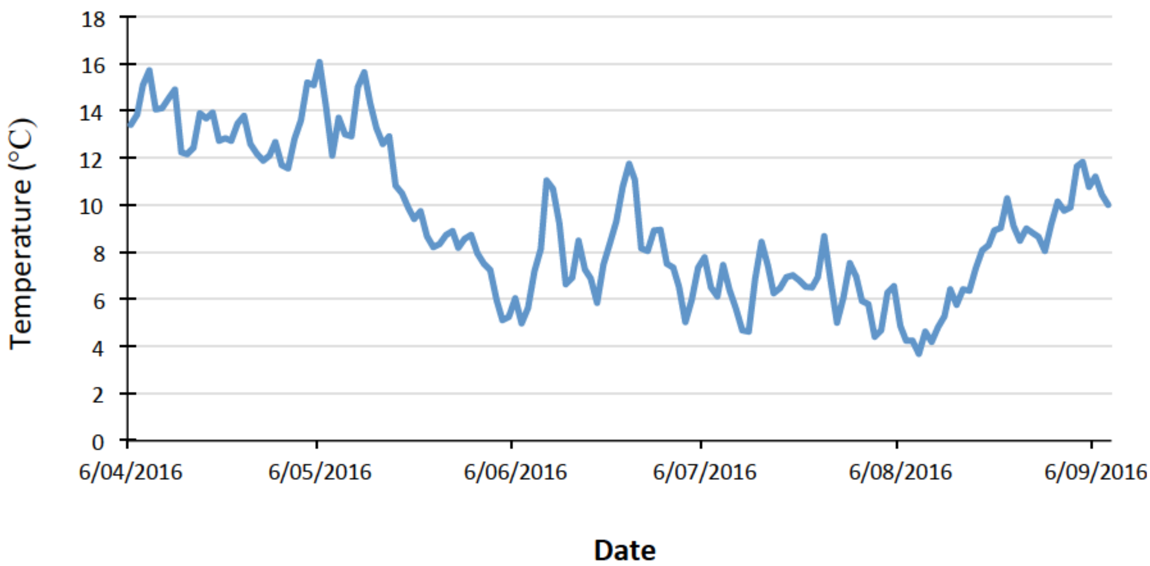


Figure 4.1.3 Average amount of drainage (mm) collected from treatments 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

Temperature

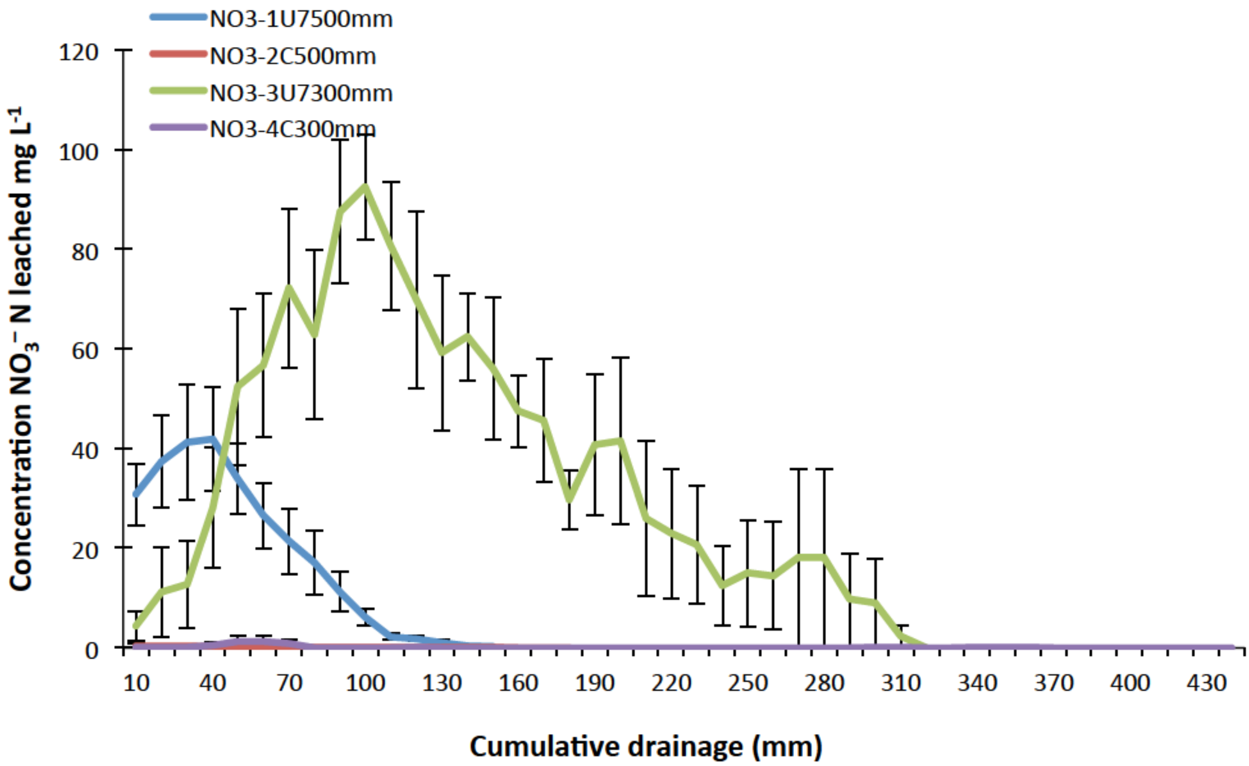
Daily 10 cm depth soil temperatures (Fig 4.4) were highest on the 6th of May 2016 at 16.1°C, one month after treatment application and lowest on the 9th of August 2016 at 3.7°C, coinciding with the final leachate collection. After the 9th of August soil temperature began to climb again, reaching ~10 °C. in early September when the final pasture cut was taken. Average 10cm soil temperature between treatment application and the final leachate collection was 9.18°C.



