LEACHING AND UPTAKE OF NITROGEN, AND PASTURE PRODUCTION, ASSOCIATED WITH IRRIGATION OF TREATED WASTEWATER, TAUPŌ, NEW ZEALAND

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ABSTRACT

Secondary-treated wastewater from Taupō Township is irrigated onto perennial ryegrass (*Lolium perenne*) which is harvested and removed from the View Road wastewater treatment site. To determine the fate of the applied wastewater nitrogen, 48 undisturbed barrel lysimeters (30 cm diameter x 43 cm depth) were installed throughout 29 hectares. Centre pivot travelling irrigators were programmed to vary in speed to provide target wastewater application rates of about 0, 450, 550 and 650 kg N ha^{-1} yr^{-1}.

The targeted application treatments were not achieved, with the achieved nitrogen loading rates grouped into a low treatment (286 - 380 kg N ha^{-1} yr^{-1}), a medium treatment (380 - 445 kg N ha^{-1} yr^{-1}), and a high treatment (445 - 567 kg N ha^{-1} yr^{-1}). Nitrogen input in control sectors was assumed to be 5 kg N ha^{-1} yr^{-1} from atmospheric nitrogen deposition.

A mean of 4 to 6% of the applied nitrogen was leached. The mean amount of nitrogen leached from the high treatment (28.6 ± 10.1 kg N ha^{-1} yr^{-1}) was higher ($P < 0.05$) than from the low treatment (12.7 ± 4.2 kg N ha^{-1} yr^{-1}). The medium treatment (16.0 ± 7.2 kg N ha^{-1} yr^{-1}) was not significantly different than the low treatment or the high treatment. The mean amount of nitrogen leached from the control treatment was 2.8 ± 0.6 kg N ha^{-1} yr^{-1}. Nitrogen leaching that occurred in the high application treatment was below the consented limit of 30 kg N ha^{-1} yr^{-1}.

A mean of 79 to 100% of the applied nitrogen was removed by pasture. There were no significant differences in pasture dry matter production, or nitrogen removal, between the low treatment (13 922 ± 1196 kg DM ha^{-1} yr^{-1} and 341 ± 25 kg N ha^{-1} yr^{-1}), the medium treatment (13 543 ± 1475 kg DM ha^{-1} yr^{-1} and 360 ± 51 kg N ha^{-1} yr^{-1}), and the high treatment (15 285 ± 1919 kg DM ha^{-1} yr^{-1} and 385 ± 43 kg N ha^{-1} yr^{-1}). Pasture production was higher ($P < 0.001$) in irrigated pastures (mean of all irrigated treatments, 14 250 ± 349 kg DM ha^{-1} yr^{-1}) than unirrigated controls (5300 ± 839 kg DM ha^{-1} yr^{-1}).

A mean of -4 to 16% of the applied wastewater nitrogen was unaccounted for. The majority of unrecovered nitrogen was presumed to be volatilised with lower potential for denitrification and soil storage.

A second experiment was undertaken to determine whether a five week or a ten week harvesting frequency would result in greater pasture production and nitrogen removal. During the ten month trial, 265 kg N ha^{-1} of wastewater nitrogen was irrigated and pasture plots (1 m x 1 m) were cut with a mower. Nitrogen removal and pasture production were higher ($P < 0.05$) with a five week harvesting interval (8231 ± 186 kg DM ha^{-1} and 250 ± 5 kg N ha^{-1}) than a ten week harvesting interval (7354 ± 67 kg DM ha^{-1} and 191 ± 3 kg N ha^{-1}). Harvesting at five week intervals during late-November to May (late-spring to late-autumn) and ten week intervals from May until early-November (late-autumn to mid-spring) is recommended to maximise both pasture production and nitrogen removal, while minimising harvesting costs.

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1.1 THE APPLICATION OF WASTEWATER TO LAND IN NEW ZEALAND

Land based application is an accepted method to dispose of and to further treat secondary-treated municipal wastewater within New Zealand (Cameron *et al.* 1997; Sparling *et al.* 2006). Land discharge is the favoured means of wastewater disposal by the indigenous Māori people, preferred over the discharge of human wastes into arawai (waterways) (Magesan *et al.* 1998; Tomer *et al.* 2000).

The lack of readily available nitrogen commonly limits vegetation growth and the productivity of cultivated crops (Whitehead 1995). Land based application is favourable as wastewater provides a large, reliable, nutrient rich water resource that can be utilised to grow high yielding pastures (Cameron *et al*. 1997; Di *et al*. 1998; Toze 2006). However, when nitrogen additions exceed plant requirements, nitrogen leaching from the soil profile may occur.

Nitrogen movement through ecosystems has been likened to a cascade, creating problems with each advance (Galloway *et al.* 2003). Problems include the loss of biodiversity, contamination of groundwater, impacts on human health, and the eutrophication and degradation of streams, rivers, lakes, and the costal marine area (McLaren and Cameron 1996; Hamilton *et al.* 2004).

The ability of a land based site to remove wastewater nutrients depends on the physical, chemical, and biological aspects of the soil and plant system (Magesan *et al*. 1998; Barton *et al.* 2005). When wastewater is irrigated onto pasture, nutrients are stripped from the effluent by plant uptake and by soil microorganisms, transferred into soil storage, or converted into gaseous nitrogen, with excess nitrogen leaching into groundwater (Couper *et al.* 2009). If pasture is cultivated, harvested, and baled — as in a cut and carry scheme — it provides the opportunity to remove wastewater nutrients from a site, and even from within a sensitive catchment. When nitrogen is removed by pasture, less nitrogen is available to be leached (Whitehead 1995).

Understanding the balance between nitrogen additions, plant uptake, and nitrogen leaching is vital to maximising the amount of wastewater disposal and pasture growth, while protecting groundwater resources and aquatic ecosystems.

1.2 LAND BASED WASTEWATER TREATMENT IN TAUPŌ

Land based wastewater disposal is attractive within the Taupō region of New Zealand (Figure 1.1). The iconic Lake Taupō is economically, recreationally, and culturally significant to New Zealand. However, the lake's high quality surface waters are threatened by nitrogen inputs from the surrounding catchment (White and Payne 1977). Prior to 1974, sewage from Taupō Township was disposed of within septic tanks or soak holes, causing high concentrations of nitrogen to leach into Lake Taupō (Gibbs 1979). Reticulation of the sewage network in Taupō occurred from 1974 to 1986, limiting nitrogen additions into the lake. Secondary-treated wastewater was then discharged into the Waikato River, which flows out of the north-east section of Lake Taupō (Figure 1.1).

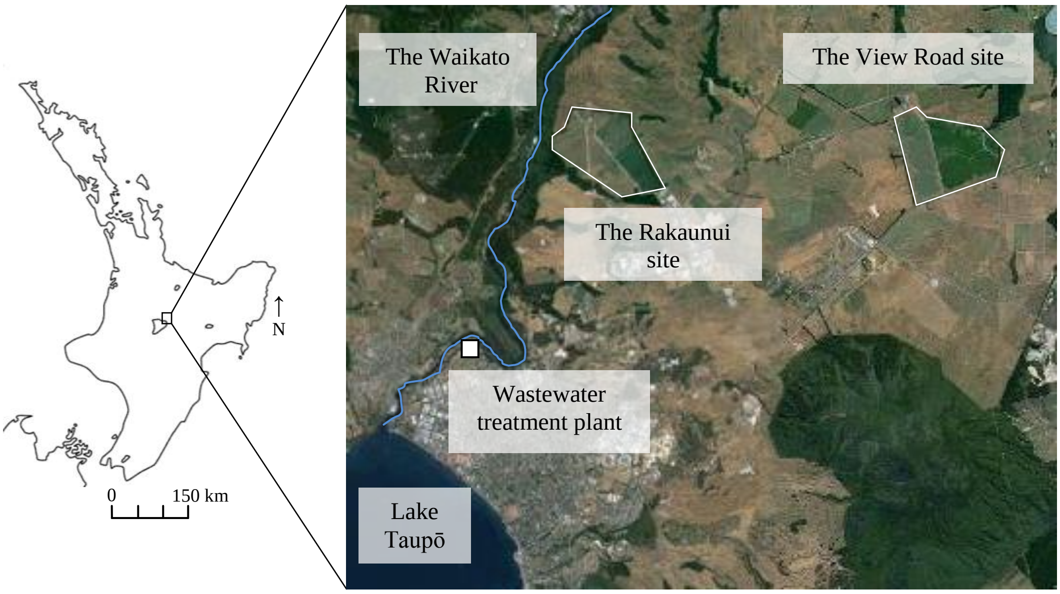

Figure 1.1. The North Island of New Zealand and the location of the View Road site in relation the Waikato River, the wastewater treatment plant, and Lake Taupō.

The discharge of human waste into the Waikato River is viewed as completely unacceptable by the local Māori people as the River is spiritually important (Stokes 1991). In 1995 a land based treatment site, the Rakaunui Road site, was installed to avoid direct discharge of wastewater into the Waikato River. Switching from direct discharge to land based disposal was viewed as a big improvement both culturally and environmentally, as nutrient inputs into the

Waikato River were reduced and the public health risk to users was eliminated (Couper *et al.* 2009). A second scheme was commissioned in 2008 at the View Road site, which was where this study was held.

The application of wastewater to land is beneficial within the Taupō area, as a lack of both water and nutrients can restrict vegetation growth. To utilise and remove wastewater nutrients, both the Rakaunui and View Road sites are cultivated with high yielding perennial ryegrass pastures (predominantly *Lolium perenne)* and are run as a cut and carry operation. Pasture is harvested four times a year, and is baled and sold to farmers as part of a sustainable re-use initiative that helps to fund the scheme (Couper *et al.* 2009). No stock is grazed on either site.

As part of the 20/20 Taupō-nui-a-Tia action plan to manage nitrogen in the greater Taupō catchment and to prevent nitrogen additions into the Waikato River, restrictions were placed on hydraulic and nutrient loading rates. The Rakaunui Road site obtained resource consent to operate up to a nitrogen loading application rate of 650 kg N ha^{-1} yr^{-1}. However, monitoring wells have shown a slow but continued increase in nitrate concentration in the groundwater (Couper *et al.* 2009). When the View Road site was commissioned, a precautionary approach was taken and a lower nitrogen application limit of 550 kg N ha^{-1} yr^{-1} was consented. However, there is a need to increase the town's wastewater disposal capacity with; expected population growth, the acquisition of part of the Rakaunui Road site by the New Zealand Transport Agency for the Eastern Taupō Bypass, the potential addition of treated wastewater from satellite communities, and a large influx of people during the summer months (Orbell 2007).

With a need to increase the wastewater disposal capacity in Taupō, the Taupō District Council has requested to increase wastewater nitrogen application limits at the View Road site from 550 to 650 kg N ha^{-1} yr^{-1}. In order to test the impacts of a higher application rate the regulator (Waikato Regional Council) has permitted the application of 650 kg N ha^{-1} yr^{-1} of wastewater on 15% of the irrigated land at the View Road site. A trial was installed to test whether an increase in nitrogen loading from 550 to 650 kg N ha^{-1} yr^{-1} would lead to leaching losses above 30 kg N ha^{-1} yr^{-1}. Resource consent conditions restrict the amount of wastewater nitrogen allowed to be applied to be no more than 120 kg N ha^{-1} yr^{-1}

above crop yield, or mean nitrogen leaching losses of up to 30 kg N ha^{-1} yr^{-1} (Environment Waikato 2008).

The Taupō District Council, in collaboration with the University of Waikato, has established a nitrogen leaching lysimeter trial at the View Road site. As well as the proposed application rate of 650 kg N ha^{-1} yr^{-1}, a lower application rate of 450 kg N ha^{-1} yr^{-1} and the original consented rate of 550 kg N ha^{-1} yr^{-1} were also targeted. The range of application rates were examined to find the optimal wastewater loading; a combination of low nitrogen leaching with high pasture production. The trial is an excellent opportunity to better understand the relationships between nitrogen application, pasture production, nitrogen uptake, and nitrogen leaching at a field sized scale and under real field conditions.

The study was installed in September 2009 and the first round of measurement was begun in December 2009 (Treweek 2011). A second round of measurement was needed to verify equilibration of the soil system and to confirm nitrogen leaching losses had not increased since the first year of monitoring. The second round of measurement began in September 2011 and finished in September 2012, with results presented within this thesis.

A second experiment was also installed to investigate measures to improve nitrogen removal by pasture and potentially reduce nitrogen leaching losses at the View Road site. Nitrogen removal and pasture production were examined under two different harvesting regimes. The harvesting frequency experiment was installed in January 2012 and finished in November 2012.

1.3 THE VIEW ROAD LAND BASED WASTEWATER TREATMENT SITE

The View Road land treatment site is located about 7 km north-east of the wastewater treatment plant in Taupō (Figure 1.1). The View Road site (Figure 1.2) is about 150 hectares, with the application of wastewater onto approximately 119 hectares. Wastewater has been applied with centre pivot travelling irrigators since December 2008. Perennial ryegrass (predominantly *Lolium perenne*) is cultivated and harvested four times a year in a cut and carry scheme.

The View Road site has a topography of low rolling hills, almost flat terraces and fans (Orbell 2007). Soil at the View Road site is characterised as a Pumice Soil (NZ Soil Classification) or a Vitrand (USDA Soil Taxonomy) (Treweek 2011), with two dominant soil types; the Atiamuri gritty sandy loam and the Whenuaroa gravelly sandy loam. The Atiamuri soil is derived from Taupō eruptive tephras and is well drained, while the Whenuaroa soil has alluvially deposited parent material and is considered to be moderately well drained (Orbell 2007).

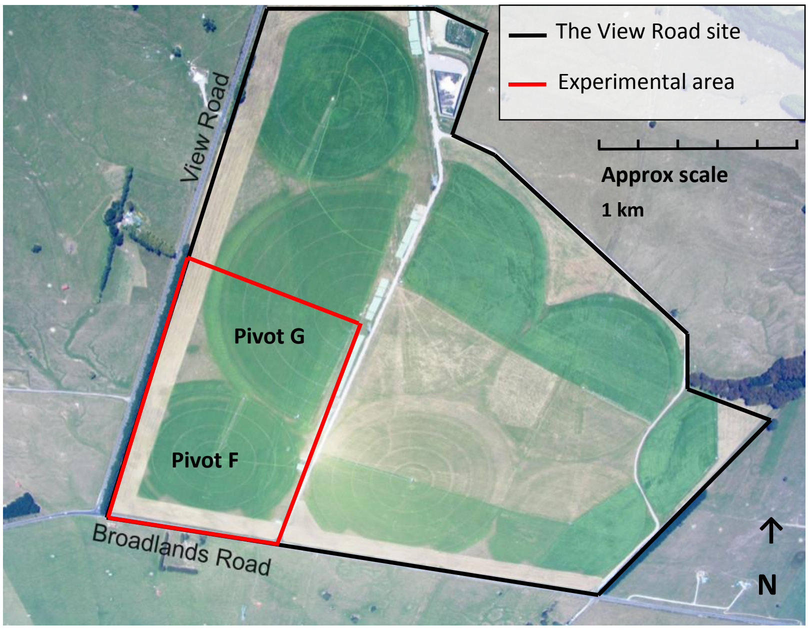

Figure 1.2. Aerial photograph of the View Road site and the experimental area underneath pivot F and half of pivot G.

The experimental area consists of 29 hectares located in the southwest corner of the View Road site (Figure 1.2). The area is beneath two irrigators; pivot F and half of pivot G. Two studies have been installed within the experimental area; a lysimeter study and a pasture harvesting frequency experiment.

1.4 STUDY OBJECTIVES

This thesis has two objectives:

1. Quantify nitrogen movement at the View Road land based treatment site under a range of wastewater application rates. Treatments include a low rate (nominally 450 kg N ha^{-1} yr^{-1}), the consented rate (nominally 550 kg N ha^{-1} yr^{-1}), a high rate (nominally 650 kg N ha^{-1} yr^{-1}), and an unirrigated soil (nominally 0 kg N ha^{-1} yr^{-1}). Specific aims are to determine;
    a. The amount of wastewater nitrogen applied to the land surface within each treatment,
    b. The total amount of nitrogen in leachate that drained through a lysimeter containing an undisturbed soil column within each treatment,
    c. The dry matter production and nitrogen removal by pasture within each treatment,
    d. The amount of unrecovered nitrogen within each treatment.
2. Quantify dry matter production and nitrogen removal by pasture harvested at two different harvesting frequencies to determine which harvesting frequency gave the greater pasture production and nitrogen removal. It is hypothesised that more pasture will be produced and more nitrogen will be removed with a five week harvesting frequency than with a ten week harvesting frequency.

CHAPTER TWO – LITERATURE REVIEW

2.1. INTRODUCTION

The application of wastewater onto land is an efficient way to dispose of, and treat municipal effluent within New Zealand (Tomer *et al.* 2000; Barton *et al.* 2005; Sparling *et al.* 2006). Land based application is the preferred method of wastewater disposal by the indigenous Māori people, as the disposal of human waste directly into waterways, regardless of treatment, is considered unacceptable (Stokes 1991).

Wastewater can be utilised to grow high yielding pasture, however, when nitrogen additions are in excess to plant requirements, nitrogen leaching may occur (Cameron *et al.* 1997). Leached nitrogen can contaminate groundwater and assist in the eutrophication and degradation of surface waters (Hamilton *et al*. 2004).

Before nitrogen movement at the View Road land based wastewater treatment site can be quantified, it is important to understand:

- nitrogen cycling and transformations,
- methods of wastewater application to land,
- methods to measure nitrogen movement (leaching and uptake) after the application of effluent to land,
- the amounts of, and influences on, nitrogen leaching after effluent application,
- pasture growth in response to effluent application, and
- the physical receiving environment.

2.2. NITROGEN WITHIN THE ENVIRONMENT

2.2.1. Nitrogen availability within the natural environment

Nitrogen (N) is an essential element for all living organisms, however, available nitrogen is scarce within the natural environment (Whitehead 1995). More than 99.9% of the nitrogen present on earth is stored within rocks or the atmosphere, and thus, not directly available to more than 99% of living organisms (Haynes 1986; Galloway *et al*. 2003).

The Earth's atmosphere is abundant in nitrogen; 78% of atmospheric gases are nitrogen gas (Knapp 1996). Nitrogen gas is non-reactive, because of its stable triple bond and is largely unavailable for plant use (Galloway *et al*. 2004).

The amount of nitrogen that is stored within the biosphere is small, accounting for less than 0.01% of the biogeochemical nitrogen on earth. The majority of nitrogen on earth is stored as N_2 gas within the ocean, with only a small fraction stored as terrestrial nitrogen (Haynes 1986). Of terrestrial nitrogen, 99% is stored as organic nitrogen within vegetation, plant litter, microorganisms and soil organic matter (Rosswall 1976). Less than approximately 1% of terrestrial nitrogen is stored as ammonia and nitrate in soil, and thus, available for plant use (Galloway *et al*. 2003). Nature provides two mechanisms to fix atmospheric nitrogen; lightning and subsequent rainfall, and fixation by bacteria within the nodules of some plant roots (Knapp 1996). However, the lack of readily available nitrogen commonly restricts vegetation growth (Hopkins and Hüner 2009).

2.2.2. Activities that increase nitrogen availability

Because of nitrogen's unavailability, many ecosystems are nitrogen limited, restricting food production worldwide. Nevertheless, over the last 60 years human activities have produced large amounts of available nitrogen (Galloway *et al*. 2003).

Nitrogen, in the form of both ammonia and nitrate, can be made available through the manufacturing of synthetic fertilisers. The industrial method of making ammonia fertiliser is called the Haber-Bosch process. During the Haber-Bosch process, nitrogen gas and hydrogen gas react at high pressures and temperatures to produce ammonia (Knapp 1996). Other forms of nitrogen based fertilisation include urea, soluble nitrate (nitrate-rock fertilisers) and manure. Fertilisers are applied to land to stimulate vegetation growth and are vital for sustaining food production worldwide (McLaren and Cameron 1996).

The widespread cultivation of crops that can biologically fix atmospheric nitrogen has also increased the amount of available nitrogen. Several species of bacteria and fungi are able to fix nitrogen, converting atmospheric nitrogen into ammonia. A common nitrogen-fixing group of bacteria is called *Rhizobium*, found in nodules on the roots of legume species (for example clover, beans, peanuts and alfalfa). Legumes are commonly grown in rotation with “nitrogen hungry” crops or on dairy farms (Knapp 1996). Once nitrogen is fixed, it enters the nitrogen cycle of the land and can be utilised by other plants, microbial communities or animals.

The final activity that has increased the amount of available nitrogen is the combustion of fossil fuels. This process converts atmospheric N_2 and fossil nitrogen to nitrous oxide. Reactive nitrous oxide can affect nitrogen cycling within soil, and is a major greenhouse gas and air pollutant (Knapp 1996).

2.2.3. The nitrogen cycle and transformations within soil

Understanding nitrogen movement and transformations within an ecosystem is important to both productivity and preventing unwanted nitrogen losses. Nitrogen is cycled continuously among soil, vegetation, animals, microorganisms, and the atmosphere (Haynes 1986). The transformation of nitrogen between organic, inorganic, and gaseous compounds is known as the nitrogen cycle (McLaren and Cameron 1996).

Soil is a dynamic environment where nitrogen forms can be transformed interchangeably (Figure 2.1). There are three forms of nitrogen within soil; organic nitrogen, inorganic nitrogen and nitrogen bound to clay minerals. Organic nitrogen is found within plant residues, soil organic matter, microbial biomass and other organic material (McLaren and Cameron 1996) and makes up a large proportion of the soil nitrogen pool (Haynes 1986). Inorganic nitrogen, present as ammonium and nitrate, is available for plant use, but only makes up a small proportion of the soil nitrogen pool (Haynes 1986). Processes that transform nitrogen within soil include mineralisation and immobilisation, soil accumulation, nitrification, denitrification, and volatilisation (Figure 2.1).

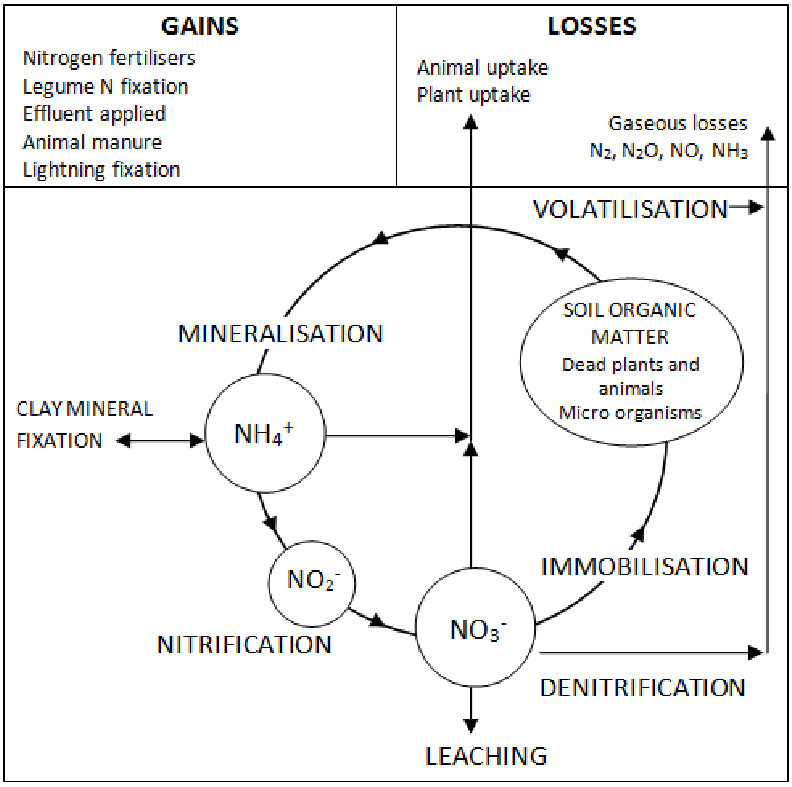

Figure 2.1. A simplified nitrogen cycle within a grassland system (modified from McLaren and Cameron 1996).

Organic nitrogen, or soil organic matter, can be converted into inorganic nitrogen by mineralisation (Figure 2.1). Mineralisation is a two-step process that occurs in aerobic conditions. The first step is ammonification; where complex organic proteins within soil organic matter are transformed into amino acids and then into ammonia by soil microorganisms. Ammonia then undergoes nitrification; being hydrolysed to ammonium and then oxidised to nitrite and nitrate (McLaren and Cameron 1996). Immobilisation is the reverse of mineralisation, where inorganic nitrogen is transformed back into organic nitrogen and stored within soil by microbial assimilation (McLaren and Cameron 1996).

Ammonium can be present in both exchangeable and non-exchangeable forms within soil. Clay and organic matter mostly have a negative charge and therefore, the ability to absorb ammonium onto their cation exchange sites. Ammonium may remain in equilibrium with other cations in soil solution and can become available to plants (McLaren and Cameron 1996). Ammonium may also enter the internal structures of certain types of clay minerals (for example, 2:1 clays), where it becomes fixed and non-exchangeable. Dry conditions and high ammonium concentrations tend to increase the amount of nitrogen fixed within soil (Whitehead 1995).

Ammonium within soil can be transformed into nitrate and then nitrogen gas by the processes of nitrification and denitrification (Figure 2.1). Nitrification occurs when bacteria (mainly *Nitrosomonas*) oxidise ammonium to nitrite, with further oxidation to nitrate by *Nitrobacter* bacteria (Whitehead 1995; Hillel 2008). Under aerobic conditions nitrification is a rapid process, removing most of the available ammonium within soil. Nitrification is an important process as it influences how much nitrogen can be leached from the soil as nitrate (Whitehead 1995). Denitrification occurs in anaerobic soils. Bacteria use nitrate instead of oxygen during metabolic reactions, producing nitrogen gas. Gaseous by-products of both denitrification and nitrification are nitric oxide and nitrous oxide.

Another transformation that produces gaseous nitrogen is volatilisation. Volatilisation occurs when nitrogen rich substances, such as animal urine patches or urea, are deposited at the soil surface and gaseous ammonia is lost to the atmosphere (Whitehead 1995; McLaren and Cameron 1996).

Nitrogen can be lost from a system by nitrogen leaching. Nitrogen leaching occurs when soluble forms of nitrogen, commonly nitrate, percolate downwards to be lost from the soil column. Nitrate is susceptible to leaching as it is negatively charged; therefore, it cannot be adsorbed onto the negatively charged clay minerals or organic colloids within soil (Whitehead 1995). Nitrate leaching can commonly occur during winter or after large rainfall or irrigation events (Whitehead 1995). Ammonium can also be leached. However, ammonium leaching is rarer as it is positively charged and is readily held by cation exchange sites within soil (McLaren and Cameron 1996).

Vegetation is also capable of removing large amounts of nitrogen. With the exception of plants engaged in symbiosis with nitrogen-fixing organisms, the majority of plants absorb nitrate and ammonium (Crawford and Glass 1998). If vegetation is removed, it represents a loss of nitrogen from the system.

2.3. THE APPLICATION OF EFFLUENT TO LAND

2.3.1. Overview

Spreading human effluent over land, as a form of treatment, dates back to ancient times. Evidence of ancient land treatment has been reported from Minoan civilization at 2600 BC (Angelakis and Spyridakis 1996) and within ancient Greek civilizations (Angelakis *et al.* 2005). Land disposal was the main method of effluent treatment in Europe during the nineteenth century; when sewage was applied to land, ploughed into soil and used to grow crops (Gray 2004). Since the nineteenth century, land based treatment has increasingly been superseded by other biological treatment methods (Gray 2004).

However, land based disposal is still common within smaller communities, the agricultural sector, and in areas of the world where water is in short supply. Examples include the disposal of treated human wastewater in Germany and New Zealand, the disposal of dairy cow effluent in New Zealand, the irrigation of raw and treated wastewater for crop irrigation in Israel, the watering of public parks and the recharge of groundwater in the southern United States of America. (U.S. EPA 1981; Gray 2004; Raven and Berg 2004; Paranychianakis *et al.* 2006). Furthermore, land based application is becoming increasingly attractive, with the combination of increased demand for water worldwide and on going degradation of water resources (Raven and Berg 2004).

Land based wastewater treatment is viewed as the most economic method of tertiary treatment (compared with lagoons, constructed wetlands, microstrainers and sand filters) (Gray 2004). The application of wastewater to land is attractive because effluent nutrients and water can be used to grow vegetation (McLaren and Cameron 1996). Vegetation can be produced for a variety of purposes which offsets the cost of treatment. Examples include energy production, animal feed, and protein production (Gray 2004).