A.1 4.1.26: Daily 10 cm soil temperature (°C) throughout the trial period from treatment application (6th April 2016) till the final pasture cut (9th September 2016)

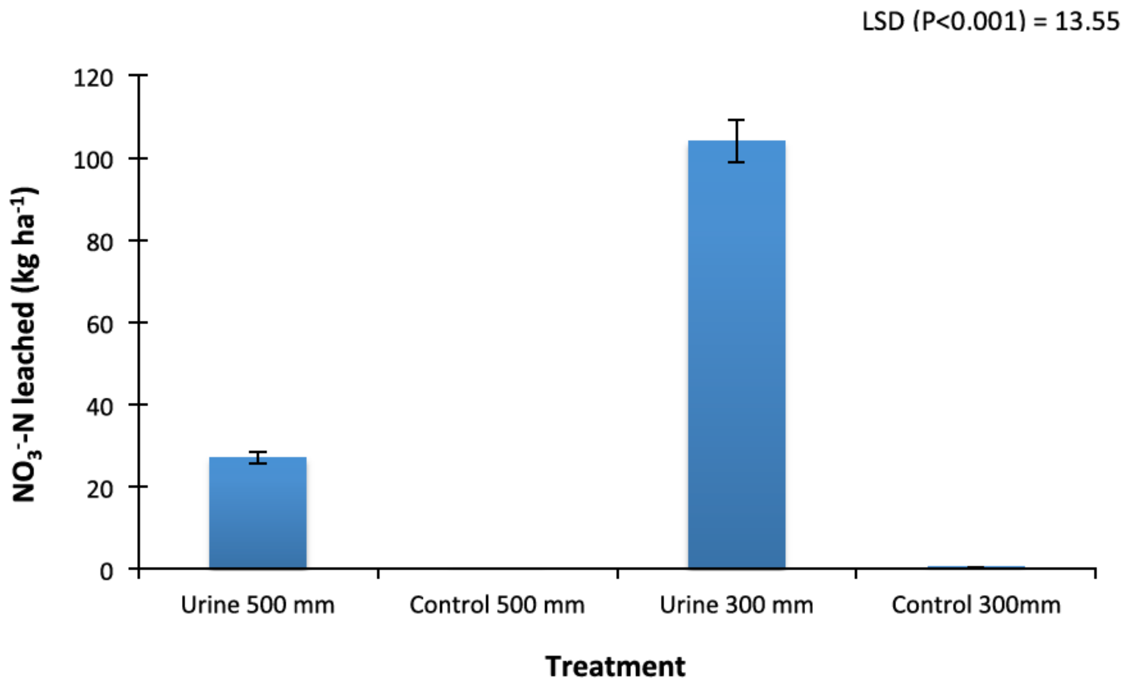
4.2 Nitrate leaching

Nitrate was measured in drainage water from the initial collection on the 12th of April 2016, 6 days after urine application. The predominant form of N in leachate was NO_3^- with little or no NH_4^+ detected throughout the trial. Drainage collected from the urine treatments differed between the 300 mm and 500 mm lysimeters (Fig 4.5) both in terms of peak NO_3^- concentration and the in amount of drainage collected before the peak NO_3^--N concentration occurred. The 300 mm lysimeters had a higher ($P<0.05$) peak NO_3^--N concentration (92 mg N/L) occurring at 100 mm cumulative drainage than the 500 mm lysimeters (52 mg N/L) where the peak concentration occurred earlier at 40 mm cumulative drainage. Drainage from urine treated lysimeters had higher ($P<0.001$) NO_3^--N concentrations than control lysimeters which had < 2 mg N/L detected at any collection throughout the trial.

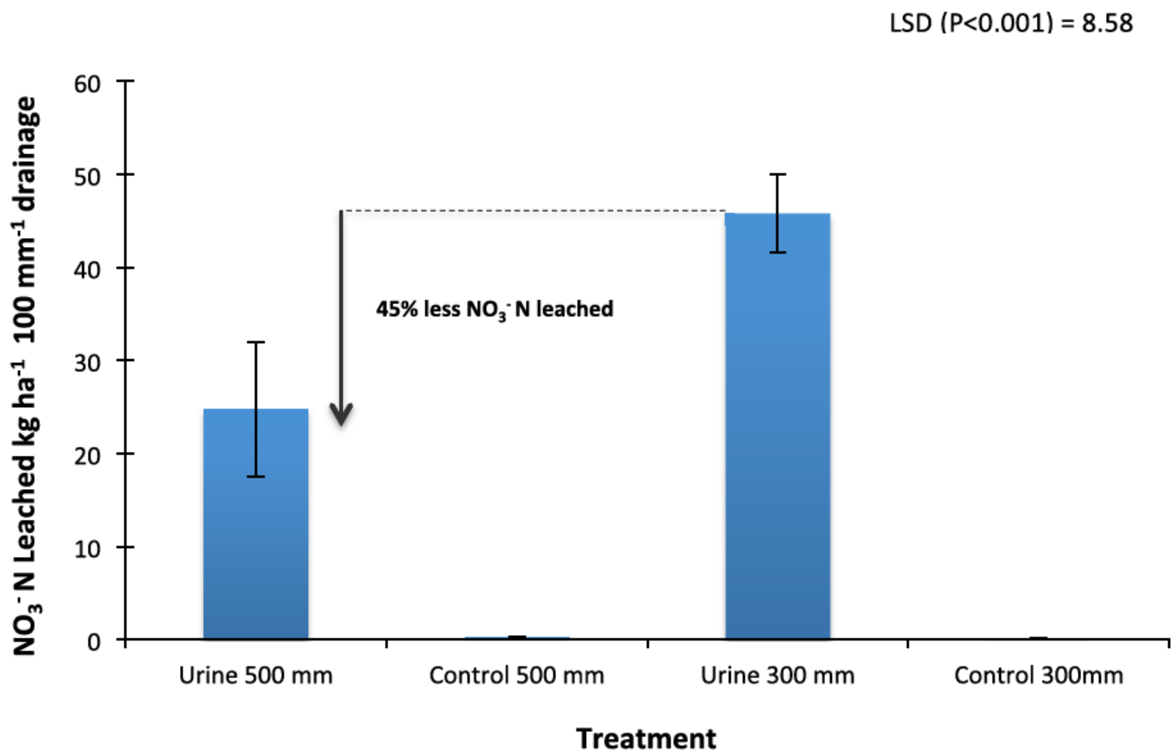


A.1 27: Nitrate concentration (mg L^{-1}) of drainage collected from treatments 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

The total amount if N leached (kg/ha) (Fig 4.6) was higher (P<0.001) for urine treated lysimeters than controls, and higher (P<0.001) for the 300 mm urine treated lysimeters (104 kg N/ha) than for 500 mm urine treated lysimeters (27 kg N/ha). However, due to the larger amount of irrigation water that was applied in error to the small 300 mm diameter lysimeters there was a larger volume of drainage collected from these lysimeters (Fig.4.3) over the duration of the trial. Therefore it was deemed more appropriate to compare NO_3^- leaching losses from the two different lysimeter sizes on a mass of N leached (kg) per 100 mm of drainage (Fig 4.7). When compared on this basis, NO_3^- leaching losses remained significantly higher (P<0.001) for urine treated lysimeters compared to controls. Leaching losses per 100 mm of drainage remained higher (P<0.001) from the 300 mm diameter lysimeters (46 kgN/ha), representing only the wetted area of the urine patch, than from the 500 mm diameter lysimeters that represented the wetted area with perimeter grass (25 kg N/ha). This represents a 45% reduction in NO_3^- leaching losses when the effect of the perimeter grass was taken into account.



A.1 28: Total NO_3^- N leached (kg/ha) from treatments 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

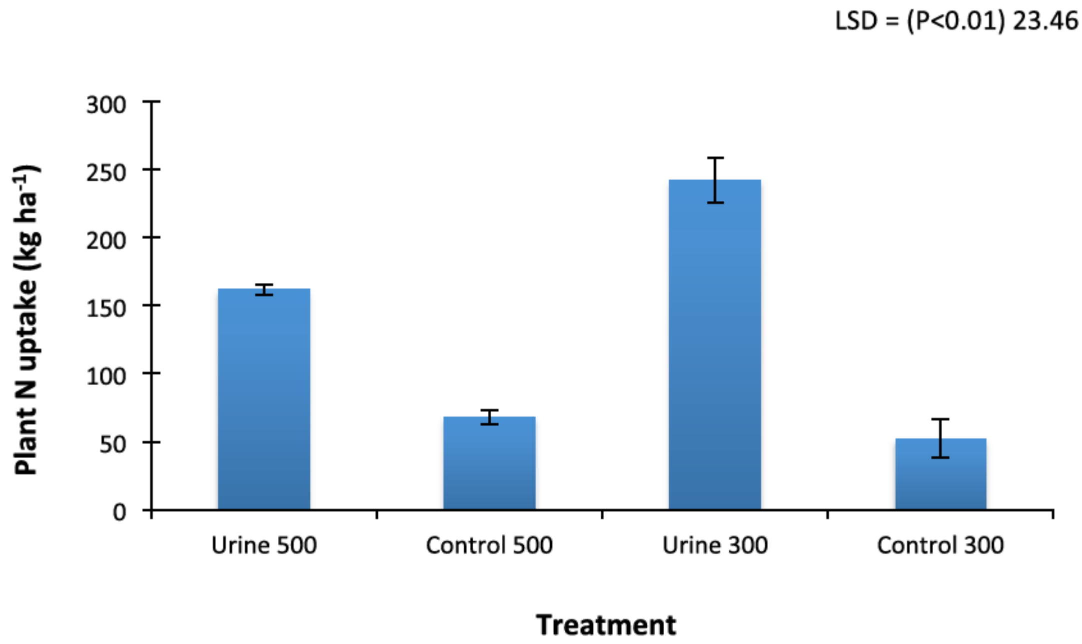


A.1 29: NO_3^- N Leached (kg/ha) per 100 mm drainage collected from treatments 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

4.3 Pasture N uptake

Pasture uptake by treatment

Total pasture N uptake (Fig 4.8) was higher (P<0.001) for urine treated lysimeters compared to their respective controls. Uptake by the urine treated 300 mm lysimeters (243 kg N/ha) was higher (P<0.01) than for 500 mm lysimeters (162 kg N/ha). Plant N uptake was not significantly different between 300 and 500 mm control lysimeters.

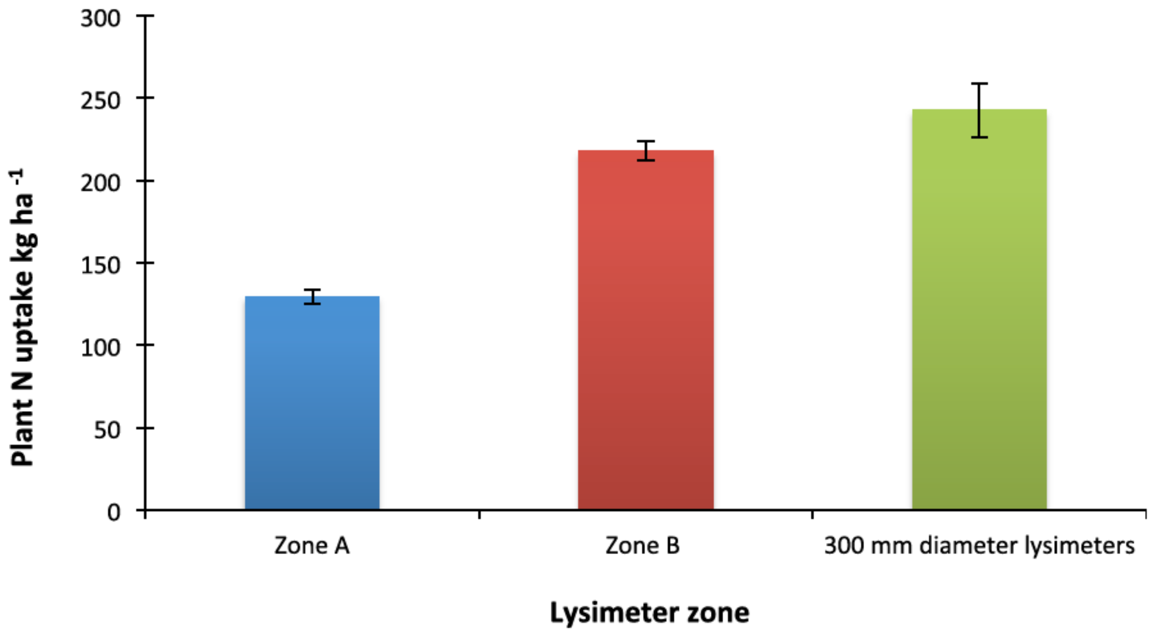


A.1 30: Average plant N uptake by treatments 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