The growth of vegetation removes nutrients, reduces erosion, maintains or increases infiltration rates, and can produce revenue (U.S. EPA 1981; Fuller and Warrick 1985; Gray 2004). The amount of nitrogen a crop is able to remove depends on the type of vegetation. A perennial ryegrass is often grown at wastewater disposal sites because the pasture can remove large amounts of nitrogen, has long growth seasons, and avoids the need for annual planting and cultivation (U.S. EPA 1981; Paranychianakis *et al.* 2006). To remove nitrogen from the site, the crop must be harvested and removed. Largest nutrient removals can be achieved from a perennial grass that is cut frequently and at early stages of growth (U.S. EPA 1981). Other types of vegetation are also grown at wastewater disposal sites, such as, maize or trees. While legumes can be grown they are deemed less suitable, as legumes can fix nitrogen from the atmosphere rather than relying on wastewater nitrogen (Paranychianakis *et al.* 2006).

There are four main methods of wastewater land disposal: subsurface infiltration, rapid infiltration, overland flow, and slow rate land application (U.S. EPA 1981; Gray 2004). Effluent disposal by slow rate land application is examined within the following sections.

2.3.2. Slow rate land application

Slow rate land application is commonly used as a tertiary treatment method to further treat secondary-treated effluents. Slow rate application involves the even distribution of wastewater over grassland via channels or irrigators (Raven and Berg 2004). Irrigation is the most common method in land treatment systems and involves the application of wastewater to land with spray guns (Fuller and Warrick 1985).

Nitrogen present within wastewater is normally fully utilised by crop uptake and subsequent harvest, nitrification and denitrification processes, volatilisation, or by soil immobilisation (Cameron *et al*. 1995). If nitrogen is not fully utilised, it can be lost from the system in the form of nitrogen leaching (McLaren and Cameron 1996).

To maximise nitrogen removal, a slow rate of application is important, therefore, irrigation is not continuous (U.S EPA 1981). Standoff periods are important for optimal nutrient removal, allowing soils to become aerobic and the growth of vegetation (Gray 2004).

2.3.3. Application of effluent to land and the nitrogen cycle

The application of effluent to land can significantly enhance nitrogen cycling within soil. Important nitrogen transformations for land based wastewater systems include; denitrification, ammonia volatilisation, mineralisation, nitrogen storage and nitrogen leaching. However, many processes are often variable and difficult to predict or measure (Barton *et al.* 1999b). Literature involving human effluent within New Zealand is sparse, so examples that applied animal effluent or international examples are given.

2.3.3.1. Denitrification

The removal of nitrate by denitrification is considered beneficial for a land based wastewater treatment site, decreasing the amount of nitrate available to be leached (Paranychianakis *et al.* 2006). Denitrification losses typically range from 15 to 25% of the applied effluent nitrogen (U.S. EPA 1981), although both lower and higher denitrification losses have been measured (Cameron *et al.* 1995; Lowrance *et al.* 1998; Barton *et al.* 1999a).

Denitrification losses after the application of pig effluent to a shallow stony soil in Canterbury New Zealand were high; 39% of the applied 200 kg N ha^{-1} (Cameron *et al.* 1995). The high losses were attributed to transient anaerobic conditions within the soil/gravel interface, soluble carbon, and available nitrate from the nitrification of slurry nitrogen (Cameron *et al.* 1995). Denitrification rates were also high with the application rates of 246 to 802 kg N ha^{-1} yr^{-1} liquid manure to a year-round forage production system in the United State of America. (Lowrance *et al.* 1998). Denitrification ranged from 11 to 37% of total applied nitrogen; with the maximum denitrification rate of 239 kg N ha^{-1} yr^{-1} (Lowrance *et al.* 1998). The high rates were explained by the soil's heavy texture becoming anaerobic, while not restricting the diffusion of carbon substrates to denitrifying microorganisms (Barton *et al*. 1999b).

Conversely, mean denitrification rates from a pine forest irrigated with tertiary-treated wastewater (2.4 kg N ha^{-1} yr^{-1}) were not much higher than the irrigated control (1.7 kg N ha^{-1} yr^{-1}) in Rotorua, New Zealand (Barton *et al.* 1999a). High aeration of the free draining soils inhibited saturation and denitrification within both treatments.

Factors that influence denitrification rates are soil texture, climate, pH, nitrate concentration, and carbon availability (Paranychianakis *et al.* 2006). Soil conditions under the application of effluent are usually ideal for denitrification because of the high supply of nitrate and organic carbon, and temporary anaerobic conditions (Cameron *et al.* 1997). However, even with the application of effluent, if conditions are not favourable, such as the high soil aeration in Barton *et al.* (1999a), denitrification may not occur to such a large extent.

2.3.3.2. Volatilisation

Volatilisation can result in significant losses (up to 66%) of applied urine nitrogen under warm and dry conditions in New Zealand (Ball and Ryden 1984). However, volatilisation is usually estimated to be lower when municipal wastewater is applied to land (Smith *et al*. 1996).

Ammonia volatilisation was measured with the application of pig slurry to land in Canterbury, New Zealand (Cameron *et al*. 1995). After the application of 200 kg N ha^{-1}, the total amount of ammonia lost by volatilisation was equivalent to 20 kg N ha^{-1} (10%) of the applied nitrogen. More than half of the total ammonia volatilisation occurred during the first 48 hours after effluent application. In addition, with the higher application of 600 kg N ha^{-1}, 48 kg N ha^{-1} (8%) of the applied nitrogen was volatilised (Cameron *et al*. 1995).

Ammonia volatilisation was also measured after the application of urban sewage to the land surface in New South Wales, Australia (Smith *et al.* 1996). Within two days of application in December 1994, 24% of the applied 6 kg N ha^{-1} was volatilised. However, when the experiment was repeated during January 1995, only 8.5% of the applied 4.8 kg N ha^{-1} was lost to volatilisation. The larger degree of volatilisation in December 1994 was explained by Smith *et al.* (1996) as a result of the highly evaporative conditions.

Ammonia volatilisation is most significant when waste is alkaline and contains a high concentration of ammonia, ammonium or urea, or if the soil has a low cation exchange capacity (Cameron *et al*. 1997).

2.3.3.3. Mineralisation

Application of effluent is likely to increase nitrogen mineralisation within soil (Cameron *et al.* 1997). The addition of 200 kg N ha^{-1} dairy shed effluent to a sandy loam in Canterbury, New Zealand, resulted in significantly higher gross nitrogen mineralisation when compared to the control soil (Zaman *et al.* 1999). Nitrogen mineralisation was also measured after the irrigation of effluent to a pine plantation in Australia (Polglase *et al.* 1995). From the addition of 374 kg N ha^{-1} of effluent during the first three irrigation seasons, 410 kg N ha^{-1} was mineralised and minimal nitrogen was leached (Polglase *et al.* 1995).

Following application, the presence of readily mineralisable organic matter and nutrients within the effluent enhances microbial activity, allowing nitrogen mineralisation (Zaman *et al.* 1999). If net mineralisation rates increase, more inorganic nitrogen will be available for plant uptake, but it may also available to be leached (Barton *et al.* 2005).

2.3.3.4. Soil immobilisation

It is difficult to measure the accumulation of nitrogen within soil, since the soil nitrogen pool is so spatially variable (Tomer *et al*. 2000). Studies have quantified nitrogen immobilisation with the use of animal urine labelled with ^{15}N, showing that a significant component of the applied wastewater nitrogen can be immobilised by soil. With the application of ^{15}N animal urine to soil, 12 to 30% of the applied nitrogen was immobilised or held in the soil by cation exchange complexes (Whitehead and Bristow 1990; Frase *et al*. 1994; Cameron *et al*. 1995). With continued effluent input over time, the rate of nitrogen storage will decrease. Eventually equilibrium may be obtained and net storage will cease. At an already established wastewater application site, it is assumed that nitrogen removal by soil storage is minimal (U.S EPA 1981).

2.4. MEASURING NITROGEN MOVEMENT AFTER THE APPLICATION OF EFFLUENT TO PASTURE WITH LYSIMETER STUDIES

2.4.1. Overview

Nitrogen movement can be estimated at a series of different scales. At a farm-sized or field-sized scale, there are three main methods to measure nitrogen leaching: suction cup samplers, barrel lysimeters and pan lysimeters (or drainage plots). Treweek (2011) discusses the relevance of each sampling method in relation to this project.

Barrel lysimeters, such as those used in this study, contain a column of undisturbed soil encased within a drum, on top of a leachate collection container (Treweek 2011). The undisturbed soil monolith is excavated and the soil column is sealed in a casing with petroleum jelly. The base of the core is cut with a steel plate and then a leachate collection container is connected underneath (Cameron *et al*. 1992). In New Zealand studies, lysimeters have been relocated and installed within a laboratory (Magesan *et al*. 1998), within a glasshouse (Popay and Crush 2009), in a trench (Williamson *et al*. 1998; Cameron and Di 2004; Cameron *et al*. 2007) or flush throughout paddocks (Burgess 2003; Treweek 2011).

A known concentration of effluent nitrogen is then applied to the top of a lysimeter over time. Water and nitrogen within the effluent is utilised to grow pasture. Excess water is leached and caught in the drainage container attached underneath the lysimeter. The volume of water leached and amount of pasture growth is measured. The subsequent amount of nitrogen leaching and nitrogen removed by pasture is determined, creating a mass balance. All unaccounted or unmeasured nitrogen is assumed to be converted into gaseous forms of nitrogen or fixed by soil storage. Barrel lysimeters also allow the direct measurement of nitrogen leaching and mass balances through ^{15}N labelling (Cameron *et al*. 1995).

2.4.2. Effluent application

New Zealand lysimeter studies have used human (Magesan *et al*. 1998; Barton *et al*. 2005; Sparling *et al*. 2006) or animal effluent. Literature involving animal effluent has been included here, as few studies involved human effluents within New Zealand. Animal effluent includes pig effluent (Cameron *et al*. 1995), cattle urine (Cameron *et al*. 2007) and dairy shed effluent (Williamson *et al.* 1998).

In lysimeter studies, effluent was applied to lysimeters by either spray irrigation (Sparling *et al*. 2006), flood irrigation (Di *et al.* 1998), or poured on at a single spot (Cameron *et al*. 2007). The purpose of pouring urine on at a single spot was to simulate urination of cattle at a point source (Cameron *et al*. 2007; Williamson *et al*. 1998). Other studies have examined the impact of nitrification inhibitors, dicyandiamide (DCD), on nitrate leaching (Di and Cameron 2005; Cameron *et al*. 2007).

2.4.3. Nitrogen leaching

Lysimeter studies have previously been used to quantify nitrogen leaching. Leachate was collected at a range of time-scales; from daily (Cameron and Di 2004), to weekly (Di *et al.* 1998; Di and Cameron 2005; Cameron *et al*. 2007), to monthly (Burgess 2003; Treweek 2011). To determine the amount of nitrogen leached, leachate volumes were recorded and nitrogen analyses were undertaken. The concentration of inorganic nitrogen (nitrate, nitrite and ammonium) within leachate was measured by automated chromatography and flow injection analysis (Di *et al.* 1998; Williamson *et al*. 1998; Barton *et al.* 2005; Cameron *et al*. 2007). The total nitrogen concentration of leachate was measured by digestion and subsequent ammonium (Williamson *et al*. 1998) or nitrate analyses (Barton *et al*. 2005; Sparling *et al.* 2006). Organic nitrogen, where reported, was calculated by subtracting inorganic nitrogen concentration from total nitrogen concentration.

2.4.4. Pasture dry matter and nitrogen uptake

Lysimeter studies have been used to determine dry matter production and nitrogen uptake. Studies collected herbage at a range of time-scales; from fortnightly (Barton *et al*. 2005; Sparling *et al*. 2006), to monthly (Burgess 2003; Di and Cameron 2005; Di and Cameron 2007), to quarterly (Treweek 2011). Some studies cut pasture to simulate a cut and carry scheme (Barton *et al.* 2005; Sparling *et al*. 2006), while other studies did not define a time period and cut pasture periodically to simulate typical grazing practices (Di *et al.* 1998; Cameron and Di 2004; Cameron *et al*. 2007).

In lysimeter studies, pasture was cut to heights of 2 cm (Barton *et al.* 2005) to 7.5 cm (Williamson *et al*. 1998). While a relationship between cutting height and pasture production is likely (Binnie *et al.* 1974; Fulkerson and Michell 1987; Kerrisk and Thomson 1990), it is difficult to isolate the effect of cutting height within the lysimeter studies that were examined.

To determine pasture dry matter, herbage was dried in an oven at 60^{0}C (Barton *et al.* 2005) to 80^{0}C (Williamson *et al.* 1998) and weighed. Nitrogen analysis was undertaken by combustion in a LECO furnace (Di *et al*. 1998, Williamson *et al*. 1998; Di and Cameron 2005; Treweek 2011) or by Kjeldahl digestion followed by flow injection analyses (Barton *et al*. 2005; Sparling *et al*. 2006). The nitrogen concentration of pasture is commonly reported in %N (Cameron *et al*. 1995) or g N kg^{-1} of dry matter (Barton *et al.* 2005)

2.5. THE APPLICATION OF EFFLUENT TO LAND AND NITROGEN LEACHING

2.5.1. Types of nitrogen within leachate

Many studies concentrate on the leaching of inorganic forms of nitrogen. Nitrate was the dominant form of the nitrogen detected in lysimeter leachates, although a small amount of ammonium or trace amounts of nitrite were measured too (Cameron *et al*. 1995; Di and Cameron 2005; Di and Cameron 2007).

Many studies ignore organic forms of nitrogen within leachate. However, organic nitrogen can be a significant component within leachate; for example, over 50% of the total nitrogen leached from wastewater irrigation was measured to be organic nitrogen (Barton *et al*. 2005; Sparling *et al.* 2006). The measurement of organic nitrogen is important, because organic nitrogen can play a role in the degradation of aquatic ecosystems. Dissolved organic nitrogen can become to available aquatic ecosystems by mineralisation, or else dissolved nitrogen can act as a direct source of nutrition for many aquatic organisms (Berman and Bronk, 2003).

2.5.2. Total nitrogen leaching

Several New Zealand lysimeter studies were examined to quantify nitrogen leaching losses from the application of effluent to land (Table 2.1). Applied effluent included dairy farm effluent, cow urine, or treated municipal wastewater. Effluent nitrogen input ranged from 300 to 1200 kg N ha^{-1}; and of the applied nitrogen, 2.3 to 56% was leached. Soil characteristics, application conditions and nitrogen removal by pasture were observed to influence nitrogen leaching losses.

Table 2.1. Mean nitrogen input, leaching, uptake and pasture dry matter production in effluent irrigated and control treatments within New Zealand lysimeter studies.

			Effluent applied treatments				**Control (no effluent application) treatments**				
Effluent type	**Study period**	**Soil type(s)**	**Nitrogen input (kg N ha^{-1})**	**Nitrogen leaching losses (kg N ha^{-1} unless stated) (% of input)**	**Nitrogen uptake (kg N ha^{-1}) (% of input)**	**Pasture dry matter (kg DM ha^{-1})**	**Nitrogen input (kg N ha^{-1})**	**Nitrogen leaching losses (kg N ha^{-1} unless stated)**	**Nitrogen uptake (kg N ha^{-1})**	**Pasture dry matter (kg DM ha^{-1})**	**Author**
Dairy farm effluent	2 years*	A fine sandy loam	400	17 kg NO_3^- ha^{-1}(4)	338 (85)	15 000	0	2.8 kg NO_3^- ha^{-1}	279	11 000	**Di *et al.* (1998)**
Dairy farm effluent	19 weeks	An Allophanic Soil	1100	620 (56)	507 (46)	14 000	0	NA	109	3 850	**Williamson *et al.* (1998)**
Dairy farm effluent	2 years*	A Pumice Soil	442	125 (28)	NA	17 508	NA	NA	NA	11 210	**Burgess (2003)**
Treated municipal wastewater	2 years*	A Gley Soil	373	92 (25)	186 (50)	8 717	100^f	7	112	6 158	**Barton *et al.* (2005)**
		A Recent Soil	386	87 (23)	390 (101)	12 613	100^f	20	88	3 284	
		An Allophanic Soil	386	9 (2.3)	437 (113)	12 547	100^f	1.3	164	6 490	
		A Pumice Soil	408	15 (3.5)	265 (65)	10 831	100^f	7	69	4 303	
Cow urine and urea (urine spot + fertiliser)	11 month	A sandy soil	1200	134 (12)	449 (37)	15 300	NA	NA	NA	NA	**Di and Cameron (2005)**
Treated municipal wastewater	4 years*	A Gley Soil	324	73 (23)	194 (60)	12 398	100^f	7	79	7 006	**Sparling *et al.* (2006)**
		A Recent Soil	347	77 (22)	303(87)	14 603	100^f	19	101	4 378	
		An Allophanic Soil	394	11 (2.8)	194 (49)	15 886	100^f	1.3	147	8 834	
		A Pumice Soil	364	17 (4.7)	229 (63)	10 864	100^f	5	71	4 553	
Cow urine (urine spot)	3 years*	A Taupō Pumice Soil	700	245 (35)	NA	NA	0	5	NA	NA	**Cameron *et al. (*2007)**
Cow urine (urine spot)	11 months	A free draining stony soil	300	60 kg NO_3^- ha^{-1} (20)	361 (120)	10 820	0	23 kg NO_3^- ha^{-1}	133	4 420	**Di and Cameron (2007)**
			700	188 kg NO_3^- ha^{-1} (27)	451 (64)	13 900					
			1000	255 kg NO_3^- ha^{-1} (26)	632 (63)	19 740					
Cow urine (urine spot)	6.5 months	A Taupō Pumice Soil	775	224 (29)	NA	NA	0	6	NA	NA	**Menneer *et al.* (2008)**
Treated municipal wastewater	1 year	A Taupō Pumice Soil	340	15 (4.4)	313 (92)	16 000	0	5	25	1 900	**Treweek (2011)**
			420	16 (3.8)	340 (81)	14 000					
			520	31 (6)	400 (77)	16 500					

NA Not applicable. * Average of time period. ^{f} Fertiliser nitrogen input

2.5.3. Nitrogen leaching from different soil types

Within New Zealand, 15 soil orders are recognised (Hewitt 1998), with varying abilities to assimilate wastewater nutrients (Magesan *et al*. 1998). Studies with minor nitrogen leaching losses were generally on Allophanic and Pumice Soils (Table 2.1); with 2.3% and 3.5% of the applied effluent leached in Barton *et al*. (2005), 2.8% and 4.7% in Sparling *et al*. (2006), and 3.8% to 6% in Treweek (2011). Much larger leaching losses were reported under Gley and Recent Soils; with 25% and 23% in Barton *et al*. (2005), and 23% and 22% in Sparling *et al.* (2006). Barton *et al.* (2005) attributed the high nitrogen leaching losses from the Gley Soil to the soil's tendency for saturation and preferential flow. Preferential flow through macropores is uneven and rapid, allowing applied effluent to pour straight through the soil (McLeod *et al*. 2008). As a result of preferential flow, wastewater has little interaction with soil, therefore, less opportunity for nitrogen uptake by plants or nitrogen utilisation by microbes.

Pumice and Allophanic Soils are rated as having a low potential for bypass flow of microbes within applied effluent (McLeod *et al.* 2008). A Pumice Soil commonly has a uniformly porous soil structure which leads to decreased flow velocity and movement of applied effluent into the soil matrix or onto soil/water interfaces (McLeod *et al.* 2008). A Pumice Soil has predominately matrix flow, allowing uniform flow and availability of nitrogen for plant uptake and microbial activity (Barton *et al.* 2005). Low leaching losses of 6% (Di *et al*. 1998) and 12% (Di and Cameron 2005) from a sandy soil in the Canterbury plains of New Zealand were also attributed to matrix flow.

While some studies measured low leaching losses from Allophanic and Pumice Soils, other studies measured much higher nitrogen leaching losses (Table 2.1). For example, from an Allophanic Soil Williamson *et al.* (1998) measured leaching of 56% from the 1100 kg N ha^{-1} applied effluent nitrogen. In addition, on a Pumice Soil, Cameron *et al*. (2007) measured leaching of 35% from the 700 kg N ha^{-1} yr^{-1} applied effluent nitrogen; while Burgess (2003) measured 32% leached from the 358 kg N ha^{-1} yr^{-1} applied effluent. These studies illustrate that while soil characteristics are an important influence to nitrogen leaching losses, other factors also influence the amount of nitrogen leached, especially application conditions.

2.5.4. Nitrogen leaching and application conditions

Application conditions influence the amount of nitrogen leached. Two characteristics that influence nitrogen leaching identified in the literature are the amount of effluent nitrogen and application intensity.

High effluent application inputs (both water and nitrogen) generally create higher nitrogen leaching losses. Treweek (2011) measured an increase in the amount of nitrogen leached when higher inputs of treated municipal wastewater were applied to a Taupō Pumice Soil. Nitrogen leaching increased from 15 to 31 kg N ha^{-1} yr^{-1} when effluent nitrogen application increased from 340 to 520 kg N ha^{-1} yr^{-1}. Di and Cameron (2007) found a similar trend. When the application of urine nitrogen increased from 300, to 700, to 1000 kg N ha^{-1}, the amount of nitrate leached increased from 60 (20%), to 188 (27%), to 255 (26%) kg NO_3^- ha^{-1}.

High nitrogen leaching can be attributed to application intensity, or in other words, large effluent inputs over a short time period or over a small surface area. For example, studies that applied cow urine to simulate a urine spot generally had higher leaching losses (Table 2.1). Cameron *et al.* (2007) applied 700 kg N ha^{-1} of cow urine to simulate the typical nitrogen loading rate under a beef cattle urine patch and 245 kg N ha^{-1} (35%) was leached. Di and Cameron (2005) reproduced a typical farm situation within a lysimeter study. Urea was applied (total 200 kg N ha^{-1} yr^{-1}) over eight applications with a single application of cow urine (1000 kg N ha^{-1}) to simulate a urine spot. With the application of 1200 kg N ha^{-1}, 134 kg N ha^{-1} (12%) was leached. The majority of nitrogen leached directly after the application of the urine spot. Leaching is amplified under a urine spot, as the large volume of liquid saturates a small area of soil. However, most papers do not mention the volume of urine applied within the simulated urine spot. Intense application (whether over a short period of time or over a small area) cause large nitrogen leaching losses, as nitrogen additions are in excess to the capacity the vegetation or microbes have to assimilate the nitrogen (McLaren and Cameron 1996).

2.6. THE APPLICATION OF EFFLUENT TO LAND AND PASTURE GROWTH

2.6.1. Dry matter production

The application of effluent promotes pasture growth (Table 2.1). For example, the application of 400 kg N ha^{-1} yr^{-1} dairy farm effluent promoted an extra 4000 kg DM ha^{-1} yr^{-1} of pasture production (Di *et al*. 1998). Water and nitrogen can limit the growth of pastures within New Zealand. Therefore, the application of effluents can cause pasture to thrive. Increasing the amount of nitrogen application increased the amount of pasture produced in Di and Cameron (2007), but caused no difference in a study by Treweek (2011). The lower effluent application rate used by Treweek (2011) provided sufficient nutrient and water inputs for maximum pasture growth, and so increasing application did not increase productivity.

2.6.2. Nitrogen uptake by vegetation

Nitrogen is essential in a variety of primary and secondary plant constituents, such as proteins, nucleic acids, hormones, and chlorophyll (Hopkins and Hüner 2009). With the exception of plants engaged in symbiosis with mycorrhiza or nitrogen-fixing organisms, plants generally absorb nitrogen from inorganic forms, such as nitrate and ammonium (Whitehead 1995; Crawford and Glass 1998). Some plants can also absorb small proportions of nitrogen through their leaves, particularly gaseous ammonia and nitrogen dioxide (Whitehead 1995). The form of nitrogen used by plants depends on the abundance and accessibility of that nitrogen as well as the ability and preference of the plant (Haynes 1986).

Nitrate is the more commonly available form of nitrogen for plants in cultivated soils, since ammonium is rapidly nitrified to nitrate, or is held in the soil by; cation exchange, fixed to clay, or immobilised by microorganisms (McLaren and Cameron 1996). Nitrate utilisation by plants involves uptake, storage, translocation, reduction and incorporation of nitrogen into organic forms (Haynes 1986). Nitrate in soil solution enters into a plant by crossing the plasma membranes of root cells into the root symplast. Nitrate must then be reduced to nitrite and then ammonium in order to be converted into organic compounds for assimilation in root or shoot tissue growth (Hopkins and Hüner 2009).

Plants generally contain 1 to 5% nitrogen on a dry weight basis (Haynes 1986; Hopkins and Hüner 2009). However, the nitrogen concentration of plant tissue declines as the plant matures. The proportion of cell wall material increases with age with the decrease in cytoplasm, which contains the enzyme proteins, the nucleic acids and chlorophyll (Whitehead 1995). Nitrogen uptake is highest during the early phase of rapid growth. Nitrogen uptake then declines as reproductive growth begins and the plant ages. Plants can then translocate nitrogen within themselves (Haynes 1986).

2.6.3. Nitrogen uptake by pasture and nitrogen yield

The cultivation, harvest and removal of pasture at a land based wastewater treatment plant, as in a cut and carry scheme, provides an opportunity to remove wastewater nutrients from site and even from a catchment. When nitrogen is removed by pasture, less is available to be leached. A large proportion of applied effluent can be removed by growing and then harvesting pasture; 37% to more than 100% (Table 2.1).

A high yielding perennial grass is best suited to assimilate, and therefore, remove high concentrations of nitrogen (McLaren and Cameron 1996). Pasture types cultivated within these studies include perennial ryegrass (Sparling *et al*. 2006; Treweek 2011) or a ryegrass and white clover mixture (Barton *et al.* 2005; Di and Cameron 2007). In studies that used a clover-rich sward (Barton *et al.* 2005; Di and Cameron 2007), 101 to 120% of the applied effluent nitrogen was removed with pasture harvest. The reason greater than 100% of the effluent nitrogen was removed may be associated with the clover’s ability to fix atmospheric nitrogen. The use of a clover-rich sward may be less suited in a land based wastewater treatment site. With the ability to fix nitrogen, clover does not depend on external nitrogen sources, and may not utilise as much of the applied effluent as a perennial ryegrass (U.S EPA 1981). However, clover will probably die out when nitrogen-rich wastewater is applied (Ledgard 2001)

2.7. THE TAUPŌ REGION AND THE RECEIVING ENVIRONMENT

2.7.1. The physical setting

2.7.1.1. Geological setting and volcanism

Geology of the Taupō region is closely linked with its volcanic history. Taupō is located in the Taupō Volcanic Zone (TVZ) within central New Zealand (Figure 2.2). The TVZ is a region of active volcanism in New Zealand that runs north-east/south-west from White Island to Ohakune, parallel to the present plate boundary (Thornton 1995).

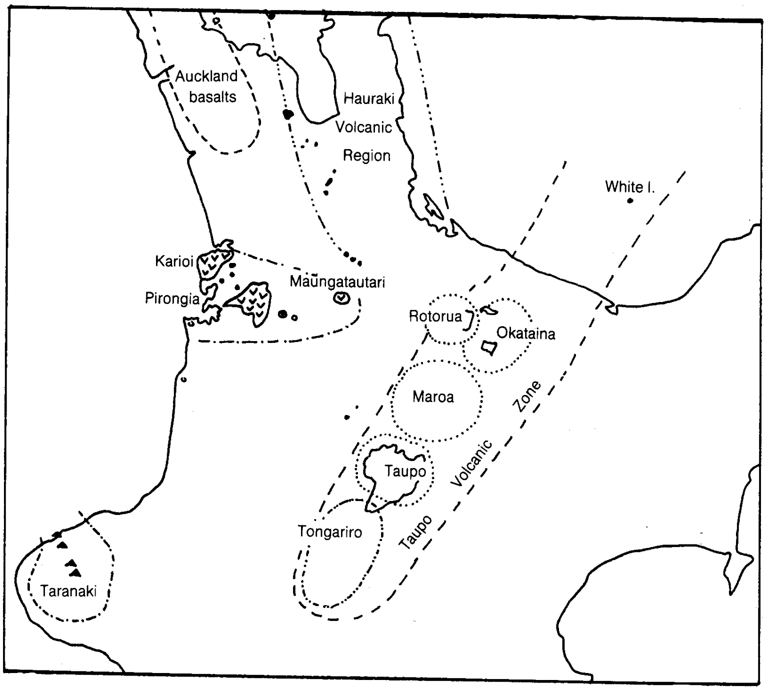

Figure 2.2. Location of Taupō in the TVZ (Thornton 1995).