Pasture uptake by lysimeter zone

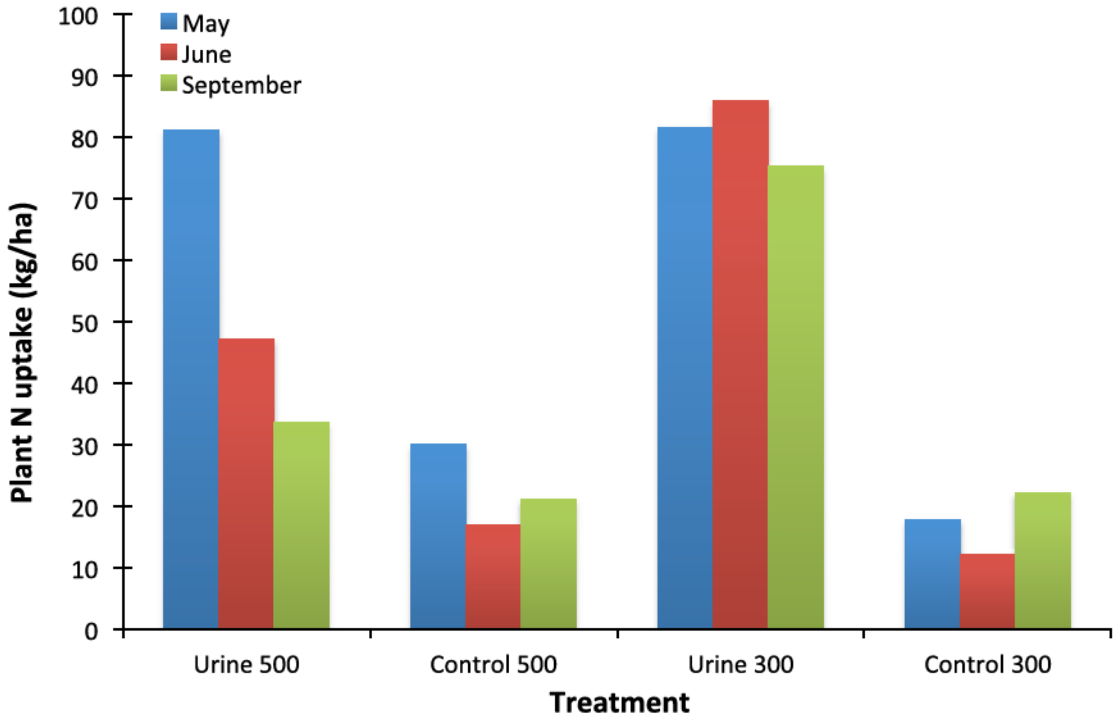
The 300 mm diameter lysimeters (Fig 4.9) had higher (P<0.001) N uptake (243 kg N/ha) compared to zone B (218 kg N/ha). Zone A had the lowest (P<0.001) N uptake of 130 kg N/ha. Fig (4.9) shows only the urine treated lysimeters, all of which had significantly higher (P<0.001) N uptake than their respective controls.

LSD (P<0.001) = 20.11



A.1 31: Total plant N uptake (kg/ha) for urine treated lysimeter zones A (perimeter grass); B (urine application area 500 mm lysimeter) and the 300 mm diameter lysimeters.

Figure 4.10 shows the breakdown of total plant N uptake over the duration of the trial. Plant N uptake for the urine treated 500 and 300 mm diameter lysimeters was not significantly different in May. However, at both the June and September harvests, N uptake was significantly higher (P<0.001) for the 300 mm diameter lysimeters compared to the 500 mm urine treated lysimeters. Nitrogen uptake by urine treated lysimeters was higher (P<0.001) than for their respective control across all three harvests.

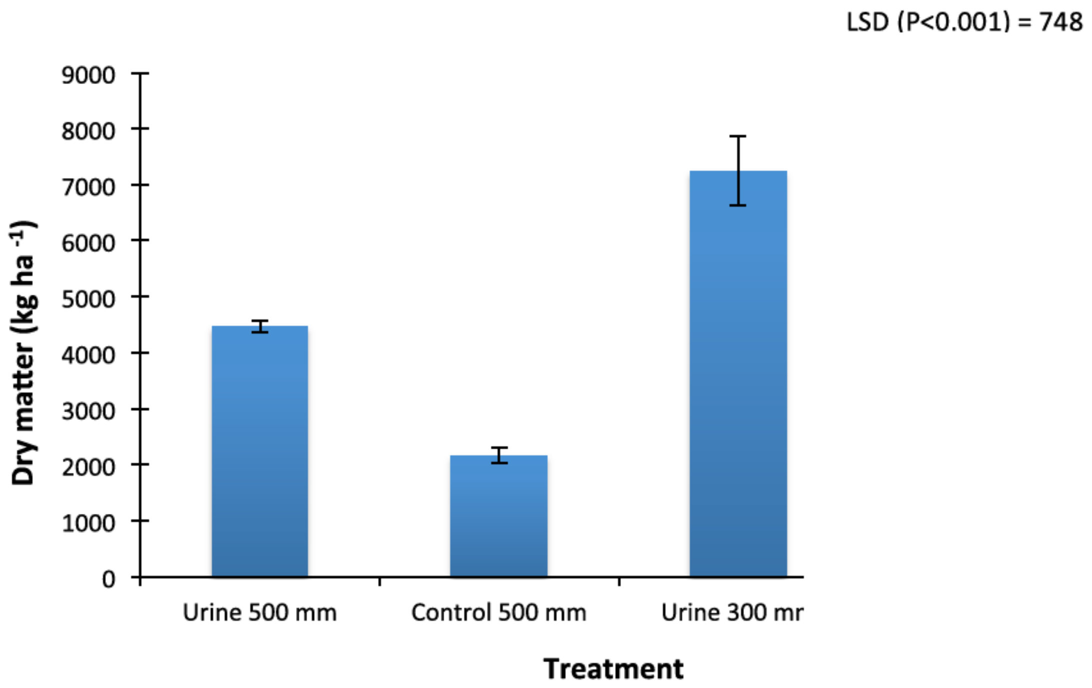


A.1 32 Comparison of plant N uptake (kg N/ha) at three harvests: May (LSD = 10.74); June (LSD = 8.91) and September (LSD = 9.94, for the treatments: 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

4.4 Pasture production

4.4.1 Total pasture production by treatment

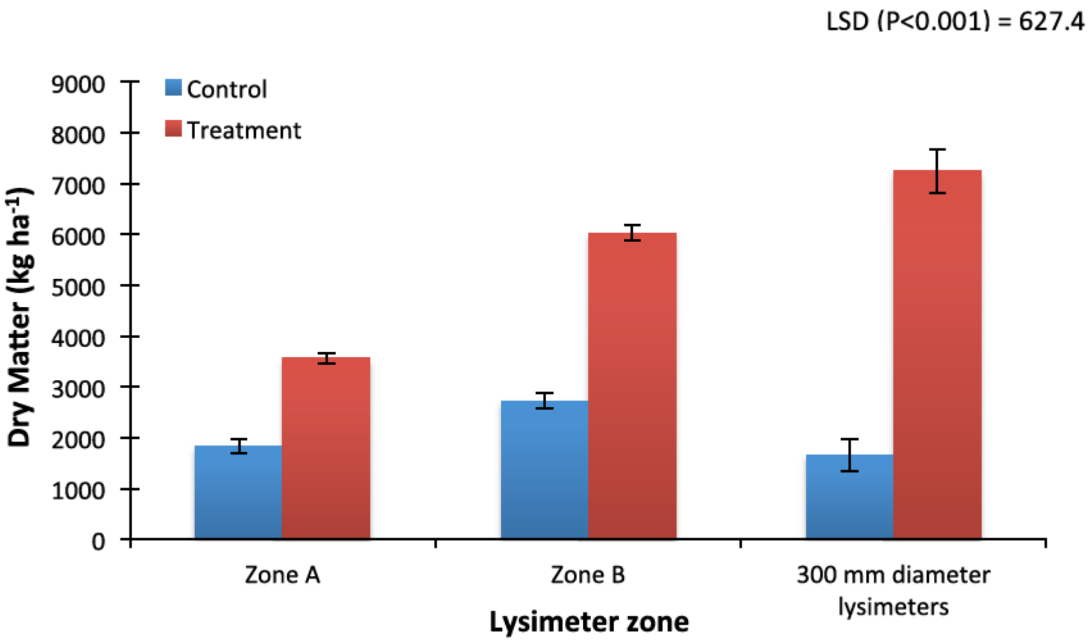
Total dry matter (kg/ha) grown (Fig 4.11) was significantly higher (P<0.001) for urine treated lysimeters than for controls. This difference was observed across all harvests (May, June and September). Dry matter production in the urine treated lysimeters was higher (P<0.001) for 300 mm (7724 kg DM/ha) than 500 mm diameter lysimeters (4467 kg DM/ha). Dry matter production on the control lysimeters was not significantly different between 300 mm and 500 mm lysimeter sizes.



A.1 33: Average total pasture production over the duration of the trial from three harvests, in May June and September.

4.4.2 Total pasture production by lysimeter zone

Total dry matter production over the duration of the trial (Fig 4.12) for the urine treated lysimeters was highest (P<0.001) for the 300 mm diameter lysimeters (7235 kg DM/ha) followed by zone B (6028 kg DM/ha), and zone A, which had the lowest (P<0.001) pasture production at 3561 kg DM/ha.



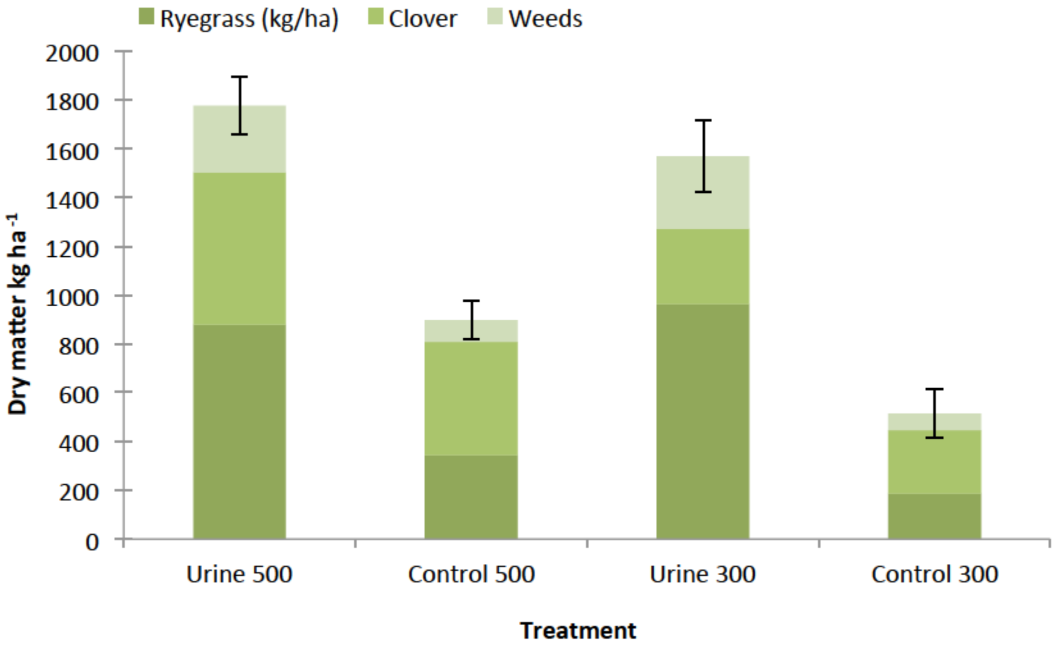
A.1 34 Total dry matter production (kg/ha) by zone A, zone B or the 300 mm diameter lysimeters (LSD (P<0.001) = 627.4) for both control and urine treated lysimeters (LSD (P<0.001) = 512.3) over the duration of the trial from three harvests, in May June and September.

Control lysimeters (Fig 4.12) all produced less (P<0.001) dry matter than their respective urine treated lysimeters. Zone B had the highest dry matter production (P<0.001) of the three control lysimeter zones at 2722 kg/ha. Dry matter production did not differ between zone A (1834) and the 300 mm diameter control lysimeters (1650 kg/ha). There was a significant interaction (P<0.001) between the treatment effect (control vs. treatment) and variation due to the different lysimeter zones.

4.4.3 Harvest 1

Pasture production

In May, dry matter production (Fig 4.13) was higher (P<0.001) for 500 and 300 mm diameter urine treated lysimeters compared to their respective control lysimeters. There was no significant difference in dry matter production for urine treated lysimeters for the two different lysimeter sizes. For the control lysimeters, dry matter production was higher (P= 0.015) for the 500 mm than 300 mm lysimeters.



A.1 35: Dry matter production (kg/ha) and botanical components ryegrass (LSD = 194.6), clover (LSD = 186.8) and weeds (LSD = 82.9) (kg/ha) for treatments 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm) at first harvest (May)

Botanical composition by treatment (kg/ha)

Ryegrass production (Fig 4.13) by urine treated 300 and 500 mm diameter lysimeters was higher ($P<0.001$) at 962 and 878 kg/ha respectively compared to their respective control lysimeters at 345 and 187 kg ryegrass/ha. There was no significant difference in ryegrass production (kg/ha) between the two different lysimeter sizes, for either control or urine treated lysimeters.