Taupō volcano has erupted at widely spaced intervals for the last 100 000 years (Thornton 1995). During the c. 26.5 ka rhyolitic Oruanui eruptive sequence, Taupō caldera and then the subsequent Lake Taupō were formed (Wilson 2001). The largest eruptive event of Taupō, the Hatepe eruption, was estimated at around 130 A.D. (dated with carbon dating) or around 186 A.D. (within historic Roman and Chinese literature) (Thornton 1995; Molloy and Christie 1998). During the eruptive event a large amount of material was erupted from the eastern part of

Lake Taupō; beginning with a series of small eruptions, followed by several large explosions which created a towering ash column several kilometres high. The final explosion created a pyroclastic flow which deposited ignimbrites for about 80 km surrounding Lake Taupō (Thornton 1995).

Eruptive events from Taupō, and other neighbouring volcanic areas, have deposited a succession of ignimbrites mantled by numerous pumiceous tephra (Collier *et al*. 2010).

2.7.1.2. Soil properties

Soils within the Taupō region are a product of the weathered pumiceous tephra and volcanic parent material (Molloy and Christie 1998). Pumice Soil is the predominant soil type within the Taupō region. Soils have a sandy or gravelly texture dominated by pumice, or contain pumice sand with large amounts of natural glass (Hewitt 1998). Pumice Soils are generally deep, weakly weathered with low cohesion and have high macroporosity, and thus, rapid drainage (Hewitt 1998; Molloy and Christie 1998; Collier *et al*. 2010). Natural fertility of a Pumice Soil is low, since soils are usually deficient in both major nutrients and trace elements (Molloy and Christie 1998). The clay content within Pumice Soils is also low, less than 10%. Those clay minerals present consist of mainly allophane and imogolite. Pumice Soils have moderate to high phosphate retention (Hewitt 1998).

2.7.1.3. Lake Taupō and the Waikato River

Lake Taupō or Taupō–nui–a–Tia (great cloak of Tia) is New Zealand’s biggest lake with a surface area of 623 km^2 (Matherson *et al.* 2011; Environment Waikato 2012a) (Figure 2.3). Lake Taupō is 160 m at its deepest point, 30 km wide, 40 km long, and contains about 59 km^3 of water (Environment Waikato 2012a). Because of the Lake’s size and depth, lake water has a residence time of about ten to thirteen years (White and Downes 1977; White *et al*. 1980). Water within Lake Taupō stratifies thermally for approximately nine months each year and mixes during the winter months (White and Payne 1977).

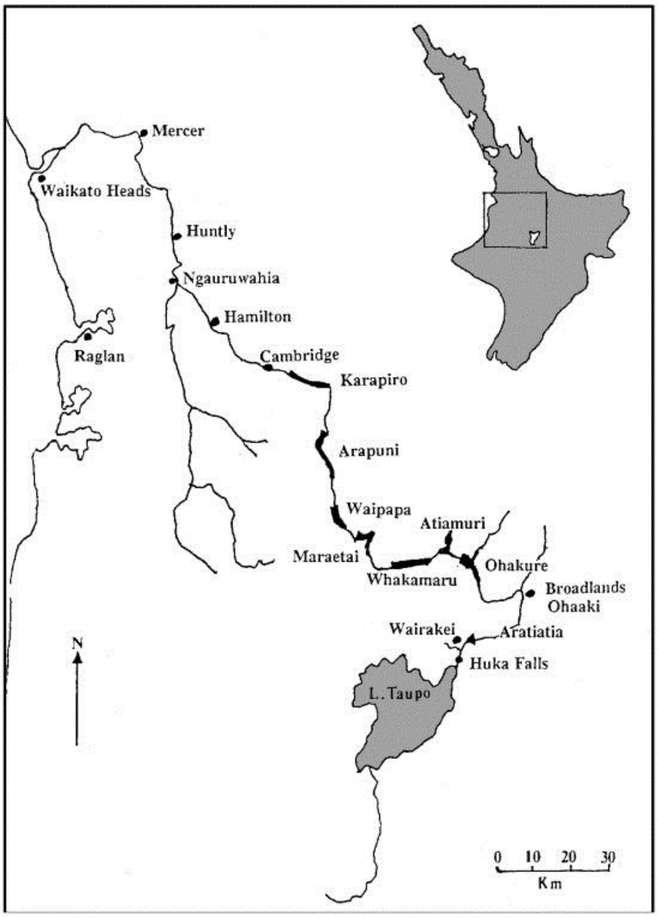

Figure 2.3. Lake Taupō and the Waikato River (Robinson *et al.* 2003).

Lake Taupō is an oligotrophic lake; with low nutrient status and high water quality (Matherson *et al.* 2011). Historically the Lake has had extremely low nitrogen inputs, limiting the growth of nuisance weeds and plants (Environment Waikato 2012a). However, the Lake's high quality water is threatened by development of agriculture, forestry and urban settlement within the surrounding catchment. Over the last 60 years, nitrogen input into the Lake has increased considerably (Environment Waikato 2012a). Major nitrogen inputs have occurred from agricultural land; leached from pastures directly into the Lake or delivered in streams (Matherson *et al*. 2011). Nitrogen inputs have also occurred from urban settlements at the Lake's edge, in particular with leaching from septic tanks (Gibbs 1979).

Lake Taupō has shown signs of water quality deterioration (Gibbs 2012). For example, from 1994 to 2004 particulate forms of phosphorus and nitrogen, and the subsequent chlorophyll a (an indicator of the amount algae), increased in the Lake's surface waters. Other factors that suggest deterioration include; the increase in dissolved nitrogen (from 1974 to 2004) in the bottom waters of the lake just prior to winter mixing, and blooms of toxic algae on the lake for the first time in 2001 and then again in autumn 2003 (Environment Waikato 2003).

More than thirty rivers and streams flow into Lake Taupō, yet the Lake's only outlet is the Waikato River. The Waikato River is New Zealand's longest river at 442 km, beginning on the eastern slopes of Mount Ruapehu. The Waikato River flows into Lake Taupō and flows northwards out of the Lake to discharge at Port Waikato (Figure 2.3) (Environment Waikato 2012b). Historically water took five to six days to travel from Lake Taupō to Port Waikato. Today, a series of eight hydro dams and nine hydroelectric power stations greatly increase the residence time in the Waikato River, to around 40 days during times of low flow (Collier *et al*. 2010).

Water quality in the Waikato River is high upon leaving Lake Taupō (Environment Waikato 2012b). However, sediment, nutrient, and mineral levels increase considerably between Lake Taupō and the first hydroelectric dam on the River, at Lake Ohakuri (Collier *et al*. 2010). Water quality of the Waikato River has improved since 1970 with the improvement of wastewater treatment from urban and industrial sources (Environment Waikato 2012b). However, nitrogen and phosphorous inputs have increased over recent decades with intensification of agriculture (Collier *et al*. 2010).

The longer residence time of water within the Waikato River promotes the growth of nuisance aquatic plants and phytoplankton (Environment Waikato 2012b). Toxic algal blooms do not regularly occur within the Waikato River, however, in the summer of 2002/2003 blue-green algae were detected in the Hamilton drinking water intake on the Waikato River (Collier *et al*. 2010). With the predicted increase of nutrients, toxic algal blooms within the Waikato River may occur more often (Collier *et al*. 2010).

2.7.1.4. Climate

The climate in the Taupō region is temperate. On average, Taupō is colder and has more rainfall than the North Island and New Zealand (Table 2.2). Rainfall in Taupō is strongly controlled by the prevailing westerly winds and the topography (Collier *et al*. 2010).

Table 2.2. Mean climate data from 1981 to 2010 for Taupō, the North Island and New Zealand (NIWA 2013).

Climate factor	Taupō	North Island	New Zealand
Air temperature (^{0}C)	11.7	14.0	12.4
Total sunshine (hours)	1947	2086	2010
Rainfall (mm)	955	1115	1364
Wet days (days with > 1mm of rain)	109	120	119
Ground frost (days in which ground frosts occurred)	83.8	32.3	54.0

From 1981 to 2010, mean air temperature in Taupō was warmest in January (17^{0}C) and February (17^{0}C) and coolest in July (6^{0}C). Mean rainfall was highest in July (96 mm), December (93.6 mm) and June (92.8 mm), while rainfall was lowest in March (66.5 mm), February (67.9 mm) and November (67.9 mm). The majority of frosts occurred between May and September, with the maximum of 16.9 days of frosts occurring in July (NIWA 2013).

2.7.2. The cultural setting

Lake Taupō and the Waikato River are of immense spiritual and cultural significance to tangata whenua (people of the land). Historically the Waikato River provided food and sustenance, spiritual and material needs, a source of cleansing and healing and a network for trade, travel and communication (Stokes and Begg 1997; Collier *et al.* 2010). The Waikato River is viewed as a taonga (treasure) and is a highly-prized physical and spiritual resource (Stokes 1991). Pollution and corruption diminish the spiritual and physical qualities of the River (Stokes 1991). Five Iwi (tribes) have kaitiakitanga (guardianship) of the Waikato River: Waikato-Tainui, Raukawa, Maniapoto, Te Arawa and Tūwharetoa (Collier *et al.* 2010). Tūwharetoa have lived in the Taupō region for generations and are kaitiaki (guardians) of Lake Taupō. Tūwharetoa also hold mana whenua (territorial rights or authority) over the Lake Taupō catchment (Environment Waikato 2003).

"A Māori perspective on the environment is holistic, embodying both spiritual and practical aspects in the management of resources" (Stokes 1991, p. V.). Disposal of wastewater in the Waikato River is unacceptable to local Iwi (Stokes 1991). The discharge of sewage directly into a taonga, regardless of the chemical or biological quality of the treated effluent, is viewed as "repugnant" (Stokes 1991, p. 2.). In agreement with the Māori concept of polluted water being purified by flowing through the earth, a land based disposal system is the preferred option to dispose of human wastewater in the Taupō region (Stokes 1991).

2.7.3. Nitrogen leaching and uptake studies in Taupō

2.7.3.1. Overview of nitrogen studies on a Taupō Pumice Soil

Because of the Lake's sensitivity to nitrogen inputs, much nitrogen research has been undertaken within the Taupō region; especially since the 20/20 Taupō-nui-a-Tia action plan (a strategy to manage nitrogen in the greater Taupō catchment) and the implementation of Variation 5 (a variation of the Waikato Regional Plan proposed to protect water quality in Lake Taupō). For example, Ledgard *et al.* (2007) investigated a range of potential nitrogen mitigation options for farmers surrounding Lake Taupō. Strategies included strategic nitrogen immobilisation in soil, the use of grasses for improved nitrogen recovery and nitrogen cycling efficiency, increasing the spread of excreted urine using salt as a diuretic, and using animals to deliver dicyandiamide in urine.

Studies have endeavoured to quantify nitrogen leaching losses from land uses surrounding Lake Taupō. According to Cameron *et al.* (2007), it is practically impossible to measure water drainage and nitrogen leaching at a paddock scale from a free draining soil, like the Taupō Pumice Soil. Overseer (a software program prepared by AgResearch and The Ministry of Agriculture and Forestry) is commonly used to establish nitrogen discharge for properties surrounding the Lake. Alternatively, studies have tried to determine nitrogen movement, in a Taupō Pumice Soil, with localised lysimeter studies and then estimated nitrogen leaching at larger scales (Burgess 2003; Barton *et al.* 2005; Sparling *et al.* 2006; Cameron *et al.* 2007; Menneer *et al.* 2008; Treweek 2011).

Literature directly relating to a Taupō Pumice Soil, similar to the soil at View Road, is summarised below to better understand potential nitrogen leaching losses from site. Nitrogen movement in the previous lysimeter study at the View Road site (Treweek 2011) is examined.

a. The use of animal effluents

Nitrogen leaching losses after the application of animal effluent to pasture grown on a Taupō Pumice Soil have been examined (Burgess 2003; Cameron *et al.* 2007; Menneer *et al.* 2008) (Table 2.1). Cow urine was applied to lysimeters to simulate nitrogen leaching under urine spots and high leaching losses were reported. Of the 700 kg N ha^{-1} applied in Cameron *et al.* (2007), 245 kg N ha^{-1} (35%) was leached, while of the 775 kg N ha^{-1} applied in Menneer *et al.* (2008), 244 kg N ha^{-1} (29%) was leached. Lysimeters within Cameron *et al.* (2007) and Menneer *et al.* (2008) were installed in a facility specifically designed to house lysimeters in trenches at the same level as the surrounding soil surface. Burgess (2003) and (Treweek 2011) were the only studies found to install lysimeters throughout a paddock, rather than in a localised trench. In Burgess (2003) dairy farm effluent was applied to paddocks with travelling irrigators and of the 442 kg N ha^{-1} yr^{-1} applied, 125 kg N ha^{-1} yr^{-1} (28%) was leached.

b. The use of human effluents

Three studies examined nitrogen leaching losses after the application of human effluent to pasture grown on a Taupō Pumice Soil (Barton *et al.* 2005; Sparling *et al.* 2006; Treweek 2011). Both Barton *et al.* (2005) and Sparling *et al.* (2006) tested the suitability of four contrasting soils for the land treatment of secondary-treated municipal effluent within New Zealand. The Pumice Soil had similar leaching losses to an Allophanic Soil, but low nitrogen leaching losses in comparison to a Gley and Recent Soil (Table 2.1).

Barton *et al.* (2005) and Sparling *et al.* (2006) installed barrel lysimeters at ground level within an outdoor trench. Secondary-treated effluent was irrigated weekly at 10 mm for 5 hours (50 mm per week) (Barton *et al.* 2005; Sparling *et al.* 2006). The application rate of 50 mm per week is described as current treatment practice within New Zealand where storage components are not economically feasible (McLeod *et al*. 1998; Speir *et al.* 1999; Tomer *et al.* 2000; Barton *et al*. 2005; Sparling *et al.* 2006).

Barton *et al.* (2005) and Sparling *et al.* (2006) harvested pasture by clipping the shoots when the mean herbage height exceeded 2 to 2.5 cm. Barton *et al.* (2005) explains cutting height as replicating a "cut and carry" treatment system. While it is not uncommon for cutting studies to cut pasture to a height of 2.5 cm (Bartholomew and Chestnutt 1977), a height of 2.5 cm is considered a low cutting height (Binnie *et al.* 1974; Fulkerson and Michell 1987; Kerrisk and Thomson 1990) and is commonly used in cutting studies that are trying to simulate pasture growth under grazing conditions (Fulkerson and Michell 1987; Hazard and Ghesquiere 1997). A more commonly used cutting height within cutting studies ranges from 5 to 7 cm (Kunelius and Calder 1978; Fulkerson and Michell 1987; Kerrisk and Thomson 1990; Zhang *et al.* 1995; Hazard and Ghesquiere 1997; Schills *et al.* 1999).

On average, 3.5% of the 408 kg N ha^{-1} yr^{-1} applied wastewater was leached from the Pumice Soil in Barton *et al.* (2005). Pasture removed 65% of the applied wastewater over the two year experiment, leaving 32% nitrogen unrecovered. Similar nitrogen losses were reported in Sparling *et al.* (2006), where 4.7% of the 364 kg N ha^{-1} yr^{-1} was leached over 4 years while 63% was removed by pasture and 32% was unrecovered.

Unrecovered nitrogen was assumed to be denitrified, volatilised or transferred into soil storage. Pumice Soils have a tendency to adsorb and fix high amounts of nitrogen (McLaren and Cameron 1996), which may account for some of the lost nitrogen. However, adsorption and fixation decreases over time with continued application. Eventually, when the soil nitrogen pool becomes full, more nitrogen may be available for plant uptake or potentially to be leached (U.S EPA 1981).

2.7.3.2. Nitrogen leaching and uptake study at the View Road site

The nitrogen leaching experiment undertaken for this thesis (refer to Chapter 3) was installed in September 2009 for a previous study (Treweek 2011). The experimental area at the View Road site had received effluent from 2008, while varied application rates began in March 2009. Treweek (2011) determined nitrogen leaching losses and pasture uptake under a range of wastewater nitrogen loading rates. However, as this experiment began less than two years after effluent application at the View Road site, it was uncertain if the soil nitrogen pool had reached equilibrium. If effluent nitrogen was still being immobilised in soil organic matter during the first two years, nitrogen leaching losses measured in Treweek (2011) might not accurately represent future losses. A second round of measurement was needed to verify equilibration of the soil nitrogen pool and to make sure nitrogen leaching losses had not increased since the first year of monitoring. The following section summarises the findings of Treweek (2011).

The targeted loading rates were 450, 550 and 650 kg N ha^{-1} yr^{-1}. However, the target loading rates were not reached, with application ranging from 280 to 520 kg N ha^{-1} yr^{-1}. Inputs were grouped into an unirrigated or a No-N treatment (0 kg N ha^{-1} yr^{-1}), a Low-N treatment (280 - 350 kg N ha^{-1} yr^{-1}) a Mid-N treatment (350 - 450 kg N ha^{-1} yr^{-1}) and a High-N treatment (450 - 520 kg N ha^{-1} yr^{-1}) (Treweek 2011).

The mean nitrogen leaching loss from all irrigated treatments was 5% of the total nitrogen applied from December 2009 to December 2010. Mean leaching losses increased with increased nitrogen input; from the No-N treatment (5 ± 3 kg N ha^{-1}), to the Low-N treatment (15 ± 1 kg N ha^{-1}), to the Mid-N treatment (17 ± 8 kg N ha^{-1}) to the High-N treatment (26 ± 4 kg N ha^{-1}). Leachate of the irrigated treatments contained, on average, 53% nitrate, 2% ammonium, and 45% total organic nitrogen. Leachate of the unirrigated treatments contained, on average, 26% nitrate, 2% ammonium and 72% total organic nitrogen. The mean concentration of nitrate was 1.3 g N m^{-3} which did not exceed Ministry of Health guidelines for drinking water (11.3 g N m^{-3}). Most nitrate leaching occurred after rainfall events during summer and autumn (Treweek 2011).

The application of wastewater substantially increased pasture dry matter production (15 800 ± 1700 kg DM ha^{-1} yr^{-1}) when compared to unirrigated treatments (1800 kg DM ha^{-1} yr^{-1}) ($P < 0.001$). Pasture uptake removed 84% of the applied nitrogen. However, there was no difference in nitrogen uptake or pasture growth between the irrigated treatments (Treweek 2011).

Unrecovered nitrogen ranged from -8 to 29% of the applied nitrogen (Treweek 2011). Negative values correspond to situations where the amount of leached nitrogen and removal of nitrogen by pasture exceeded the amount of nitrogen irrigated. Negative values can be explained by mineralisation or by measurement error.

Treweek (2011) bulked leachate and herbage samples from the set of three lysimeters within each treatment sector (Figure 3.2). However, there was variation in the amount of effluent that was irrigated within a treatment sector (measured with rain gauges) and variation of drainage volumes from lysimeters within a set. It was recommended that lysimeters were sampled and analysed separately to account for variability in irrigation volumes, soil properties within soil cores, and sparse or variable plant cover within the experimental area (Treweek 2011). Sampling the lysimeters separately increased the level of replication and allowed the range of nitrogen leaching losses and pasture uptake under the real field conditions to be measured more accurately.

2.8. LITERATURE REVIEW, SUMMARY AND CONCLUSIONS

Slow rate land based application is a generally accepted method of tertiary treatment and disposal of wastewater within New Zealand. Most of the nitrogen present in wastewater is normally utilised by crop uptake and subsequent harvest, the denitrification process, volatilisation or by soil immobilisation. If nitrogen is not fully utilised, it can be lost from the system via nitrogen leaching.

Lysimeter studies are often used to measure nitrogen leaching and pasture uptake after the application of effluent to pasture. Many lysimeter studies were installed within a trench, but only two studies were installed throughout a field (Burgess 2003; Treweek 2011). Both human and animal effluents were applied to lysimeters, but literature involving human effluent application was sparse. Many studies applied effluent by irrigation; while some studies poured animal urine on at a single spot to simulate urination of cattle at a point source. Nitrogen inputs ranged from 300 to 1200 kg N ha^{-1} (Table 2.1); and leaching losses ranged between 2.3 to 56% of the applied nitrogen. Many studies ignored the organic forms of nitrogen within leachate (even though organic nitrogen can make up a large component of leachate) and concentrated on nitrate leaching. Nitrogen losses were influenced by soil characteristics, application conditions and nitrogen removal by pasture.

If pasture is harvested and removed from a land based wastewater treatment site the opportunity to remove wastewater nitrogen is increased. Pasture can remove a significant component (37 to more than 100%) of applied effluent nitrogen, so that less nitrogen is available to be leached. The application of effluent to land significantly increases pasture production, however, increasing the amount of nitrogen application further, does not necessarily increase the amount of pasture produced.

Loading rates and application conditions influence the amount of nitrogen leached. Nitrogen leaching occurs when nitrogen additions exceed the capacity of vegetation or microbes to assimilate the wastewater nitrogen. Two characteristics that influence nitrogen leaching within literature are the amount of applied effluent and application intensity. High effluent input generally cause higher nitrogen leaching losses. Elevated nitrogen leaching can also be attributed to application intensity, where the application of large amounts of effluent over a short time period or over a small surface area leads to saturated flow and rapid movement of effluent through to the subsoil.

New Zealand’s soils have varying abilities to assimilate wastewater nutrients. Pumice Soils generally produce minor nitrogen leaching losses under suitable application conditions (Barton *et al.* 2005; Sparling *et al.* 2006; Treweek 2011). A Pumice Soil commonly has a uniformly porous soil structure which leads to predominately matrix flow, allowing uniform flow and availability of nitrogen for plant uptake and microbial activity. However, there were also studies that measured higher nitrogen leaching losses from a Pumice Soil. High leaching losses were generally associated with application conditions, for example with the simulation of a urine spot.

Nitrogen cycling research within the Taupō region of New Zealand is common, because Lake Taupō is sensitive to nitrogen inputs. To better understand nitrogen leaching from pasture on a Taupō Pumice Soil, similar to soil at the View Road land based wastewater treatment site literature was examined. New Zealand studies have applied animal or human effluent to a Taupō Pumice Soil. In two studies (Barton *et al.* 2005; Sparling *et al.* 2006), secondary-treated municipal effluent was irrigated weekly at 10 mm for 5 hours (50 mm per week). Leaching losses were low, pasture uptake was moderately high, and a significant component was unrecovered, assumed to be converted into gaseous forms or transferred into soil storage.

The nitrogen leaching experiment undertaken for this thesis (refer to Chapter 3) was installed in September 2009 for a previous study (Treweek 2011). The mean amount of nitrogen leached in the previous study increased from 5 ± 3 kg N ha^{-1} within the unirrigated treatment (0 kg N ha^{-1}), to 15 ± 1 kg N ha^{-1} (4.8%) within the low treatment (280 - 350 kg N ha^{-1} yr^{-1}), to 17 ± 8 kg N ha^{-1} (4.3%) within the medium treatment (350 - 450 kg N ha^{-1} yr^{-1}), to 26 ± 4 kg N ha^{-1} (5.4%) within the high treatment (450 - 520 kg N ha^{-1} yr^{-1}) (Treweek 2011). Since the first year of measurement began less than two years after effluent application began at the View Road site, it was uncertain if net soil immobilisation ceased. If effluent nitrogen was still accumulating within soil storage during the first experiment, nitrogen leaching losses measured in Treweek (2011) might not represent future losses. A second round of measurement was needed to verify equilibration of the soil nitrogen pool and to make sure nitrogen leaching losses have not increased since the first year of monitoring. Analysing each lysimeter separately would allow a higher degree of replication and a more accurate measurement of the range of nitrogen leaching losses and pasture uptake under field conditions.

From literature, it is expected nitrogen leaching losses at the View Road site will be less than about 6% of the applied effluent. However, leaching losses depend on the amount of effluent input and application conditions. This conclusion may be inaccurate, because of gaps within the literature; few New Zealand have applied human effluent, under real field conditions, with lysimeters installed throughout a field, rather than in a trench.

CHAPTER THREE – NITROGEN LEACHING AND PASTURE UPTAKE FROM LAND IRRIGATED WITH VARIED WASTEWATER APPLICATION RATES

3.1. INTRODUCTION

A field scale lysimeter experiment was undertaken at the View Road land based wastewater treatment site. The purpose of the study was to quantify the amount of nitrogen that was leached and removed by pasture, and the amount of pasture production, under a range of wastewater application rates. The target rates were 450, 550 and 650 kg N ha^{-1} yr^{-1}.

Secondary-treated municipal wastewater has been applied at the View Road site with centre pivot travelling irrigators since December 2008. To produce the range of target wastewater loads varied irrigation rates were implemented, starting in March 2009.

In order to measure nitrogen leaching and pasture uptake, 48 barrel lysimeters were installed during September 2009. A first round of measurement took place from December 2009 to December 2010 (Treweek 2011). A second round of measurement was needed to confirm equilibration of the soil system and to provide a longer time-series of data.

The second round of measurement began on the 8th of September 2011 and finished on the 17th of September 2012 with results presented in this thesis. The amount of wastewater nitrogen applied to each lysimeter was calculated and then the volume and nitrogen concentration of leachate, the pasture dry matter weight, and nitrogen content were measured.

Nitrogen input values (wastewater and atmospheric), pasture production, nitrogen uptake, nitrogen leaching, and unrecovered nitrogen values are reported, discussed and compared to values in the literature and the previous year of measurement at the View Road site (Treweek 2011).

3.2. METHODOLOGY

3.2.1. Experimental design

3.2.1.1. Overview

The lysimeter experiment was installed within 29 hectares in the southwest corner of the View Road land based wastewater treatment site. (38^{0}39'19.0"S 176^{0}09'31.7"E) (Figure 3.1). The experimental area is underneath two irrigators; pivot F and half of pivot G. A high yielding perennial ryegrass (predominantly *Lolium perenne*) is grown within the experimental area and is harvested four times a year. Soils are characterised as a Pumice Soil (NZ Soil Classification) or Vitrand (USDA Soil Taxonomy) (Treweek 2011).

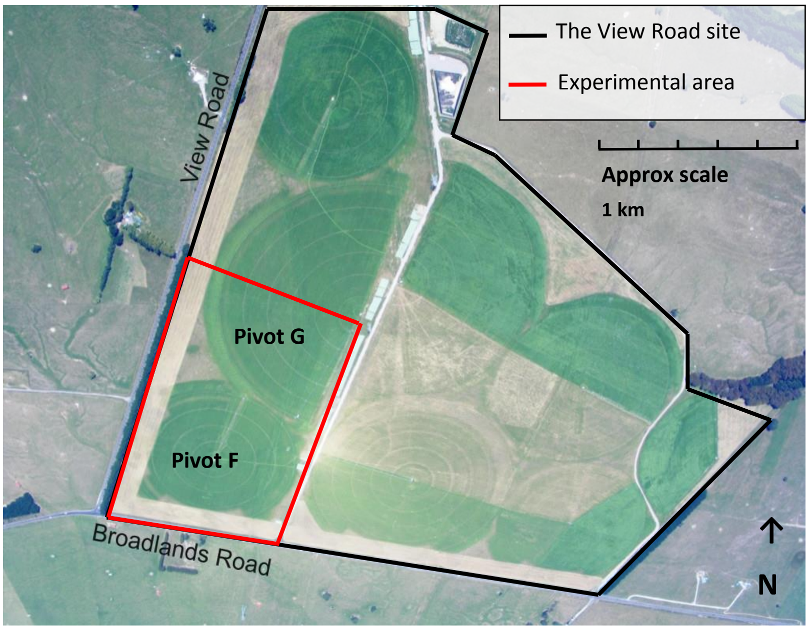

Figure 3.1. Aerial photograph of the View Road site and the lysimeter study experimental area underneath pivot F and half of pivot G.