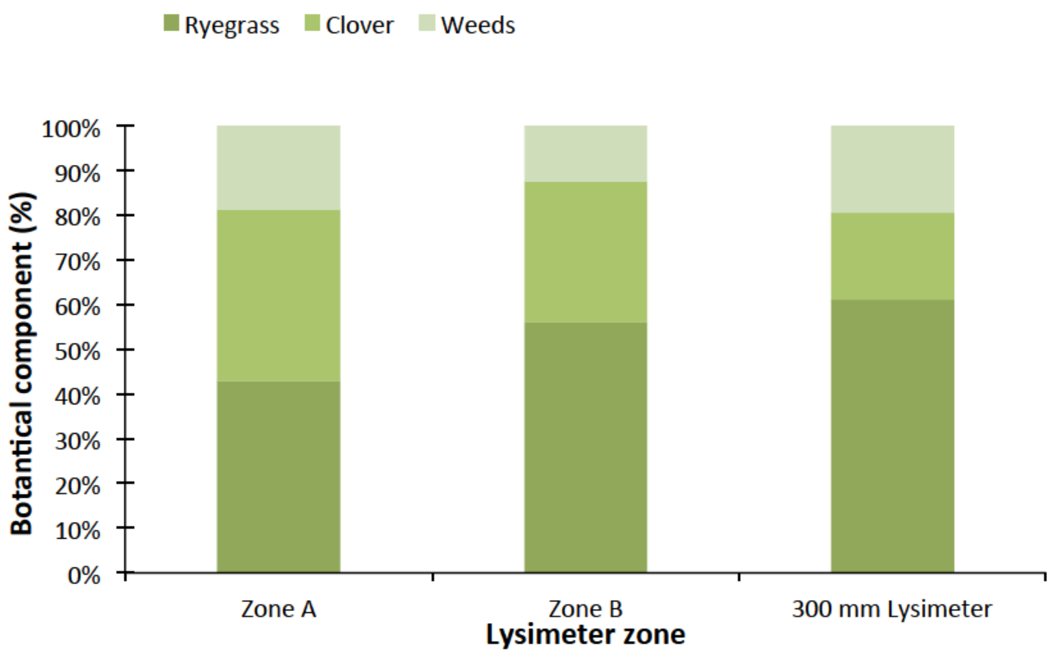
Clover production was higher ($P = 0.008$) for the 500 mm diameter lysimeters, which produced 625 and 464 kg clover/ha for urine treated and control lysimeters respectively, compared to 300 mm diameter lysimeters, which produced 309 and 259 kg clover/ha respectively.

The presence of weeds was higher ($P<0.001$) for urine treated lysimeters with 298 and 273 kg/ha present in the 300 and 500 mm diameter lysimeters respectively, compared to the control lysimeters with 70 and 88 kg/ha present in 300 and 500 mm diameter lysimeters respectively. Weed presence did not differ between the two different lysimeter sizes for control or urine treated lysimeters.

Botanical composition by lysimeter zone

The urine treated 300 mm diameter lysimeters (Fig 4.14) and zone B had higher (P<0.05) ryegrass contents (61% and 56% respectively) compared to zone A, which produced 43% ryegrass. Ryegrass content in zone B and the 300 mm diameter lysimeters did not differ significantly.

Conversely, zone A had higher (P<0.05) clover content (38%) than the 300 mm diameter lysimeters (19%). Zone B of the 500 mm diameter urine treated lysimeters did not differ from zone A, but had higher (P<0.05) clover content than the 300 mm urine treated lysimeters. Weed content did not differ significantly between any of the three different lysimeter zones.

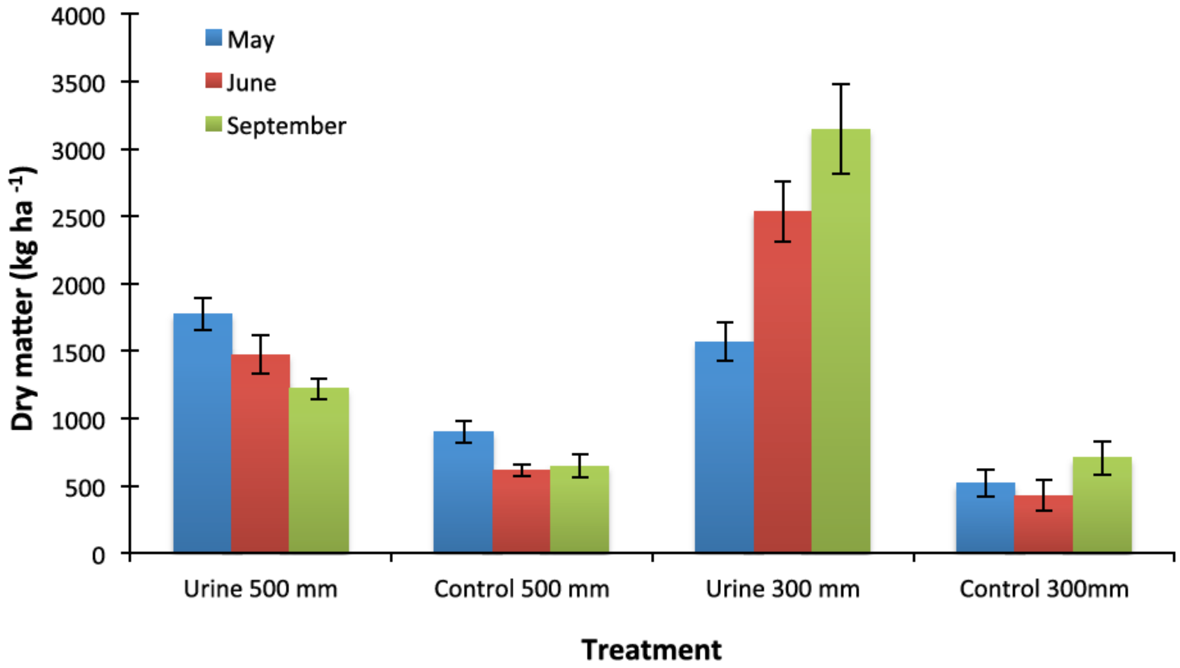


A.1 36: Botanical components, ryegrass (LSD = 0.1485); clover (LSD = 0.1527 and weeds (LSD = 0.1095) of urine treated lysimeters in zone A (perimeter grass 500 mm diameter lysimeters); B (urine patch area 500 mm lysimeters) and 300 mm diameter lysimeters at first harvest (May).

4.4.4 Harvests 2 and 3

Pasture production

The 300 mm urine treated lysimeters had higher (P<0.001) dry matter production than the 500 mm urine treated lysimeters at both June and September harvests (Fig.4.15). For the control lysimeters there was no significant difference in pasture production between the 300 and 500 mm lysimeters, again this differed from the May harvest where 500 mm controls had higher (P = 0.015) dry matter production than the 300 mm control lysimeters. For June and September harvests, there was also an interaction (P<0.001) between the urine vs. control treatment effect and the variation due to lysimeter size.