3.2.1.2. Varied wastewater loading rates

The experimental area was separated into 12 treatment sectors and each sector was assigned one of three wastewater loading rates (Figure 3.2). To apply varying application rates, the irrigators were programmed to slow down by 18% to give a higher wastewater loading rate (more wastewater per unit area) and speed up by 18% to give a lower loading rate (less wastewater per unit area). The "normal" speed (the rate used over the rest of the irrigation treatment site) gave a medium loading rate. Control sites were areas that did not receive wastewater and were not affected by spray drift.

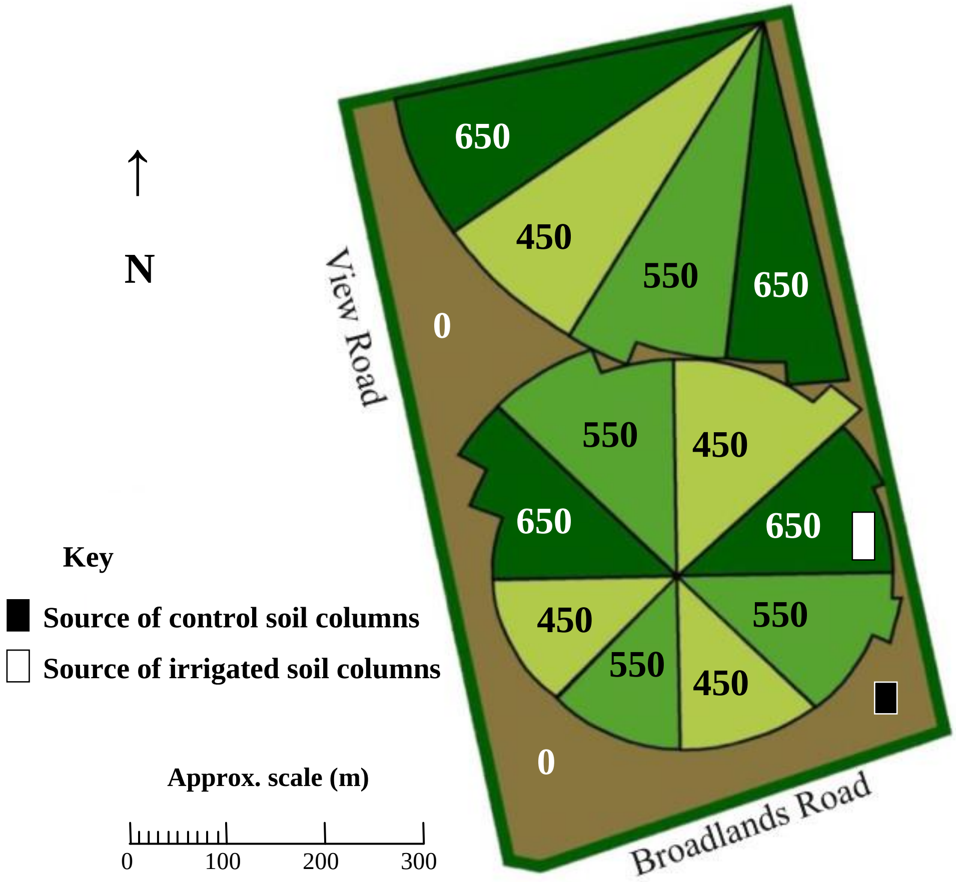

Figure 3.2. Target treatment loads (kg N ha^{-1} yr^{-1}) and the location of soil used to construct soil columns within irrigated and control lysimeters (after Treweek 2011).

Treatments were targeted to be a lower rate (450 kg N ha^{-1} yr^{-1}), the medium or consented rate (550 kg N ha^{-1} yr^{-1}), a higher rate (650 kg N ha^{-1} yr^{-1}), and the control (0 kg N ha^{-1} yr^{-1}). To measure the actual wastewater application at each lysimeter, plastic rain gauges (capacity of 160 mm) were installed.

During the experiment, wastewater was not irrigated to pivot F for 6 weeks and to pivot G for 8 weeks as stand-down periods during field harvests.

3.2.1.3. Lysimeter construction

In order to measure the amount of nitrogen leached and taken up by pasture within the treatment sectors, 48 barrel undisturbed barrel lysimeters (30 cm diameter x 43 cm depth) were constructed (Figure 3.3).

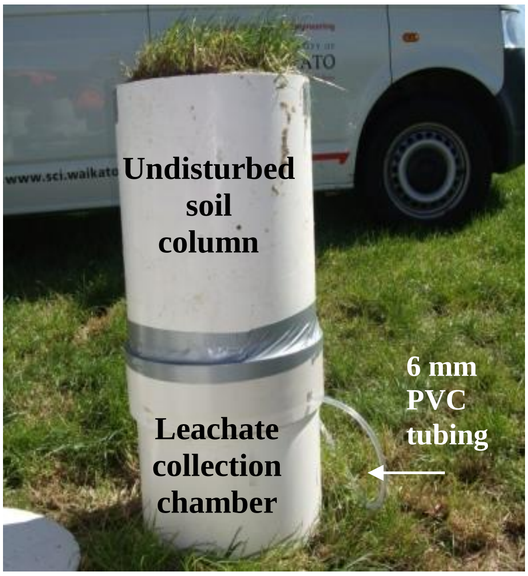

Figure 3.3. Example of barrel lysimeter before installation. ***Photo, Glen Treweek.***

Lysimeters were built in September 2009 following the method developed by Cameron *et al*. (1992). Undisturbed soil columns were extracted from one of two areas at the View Road site (Figure 3.2). Thirty-eight soil columns were extracted from an area that had previously received wastewater and twelve soil columns were extracted from a nearby unirrigated soil to be used as controls (Treweek 2011).

Figure 3.4.Construction of the barrel lysimeters. ***Photo, Glen Treweek.***

The soil columns were extracted using heavy-duty PVC pipes (30 cm diameter x 43 cm depth) with a sharpened edge. The PVC pipes were placed on the ground surface next to an access trench. The pipes were then pushed down by small increments and soil from around the outside of the casing was removed

(Figure 3.4). Once the piping reached 43 cm depth, the undisturbed soil column was cut at the base with a cutting plate.

The soil column was then sealed inside the piping with petroleum jelly to prevent edge-flow effects. A perforated bottom plate was installed below the soil column to allow the collection of drainage into a collection chamber. The chamber was attached with screws and PVC tape. To allow leachate to be pumped from the catchment chamber 6 mm PVC tubing was attached to the chamber.

3.2.1.4. Lysimeter installation and design

Lysimeters were installed throughout the experimental area; 36 lysimeters were installed within the irrigated areas and 12 lysimeters were installed within unirrigated areas as controls (Figure 3.5).

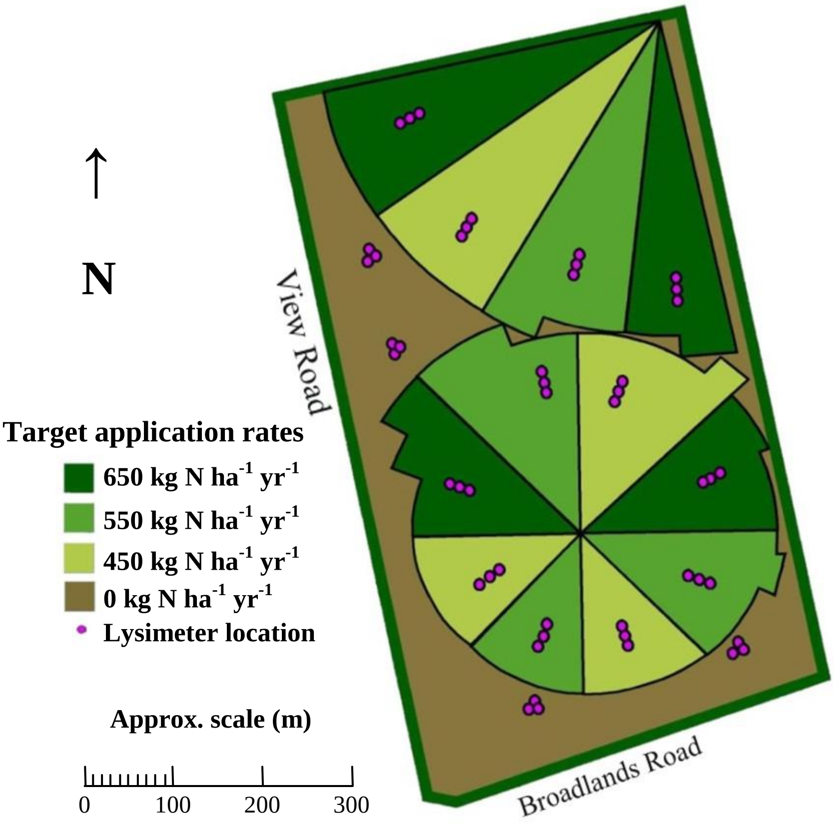

Figure 3.5. Location of lysimeters within treatment sectors (after Treweek 2011).

Within each of the irrigated treatments, three lysimeters were installed 10 m apart with a rain gauge next to each lysimeter. Within unirrigated areas, control lysimeters were installed together in a group of three with one rain gauge per group.

Each lysimeter was transported to its assigned location in the field, a hole was dug, the lysimeter was installed flush with the ground surface, and soil was backfilled (Figure 3.6 and Figure 3.7). The 6 mm tubing was extended above the ground surface and then placed beneath a concrete pad (40 cm x 40 cm) to aid in location of the lysimeter (Figure 3.8).

Figure 3.6. Installation of lysimeter within the field. *Photo, Glen Treweek.*

Figure 3.7. Lysimeter installed flush with the ground surface.

Figure 3.8. Lysimeter set up —plastic rain gauge, concrete pad, and sampling tube are visible.

3.2.2. Field work and sample collection

3.2.2.1. Sampling period

Lysimeters were pumped dry and rain gauges were installed on the 8th of September 2011, with irrigation for this measurement period beginning on the 10th of September 2011. Each lysimeter was sampled separately, with lysimeter leachate collected monthly. Four harvests occurred during the measurement period and pasture was collected off the lysimeters before each field harvest. Rain gauges were read approximately once a fortnight to once a month, depending on the amount of rainfall during the measurement time period.

Irrigation for this experiment ended on the 14th of September 2012 and rain gauges were removed on the 17th of September 2012. The final leachate collection occurred on the 25th of September to allow water to leach into the catchment chamber. No irrigation occurred from the 14th to the 25th of September. As the sampling period was not exactly a year, all results were adjusted by dividing the value by 370 days (initiation of irrigation on the 10th of September 2011 and conclusion of irrigation on the 14th of September 2012. The year of 2012 was also a leap year) and then multiplying by 365.

Two lysimeters within irrigated treatments were broken and no leachate was collected.

3.2.2.2. Lysimeter leachate collection

Lysimeter leachate was collected monthly. The PVC tube that was connected to the lysimeter leachate chamber was removed from beneath the concrete pad and attached to a self-priming pump. To obtain a measurement of drainage volume, leachate was pumped into a large bucket and was weighed with a portable electronic scale (Figure 3.9). Leachate was subsampled into two 60 ml pottles and placed in a freezer until returned to the laboratory for analysis. The remaining leachate was disposed of on the ground and the bucket and pump were rinsed with tap water. Rain gauge measurements were recorded and water was emptied.

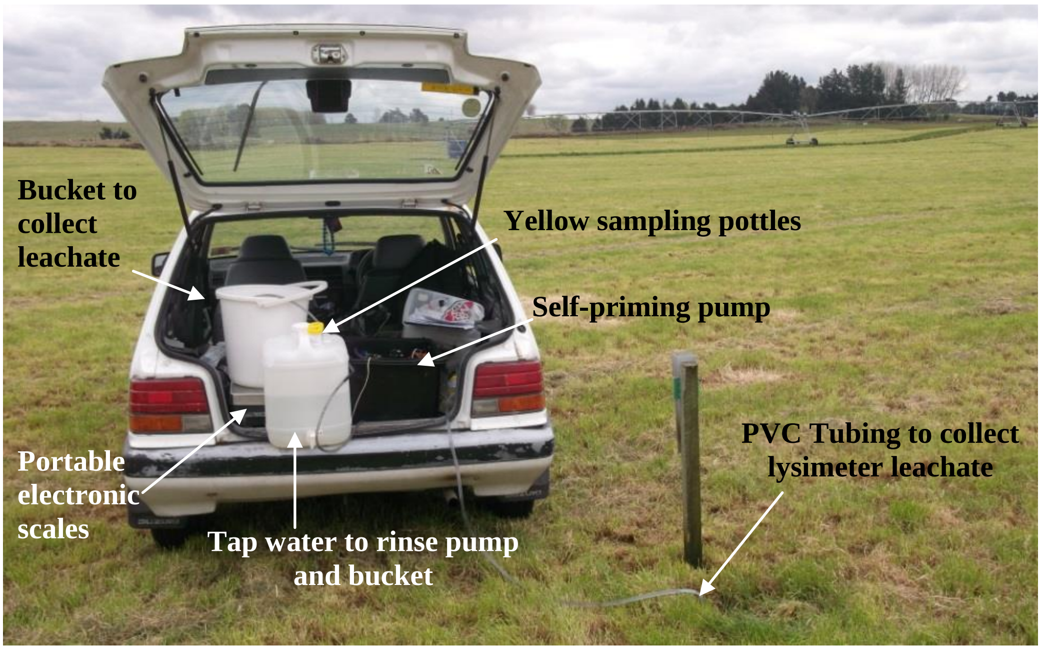

Figure 3.9. Sampling set up for collection of lysimeter leachate.

3.2.2.3. Lysimeter pasture collection

Prior to each commercial field harvest, grass growing on top of each lysimeter was collected (Figure 3.10 and Figure 3.11). Pasture was cut with scissors to approximately 7 cm (the same height as cut by the harvest machinery). The grass was placed into a labelled paper bag and returned to the laboratory for analysis. Rain gauges were dismantled and removed before each harvest and were later reinstalled after the field harvest was complete.

Figure 3.10. Grass growing within a lysimeter before pasture collection.

Figure 3.11. Grass cut to a height of 7 cm with scissors and collection into a paper bag.

3.2.3. Laboratory analysis

3.2.3.1. Nitrogen analysis of leachate

Leachate samples were analysed at the University of Waikato and Taupō District Council. Replicates were run between laboratories to ensure results from the two laboratories were comparable. To further check reliability, nitrogen analysis of leachate sampled during July was also replicated at a commercial laboratory.

a) Nitrogen analysis at the University of Waikato and at the Taupō District Council

Nitrogen analyses were performed using an AQUAKEM 200 QD (discrete photometric analyser) at both the University of Waikato and the Taupō District Council. The same type of machine and analysis method was used at both laboratories.

The lysimeter leachate was separated into two subsamples for analysis. One subsample was filtered through a 0.45 µm filter and analysed for total ammonical nitrogen (NH_4-N), total oxidised nitrogen (NO_x-N) and nitrite nitrogen (NO_2-N) using standard colorimetric methods (APHA, 1998).

The other subsample was not filtered and was analysed for total nitrogen (TN). The sample was digested at 120^{0}C using a modified simultaneous persulfate digestion method (Ebina *et al*. 1983; Johnes and Heathwaite 1992). Samples were analysed on the AQUAKEM 200 QD analyser using a modified U.S. Environmental Protection Agency method 353.1 (EPA 1983).

Total organic nitrogen (ToN) was calculated as: ToN= TN – NO_x-N – NH_4-N

b) Nitrogen analysis at the commercial laboratory

Replicates of leachate sampled during July 2012 were analysed at Hills Laboratory. Analysis included:

- Total Kjeldahl Nitrogen (TKN). TKN was obtained by sulphuric acid digestion with copper sulphate catalyst and then phenol/hypochlorite colorimetry with a discrete analyser (APHA 4500-Norg C. (modified) 4500 NH_3 F (modified) 21st ed. 2005).

- Total oxidised nitrogen (NO_x-N). NO_x-N was obtained by automated cadmium reduction with a flow injection analyser (APHA 4500-NO_3^- I (Modified) 21st ed. 2005).
- Total Ammoniacal-N (NH_4-N). NH_4-N was obtained by phenol/hypochlorite colorimetry with a discrete analyser. NH_4-N was calculated as: NH_4-N= NH_4^+-N + NH_3-N (APHA 4500-NH_3 F (modified from manual analysis) 21st ed. 2005).
- Total Nitrogen (TN). TN was calculated as: TN= TKN + NO_x-N.
- Total organic Nitrogen (ToN). ToN was calculated as: ToN= TKN- NH_4-N.

c) Accidental filtration of total nitrogen samples

Leachate samples taken in September 2011 and October 2011 were accidentally filtered. Only half of each sample was supposed to be filtered for inorganic analysis, with an unfiltered sample needed for TN analysis. To obtain TN concentration from the filtered samples, the relationship between the filtered TN and the actual TN was investigated using 26 replicates from June 2012. A filtered and an unfiltered sample were analysed for TN.

When the unfiltered TN and the filtered TN concentrations were plotted against each other there was a very strong positive relationship (R^2= 0.98) (Appendix 6). The regression equation was used to correct the filtered samples and predict the unfiltered TN concentrations of leachate sampled in September 2011 and October 2011 (Appendix 7).

3.2.3.2. Dry matter and nitrogen component of pasture

To determine pasture dry matter, paper bags which contained the harvested grass were dried in an oven at 65^0C until a constant weight was reached. Samples were cooled in an incubator as the bags were too bulky to fit in a conventional desiccator. The samples were weighed, and the weight of the paper bag was subtracted to give the dry matter content of the pasture.

To determine the nitrogen concentration of the pasture, a representative subsample was ground in a domestic coffee grinder and then a Retsch MM 2000 mill grinder. Approximately 10 mg of the finely ground powder was weighed into a tin capsule and the weight was recorded. Samples were analysed in a LECO TN furnace (Elemental Analyser - Vario EL Cube) to measure percentage nitrogen (%N).

3.2.4. Data collection

3.2.4.1. Rainfall data

Rainfall data was supplied by an onsite weather station (Vaisala WXT520 Weather Transmitter). The data was compared to rainfall data from a weather station at the Taupō airport (38°44’23.6”S 176°04’59.3E), 8 km south-west of the View Road site.

Control rain gauges were also used to measure rainfall. As rain gauges were not installed during harvesting events, rainfall values that were measured at the View Road weather station during the harvesting events were added to the rain gauge measurements.

3.2.4.2. Wastewater application data

The amount of wastewater nitrogen applied to the surface of each lysimeter was calculated using measurements of irrigated wastewater (recorded in rain gauges) (3.2.4.2a) and the nitrogen concentration of wastewater (3.2.4.2b). Loading rates were calculated (3.2.4.2c).

a) Measurement of irrigated wastewater

Within irrigated sectors, rain gauges measured the depth of irrigated wastewater and rainfall. Rain gauges were read 21 times over the duration of the study. To determine how much of each rain gauge measurement was actually wastewater, rainfall values (measured in control rain gauges) were subtracted from each irrigated rain gauge measurement. Rainfall values measured in control rain gauges were subtracted, preferably used over rainfall values measured at the weather stations, as control rain gauges underwent the same measurement and environmental conditions as the irrigated rain gauges.

On occasion, such as during periods of intense rainfall, irrigated rain gauges overflowed. To determine the amount of wastewater that was applied during an overflowed measurement period, each rain gauge was assigned a value. Values were the proportion of irrigated wastewater that was measured during a measurement period in which the rain gauge did not overflow. Wastewater application depth was calculated as the irrigation volume (volume data supplied by Taupō District Council) divided by the pivot area. For the period of overflow, the assigned value was multiplied by the calculated value of irrigated wastewater (Appendix 3).

The depth of irrigated wastewater measured at each lysimeter was converted into a volume by multiplying the rain gauge value by the lysimeter area.

b) Measurement of wastewater nitrogen

To obtain the nitrogen concentration of the irrigated wastewater, technicians at Taupō District Council took a weekly grab-sample of raw wastewater at the wastewater treatment plant. The wastewater was analysed for total nitrogen by a commercial laboratory (following the method described in 3.2.3.1.b), and from May 2012 at the Taupō District Council (following the method described in 3.2.3.1.a). Nitrogen concentration data was supplied by Taupō District Council and the mean concentration during each rain gauge measurement period was calculated.

c) Wastewater nitrogen loading rates

The volume of applied wastewater during each rain gauge measurement period was multiplied by the mean nitrogen concentration of wastewater, during that same time period, to give wastewater nitrogen application to the surface of the lysimeter. The volume of wastewater nitrogen irrigated at each lysimeter was converted into kg N ha^{-1}, grouped into treatments (related to nitrogen input) and corrected to 365 days to give application values of kg N ha^{-1} yr^{-1}.

3.2.5. Statistical analysis

Statistical analysis was undertaken with STATISTICA Version 11. One way ANOVA and Factorial ANOVA were performed and post hoc tests (Tukey HSD test for unequal sample sizes) were undertaken. The differences between treatments were considered significant if $P < 0.05$. Regression analysis was used to examine relationships between variables. Means are presented ± 1.96 x standard error.

3.3. RESULTS

3.3.1. Overview

Results examined below include rainfall values, wastewater irrigation depths, nitrogen inputs (wastewater and atmospheric), and loading treatments definitions for the year of September 2011 to September 2012. Pasture dry matter, the nitrogen concentration of pasture, and total amount of nitrogen removed by pasture within each loading treatment are quantified. Drainage values, and the concentration, amount, and types of nitrogen within the leachate are presented. Lastly, a nitrogen balance is presented and unrecovered nitrogen is quantified. Full datasets are presented in Appendices 1 - 10.

3.3.2. Rainfall

Rainfall was measured at three locations over the duration of this study using: 1.) control rain gauges within the experimental area, 2.) the View Road weather station, and 3.) the Taupō Airport weather station (Table 3.1).

Table 3.1. Rainfall measurements for the year of September 2011 to September 2012.

Measurement method	Rainfall (mm)
Control rain gauges	1237
Weather station at View Road	1046
Weather station at Taupō Airport	1030

More rainfall was measured in control rain gauges than at the View Road and Taupō Airport weather stations. The 2011 - 2012 period had higher rainfall than the previous five year mean (Figure 3.12).

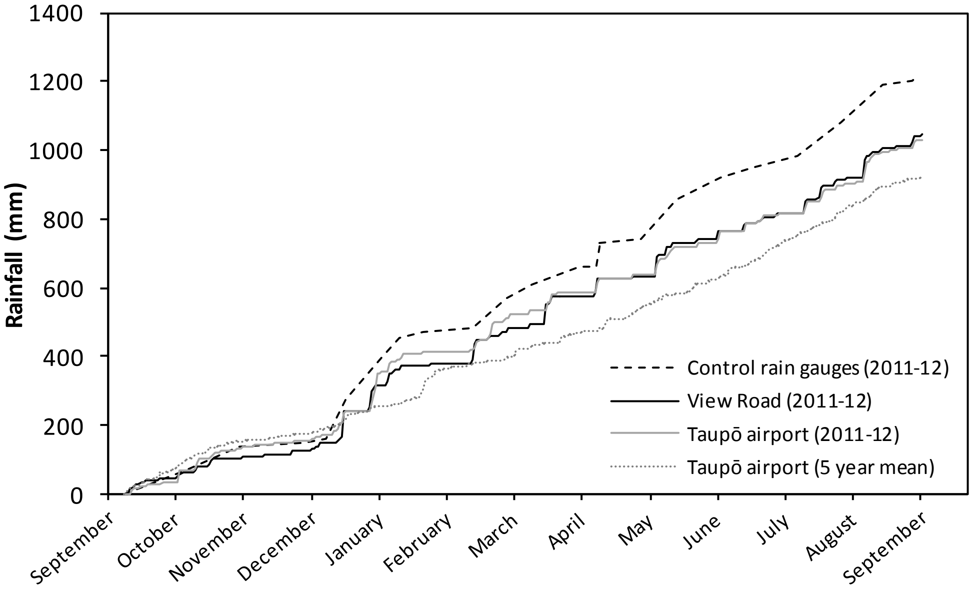

Figure 3.12. Cumulative rainfall for the year of September 2011 to September 2012 at the View Road weather station, the Taupō airport weather station, within control rain gauges throughout the experimental area, and a five year mean (2006 - 2011).

3.3.3. Wastewater application and nitrogen inputs

3.3.3.1. Depth and of irrigated wastewater

The depth of irrigated wastewater at each lysimeter was measured (Table 3.2 and Figure 3.13) and then grouped into low medium and high, defined by nitrogen input in section 3.3.2.6.

Table 3.2. Mean depth of wastewater irrigated within loading treatments for the year of September 2011 to September 2012.

Treatment	**Wastewater input ± 1.96 x SE (mm yr^{-1})**
Control	0
Low	663 ± 26
Medium	812 ± 21
High	978 ± 57

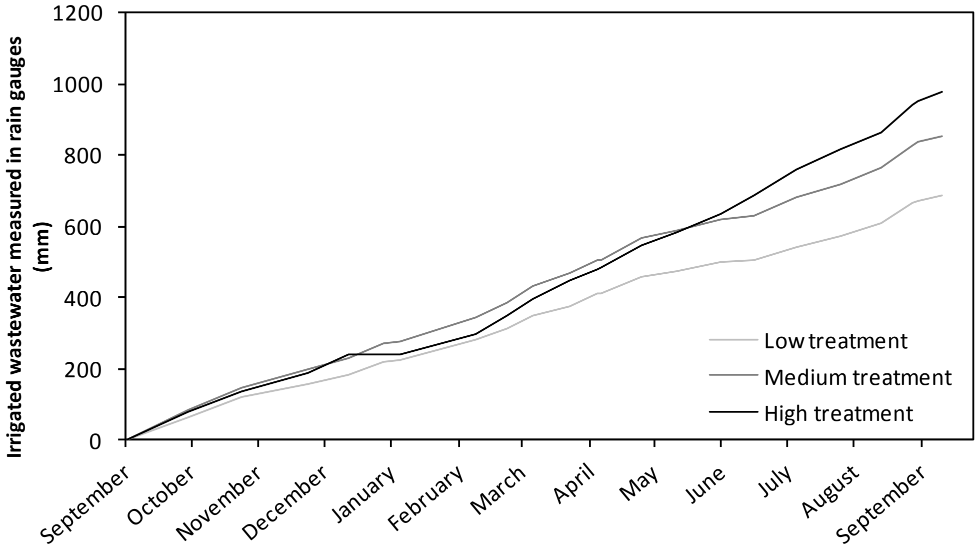

Figure 3.13. Cumulative depth of wastewater irrigated (recorded in rain gauges) within loading treatments for the year of September 2011 to September 2012.

3.3.3.2. Forms of nitrogen within applied wastewater

Of the applied wastewater nitrogen, 88.8% was in the form of ammoniacal nitrogen, 7.7% was in the form of organic nitrogen and 3.5% of the applied wastewater nitrogen was in the form of nitrate nitrogen (Table 3.3).

Table 3.3. Mean annual concentration of nitrogen forms within the secondary-treated municipal wastewater for the year of September 2011 to September 2012.

Nitrogen type	**Mean concentration ± 1.96 x SE (mg L^{-1})**
Total nitrogen	48.4 ± 1.7
Nitrate nitrogen	1.7 ± 0.4
Ammoniacal nitrogen	43.0 ± 1.7
Organic nitrogen	3.8 ± 0.7

3.3.3.3. The nitrogen concentration of wastewater

To calculate the amount of applied wastewater nitrogen, the mean wastewater nitrogen concentration during each rain gauge measurement period was calculated (Figure 3.14). Rain gauge measurement periods ranged from a couple of days to nearly a month.

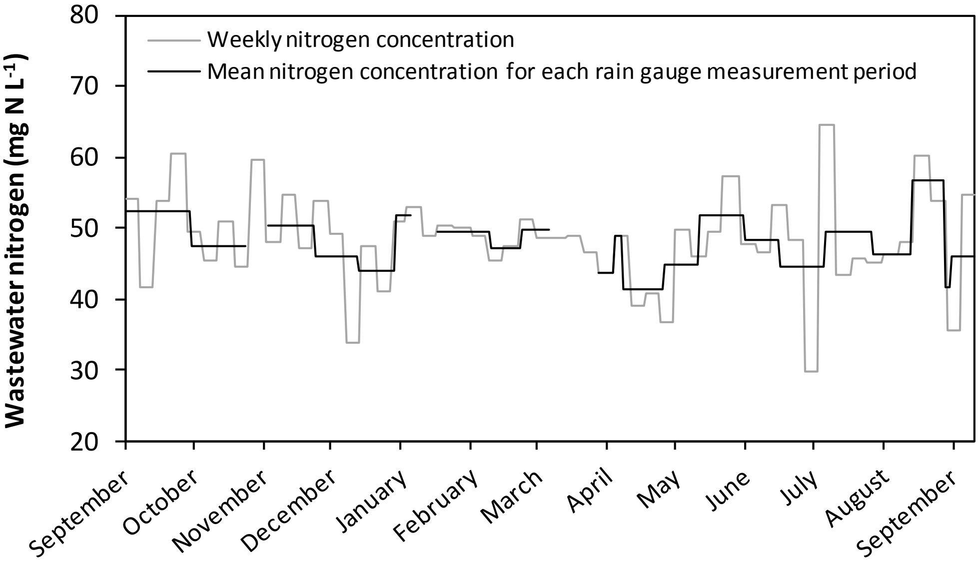

Figure 3.14. Nitrogen concentration of wastewater sampled weekly at the Taupō wastewater treatment plant and the mean nitrogen concentration during each rain gauge measurement period for the year of September 2011 to September 2012. Gaps represent irrigator stand-down periods when no wastewater was irrigated prior to field harvests.

3.3.3.4. Atmospheric nitrogen input

To account for atmospheric nitrogen that was deposited in rainfall over the duration of this study, 5 kg N ha^{-1} yr^{-1} was added to the nitrogen input. The expected value of 5 kg N ha^{-1} yr^{-1} was used in the first year of the trial (Treweek 2011) and has previously been used when calculating nitrogen budgets for the Taupō land treatment scheme by the Taupō District Council (Power and Wheeler 2007).

3.3.3.5. Nitrogen loading rates

The target nitrogen application inputs were 450, 550, and 650 kg N ha^{-1} yr^{-1}. However, the nitrogen loadings achieved were lower (Table 3.4 and Figure 3.15). Nitrogen input (wastewater plus atmospheric nitrogen) ranged from 286 to 567 kg N ha^{-1} yr^{-1} within irrigated sectors. The nitrogen loading values were grouped into low (286 - 380 kg N ha^{-1} yr^{-1}), medium (from 380 to 445 kg N ha^{-1} yr^{-1}), and high (445 - 567 kg N ha^{-1} yr^{-1}) treatments. Nitrogen input within control sectors was assumed to be 5 kg N ha^{-1} yr^{-1}.

Table 3.4. Nitrogen inputs in loading treatments for the year of September 2011 to September 2012.

Treatment	Treatment definition (kg N ha^{-1} yr^{-1})	Mean ± 1.96 x SE (kg N ha^{-1} yr^{-1})	Number of replicates
Control	5	5 ± 0	6
Low	286 - 380	338 ± 12	14
Medium	380 - 445	412 ± 11	12
High	445 - 567	491 ± 27	10

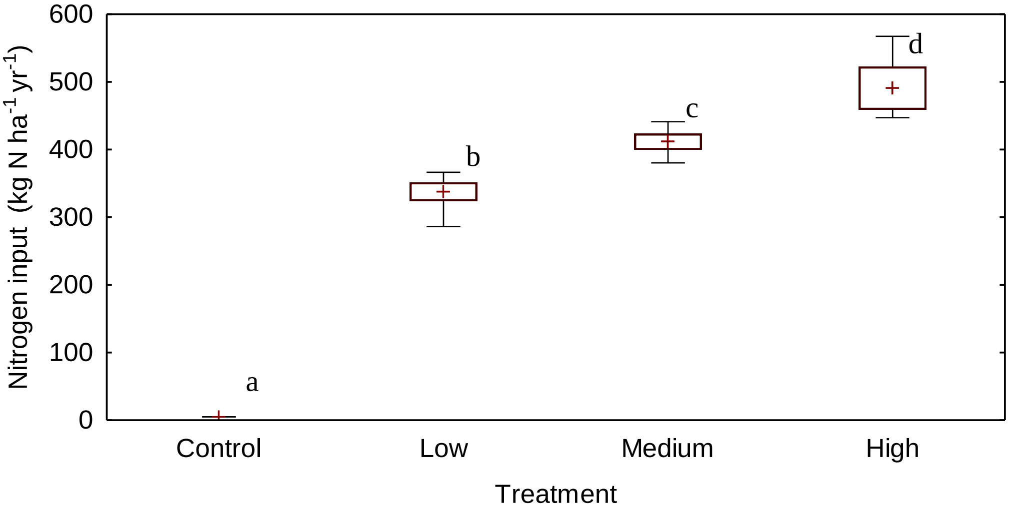

Figure 3.15. Annual nitrogen input within loading treatments for the year of September 2011 to September 2012. Treatments include wastewater and atmospheric nitrogen inputs. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments (P < 0.05).***

While irrigators were programmed to vary in speed, theoretically producing even irrigation volumes within each treatment sector (Figure 3.16a). The pre-determined variation did not occur exactly as was programmed (Figure 3.16b). Lysimeters within the same treatment sector did not necessarily receive the same amount of applied wastewater. There were four sections in which lysimeters towards the outside of the irrigation circle did not receive as much wastewater as lysimeters closer to the centre of the irrigator circle.

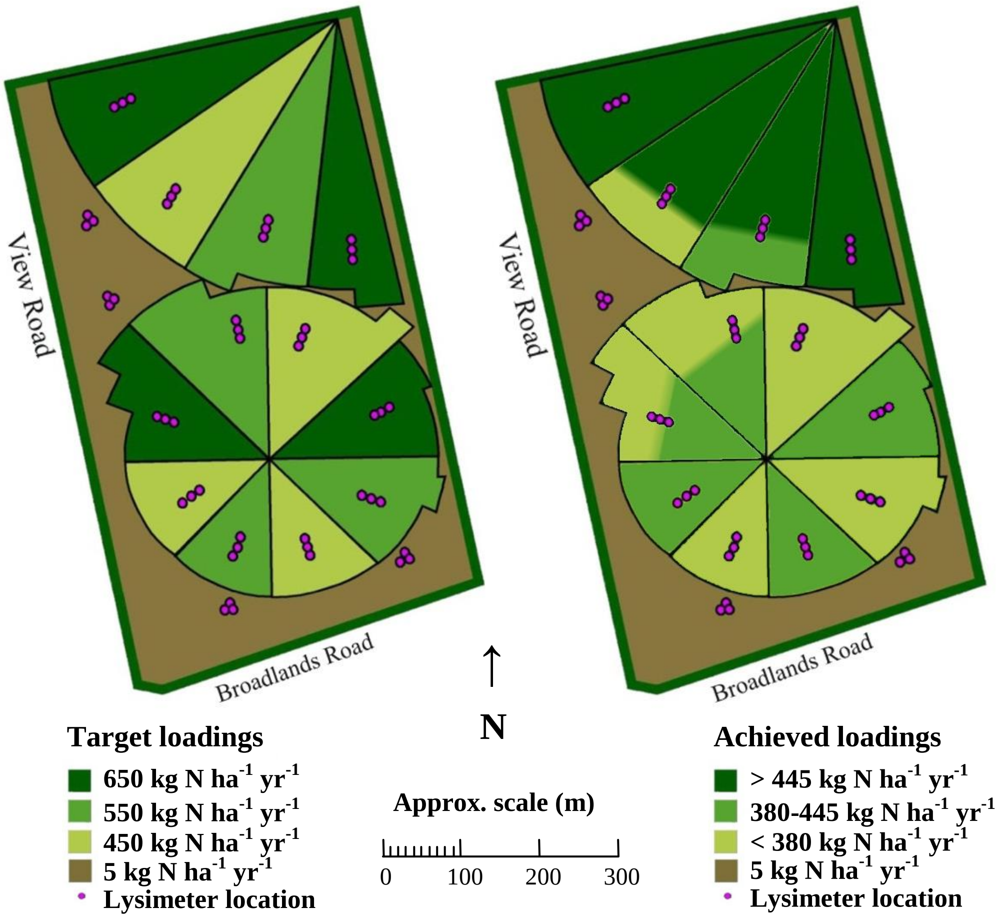

Figure 3.16. Nitrogen loading rates in the experimental area. a) Targeted loading rates for each treatment sector. b) Achieved loading rates for the year of September 2011 to September 2012. Nitrogen loads include 5 kg N ha^{-1} yr^{-1} to account for atmospheric nitrogen input.

3.3.4. Pasture production and nitrogen removal

3.3.4.1. Dry matter production

Annual pasture dry matter yield under wastewater irrigation ranged from 9905 to 18 516 kg DM ha^{-1} yr^{-1} with no significant difference in the low, medium and high treatments (Table 3.5 and Figure 3.17). Within the control sections, annual pasture dry matter yield ranged from 3573 to 6501 kg DM ha^{-1} yr^{-1} and was significantly lower than pasture production in irrigated treatments.

Table 3.5. Mean pasture dry matter yield within loading treatments for the year of September 2011 to September 2012.

Treatment	Nitrogen input (kg N ha^{-1} yr^{-1})	Dry matter ± 1.96 x SE (kg DM ha^{-1} yr^{-1})	Number of replicates
Control	5	5300 ± 839	6
Low	<380	13 922 ± 1196	14
Medium	380 to 445	13 543 ± 1475	12
High	>445	15 285 ± 1919	10

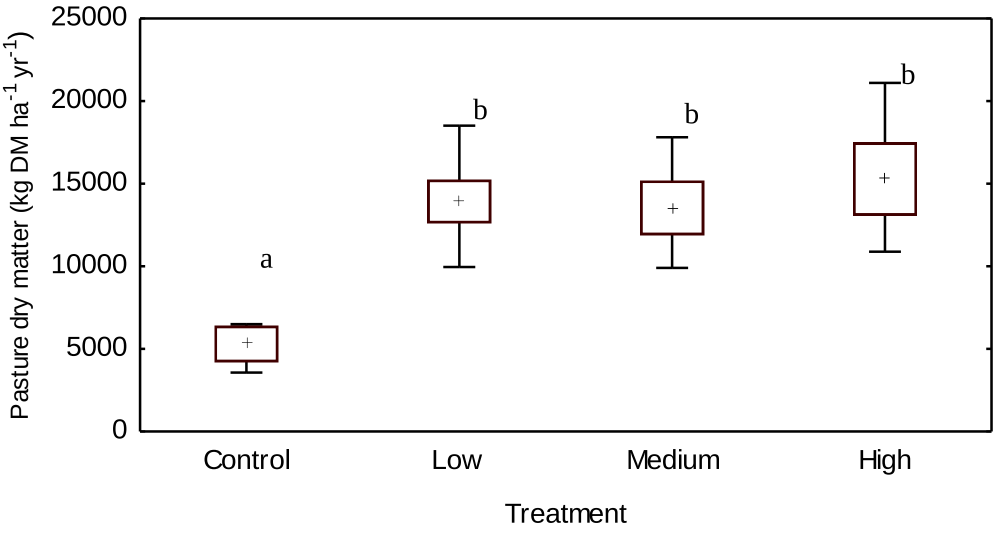

Figure 3.17. Annual pasture dry matter yield within loading treatments for the year of September 2011 to September 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments ($P < 0.05$).***

a) Seasonality of pasture production

Four harvests occurred at the View Road site during the study. Pasture production within irrigated sectors varied (Figure 3.18). Harvest one, which was harvested towards the end of spring, produced the most pasture dry matter (Table 3.6). Harvest four, which was harvested at the end of winter, had the least pasture production. There was generally no difference in the amount of pasture produced within the three irrigated treatments at each harvesting event. There was also no significant difference in the amount of pasture produced within the control sectors at each harvest over the duration of the study.

Table 3.6. Percentage of the total annual pasture produced at each harvesting event.

Harvest	Date	Proportion of annual pasture production (%)
1	31/10/11	37
2	21/1/12	26
3	16/3/12	21
4	17/9/12	18

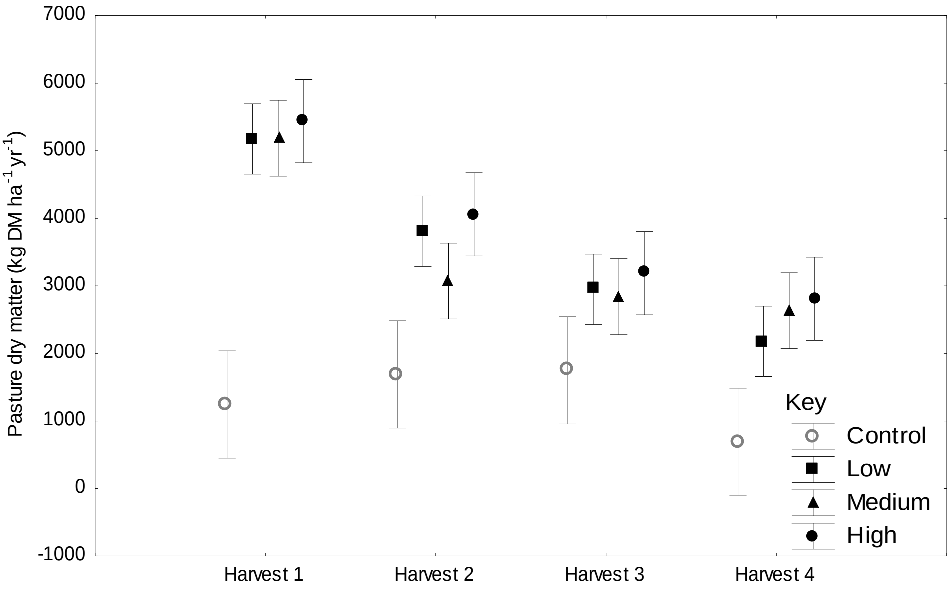

Figure 3.18. Pasture production within loading treatments at each harvesting event. ***Dots represent the mean while vertical bars denote 0.95 confidence intervals.***

3.3.4.2. Nitrogen uptake by pasture

The concentration of pasture nitrogen differed between the irrigated and control treatments. Within control pastures, the nitrogen component ranged from 1.1 to 2.9% with a mean of 1.8%. Within irrigated pastures, nitrogen ranged from 1.4 to 4.9% with a mean of 2.6%.

The mean nitrogen concentration was multiplied by dry matter weight to give a measure of pasture nitrogen uptake and removal. Within irrigated treatments, nitrogen removal ranged from 261 to 523 kg N ha^{-1} yr^{-1} and there was no significant difference between the low, medium, and high treatments (Table 3.7. and Figure 3.19).

Table 3.7. Mean nitrogen removal by pasture within loading treatments for the year of September 2011 to September 2012.

Treatment	Nitrogen input (kg N ha^{-1} yr^{-1})	Nitrogen removal ± 1.96 x SE (kg N ha^{-1} yr^{-1})	Number of replicates
Control	5	91 ± 13	6
Low	<380	341 ± 25	14
Medium	380 to 445	360 ± 51	12
High	>445	385 ± 43	10

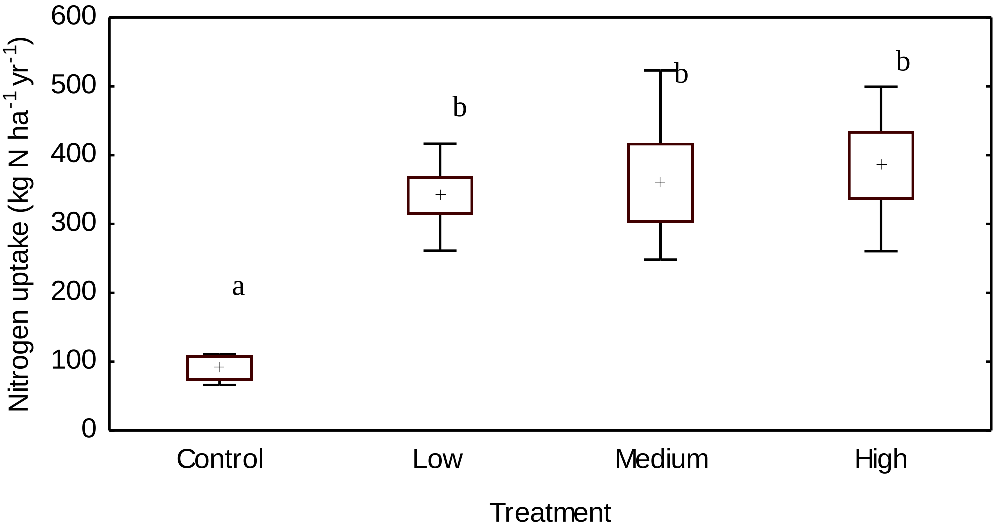

Figure 3.19. Annual nitrogen removal by pasture within loading treatments for the year of September 2011 to September 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments ($P < 0.05$).***

There was only a very weak positive correlation (R^2= 0.12) between the amount of nitrogen input and nitrogen uptake by pasture (Figure 3.20).

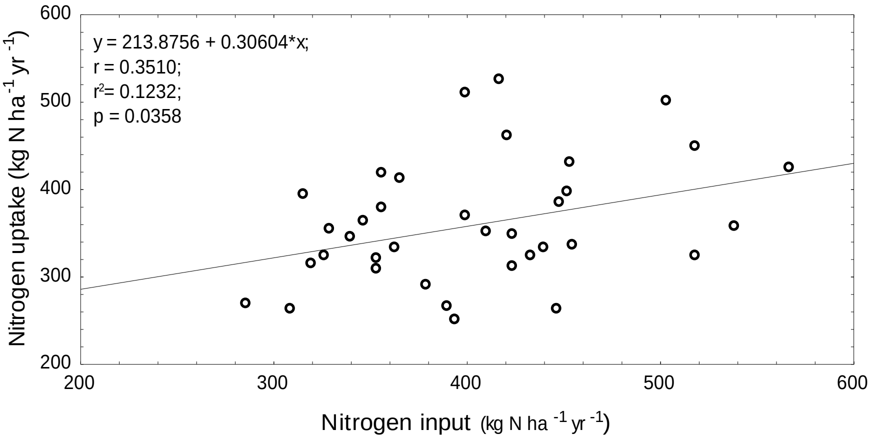

Figure 3.20. Relationship between nitrogen input and nitrogen uptake by pasture.

3.3.5. Leaching of water and nitrogen

3.3.5.1. Water drainage

Lysimeter leachate was weighed and the weight was converted from L to mm yr^{-1} to allow easy comparison with water inputs (Table 3.8). The amount of water drainage was not significantly different between the control, low, and medium treatments, however, the amount of water drainage from the high treatment was higher ($P < 0.05$) (Figure 3.21). There was a weak positive correlation (R^2= 0.30) between the amount of water input (wastewater and rainfall) and the amount of water leached (Figure 3.22).

Table 3.8. The mean amount of water drainage from loading treatments for the year of September 2011 to September 2012.

Treatment	Wastewater plus rainfall input ± 1.96 x SE (mm yr^{-1})	Water leached ± 1.96 x SE (mm yr^{-1})	Number of replicates
Control	1237 ± 0	680 ± 101	6
Low	1900 ± 26	849 ± 163	13
Medium	2004 ± 21	781 ± 215	11
High	2215 ± 57	1316 ± 176	10

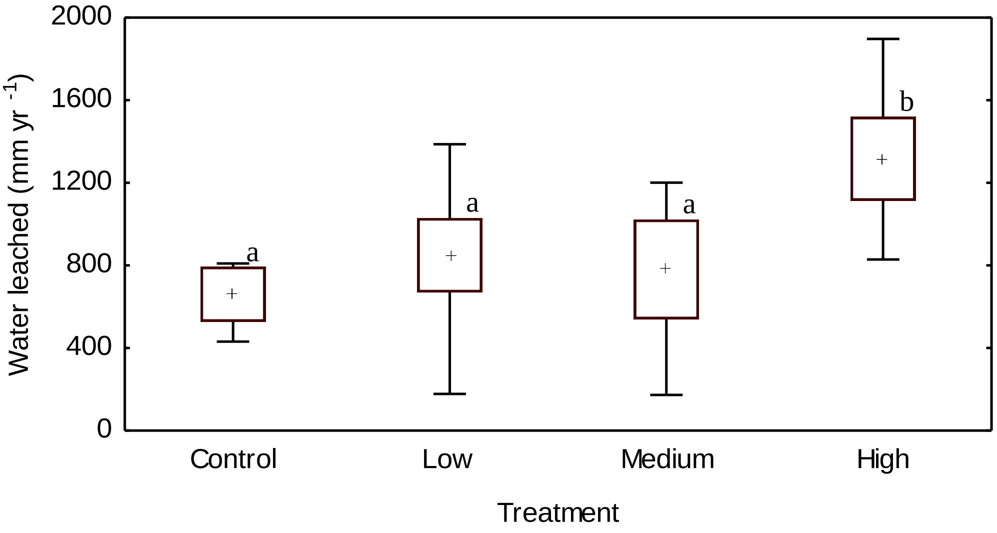

Figure 3.21. The annual amount of water drainage from loading treatments for the year of September 2011 to September 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values Letters illustrate significant difference between treatments (P < 0.05).***

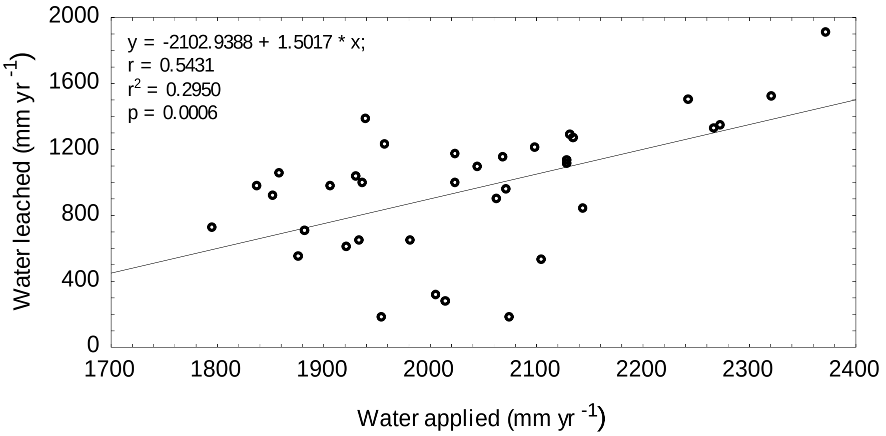

Figure 3.22. Relationship between the amount of water that was applied (rainfall + wastewater) and the amount of water that was leached.

3.3.5.2. Total nitrogen leached

Within irrigated treatments the mean concentration of nitrogen within leachate was 2.4 mg L^{-1}. The total nitrogen (TN) concentration of the leachate was multiplied by the amount of water that was leached to give a measure of nitrogen leached (Table 3.9). The amount of nitrogen leached from irrigated treatments ranged from 5.0 to 61.1 kg N ha^{-1} yr^{-1}. Nitrogen leached within the high treatment was not significantly different the medium treatment, but was higher than the low and control treatments ($P < 0.05$) (Figure 3.23).

Within control treatments the mean concentration of nitrogen within leachate was 0.7 mg L^{-1}. The amount of nitrogen leached from control treatments ranged from 1.5 to 3.6 kg N ha^{-1} yr^{-1} was leached from control lysimeters (Figure 3.23).

Table 3.9. The mean amount of nitrogen leached from loading treatments for the year of September 2011 to September 2012.

Treatment	Nitrogen input (kg N ha^{-1} yr^{-1})	Nitrogen concentration ± 1.96 x SE (mg L^{-1})	TN leached ± 1.96 x SE (kg N ha^{-1} yr^{-1})	Number of replicates
Control	5	0.7 ± 0.3	2.8 ± 0.6	6
Low	<380	2.0 ± 0.9	12.7 ± 4.2	13
Medium	380 to 445	2.7 ±1.7	16.0 ± 7.2	11
High	>445	2.8 ±1.2	28.6 ± 10.1	10

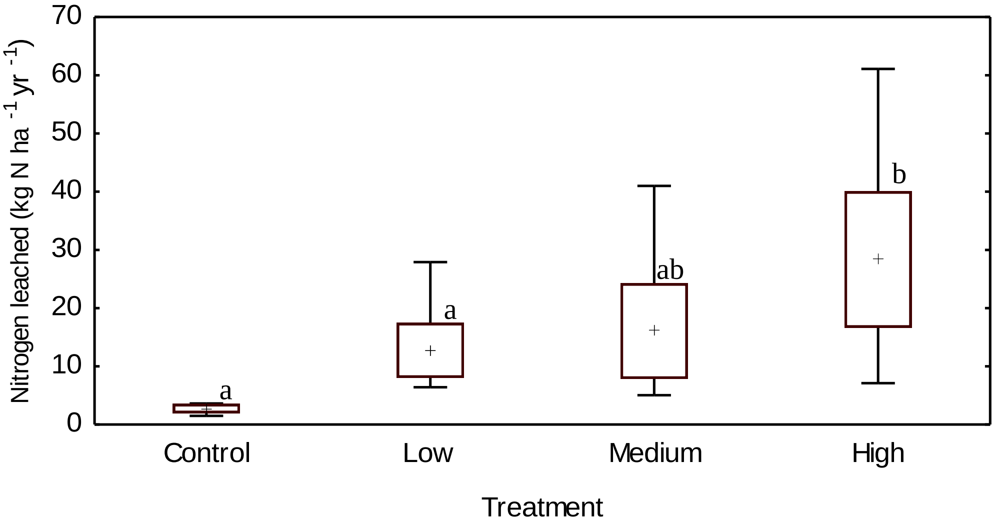

Figure 3.23. The annual amount of nitrogen leached from loading treatments for the year of September 2011 to September 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments (P < 0.05).***

There was a moderate positive correlation (R^2= 0.44) between the amount of nitrogen input and the amount of nitrogen leached (Figure 3.24a). There was a positive correlation (R^2= 0.54) between the amount of water leached and the amount of nitrogen leached (Figure 3.24b). There was effectively no correlation (R^2= 0.03) between the amount of nitrogen uptake and the amount of nitrogen leached (Figure 3.24c).

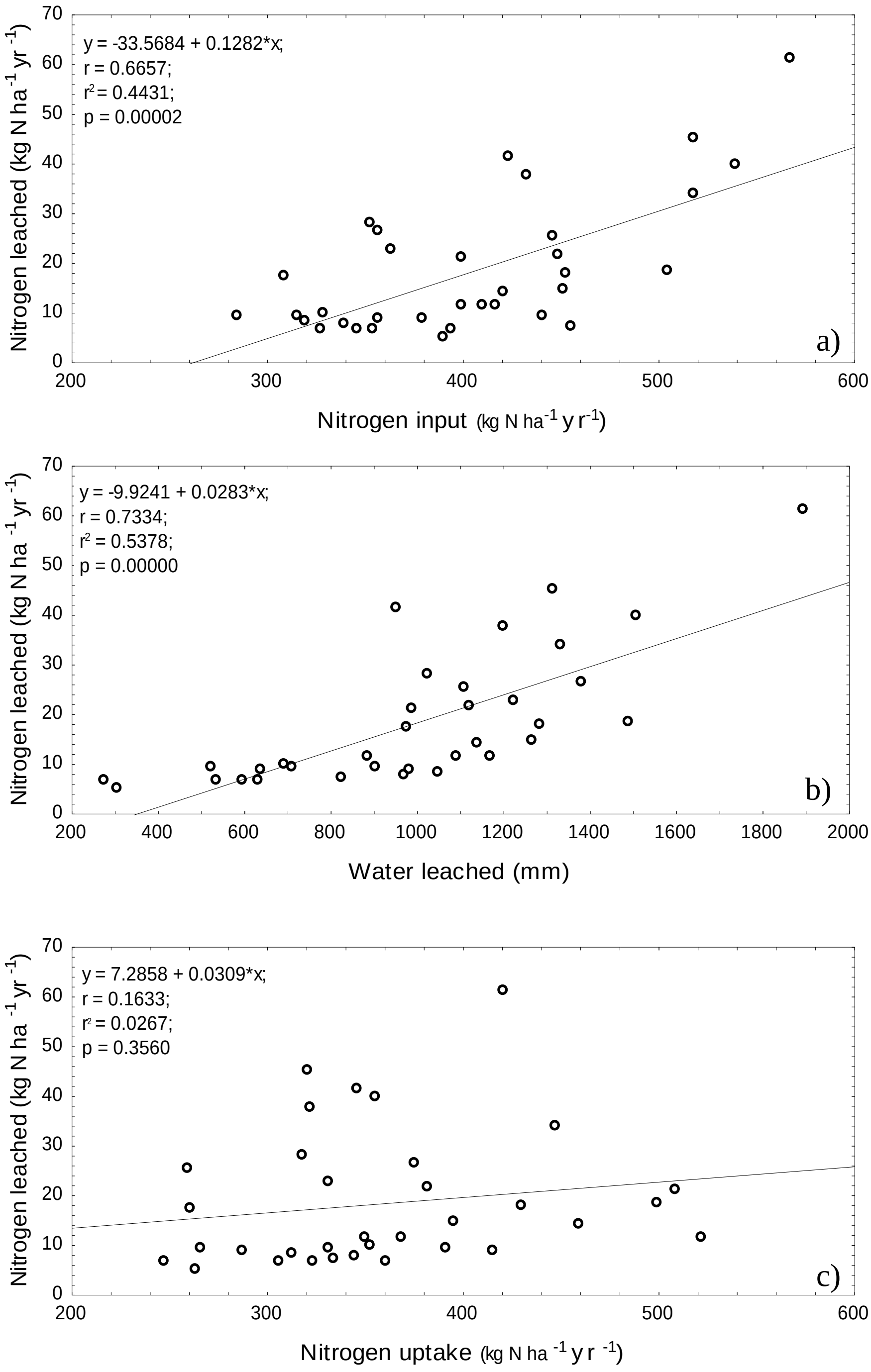

Figure 3.24. Relationship between the amount of nitrogen leached from the irrigated treatments and a) nitrogen input b) water leached and c) nitrogen uptake by pasture.

a) Seasonal total nitrogen leaching

Within irrigated treatments, the largest proportion of nitrogen was leached during the autumn or winter months (Table 3.10). The highest rate of nitrogen leaching was also during the autumn and winter months within the high treatment, illustrated by the steeper gradient of the high treatment in Figure 3.25. Within control sectors there was minimal seasonal change in the amount of nitrogen leached, illustrated by the steady increase throughout the year (Figure 3.25).