A.1 37 Comparison of dry matter production (kg/ha) at three harvests: May (LSD = 233.3); June (LSD = 301.9) and September (LSD = 384.6), for the treatments: 1 (Urine 500 mm); 2 (Control 500 mm); 3 (Urine 300 mm) and 4 (Control 300 mm).

Chapter 5

Discussion

5.1 Drainage and leaching losses

Drainage collected from control lysimeters was higher (P=0.048) than for urine treated lysimeters. This was likely due to higher N uptake by the urine treatment lysimeters, which allowed them to produce more dry matter than the control lysimeters, consequently demanding higher volumes of water to be taken up by plant roots for evapotranspiration. Therefore the urine treated soils had less potential to become saturated and consequently produced lower drainage volumes than the slower growing control lysimeters.

The nitrate leaching results from this trial were confounded by unequal irrigation amounts that were applied to the 300 mm and 500 mm lysimeters in error. Therefore, comparison of the data on a total N leached (kg/ha) per treatment basis could not be considered reliable. In order to draw a more accurate comparison, the results have been presented on a NO_3^- leached (kg/ha) per 100 mm drainage basis. The amount of nitrate leached (kg/ha) per 100 mm drainage was 45% higher ($P<0.001$) from the wetted area of a urine patch (300 mm diameter lysimeters) than for urine patches with perimeter grass (500 mm diameter lysimeters). Initially, this result indicated that plant N uptake in the perimeter of a urine patch could reduce nitrate leaching and suggested that the total effective area of a urine patch is larger than the directly wetted area, concurring with reports from Nye and Tinker (1977), Lantinga et al. (1987) and Lotero et al. (1966). However, the difference in drainage volumes, which were higher ($P<0.001$) for 300 mm diameter lysimeters than 500 mm diameter lysimeters due to the error in irrigation application, affected the validity of this result.

The difference in irrigation application amounts was a result of the design of the irrigation sprinklers used. The sprinklers were designed for use on 500 mm diameter lysimeters and were originally placed over the 300 mm diameter lysimeters at the same height, causing a higher volume of water to be applied to the smaller lysimeters. The sprinklers apply a higher volume of water directly beneath the sprinkler nozzle, than at the edges of their reach. Thus when the 500 mm diameter lysimeter sprinkler was placed over a 300 mm diameter lysimeter, water received by the small lysimeter was not relative to the amount that would be received by a larger lysimeter. The effect of this discrepancy only became clear when only the 300 mm diameter lysimeters produced drainage in the first two weeks of the trial.

Two weeks into the trial, an attempt was made to remedy unequal irrigation application by re-calibrating the height that the 300 mm diameter lysimeter sprinklers would need to be at in order to apply the same amount of water (mm), as was being applied to the 500 mm diameter lysimeters. The improvement in similarity of drainage volumes between the two-lysimeter sizes in the subsequent leachate collections indicated that this adjustment had improved the situation. However, since the unequal amounts of irrigation occurred at the beginning of the trial, this is thought to have caused a lasting difference in soil moisture contents between the two different lysimeter sizes. During the first half of the trial period, soil in the 300 mm diameter lysimeters appeared to remain closer to saturation point than in the 500 mm diameter lysimeters. Consequently, the 300 mm diameter lysimeters produced almost twice the volume of drainage that was produced by the 500 mm diameter lysimeters over the duration of the trial. This is likely to have caused the profound difference in the amounts of NO_3^--N leached within the first 100 mm of drainage between the two treatments.

Preferential flow is likely to have occurred in the 300 mm diameter lysimeters, due to the large volume of water applied in error to the relatively free-draining Templeton soil. This assumption is supported by the asymmetrical shape of the 300 mm diameter lysimeter breakthrough curve (Fig 4.5) which is an indication that preferential flow has occurred (Nye & Tinker, 1977). Consequently, there was little opportunity for the applied urine N to diffuse into soil aggregates or to undergo immobilisation by microbes before irrigation water caused it to be leached down the soil profile. The higher and earlier peak N concentration in the drainage water collected from the 300 mm diameter lysimeters supports this assumption. In the 500 mm diameter lysimeters where irrigation volumes were lower, urinary N was able to remain in the topsoil for a longer period of time before leaching occurred. Therefore, during the first two weeks after urine deposition, mineral N in the 500 mm lysimeters had more time to disperse horizontally within the topsoil, diffuse into soil aggregates, be taken up by plants or undergo immobilisation by soil microbes, thus protecting it against leaching. The removal of urine N from soil via these processes explains the lower peak NO_3^- concentration in drainage collected from the 500 mm lysimeters. Due to the longer period where N uptake and transformation processes were occurring in the 500 mm lysimeters it is likely that there was significantly less NO_3^- present in soil solution when the first significant drainage event occurred for the 500 mm lysimeters. Whereas, a high concentration of N was present immediately after treatment application when drainage began for the 300 mm lysimeters.

This peak also occurred later in the trial for 500 mm lysimeters, as soil moistures in the 500 mm lysimeters were too low to cause any significant drainage events until the 5-day period of high rainfall that occurred from 29 May - 2 June. A higher volume of water had drained from the 300 mm diameter lysimeters than the 500 mm diameter lysimeters before peak NO_3^- concentration in drainage occurred. In the 300 mm diameter lysimeters, a large amount of nitrate would have been present in soil immediately following urine treatment application. Therefore a large amount of drainage water was required to flush the nitrate through the lysimeter. Thus, it took 300 mm of drainage water before almost all of the urine N present in the 300 mm lysimeters was flushed through the profile and drainage NO_3^- concentrations returned to zero (mg N/L). Because less NO_3^- was present once the 500 mm diameter lysimeters began to produce drainage, NO_3^-N it only took approximately 120 mm drainage to flush the remaining N from the 500 mm diameter lysimeters.

5.2 Pasture production

Plant N uptake and pasture production results from this trial confirm that than plant N uptake in the perimeter of the urine patch was not the cause of lower N leaching losses by the lysimeters with perimeter grass. Therefore the potential effect of plant N uptake in the perimeter of a urine patch remains to be determined and quantified. The primary factor that led to lower NO_3^- leaching loss from the 500 mm diameter lysimeters was instead due to the error in irrigation application to the 300 mm diameter lysimeters.

There were no significant differences in N uptake or pasture production between 500 and 300 mm diameter lysimeters at first harvest in May, one month following treatment application. However, at both the June and September harvests, the 300 mm urine treated lysimeters had significantly higher ($P<0.001$) N uptake and pasture production than the 500 mm urine treated lysimeters. This contributed to the overall higher N uptake and pasture production by 300 mm diameter lysimeters.