Table 3.10. Percentage of the total annual nitrogen that was leached from irrigated treatments during each season.

Season	**Proportion of annual nitrogen leached (%)**
Spring	24
Summer	19
Autumn	28
Winter	29

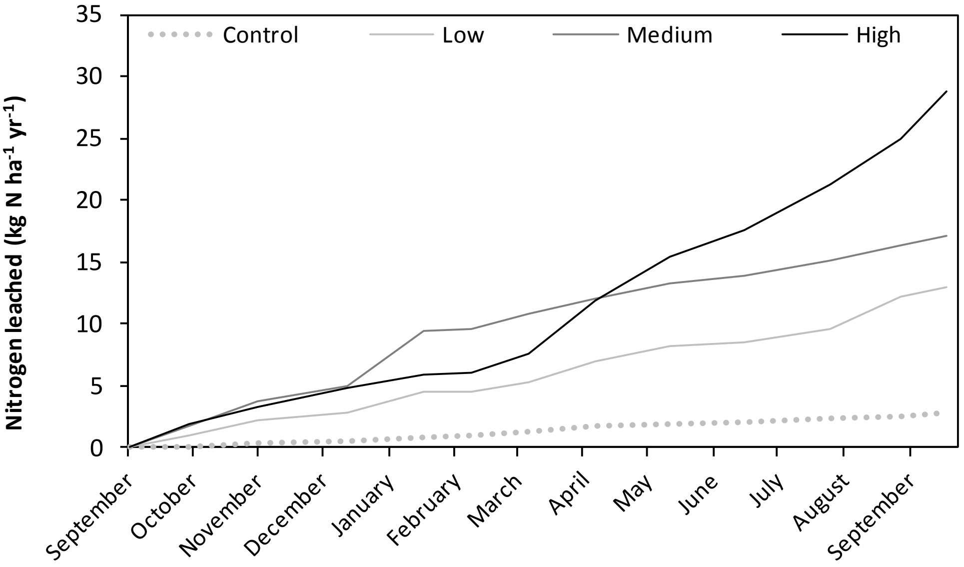

Figure 3.25. Cumulative mean nitrogen leaching from loading treatments for the year of September 2011 to September 2012.

b) Rainfall and nitrogen leaching

Following a large rainfall event at the end of December 2011, there was an increase in the amount of nitrogen leached, illustrated by the steeper gradient in Figure 3.26. From January 2012 to September 2012 there were multiple rain events with subsequent steady nitrogen leaching.

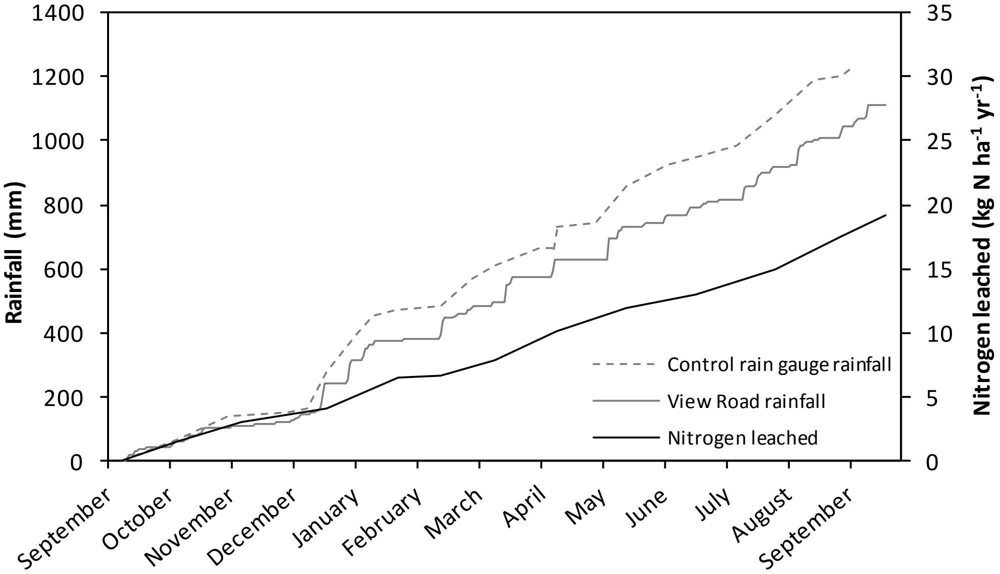

Figure 3.26. Cumulative rainfall at the View Road site (measured at the weather station and with control rain gauges) and the mean amount of nitrogen leached from all irrigated treatments for the year of September 2011 to September 2012.

3.3.5.3. Forms of nitrogen within leachate

Within irrigated treatments, leachate nitrogen was predominantly total oxidised nitrogen (NO_x-N). Total oxidised nitrogen was primarily in the form of nitrate (more than 99% was nitrate and less than 1% was nitrite). As application rate increased so did the total oxidised nitrogen concentration and fraction (Table 3.11 and Figure 3.27). The mean nitrate concentration of lysimeter leachate was 1.6 mg L^{-1}. Total organic nitrogen (ToN) was the second major component in leachate. Total organic nitrogen increased in concentration but decreased in fraction with increased application rate. The mean organic nitrogen concentration of lysimeter leachate was 0.8 mg L^{-1}. Total ammoniacal nitrogen (NH_4-N) was a minor component within leachate and the mean concentration of was 0.05 mg L^{-1}.

Within control treatments, leachate nitrogen was predominantly organic nitrogen, with lesser nitrate, a small proportion of ammonium, and nitrite below detection limits.

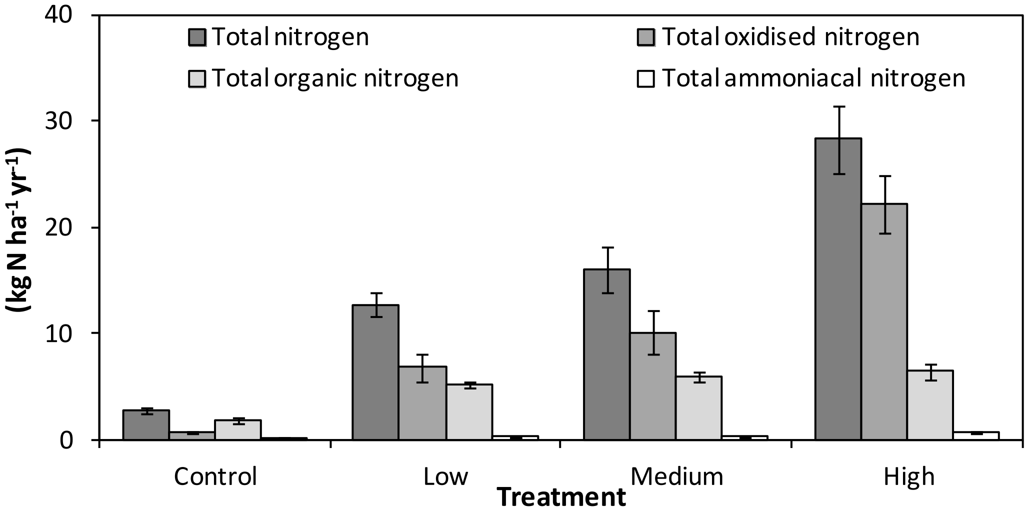

Figure 3.27. Types of leachate nitrogen within loading treatments for the year of September 2011 to September 2012. ***Vertical bars denote 0.95 confidence intervals.***

Table 3.11. Percentage of nitrogen types within leachate total nitrogen from loading treatments.

Treatment	**Total oxidised nitrogen (%)**	**Total organic nitrogen (%)**	**Total ammoniacal nitrogen (%)**
Control	29	68	5.0
Low	54	41	2.1
Medium	67	37	1.6
High	78	23	2.2

3.3.5.4. Nitrate leached

The amount of nitrate leached from irrigated treatments ranged from 1.3 to 48.7 kg N ha^{-1} yr^{-1} while 0.3 to 1.5 kg N ha^{-1} yr^{-1} was leached from control lysimeters (Table 3.12. and Figure 3.28). Nitrate leached from the high treatment was comparable with nitrate leached from the medium treatment but was higher than in the low and control treatments.

Table 3.12. The mean amount of nitrate leached from loading treatments for the year of September 2011 to September 2012.

Treatment	**Nitrogen input (kg N ha^{-1} yr^{-1})**	**Nitrate leached ± 1.96 x SE (kg N ha^{-1} yr^{-1})**	**Number of replicates**
Control	5	0.8 ± 0.16	6
Low	<380	6.8 ± 1.0	13
Medium	380 to 445	10.7 ± 2.0	11
High	>445	22.1 ± 2.7	10

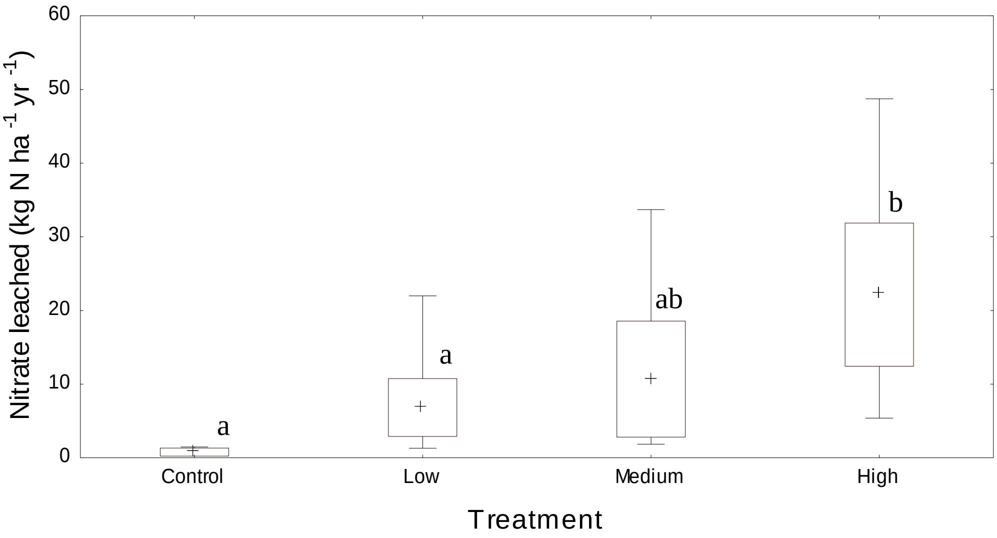

Figure 3.28. The annual amount of nitrate leached from loading treatments for the year of September 2011 to September 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values Letters illustrate significant difference between treatments ($P < 0.05$).***

Nitrate concentrations exceeded the Ministry of Health guidelines for drinking water (11.3 mg L^{-1}) (Ministry of Health 2005) four times (out of ~520 measurements) throughout the trial period; with a maximum of 19.0 mg L^{-1}. Nitrate concentrations above 11.3 mg L^{-1} were measured from one lysimeter within the high treatment during October 2011 and November 2011 and from one lysimeter within the medium treatment during January 2012 and February 2012.

a) *Seasonal nitrate leaching*

Reflecting trends in total nitrogen, the highest proportion of nitrate leaching occurred during the autumn or winter months within irrigated treatments (Table 3.13).

Table 3.13. Percentage of annual nitrate that was leached from irrigated treatments during each season.

Season	Proportion of annual nitrate leached (%)
Spring	21
Summer	19
Autumn	30
Winter	33

The highest rate of nitrate leaching also occurred during the autumn and winter months within the high treatment, illustrated by the steeper gradient in Figure 3.29. Minimal nitrate was leached from control lysimeters.

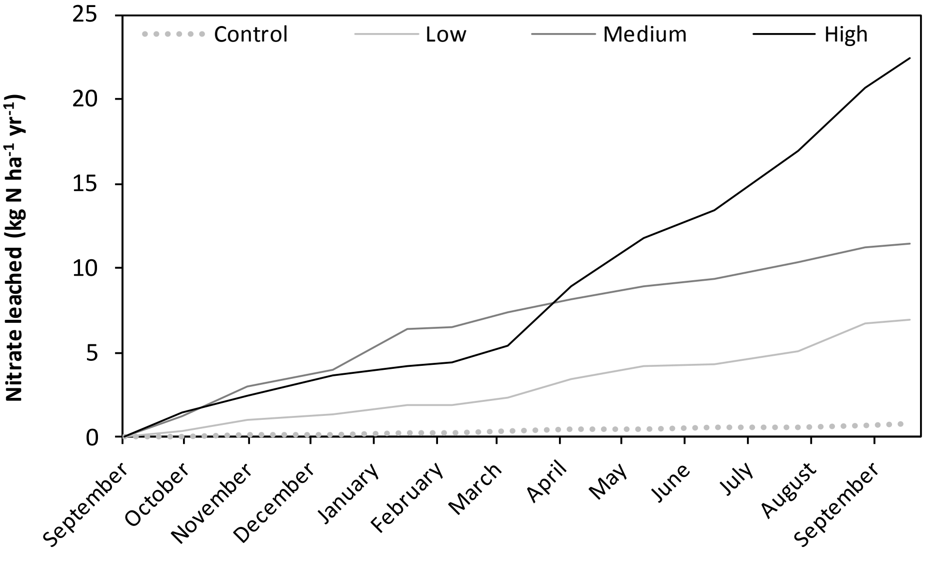

Figure 3.29. Cumulative mean nitrate leaching within treatments for the year of September 2011 to September 2012.

3.3.5.5. Organic nitrogen leached

The amount of total organic nitrogen leached from irrigated treatments ranged from 1.9 to 13.07 kg N ha^{-1} yr^{-1} while 1.1 to 3.1 kg N ha^{-1} yr^{-1} was leached from control lysimeters (Table 3.14. and Figure 3.30). Organic nitrogen leached from the high treatment was comparable with organic nitrogen leached from the low and medium treatments but was higher than in the control treatment.

Table 3.14. The mean amount of organic nitrogen leached from loading treatments for the year of September 2011 to September 2012.

Treatment	**Nitrogen input (kg N ha^{-1} yr^{-1})**	**Organic nitrogen leached ± 1.96 x SE (kg N ha^{-1} yr^{-1})**	**Number of replicates**
Control	5	1.9 ± 0.2	6
Low	<380	5.2 ± 0.3	13
Medium	380 to 445	5.9 ± 0.5	11
High	>445	6.4 ± 0.8	10

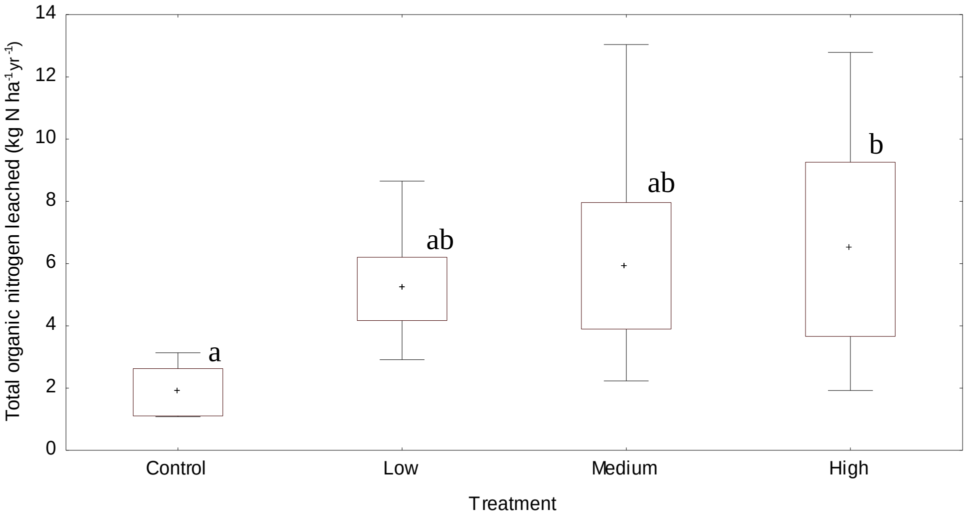

Figure 3.30. The annual amount of organic nitrogen leached from loading treatments for the year of September 2011 to September 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments (P < 0.05).***

3.3.5.6. Replication of nitrogen analyses

To check the reliability of nitrogen analyses, replicated leachate samples were analysed at separate laboratories. There was no significant difference between TN, NOx or ToN values produced from at the Taupō District Council or the University of Waikato laboratories. There was also no significant difference between analyses at Taupō District Council or the commercial Hill Laboratories.

3.3.6. Nitrogen balance and unrecovered nitrogen

Within irrigated sectors, a large portion (79 to 100%) of the applied nitrogen was removed by pasture (Table 3.15 and Figure 3.31). A small component of the nitrogen input was leached (4 to 6%), while -4 to 16% remained unrecovered.

Table 3.15. Mean nitrogen input, mean unrecovered nitrogen, and what proportion of input nitrogen was unrecovered, leached or taken up by pasture within loading treatments for the year of September 2011 to September 2012.

Treatment	Nitrogen input ± 1.96 x SE (kg N ha^{-1} yr^{-1})	Unrecovered nitrogen ± 1.96 x SE (kg N ha^{-1} yr^{-1})	Unrecovered ± 1.96 x SE (%)	Leached ± 1.96 x SE (%)	Plant removal ± 1.96 x SE (%)
Low	338 ± 12	-13 ± 19	-4 ± 6	4 ± 1	100 ± 6
Medium	412 ± 11	30 ± 52	7 ± 13	4 ± 2	89 ± 13
High	491 ± 27	77 ± 39	16 ± 8	6 ± 2	79 ± 9

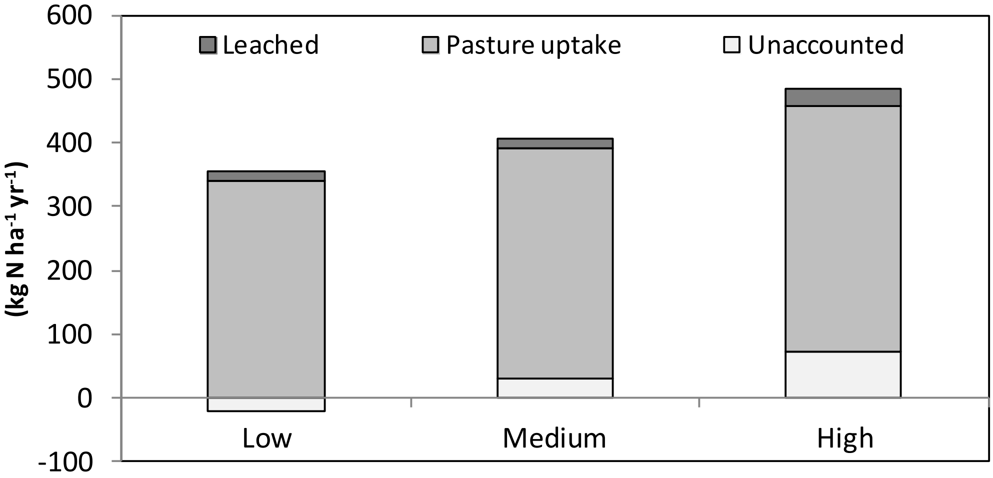

Figure 3.31. Proportion of input nitrogen that was leached, taken up by pasture or was unaccounted for within irrigated treatments for the year of September 2011 to September 2012.

3.4. DISCUSSION

3.4.1. Introduction

The purpose of this experiment was to quantify pasture production, nitrogen removal by pasture, nitrogen leaching, and unrecovered nitrogen at the View Road site under a range of wastewater application rates. The target application rates were 0, 450, 550 and 650 kg N ha^{-1} yr^{-1}.

The following section will examine the applied wastewater nitrogen loads. This discussion will present a table (Table 3.16) that summarises results from this thesis and the previous study held at the View Road site during 2009/10 (Treweek 2011). Pasture production, nitrogen removal by pasture, and nitrogen leaching within application treatments will be discussed and compared to literature and to Treweek (2011). A nitrogen balance for the View Road site is examined and possible explanations are given for unrecovered nitrogen. Lastly, discussion of the experiment limitations, targeted versus achieved loading rates, and measurement error is presented.

3.4.2. Wastewater nitrogen application rates

The targeted wastewater nitrogen application loads of 450, 550 and 650 kg N ha^{-1} yr^{-1} were not achieved; nitrogen application to the land surface ranged from 286 to 567 kg N ha^{-1} yr^{-1}. The nitrogen loading values were grouped into a low treatment (286 - 380 kg N ha^{-1} yr^{-1}), a medium treatment (380 - 445 kg N ha^{-1} yr^{-1}), and a high treatment (445 - 567 kg N ha^{-1} yr^{-1}). Reasons for not achieving the higher application rates (discussed in section 3.4.6.2) were out of the control of the author of this thesis. Nitrogen input within control sectors was assumed to be primarily atmospheric nitrogen that was deposited with rain water, and was expected to be 5 kg N ha^{-1} yr^{-1}, as no legumes were observed in the control areas.

Table 3.16. Summary of results from this thesis and Treweek (2011). All values within grey bands are results reported in Treweek (2011). All values with { } are the percentage of the total nitrogen input. ***Many value are presented with ± 1.96 x SE. For data within the same row, letter superscripts illustrate a significant difference between treatments and between the corresponding treatments within the two studies ($P < 0.05$).***

Result	**Control treatment**	**Irrigated treatments***		
		Low	**Medium**	**High**
Wastewater input (mm)	0	662	812	978
	0	638	760	1000
Water input (mm)	1237	1890	2049	2215
	890	1528	1650	1890
Nitrogen input - range ($kg\ N\ ha^{-1}\ yr^{-1}$)	5	286 – 380	380 – 445	445 – 567
	5	280 – 340	360 – 450	450 – 520
Nitrogen input - mean ($kg\ N\ ha^{-1}\ yr^{-1}$)	5^{a}	338^{b}	412^{c}	491^{d}
	5^{a}	325^{b}	369^{c}	493^{d}
Pasture dry matter ($kg\ DM\ ha^{-1}\ yr^{-1}$)	5300 ± 839^{a}	13 922 ± 1196^{b}	13 543 ± 1475^{b}	15 285 ± 1919^{b}
	1800	15 800^{**}		
Nitrogen removal by pasture ($kg\ N\ ha^{-1}\ yr^{-1}$) {% of nitrogen input}	91 ± 13^{a}	341 ± 25^{b} {100 ± 6}	360 ± 51^{b} {89 ± 13}	385 ± 43^{b} {79 ± 9}
	25 ± 3.6^{a}	308 ± 20^{b} {95}	310 ± 16^{b} {78}	387 ± 19^{b} {78}
Volume leached (mm)	680 ± 101^{a}	849 ± 163^{a}	781 ± 215^{a}	1316 ± 176^{b}
	485 ± 55	598 ± 21	700 ± 79	967 ± 9
Amount of total nitrogen leached ($kg\ N\ ha^{-1}\ yr^{-1}$) {% of nitrogen input}	2.8 ± 0.6^{a}	12.7 ± 4.2^{a} {4}	16.0 ± 7.2^{ab} {4}	28.6 ± 10.1^{b} {6}
	4.8 ± 1.2^{a}	14.8 ± 0.6^{ab} {5}	16.9 ± 3.4^{ab} {4}	26.4 ± 2.3^{b} {5}
Leachate nitrogen (%)				
Total oxidised N	29 [26]	54 $[53]^{**}$	67	78
Organic N	68 [72]	41 $[46]^{**}$	37	23
Ammonical N	5 [2]	2 $[2]^{**}$	2	2
Un recovered nitrogen ($kg\ N\ ha^{-1}\ yr^{-1}$) {% of nitrogen input}	-88 ± 7^{a}	-13 ± 19^{ab} {-4 ± 6}	30 ± 52^{bc} {7 ± 13}	77 ± 39^{c} {16 ± 8}
	-24 ± 4^{ab}	[4.5 ± 22^{ab}] {1}	[67 ± 14^{bc}] {17}	[84 ± 37^{bc}] {17}

* Irrigated treatments were defined by the range of nitrogen inputs

** Mean of all of the irrigated treatments within Treweek (2011).

The target applications of 450, 550 and 650 kg N ha^{-1} yr^{-1} were also not achieved in the previous study (Treweek 2011) where nitrogen application to the land surface ranged from 280 to 520 kg N ha^{-1} yr^{-1} (Table 3.16). Treweek (2011) grouped wastewater application sectors into a Low-N treatment (280 - 350 kg N ha^{-1} yr^{-1}), a Mid-N treatment (350 - 450 kg N ha^{-1} yr^{-1}), and a High-N treatment (450 - 520 kg N ha^{-1} yr^{-1}). While the treatment definitions in Treweek (2011) were different than those used within this thesis, nitrogen inputs were not significantly different between the low (within this thesis) and Low-N (Treweek 2011) treatments, medium and Mid-N treatments, or the high and High-N treatments within the two studies. The amount of wastewater irrigated in Treweek (2011) and during this experiment was too low to reach the high nitrogen loading input of 650 kg N ha^{-1} yr^{-1}.

The amount of nitrogen that was applied to the land surface during this experiment (286 to 567 kg N ha^{-1} yr^{-1}) was similar to nitrogen inputs within other New Zealand effluent applied leaching studies (Table 2.1) (Di et *al*. 1998; Burgess 2003; Barton *et al*. 2005; Sparling *et al*. 2006), but were lower than those of Williamson *et al*. (1998) and studies that simulated urine spots with high localised nitrogen inputs (Di and Cameron 2005; Cameron *et al.* 2007; Di and Cameron 2007; Menneer *et al*. 2008).

Nitrogen input within control sectors was assumed to be primarily atmospheric nitrogen that was deposited in rain water, and was expected to be 5 kg N ha^{-1} yr^{-1} (Power and Wheeler 2007; Treweek 2011). Within lysimeter literature, control lysimeters were subjected to different “control” conditions. Some lysimeters underwent normal rainfall (Burgess 2003; Cameron *et al*. 2007; Treweek 2011), simulated rainfall (Cameron *et al.* 2007), applied or irrigated water (Di *et al.* 1998; Williamson *et al.* 1998; Burgess 2003; Cameron *et al.* 2007; Menneer *et al.* 2008), or were unirrigated and received the application of nitrogen fertiliser (Barton *et al.* 2005; Sparling *et al.* 2006). No nitrogen fertiliser or water (other than natural rainfall) were applied to control lysimeters within this experiment.

3.4.3. Pasture production and nitrogen removal

3.4.3.1. Pasture dry matter production

The application of wastewater stimulated higher pasture production at the View Road site. Mean pasture dry matter production from irrigated treatments was 14 250 ± 349 kg DM ha^{-1} yr^{-1} and 5300 ± 839 kg DM ha^{-1} yr^{-1} from the unirrigated controls. Wastewater provided water and nutrients that are vital to pasture growth but are often limited, allowing the ryegrass pasture at the View Road site to thrive. Similar substantial increases in dry matter production with the application of effluents have been widely observed within New Zealand lysimeter studies (Di *et al*. 1998; Williamson *et al.* 1998; Burgess 2003) (Table 2.1). For example, on a Taupō Pumice Soil, Barton *et al.* (2005) reported higher pasture yields (10 831 kg DM ha^{-1} yr^{-1}) with the application of treated municipal wastewater (408 kg N ha^{-1} yr^{-1}) when compared to the unirrigated controls (4303 kg DM ha^{-1} yr^{-1}).