Given that plants in the 500 mm lysimeters had a longer window of opportunity to take up N present in the topsoil before leaching occurred, it could be expected that the 500 mm lysimeters had higher dry matter production than the 300 mm diameter lysimeters. However, due to the abnormally warm and dry autumn and early winter season of 2016, it appears that soil moisture became the limiting factor for plant growth in the 500 mm diameter lysimeters. Sufficient soil moisture and available N for both 300 and 500 mm diameter lysimeters in the first month following treatment application would explain the higher, although not significantly different dry matter production from 500 mm diameter lysimeters. However, from May onwards, the 300 mm diameter lysimeters had considerably higher ($P<0.001$) N uptake and plant growth than the 500 mm diameter lysimeters. This indicates that conditions were superior for plant growth in the 300 mm diameter lysimeters. This was likely due to the higher soil moisture content in the 300 mm lysimeters as a result of the greater volume of irrigation applied. In a typical winter season where temperatures were lower and rainfall was higher, the opposite may have occurred where excess irrigation caused soil temperatures to drop more quickly and plant growth to slow much earlier in the winter season for the higher irrigation treatment. However, a lack of rainfall and warmer temperatures during the trial period allowed plants in the 300 mm diameter lysimeters to continue growing under excess irrigation, while causing a soil moisture deficit in the 500 mm diameter lysimeters, which limited plant growth despite surplus N supply.

Pasture N uptake and dry matter results in this trial indicated that soil moisture, rather than N supply became the most limiting factor for plant growth in the late autumn, early winter period when irrigation was applied at typical rates. These autumn conditions, which limited the removal of N from soil via plant uptake, could be expected to produce higher than usual amounts of NO_3^- loss to groundwater if followed by a typical amount of winter rainfall. However, as rainfall remained low until springtime when plants had begun actively growing again, it is expected that much of the urine applied N in the 500 mm lysimeters, which remained in soil aggregates, organic matter and microbes, will be utilised by plants during spring growth. Therefore, it is expected that nitrate leaching losses on a typical irrigated Canterbury dairy farm will be lower than usual for the 2016 winter period.

Results from the 500 mm urine treated lysimeters show that in the 2016 season urine patch leaching losses from typically irrigated Canterbury dairy pastures on free draining soils were approximately 27 kg N/ha. Considering that this was the loss from urine patches, which are the greatest source of leaching loss in dairy farm systems, (Cameron et al., 2013; Di & Cameron, 2002a, 2002b; Haynes & Williams, 1993; O'Connor & Gregg, 1971) it could be expected that average leaching losses on a whole farm basis would have been much lower than this. Using data collected from the 500 mm diameter control and urine treated lysimeters, and based on the assumption of a 3.5 cow/ha stocking rate where urine patches make up 25% of the grazing area (Di & Cameron, 2002a) it can be calculated that the average NO_3^- leaching loss for Canterbury dairy farms over the 2016 winter period was approximately 7 kg N/ha.

5.3 Botanical composition

The urine treated 500 mm diameter lysimeters produced more clover than 300 mm diameter lysimeters ($P<0.01$). Upon comparison between lysimeter zones it appears that higher clover production in Zone A compared to the 300 mm diameter lysimeters was the leading cause of the higher overall clover content in the 500 mm diameter lysimeters. Zone A had the lowest ($P<0.05$) ryegrass proportion of the three zones, however it had the highest clover production. Zone A clover content was 7% higher than for zone B, although this difference was not significant, and was 19% higher ($P<0.05$) than the 300 mm diameter lysimeter. High clover production in Zone A was likely due to the perimeter grass being less able to access the urine patch N, thus producing more clover in order to source its own nitrogen via biological fixation. This result indicates that within the first month of the trial, the perimeter grass (zone A) was unable to access sufficient mineral N in soil as a result of urine treatment in the zone B area. This assumption is supported by the fact that there was no significant difference in plant N uptake or dry matter production between the 300 and 500 mm urine treated lysimeters at first harvest. This result suggests that plant N uptake in the perimeter of a urine patch may not be able to contribute to reducing nitrate leaching. However, the trial will need to repeated as it is not possible to determine whether the difference in irrigation also affected this result. Future investigation could involve taking botanical composition samples at every harvest, to determine whether clover content in zone A changed throughout the trial, as grass in the perimeter of the urine patch may take longer than 4 weeks to be able to access and respond to the presence of a high N concentration patch nearby.

Chapter 6

Conclusions and implications for future research

Drainage and leaching results from this trial supported the reports by Lantinga et al. (1987) and Nye and Tinker (1977) and Lotero et al. (1966) that the area of a urine patch is larger than the wetted area. When first examined, nitrate leaching results implied that perimeter grass around a urine patch could reduce the potential nitrate leaching from the patch by up to 45%. However, plant N uptake results confirmed that it was not additional plant uptake but the difference in irrigation volumes applied to each lysimeter size that was the prevailing factor that caused lower NO_3^- losses from the 500 mm diameter lysimeters. Due to the error in irrigation application, this trial would need to be repeated again using a revised sprinkler design in order to answer the original hypotheses question of the effect about plant N uptake in the perimeter of a urine patch on nitrate leaching.

If after repeating this trial with equal irrigation to treatments it was found that the inclusion of perimeter grass in the lysimeter did cause a reduction in NO_3^- leaching, this would imply that future lysimeter studies that aim to quantify NO_3^- leaching losses from urine patches could benefit from taking into account the effect of perimeter grass. This may involve using larger lysimeters and applying treatments to the central area only, to simulate the perimeter grass effect. Alternatively, future research could aim to quantify the effect of perimeter plant N uptake on nitrate leaching over a number of different urine N concentrations and build a predictive model so that this effect can be accounted for when measuring NO_3^- leaching losses with treatments applied to only the wetted area of a urine patch.

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Appendix A: Trial design – randomised design

Lysimeter #	Size	Treatment
1	500 mm	Urine
2	500 mm	Urine
3	500 mm	Control
4	500 mm	Control
5	500 mm	Control
6	500 mm	Urine
7	500 mm	Urine
8	500 mm	Urine
9	500 mm	Urine
10	500 mm	Control
11	500 mm	Urine
12	500 mm	Control
13	500 mm	Control
14	500 mm	Control
15	300 mm	Control
16	300 mm	Control
17	300 mm	Urine
18	300 mm	Control
19	300 mm	Control
20	300 mm	Urine
21	300 mm	Urine
22	300 mm	Urine
23	300 mm	Control
24	300 mm	Control
25	300 mm	Urine
26	300 mm	Control
27	300 mm	Urine
28	300 mm	Urine

Figure A.1: Trial design – randomized design