While the irrigation of wastewater increased pasture production, when compared to the unirrigated treatment, there was only a very weak positive correlation (R^2= 0.12) between the amount of wastewater nitrogen input and nitrogen uptake by pasture (Figure 3.20). The lack of significant difference between pasture dry matter production between the low (13 922 ± 1196 kg DM ha^{-1} yr^{-1}), medium (13 543 ± 1475 kg DM ha^{-1} yr^{-1}) and high nitrogen loading treatments (15 285 ± 1919 kg DM ha^{-1} yr^{-1}) (Table 3.16) suggest that maximum pasture growth may have occurred under the low application treatment; increasing wastewater input past the lower application did not lead to further increases in pasture production. With the current harvesting practices at the View Road site, increasing the consented nitrogen application limit to 650 kg N ha^{-1} yr^{-1} will not increase pasture production.

During the previous year of this experiment, Treweek (2011) also reported no significant difference in pasture production between the low, medium and high treatments. Treweek (2011) suggested that the lower wastewater application rate provided sufficient nutrient and water inputs for maximum pasture growth. More pasture dry matter was reported within the irrigated treatments of Treweek (2011) (15 800 ± 563 kg DM ha^{-1} yr^{-1}) than within this study (14 250 ± 349 kg DM ha^{-1} yr^{-1}) (Table 3.16), suggesting different management conditions or better growing conditions during the 2009/10 period.

3.4.3.2. Nitrogen removal by pasture

The concentration of pasture nitrogen was higher ($P < 0.001$) in irrigated treatments (2.6%) than in control treatments (1.8%). The application of wastewater stimulated higher pasture dry matter production, therefore, supported higher nitrogen removal by pasture (360 ± 23 kg N ha^{-1} yr^{-1}), relative to the control treatments (91 ± 14 kg N ha^{-1} yr^{-1}). Nitrogen removal by pasture in irrigated treatments ranged from 261 kg N ha^{-1} yr^{-1} to 523 kg N ha^{-1} yr^{-1}. Like pasture production, there was also no significant difference in the amount of nitrogen removal between the low (341 ± 25 kg N ha^{-1} yr^{-1}), medium (360 ± 51 kg N ha^{-1} yr^{-1}), and high nitrogen loading treatments (385 ± 43 kg N ha^{-1} yr^{-1}).

During 2009/10 (Treweek 2011), nitrogen removal by pasture within the irrigated treatments at the View Road site were not significantly different than the corresponding treatment within this thesis (Table 3.16). In addition, the proportion of applied wastewater nitrogen removed by pasture decreased with increased nitrogen input in both studies. For example, Treweek (2011) reported 308 kg N ha^{-1} yr^{-1} (equivalent to 95% of applied nitrogen) was removed within the Low-N treatment, 310 kg N ha^{-1} yr^{-1} (78%) was removed within the Mid-N treatment, and 387 kg N ha^{-1} yr^{-1} (78%) was removed within the High-N treatment. Within this thesis, pasture uptake removed 100 ± 6 % of the applied wastewater nitrogen within the low treatment, 89 ± 13 % within the medium treatment, and 79 ± 9% within the high treatment, suggesting the maximum amount of nitrogen uptake possible by pasture may have occurred within the low application treatment.

Nitrogen uptake by pasture, within New Zealand lysimeter studies, has been reported to remove 37 - >100% of the applied wastewater nitrogen (Table 2.1). The lower nitrogen removals were associated with application of cow urine to simulate a urine spot (Di and Cameron 2005) or the application of 1100 kg N ha^{-1} over a short time period (Williamson *et al*. 1998).

With the application of 408 kg N ha^{-1} yr^{-1} secondary-treated municipal wastewater to a Taupō Pumice Soil, Barton *et al*. (2005) reported 265 kg N ha^{-1} yr^{-1} (65%) was removed in pasture. Sparling *et al*. (2006) reported similar findings, with 229 kg N ha^{-1} yr^{-1} (63%) of the 364 kg N ha^{-1} yr^{-1} applied wastewater nitrogen was removed by pasture. While Barton *et al*. (2005) and Sparling *et al*. (2006) only reported intermediate recovery by pasture, little nitrogen was leached in either study, while 31% and 32% respectively of the nitrogen input was unrecovered, assumed to be immobilised by soil, denitrified or volatilised. (Barton *et al*. 2005 and Sparling *et al*. 2006).

Nitrogen uptake depends on pasture growth rate and time since the previous harvest. If conditions are favourable pasture can remove more than 500 kg ha^{-1} yr^{-1} (Whitehead 1995). For example, with the increased application of cow urine from 300, to 700, to 1000 kg N ha^{-1}, nitrogen pasture yield was increased from 361 kg N ha^{-1} (equivalent to 120% of applied nitrogen), to 451 kg N ha^{-1} (64%), to 632 kg N ha^{-1} (63%) (Di and Cameron 2007).

A resource consent condition for the Taupō wastewater disposal scheme was that nitrogen application could be no more than 120 kg N ha^{-1} yr^{-1} higher than the mean amount of nitrogen removed by the pasture crop (Environment Waikato 2008). On average, nitrogen removal within each irrigated treatment did meet the condition. However, six out of the thirty five irrigated lysimeters (four in the high treatment and two in the medium treatment) did not meet the consent conditions; for example, the nitrogen applied in the wastewater was more than 120 kg N ha^{-1} yr^{-1} greater than nitrogen removed in pasture.

3.4.4. Nitrogen leached

3.4.4.1. The amount of total nitrogen leached

Applying wastewater to land at the View Road site increased the nitrogen concentration of water after it drained through 43 cm of soil. Within irrigated treatments, the mean nitrogen concentration of leachate was 2.4 ± 0.7 mg L^{-1}, while the mean nitrogen concentration of control leachate was 0.7 ± 0.3 mg L^{-1} (Table 3.9). Nitrogen concentrations measured in this thesis were lower than what the U.S EPA (1981) expects the mean nitrogen concentration (3 mg L^{-1}) of leachate that percolated through 1.5 m of unsaturated soil in a land treatment system. The lower nitrogen concentrations suggest that the plant-soil system at the View Road site is more effective at removing wastewater nitrogen than the systems examined by U.S. EPA (1981). The mean nitrogen concentration of applied wastewater over the duration of this experiment was 48.4 ± 1.7 mg L^{-1} (Table 3.3). Therefore, a great deal of nitrogen was removed from the water before it was able to be leached.

Within control treatments, the mean amount of nitrogen leached over the duration of the study was 2.8 ± 0.6 kg N ha^{-1} yr^{-1} (Table 3.9). Within the irrigated treatments, the total amount of nitrogen leached was, on average, higher ($P < 0.05$) in the high treatment (28.6 ± 10.1 kg N ha^{-1} yr^{-1}) than in the low treatment (12.7 ± 4.2 kg N ha^{-1} yr^{-1}) (Figure 3.23). The medium treatment (16.0 ± 7.2 kg N ha^{-1} yr^{-1}) was not significantly different than the low treatment or the high treatment. The amount of nitrogen leached from within the medium treatment was similar to nitrogen leaching losses from Taupō Pumice Soils in Barton *et al.* 2005 (15 kg N ha^{-1} yr^{-1}) and Sparling *et al.* 2006 (17 kg N ha^{-1} yr^{-1}) the application rates of 408 kg N ha^{-1} yr^{-1} and 364 kg N ha^{-1} yr^{-1} wastewater respectively. Leaching losses, even within the high treatment, were lower than losses reported in all other New Zealand lysimeter studies presented in Table 2.1.

In the previous study at the View Road site, the mean amount of nitrogen leached from control treatments was 4.8 ± 1.2 kg N ha^{-1} (Treweek 2011). Over the duration of Treweek (2011), 14.8 ± 0.6 kg N ha^{-1} was leached from the Low-N treatment (input of 280 - 350 kg N ha^{-1}), 16.9 ± 3.4 kg N ha^{-1} was leached within the Mid-N treatment (input of 350 - 450 kg N ha^{-1}), and 26.4 ± 2.3 kg N ha^{-1} was leached within the High-N treatment (input of 450 - 520 kg N ha^{-1}). The High-N treatments leached significantly more ($P < 0.005$) nitrogen than the Low-N (Treweek 2011), but there was no significant difference in nitrogen leached between the Mid-N treatment and the Low-N treatment or the High-N treatment; a similar result to this thesis.

Leaching losses from treatments within this thesis were not significantly different than within the corresponding treatments in Treweek (2011) (Table 3.16). Within this thesis, 4% of the applied nitrogen was leached within the low treatment, 4% was leached within the medium treatment, and 6% was leached within the high treatment. In Treweek (2011), 5% of the applied nitrogen was leached within the low treatment, 4% was leached within the medium treatment, and 5% was leached within the high treatment.

Being an experiment that was under field irrigation and harvesting conditions, it was difficult to isolate drivers of leaching losses in relation to the real field conditions. There was a positive correlation between the amount of nitrogen leached and input ($R^2 = 0.44$) and the amount of water drained through the soil ($R^2 = 0.54$). However, there was effectively no relationship between the amount of nitrogen leached and the amount of nitrogen uptake. Within Treweek (2011), there was poor correlation between the amount of nitrogen leached and the rate of wastewater irrigation, but there was a positive correlation (R^2= 0.7) with the volume of water that drained through the soil.

A resource consent condition restricts the mean amount of nitrogen allowed to be leached at the Taupō wastewater disposal scheme to below 30 kg N ha^{-1} yr^{-1}. The mean amount of nitrogen leached from within the high treatment was 28 kg N ha^{-1} yr^{-1}, which is below the leaching limit. While the mean was lower than 30 kg N ha^{-1} yr^{-1}, nitrogen values above the limit were measured from six lysimeters (out of the 46); four within the high, and two within the medium, treatment. The maximum nitrogen leaching value (61 kg N ha^{-1} yr^{-1}) was measured under the highest wastewater application (567 kg N ha^{-1} yr^{-1}).

Within irrigated treatments, the largest proportion of nitrogen that was leached was during the autumn and winter months (Table 3.10). Differentiation of nitrogen leaching losses within irrigated treatments did not occur until May (late-autumn), when nitrogen leaching losses within the high treatment accelerated in comparison to other treatments (Figure 3.25). Treweek (2011) reported differentiation between the irrigated treatments beginning in June; six months after the trial began. It is difficult to relate nitrogen leaching to rainfall events (Figure 3.26). However, following a large rainfall event at the end of December 2011, there was an increase in the amount of nitrogen leached, illustrated by the steeper gradient in Figure 3.26. From January 2012 to September 2012 there were multiple rain events with subsequent steady nitrogen leaching.

3.4.4.2. Nitrogen forms in irrigated treatment leachate

a. Inorganic nitrogen

Inorganic nitrogen consists of nitrate, nitrite and ammonium. Nitrate was the predominant form of nitrogen within the irrigated treatment leachate (Table 3.11 and Figure 3.27). Virtually none of the wastewater nitrogen was in the form of nitrite which was similar to nitrite concentrations within other leaching studies (Cameron *et al.* 1995; Di and Cameron 2005; Di and Cameron 2007). The concentration and proportion of nitrate within leachate increased with increased application from; 6.8 kg N ha^{-1} yr^{-1} (equivalent to 54% of nitrogen the within leachate) within the low treatment, to 10.7 kg N ha^{-1} yr^{-1} (67%) within the medium treatment, to 22.2 kg N ha^{-1} yr^{-1} (78%) within the high treatment. Di *et al.* (1998) reported similar nitrate leaching losses of 17 kg N ha^{-1} from the irrigation of 400 kg N ha^{-1} yr^{-1} dairy shed effluent. Ammonium was a minor nitrogen component within irrigated leachate; 2.1 % in the low, 1.6% in the medium, and 2.2% in the high treatment (Table 3.11).

In effluent application studies, nitrate is commonly reported as the major component in lysimeter leachate. However, many studies only concentrate on inorganic and ignore organic forms of nitrogen within leachate (Cameron *et al.* 1995; Di and Cameron 2005; Di and Cameron 2007). For example, only 29% of the 15 kg N ha^{-1} yr^{-1} total leachate nitrogen was inorganic in Barton *et al.* (2005) and 36% of 17 kg N ha^{-1} yr^{-1} within Sparling *et al.* (2006).

The mean concentration of nitrate within leachate also increased from the low treatment (1.0 mg L^{-1}), to the medium treatment (1.8 mg L^{-1}), to the high treatment (2.1 mg L^{-1}). Nitrate concentrations only exceeded the Ministry of Health guidelines for drinking water (11.3 mg L^{-1}) (Ministry of Health 2005) four times, out of approximately 520 measurements, throughout the trial period; with a maximum of 19.0 mg L^{-1}. Nitrate concentrations above 11.3 mg L^{-1} were measured from one lysimeter within the high treatment during October 2011 and November 2011 and from one lysimeter within the medium treatment during January 2012 and February 2012. Mean concentration of ammoniacal nitrogen within irrigated leachate was 0.05 mg L^{-1}, which is lower than what the U.S EPA (1981) expect the mean ammonia concentration (0.5 mg L^{-1}) of leachate within a wastewater treatment site.

Within the irrigated treatments, the largest proportion of nitrate (63%) (Table 3.13), like total nitrogen, was leached during the autumn and winter months. Differentiation of leaching losses from irrigated treatments did not occur until April (a month earlier than total nitrogen), when nitrate leaching losses within the high treatment accelerated in comparison to other treatments (Figure 3.29). While the seasonal pattern of nitrate and total nitrogen (Figure 3.25) were similar, nitrate leaching losses were more pronounced towards the end of the trial (winter).

Nitrate was originally a small component (3.5%) of the total wastewater nitrogen (when wastewater was sampled at the wastewater treatment plant) and ammonium was a major component (88%) (Table 3.3). Therefore, it is assumed much of the wastewater ammonium was volatilised, removed by pasture, or was oxidised to nitrate; upon transport to the View Road site, during irrigation, or by the nitrification process in soil. Bacteria within soil (mainly *Nitrosomonas*) oxidise ammonium to nitrite, with further oxidation to nitrate by *Nitrobacter* (Whitehead 1995; Hillel 2008). Nitrification is rapid in aerobic conditions which occur with the slow rate application and resting of irrigation at the View Road site. The minimal amounts of nitrite present within leachate was most likely due to the rapid and complete reduction of ammonium to nitrate which would be expected to occur within aerobic conditions (free draining nature and coarse texture) of the Pumice Soil (McLaren and Cameron 1996; Barton *et al*. 1999a). Ammonium can also be removed from soil solution by absorption onto cation exchange sites or fixation into the internal structures of some clay minerals (McLaren and Cameron 1996).

b. Total organic nitrogen

The mean concentration of organic nitrogen in irrigated treatment leachate was 0.8 mg L^{-1} and the total amount of organic nitrogen leached ranged from 1.9 to 13.1 kg N ha^{-1} yr^{-1}.

Many studies ignore organic forms of nitrogen within leachate (Di and Cameron 2005; Di and Cameron 2007). However, organic nitrogen was a significant component of leachate nitrogen within the low treatment (equivalent to 41% of nitrogen the within leachate), the medium treatment (37%), and the high treatment (23%). While the proportion of organic nitrogen declined with increased application, the amount of organic nitrogen leached was not significantly different between the medium treatment (5.9 ± 0.5 kg N ha^{-1} yr^{-1}) and the low (5.2 ± 0.3 kg N ha^{-1} yr^{-1}), or between the medium treatment and the high treatment (6.4 ± 0.8 kg N ha^{-1} yr^{-1}) (Figure 3.30). However, on average, the amount of organic nitrogen leachate within the high treatment was higher ($P < 0.05$) than within the low treatment.

Barton *et al.* (2005) and Sparling *et al.* (2006) reported even higher proportions of organic nitrogen within leachate from municipal wastewater application; 71% of the 15 kg N ha^{-1} yr^{-1} total leachate nitrogen was inorganic in Barton *et al.* (2005)

and 64% of the 17 kg N ha^{-1} yr^{-1} within Sparling *et al.* (2006). The measurement of organic nitrogen is important as organic nitrogen can play a role in the degradation of aquatic ecosystems. Organic nitrogen can become available through mineralisation (and subsequent nitrification) or can act as a direct source of nutrition for many aquatic organisms (Berman and Bronk, 2003).

3.4.4.3. Nitrogen leaching from control lysimeters

With no application of wastewater, the nitrogen input to control lysimeters was assumed to be primarily atmospheric nitrogen that was deposited with rain water (5 kg N ha^{-1} yr^{-1}). The mean amount of nitrogen leached within control treatments over the duration of the study was 2.8 ± 0.6 kg N ha^{-1} yr^{-1} (Table 3.9). Control lysimeters showed what normal leaching losses were from a Taupō Pumice Soil under ryegrass pasture. Leaching losses were lower than reported losses from unirrigated Taupō Pumice Soils within lysimeter literature (Barton *et al.* 2005; Sparling *et al.* 2006; Cameron *et al.* 2007; Menneer *et al.* 2008) (Table 2.1).

Organic nitrogen was the predominant component in leachate from the control treatments (1.9 kg N ha^{-1} yr^{-1} or 68% of the total nitrogen within leachate). Oxidised nitrogen (primarily nitrate) was the next largest component (0.8 kg N ha^{-1} yr^{-1} or 29%), and ammoniacal nitrogen was the smallest component (0.1 kg N ha^{-1} yr^{-1} or 5%) within leachate from control lysimeters (Figure 3.27). Similar proportions were reported in Treweek (2011); organic nitrogen was also the dominant component (72%), nitrate the next largest component (26%) and ammoniacal nitrogen (2%) a minor component of nitrogen within control leachate.

Control leachate contained a higher proportion of inorganic nitrogen than within the irrigated treatments, which contained a higher proportion of nitrate. Nitrate within control leachate may have originated from the mineralisation of soil organic matter and the nitrification of ammonium.

3.4.5. Nitrogen balance and other nitrogen losses

Within irrigated treatments, nitrogen input (wastewater plus atmospheric nitrogen) ranged from 286 to 567 kg N ha^{-1} yr^{-1}. Pasture removal represented the greatest loss of wastewater nitrogen; 100 ± 6% within the low treatment, 89 ± 13% within medium treatment, and 79 ± 9% within the high treatment (Table 3.15). Total nitrogen leached was minimal; 4 ± 1% within the low treatment, 4 ± 2% within the medium treatment, and 6 ± 2% within the high treatment. Therefore, on average, -4 to 16% of the applied wastewater nitrogen remained unrecovered.

Mean unrecovered nitrogen increased with increased wastewater application from -13 ± 19 kg N ha^{-1} yr^{-1} (equivalent to -4 ± 6% of applied wastewater nitrogen) in the low treatment, to 30 ± 52 kg N ha^{-1} yr^{-1} (7 ± 13%) in the medium treatment, to 77 ± 39 kg N ha^{-1} yr^{-1} (16 ± 8%) in the high treatment. Negative values indicate higher nitrogen outputs (nitrogen removal by pasture and leaching) than the nitrogen inputs. Negative values may represent measurement error or nitrogen released through soil processes such as net mineralisation. Mineralisation has been reported to increase soil nitrogen availability following the application of effluent to land (Polglase *et al*. 1995; Zaman *et al*. 1999).

In literature, it is often assumed that unmeasured or unrecovered nitrogen in a lysimeter study is either stored as soil nitrogen, denitrified or volatilised. Gaseous losses and transfer to soil storage in numerous studies ranged from; 31 % of the 408 kg N ha^{-1} yr^{-1} applied wastewater (Barton *et al*. 2005), 32% of the 364 kg N ha^{-1} yr^{-1} (Sparling *et al*. 2006), and 61 % of the 200 kg N ha^{-1} yr^{-1} (Cameron *et al*. 1995). In the previous study at the View Road site, on average, 4.5 ± 22 kg N ha^{-1} (1%) was unrecovered within the low treatment, 67 ± 14 kg N ha^{-1} (17%) within the medium treatment, and 84 ± 37 kg N ha^{-1} (17%) within the high treatment (Treweek 2011).

While volatilisation losses have been reported to account for up to 66% of applied urine nitrogen under warm and dry conditions in New Zealand (Ball and Ryden 1984), losses are usually estimated to be lower when municipal wastewater is applied to land (Smith *et al*. 1996). Cameron *et al*. (1995) measured ammonia loss by volatilisation equivalent to 20 kg N ha^{-1} (or 10%) of the 200 kg N ha N^{-1} applied urine, and 48 kg N ha^{-1} (or 8%) of the 600 kg N ha^{-1} applied nitrogen. It is assumed volatilisation will account for a major component of the unmeasured nitrogen within this study; the applied wastewater contains high concentrations of ammoniacal nitrogen and has a mean pH of 7.3 to 7.8 (neutral to slightly alkaline). It is likely that some nitrogen was volatilised during sprinkler application, and following deposition onto the ground surface, and interception on the grass.

The removal of nitrogen by denitrification decreases the amount of nitrate available to be leached (Paranychianakis *et al*. 2006). Low denitrification losses were reported from a soil with a similar free draining nature and coarse texture (Barton *et al*. 1999a). Therefore, it was assumed denitrification losses at the View Road site were also low. While conditions may be ideal for denitrification, with the high input of nitrate and organic carbon and temporary anaerobic conditions (Cameron *et al*. 1997), anaerobic conditions should not last long enough for major losses by denitrification to occur, especially within the warmer months (Barton *et al*. 1999a).

While a significant component of applied wastewater can be immobilised in soil, for example 12 to 30% of the ^{15}N laced animal urine was reported to be immobilised (Whitehead and Bristow 1990; Frase *et al*. 1994; Cameron *et al*. 1995), it is assumed nitrogen removal by soil storage is minimal in an already established wastewater application site (U.S EPA 1981). However, there was no direct measurement of soil nitrogen within this thesis.

The amounts of unrecovered nitrogen from irrigated treatments, within this thesis, were not significantly different than the corresponding irrigated treatments in Treweek (2011) (Table 3.16). For example, there was no significant difference between the amounts of unrecovered nitrogen in the High-N treatment (84 ± 37 kg N ha^{-1}) reported in Treweek (2011) and within the high treatment of this thesis (77± 39 kg N ha^{-1} yr^{-1}).

The View Road disposal site was commissioned in 2008 and the first year of measurement begun in December 2009 by Treweek (2011). The second round of measurement in 2011/12 was needed to verify equilibration of the soil system and to confirm nitrogen leaching losses had not increased since the first year of monitoring.

Due to the lack of significant difference in nitrogen leaching values, pasture uptake values and unrecovered nitrogen values (Table 3.16) between corresponding treatments within the 2009/10 measurement period (Treweek 2011) and the 2011/12 measurement period (reported within this thesis), it is suggested that the soil system within the irrigated experimental area at the View Road site had reached equilibrium before the 2009/10 measurement period (Treweek 2011).

Therefore, leaching losses measured during this thesis and within the previous study (Treweek 2011) are likely to be representative of future leaching losses, when similar nitrogen loads are applied. However, further monitoring would be advised, especially at the higher loading rates.

3.4.6. Limitations and measurement error

3.4.6.1. Measurement of wastewater nitrogen

To determine nitrogen application, a weekly grab sample of wastewater was taken at the Taupō wastewater treatment plant and nitrogen analyses were performed. It was assumed that the grab-sample was representative of the entire week's wastewater. Although nitrogen concentration probably fluctuated during that week, sampling more frequently than weekly was not logistically or economically feasible. Another limitation was that the concentration of wastewater nitrogen was averaged over each rain gauge measurement period (Figure 3.14).

The sampled wastewater was taken at the Taupō wastewater treatment site, which was located about 7 km away from the View Road site. Nitrogen forms and concentrations may have changed before application. Treweek (2011) installed a composite sampler in the pump house at the View Road site. The composite sampler was supposed to provide a method for more accurate wastewater nitrogen measurement. At the conclusion of the study (Treweek 2011) the composite sampler had not produced a sufficient number of samples to compare the nitrogen concentrations measured by the two methods. However, in the limited number of samples taken by the composite sampler showed a high proportion of the wastewater nitrogen was in the form of ammoniacal-nitrogen (> 90%) and a low proportion was in the form of total oxidised nitrogen (< 1%) (Treweek 2011). Wastewater nitrogen measured at the Taupō wastewater treatment plant was also predominantly in the form of ammoniacal-nitrogen (89%) with a small proportion was in the form of total oxidised nitrogen (3.5%) (Table 3.3). The similar proportions would suggest that there were minimal changes in nitrogen forms during transport to the View Road site.

The total nitrogen concentration of wastewater applied at the View Road site may have been different than that measured at the Taupō wastewater treatment site. It was possible nitrogen may have been lost during the transport to, storage, and application at, the View Road site. For example, volatilisation can occur during the irrigation process. The concentration of wastewater nitrogen measured at the Taupō wastewater treatment plant is likely to represent the maximum possible nitrogen application.

3.4.6.2. The irrigation of wastewater and loading treatments

a. Nitrogen loading rates

The target wastewater nitrogen rates of 450, 550 and 650 kg N ha^{-1} yr^{-1} were not achieved. The high application load was required to allow the quantification of nitrogen leaching losses, to hence test the suitability of increasing resource consent limits from 550 to 650 kg N ha^{-1} yr^{-1}, at the View Road site. The reasons for not achieving the higher application rates involved periods where no wastewater was applied to the experimental area for reasons of grass harvest, lack of available wastewater, and other activities such as tree felling adjacent to the irrigation area.

While most non-irrigation events were unavoidable, they did contribute to less wastewater being applied during the experiment. Wastewater was not irrigated for 5.5 weeks at pivot F and 8.4 weeks at pivot G as stand-down periods during field harvests (Figure 3.32). The stand-down periods were anticipated before the experiment began. However, there were occasions when wastewater was not irrigated that were not anticipated and thus the missed loading could not be readily rectified. For example, pivot F was turned off for 39 days during May and June 2012 to allow pine trees along the View Road boundary to be cut down and removed.

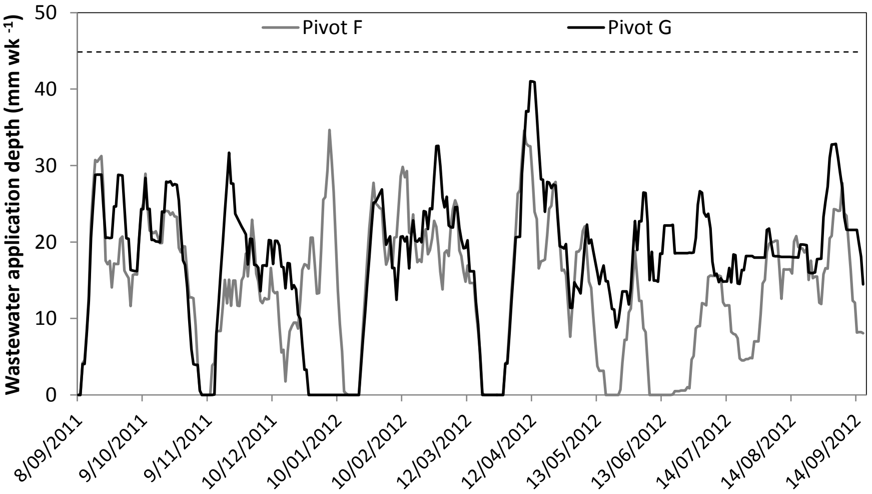

Figure 3.32. Mean weekly wastewater application depth from pivot F and pivot G during the year of September 2011 to September 2012 at the View Road site. ***Resource consent conditions restrict the amount of wastewater that is allowed to be applied at the View Road site to 45 mm per week, represented by the dashed line.***

The main reason the target nitrogen loads rates were not achieved, was not enough wastewater was irrigated to the experimental area over the duration of the study. Less wastewater was irrigated at pivot F (760 mm with a mean of 2.6 mm day^{-1} (excluding the stand-down periods in the average)) than was irrigated at pivot G (934 mm with a mean of 3.0 mm day^{-1}(excluding the stand-down periods in the average)). Within the varied application treatments, the mean amount of wastewater applied to lysimeters was 662 mm in the low treatment, 812 mm in the medium treatment, and 978 mm in the high treatment.

Resource consent conditions restrict the amount of wastewater that is allowed to be applied at the View Road site to 45 mm per week, with no more than 15 mm to be applied within 24 hour, and with a maximum application rate of 5 mm hr^{-1}. However, the application rates achieved were well below the consented limits (Figure 3.32). While no special exemptions in water loading consent limits were given for this experiment, the higher nitrogen loads would have been reached if more wastewater was applied. Wastewater was applied evenly over the View Road site to maintain grass growth over the entire area, rather than giving preference to and applying the target wastewater loads within the experimental area.

Assuming twelve weeks for stand-down a year, to achieve the target application loads; 42 mm wk^{-1} had to be irrigated to achieve application of 650kg N ha^{-1} yr^{-1}, 36 mm wk^{-1} to achieve 550 kg N ha^{-1} yr^{-1}, and 29 mm wk^{-1} to achieve 450 kg N ha^{-1} yr^{-1} (Couper *et al.* 2009). Excluding stand-down periods, mean weekly application was 18.9 mm wk^{-1} at pivot F and 20.8 mm wk^{-1} at pivot G. These irrigation rates were lower than what Di and Cameron (2007) reported to be typical irrigation practise on New Zealand farms (30 to 40 mm week^{-1}).

Both Barton *et al*. (2005) and Sparling *et al*. (2006) irrigated secondary-treated wastewater at 10 mm for 5 hours. The application rate of 10 mm for 5 hours (50 mm wk^{-1}) was explained to reflect current wastewater treatment practices within New Zealand where storage components are not economically feasible. However, the rate examined in Barton *et al*. (2005) and Sparling *et al*. (2006) was higher than both resource consent limits for the View Road site and the actual applied rates over the duration of the study.

The target application rates of 450, 550 and 650 kg N ha^{-1} yr^{-1} were also not achieved in the previous study (Treweek 2011) where nitrogen application to the land surface ranged from 280 to 520 kg N ha^{-1} yr^{-1}. Inputs were grouped into a Low-N treatment (280 - 350 kg N ha^{-1} yr^{-1}) a Mid-N treatment (350 - 450 kg N ha^{-1} yr^{-1}) and a High-N treatment (450 - 520 kg N ha^{-1} yr^{-1}) (Treweek 2011). The amount of wastewater irrigated in Treweek (2011) and during this thesis was too low to reach the high application rate of 650 kg N ha^{-1} yr^{-1}.

b. Target and actual treatment sectors

Irrigators were programmed to vary in speed at certain angles around the irrigation circle, theoretically producing different irrigation volumes within treatment sectors (Figure 3.16a). However, the programmed treatment sectors did not occur due to sprinkler variability and other technical problems (Figure 3.16b).

The predetermined irrigation programme was likely to have shifted over time and the irrigators did not slow down or speed up at the correct angles. For example, sectors which were originally programmed to be a high or a low treatment ended up as a medium and vice versa. The predetermined application treatments also were not achieved during the previous study (Treweek 2011). Treatments sectors that were recorded in Treweek (2011) (Figure 3.33) were different to treatment sectors that occurred within this thesis (Figure 3.16b)

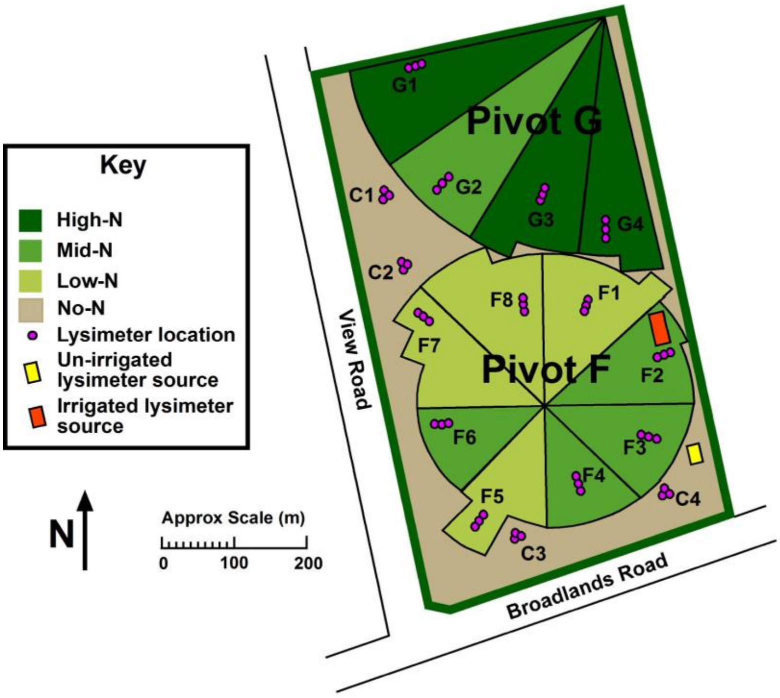

Figure 3.33. Overview of wastewater nitrogen applied in Treweek (2011). The No-N treatment is defined as 0 kg N ha^{-1} yr^{-1}. The Low-N treatment is defined as 280 - 350 kg N ha^{-1} yr^{-1}. The Mid-N treatment is defined as 350 - 450 kg N ha^{-1} yr^{-1}. The High-N treatment is defined as 450 - 520 kg N ha^{-1} yr^{-1} (Treweek 2011). The targeted loading rates are presented in Figure 3.16a and the loading rates achieved in this thesis are presented in Figure 3.16b.

Within this thesis, pivot G received more wastewater than pivot F. Therefore, lysimeters within the low and medium treatments in pivot G received more wastewater than the programmed high treatments in pivot F.

Lysimeters within the same treatment sector did not necessarily receive the same amount of applied wastewater (Figure 3.16b). There were four sectors in which lysimeters towards the outside of the irrigation circle did not receive as much wastewater as lysimeters closer to the centre of the irrigator circle. Variation within a treatment sector may be associated with the end gun on the irrigator shutting off either due to; irrigator drift from the predetermined programme, sprinkler variability, or the irrigators were deactivated within that area by operators. The variation of irrigated wastewater within a treatment sector was reported in the previous study (Treweek 2011). Because of the variation in applied wastewater within treatment sectors reported in Treweek (2011), each lysimeter was sampled independently in this thesis.

c. Control lysimeters

Nitrogen input within control sectors was expected to be solely from atmospheric nitrogen that was deposited in rain water, and was assumed to be 5 kg N ha^{-1} yr^{-1} (Power and Wheeler 2007; Treweek 2011). However, two areas of control lysimeters (six lysimeters in total) appeared to receive wastewater during the study. Rain gauges installed next to the two sets of three lysimeters, closest to Broadlands Road (Figure 3.5), systematically measured more liquid than rain gauges installed next to the other two sets of control lysimeters closer to View Road. The rain gauge measurements were usually similar to nearby irrigated treatments. Visual assessments of grass growth and colour confirmed that the control sectors had received wastewater irrigation. The irrigator end gun was apparently inadvertently activated and wastewater was irrigated onto two out of the four sets of the control lysimeters. The results from the inadvertently irrigated control lysimeters were excluded from some laboratory analyses and from all statistical analyses, which decreased the replication of control lysimeters from twelve to six. Within the previous View Road study it was thought that the same two sets of lysimeters could have also received wastewater (G. Treweek, pers. com. 2011).

3.4.6.3. Lysimeter limitations

Lysimeters within this experiment had a diameter of 30 cm and a depth of 43 cm. Lysimeters in literature were commonly at a depth of, or deeper than, 70 cm (Di *et al*. 1998; Cameron and Di 2004; Barton *et al.* 2005; Di and Cameron 2005; Sparling *et al.* 2006; Di and Cameron 2007). However, shallower lysimeters did occur in literature; 35 cm (Burgess 2003), 45 cm (Cameron *et al.* 2005), and 50 cm (Williamson *et al.* 1998; Cameron *et al.* 2007). A depth of 43 cm is considered shallow and may not represent the rooting zone of the ryegrass outside of lysimeters at the View Road site. The roots of ryegrass may grow deeper than 43 cm (Jacques 1943; Crush *et al.* 2010).

There was variability in the amount of pasture plants grown in lysimeters (Figure 3.34). With sparse ground cover, the ability of pasture to remove wastewater nitrogen was decreased; therefore, more nitrogen is available to be leached. However, variability is considered representative of ground cover at the View Road site. Ground cover was sparse, estimated at approximately 50%, during the 2009/10 measurement period (Treweek 2011). It was important to measure nitrogen leaching losses under this variability to account for the real field conditions at the View Road site and to measure representative nitrogen leaching losses.

Figure 3.34. Examples of grass cover variability within, and around, lysimeters at the View Road site. Umbrellas mark the edge of lysimeters.

A limitation of lysimeter studies is the base of the lysimeter would have to become saturated before leachate could drip through the false bottom and into the collection container. The large amount of drainage (Table 3.8) would have meant saturated conditions at the base of the lysimeters and consequently the capillary fringe above it which would have impeded drainage, and possibly stimulated denitrification.

3.4.6.4. Measurement error

Errors associated with field experiments are generally larger than within a controlled laboratory study. Treweek (2011) calculated conventional measurement errors for his study, a summary of his results are:

- The nitrogen application loads had a measurement error of ± 35%.
- The amount of nitrogen leached had an associated measurement error of ±40%.
- The pasture growth values had ± 20% measurement error.
- The amount of nitrogen removed by the pasture had a measurement error of ± 30%.

Error is also present when scaling up from a small area (the top of a lysimeter) to a field size or hectare. The large measurement errors and field variability are partially counteracted by having large number of replicate samples. However, the variability and measurement limitations should not be overlooked when considering the implications of the results.

3.5. SUMMARY AND CONCLUSION

Secondary-treated municipal wastewater was applied to land at the View Road site as a method of disposal and further treatment. Nutrients and water were utilised by a perennial ryegrass (predominantly *Lolium perenne*) and pasture was harvested four times a year in a cut and carry scheme. With a need to increase the wastewater disposal capacity in Taupō, the Taupō District Council has requested to increase wastewater application limits at the View Road site from 550 to 650 kg N ha^{-1} yr^{-1}. The overall purpose of this trial was to quantify pasture production, nitrogen removal by pasture, nitrogen leaching and unrecovered nitrogen under the target applications of 450, 550 and 650 kg N ha^{-1} yr^{-1}. Results from this thesis will help to assess whether an increase in nitrogen application, from 550 to 650 kg N ha^{-1} yr^{-1}, is suitable when resource consent conditions are reviewed. Conditions of the Taupō land based disposal scheme restrict the amount of wastewater nitrogen allowed to be applied to be no more than 120 kg N ha^{-1} yr^{-1} above crop yield, or mean nitrogen leaching losses of up to 30 kg N ha^{-1} yr^{-1}.

Wastewater irrigation began in December 2008 at the View Road land based wastewater site. In March 2009, the centre pivot travelling irrigators were programmed to vary in speed, theoretically producing varied application treatments. Forty eight undisturbed barrel lysimeters (30 cm diameter x 43 cm depth) were installed within 29 hectares at the View Road site in September 2009 (Treweek 2011). The first round of measurement was undertaken from December 2009 to December 2010 (Treweek 2011). However, a second round of measurement was needed to confirm equilibration of the soil nitrogen system, confirm nitrogen leaching losses had not increased from the first year of measurement, and to provide a longer time-series of data.

The second round of measurement began in September 2011 and finished in September 2012, with results presented in this thesis. The amount of wastewater nitrogen applied to each lysimeter was quantified. Lysimeters were pumped monthly, and leachate volume and nitrogen concentration were determined. Pasture growing in lysimeters was harvested before each commercial field harvest, and dry matter and nitrogen content were measured. A nitrogen balance was constructed and the amount of unrecovered nitrogen was determined.

Results from this experiment and results from the previous year of measurement (Treweek 2011) are summarised in Table 3.16. The target application treatments of 450, 550 and 650 kg N ha^{-1} yr^{-1} were not achieved, with nitrogen inputs ranging from 286 to 567 kg N ha^{-1} yr^{-1}. The nitrogen loading values were grouped into a low treatment (286 - 380 kg N ha^{-1} yr^{-1}), a medium treatment (380 - 445 kg N ha^{-1} yr^{-1}), and a high treatment (445 - 567 kg N ha^{-1} yr^{-1}). Nitrogen input within control sectors was assumed to be primarily atmospheric nitrogen that was deposited with rain water, and was expected to be 5 kg N ha^{-1} yr^{-1}.

Pasture production was higher ($P < 0.001$) under wastewater irrigation (mean of all irrigated treatments, 14 250 ± 349 kg DM ha^{-1} yr^{-1}) in comparison to unirrigated control pastures (5300 ± 839 kg DM ha^{-1} yr^{-1}). However, there was no significant difference in pasture growth between loading treatments (Table 3.16). The concentration of nitrogen in pasture was higher ($P < 0.001$) in irrigated treatments than in control treatments. However, there was also no significant difference in the amount of nitrogen removed between the low treatment (341 ± 25 kg N ha^{-1} yr^{-1}), the medium treatment (360 ± 51 kg N ha^{-1} yr^{-1}), and high treatment (385 ± 43 kg N ha^{-1} yr^{-1}) (Table 3.16). Therefore, under the current harvesting regime at the View Road site, increasing wastewater application rates did not lead to further significant increases in pasture production or nitrogen removal by pasture. Pasture was effective at nitrogen uptake, removing a mean of 79 to 100% of the applied wastewater nitrogen.

On average, nitrogen leaching losses ranged from 4 to 6% of the applied wastewater nitrogen. Applying wastewater to land at the View Road site increased the nitrogen concentration of water after it drained through 43 cm soil (Table 3.16). Within the irrigated treatments, the mean amount of nitrogen leached was higher ($P < 0.05$) in the high treatment (28.6 ± 10.1 kg N ha^{-1} yr^{-1}) than in the low treatment (12.7 ± 4.2 kg N ha^{-1} yr^{-1}); however, the medium treatment (16.0 ± 7.2 kg N ha^{-1} yr^{-1}) was not significantly different than the low treatment or the high treatment (Table 3.16). There was a positive correlation between the amount of nitrogen leached and wastewater input ($R^2= 0.44$), and the amount of water drained through the soil ($R^2= 0.54$). However, there was effectively no relationship between the amount of nitrogen leached and the amount of nitrogen uptake by pasture.

Nitrogen in leachate from irrigated treatments was predominantly nitrate (66%) and organic nitrogen (33%), with minimal ammonium (2%) and nitrite below detection limits. Nitrogen within control treatment leachate was predominantly organic nitrogen (68%) and nitrate (29%), with a small amount of ammonium (5%) and no nitrite detected. Nitrate concentrations only exceeded the Ministry of Health guidelines for drinking water (11.3 mg L^{-1}) four times, out of approximately 520 measurements, throughout the trial period.

The amount of unrecovered nitrogen increased with increased nitrogen application. Mean unrecovered nitrogen was equivalent to -4 to 16 % of the applied wastewater nitrogen (Table 3.16). The majority of unrecovered nitrogen was assumed to be volatilised with minor denitrification and soil storage.

Results from this experiment and results from the previous year of measurement (Treweek 2011) are compared in Table 3.16. Due to the lack of significant difference in nitrogen leaching values, pasture uptake values and unrecovered nitrogen values between corresponding treatments within the 2009/10 measurement period (Treweek 2011) and the 2011/12 measurement period reported within this thesis (Table 3.16), it is suggested that the soil system within the irrigated experimental area at the View Road site had reached equilibrium before the 2009/10 measurement period (Treweek 2011). Therefore, nitrogen leaching losses measured during Treweek (2011) and within this thesis are likely to be representative of future leaching losses when similar nitrogen loads are applied. However, further monitoring would be advised, especially at the higher loading rates.

Results from this thesis will help to assess whether an increase in nitrogen loading from 550 to 650 kg N ha^{-1} yr^{-1} would lead to leaching losses above 30 kg N ha^{-1} yr^{-1}. Mean nitrogen leaching losses from the high treatment were below the consented nitrogen leaching limit of 30 kg N ha^{-1} yr^{-1}. However, the application of 650 kg N ha^{-1} yr^{-1} was not achieved during this thesis, with a maximum of 567 kg N ha^{-1} yr^{-1}. For further discussion and recommendations about increasing the wastewater nitrogen application limits at the View Road site refer to Section 5.5.

CHAPTER FOUR – PERENNIAL RYEGRASS PRODUCTION AND NITROGEN REMOVAL UNDER WASTEWATER IRRIGATION AT TWO HARVESTING FREQUENCIES

4.1. INTRODUCTION

A perennial ryegrass crop (predominantly *Lolium perenne*) is cultivated at the View Road site. The pasture is harvested and sold in a cut and carry operation which removes wastewater nutrients and generates substantial income that helps to fund the wastewater irrigation scheme.

The ryegrass removes, on average, 84% of applied wastewater nitrogen (Treweek 2011). However, Treweek (2011) suggested there is potential to remove more nitrogen by increasing the frequency of harvesting events above four times a year. In order to prevent nitrogen leaching at the View Road site it is important to promote nitrogen removal by maximising pasture productivity, and thus, nitrogen uptake. Minimising nitrogen leaching protects groundwater resources and aquatic ecosystems, and promotes the sustainability of the wastewater disposal scheme. Maximising pasture production also improves economic return on pasture growth.

The objective of this experiment was to quantify dry matter production and nitrogen removal by pasture harvested at two harvesting frequencies in order to determine which harvesting frequency gave the greater pasture production and nitrogen removal thus, minimising nitrogen that is available to be leached. It is hypothesised that more pasture will be produced and nitrogen will be removed with a five week harvesting frequency than with a ten week frequency.

4.2. LITERATURE REVIEW

4.2.1. Overview

Harvesting frequency is defined as the interval of time between successive cutting events (Korte 1981). Frequent harvesting may lead to less pasture dry matter production than when a longer regrowth interval is allowed (Anslow 1967;

Bartholomew and Chestnutt 1977; Hazard and Ghesquiere 1997; Vinther 2006). For example, decreasing regrowth interval from five weeks (14.3 t ha^{-1} yr^{-1}) to four weeks (10.8 t ha^{-1} yr^{-1}), to three weeks (9.1 t ha^{-1} yr^{-1}) to two weeks (7.5 t ha^{-1} yr^{-1}), reduced the production of a perennial ryegrass pasture in Aberystwyth, Wales (Wilkins 1997). However, many studies aimed to find the minimal regrowth time that produced the highest pasture yield, or to examine pasture growth under low cutting height to simulate grazing.

Conversely, an infrequent harvesting regime may also produce less pasture than a shorter regrowth interval (Burton *et al.* 1963; Collins and McCarrick 1969; Le Clerc 1976; Bartholomew and Chestnutt 1977; Kunelius and Calder 1978; Fulkerson and Michell 1987; Kerrisk and Thomson 1990; Binnie *et al.* 1997; Schills *et al.* 1999; Onyeonagu and Asiegbu 2005). For example, more perennial ryegrass dry matter was produced a year under an 11 week harvesting regime than under a 16 week regime in a cutting study in Northern Ireland (Bartholomew and Chestnutt 1977). In addition, harvesting ryegrass pasture at six week intervals produced more pasture a year than harvesting at twelve week intervals in Nigeria (Onyeonagu and Asiegbu 2005). Onyeonagu and Asiegbu (2005) reported that harvesting at the nine week interval produced the same pasture yield as the six week interval; suggesting maximum possible pasture growth occurred before six weeks. Longer regrowth periods can create lower pasture yields due to a lower growth rate (less photosynthetic ability) of the older grass or by the loss of pasture through death and decomposition (Korte 1981).

4.2.2. Harvesting experiments

Mowing or cutting studies have been undertaken around the world with the majority of studies from Europe; Ireland (Collins and McCarrick 1969; Bartholomew and Chestnutt 1977; Binnie and Chestnutt 1991; Binnie *et al*. 1997), Wales (Wilman and Mares Martin 1977; Wilkins 1997), France (Hazard and Ghesquiere 1997), or the Netherlands (Schills *et al.* 1999). Studies from New Zealand include Hunt (1970), Hunt (1971) and Kerrisk and Thomson (1990).

Pastures within harvesting studies were unfertilised (Wilman and Mares Martin 1977; Schills *et al.* 1999) or had fertiliser application of up to 1500 kg N ha^{-1} yr^{-1} (Bartholomew and Chestnutt 1977). Nitrogen application was in the form of;

ammonia nitrate fertiliser (Kunelius and Calder 1978), a series of NPK compound fertilisers (Bartholomew and Chestnutt 1977; Kerrisk and Thomson 1990; Binnie *et al.* 1997; Wilkins 1997), nitro-chalk (Wilman and Mares Martin 1977), and calcium ammonium nitrate fertiliser (Schills *et al.* 1999). None of the pasture harvesting studies, which were examined, applied wastewater was or effluents.

Pasture was cut with; electric shears (Fulkerson and Michell 1987), a Haldrup plot harvester (Wilkins 1997), an Allen-Mayfield motor-scythe (Bartholomew and Chestnutt 1977), or an electric mower (Kerrisk and Thomson 1990; Binnie and Chestnutt 1991; Binnie *et al.* 1997; Hazard and Ghesquiere 1997; Schills *et al.* 1999; Vinther 2006).

In the literature examined, pasture in harvesting experiments was predominantly a perennial ryegrass. An important factor in the regrowth of perennial ryegrasses is cutting height (Whitehead 1995). Many studies cut pasture to a height of more than about 5 cm above the soil surface (Binnie *et al.* 1974; Kunelius and Calder 1978; Kerrisk and Thomson 1990; Hazard and Ghesquiere 1997; Schills *et al*. 1999). Yet there are also studies that cut pasture to a lower height of 2 to 3 cm (Bartholomew and Chestnutt 1977; Fulkerson and Michell 1987). Numerous studies have examined pasture production in grazed swards or have compared pasture yields of cut swards with shorter cutting heights to simulate grazed swards (Anslow 1967; Hazard and Ghesquiere 1997; Vinther 2006; Søegaard 2009).

Dry matter weight was generally determined by weighing fresh pasture, taking a subsample and then placing the subsample into an oven. Pasture samples were dried at 70^0C to 100^0C (Wilkins 1997; Zhang *et al.* 1995; Schills *et al*. 1999; Lee *et al*. 2009). However, some papers did not mention their dry matter methodology or temperature (Hunt 1970; Hunt 1971; Binnie and Chestnutt 1991; Onyeonagu and Asiegbu 2005). Herbage yield was calculated by multiplying the weight of the fresh sample by the mean dry matter content of each plot (Lee *et al*. 2009), and regrowth rate was calculated by dividing the dry matter produced by regrowth period (Anslow 1967). Where nitrogen yield was examined, samples were analysed for nitrogen content by the kjeldahl digestion method (Bartholomew and Chestnutt 1977; Zhang *et al*. 1995).

4.2.3. Growth phase, pasture production and pasture death

A grass leaf has limited growth. Once it reaches a final size, it remains on the plant without any active growth and then eventually dies (Korte 1981). The stages of herbage growth after a defoliation event have been established; the exponential growth phase, the linear growth phase, the asymptotic growth phase, and then death (Brougham 1955).

During the final phase of leaf growth (the asymptotic phase), pasture has little or no photosynthetic capacity, hence growth rate declines exponentially (Brougham 1955) and the pasture exerts energy on reproduction or flowering rather than elongation and growth (Hopkins and Hüner 2009). Metabolic changes involved in pasture aging (senescence) are controlled genetically. As a leaf ages, enzymes involved with degradation (for example, peptide hydrolases) increase while other enzymes become inactive, such as enzymes involved in nitrogen assimilation (for example, nitrate reducatse). However, timing and rate of senescence are influenced by external factors such as nutrient supply, light intensity and water stress (Whitehead 1995).

Pasture within the asymptotic phase creates a ceiling, intercepts light and shades younger tillers; further reducing photosynthesis and ability of pasture to grow (Brougham 1966; Hunt 1970). In a New Zealand study during spring, the maximum growth rate of a ryegrass and clover sward was reached after six weeks, at which point 95% of light was intercepted above the ground surface and photosynthesis was reduced (Hunt 1970). The decline of pasture production during asymptotic growth may be due to the increase of respiration rate relative to photosynthesis, or due to herbage loss from death and decay (Davidson and Donald 1958; Brougham 1959; Hunt 1971).

Harvesting frequency has an important influence on herbage death (Campbell 1964). Death and decomposition of herbage occurs during regrowth periods between cutting events. The dead pasture reduces the quantity and quality of herbage available at the subsequent harvesting event (Wilman and Mares Martin 1977). Too long an interval between cutting events allows the death of asymptotic pasture, resulting in the loss of dry matter through decay (Tayler and Deriaz 1963; Hunt 1970; Hunt 1971; Wilman and Mares Martin 1977). A higher percentage of dead herbage was measured with cutting frequencies longer than six weeks (Hunt 1971; Wilman and Mares Martin 1977), and it was suggested dead herbage can reduce dry matter production. In the absence of cutting and removal, the accumulation of plant litter can cause death of a pasture plant (Luff 1965).

4.2.4. Best harvesting frequencies

4.2.4.1. Seasonal harvesting frequencies

Grass growth generally follows a characteristic seasonal pattern in temperate regions; slow growth in late-winter, accelerating to a maximum in early-summer and then declining slowly until it halts in late-autumn (Whitehead 1995). Hunt and Brougham (1966) reported that a new leaf of unharvested Italian ryegrass grows approximately every 8 days in spring and about every 2.5 weeks in winter. Life of grass leaves differed from 3.5 weeks in spring to 8 weeks in winter (Hunt and Brougham 1966), illustrating a longer harvesting frequency is better in winter months. The need for seasonal variation in harvesting frequency within New Zealand was confirmed when daily pasture growth in response to cutting frequency was measured throughout different seasons (Kerrisk and Thomson 1990). Kerrisk and Thomson (1990) reported higher pasture growth rates in summer and autumn from pasture cut at a two week regrowth interval when compared to a four week interval. However, during winter the same pasture growth rates were measured within the four week and the thirteen week regrowth treatments (Kerrisk and Thomson 1990).

Many studies indicate that during the growing season in a temperate region there is little advantage in a harvesting interval longer than six weeks (Wilman *et al*. 1976; Frame *et al*. 1989; Kerrisk and Thomson 1990; Binnie *et al*. 1997; Chestnutt *et al*. 2006). In addition, extending the regrowth interval beyond six weeks decreases herbage digestible organic matter and thus, pasture quality (Binnie *et al*. 1997). When growth rates are reduced during the winter months, incorporation of a nine week regrowth interval may be suitable to produce maximum pasture yields (Binnie *et al*. 1997; Chestnutt *et al*. 2006).

4.2.4.2. Nitrogen application, harvesting frequency and pasture productivity

With the application of nitrogen fertiliser, pasture productivity increases (Whitehead 1995), therefore, so does the need to remove that pasture. For example with no nitrogen application, more dry matter was produced with a sixteen week regrowth interval than with a six week interval in Northern Ireland (Bartholomew and Chestnutt 1977). However, with the application of 600 kg N ha^{-1} fertiliser, Bartholomew and Chestnutt (1977) reported more total pasture production with a six week regrowth interval than with a sixteen week interval. The combination of greater herbage mass and a long regrowth interval produces longer periods of intense shading, which can increase pasture death (Williams 1970). The application of fertiliser hinders the death of pasture leaves up to two to three weeks after application. However, after three weeks, fertiliser application subsequently accelerates leaf death (Whitehead 1995). More dead herbage (2180 kg DM ha^{-1}) was harvested when 525 kg N ha^{-1} of nitrogen fertiliser was applied at an infrequent harvesting regime of ten weeks, when compared to dead herbage (1160 kg DM ha^{-1}) with no fertiliser application (Wilman *et al*. 1976). Damage caused with the combination of infrequent cutting and high nitrogen application can reduce ground cover (Bartholomew and Chestnutt 1977). Decreased ground cover damage can be reduced by increasing the frequency of harvesting events (Simons *et al*. 1974).

4.2.5. Nitrogen removal and harvesting frequency

The nitrogen concentration of perennial ryegrasses were been reported as lower in an infrequent harvesting regime than with an increased harvesting frequency (Zhang *et al*. 1995; Binnie *et al*. 1997; Vinther 2006). For example, in Atlanta, United States of America, Kunelius and Calder (1978) reported the total nitrogen component of an Italian ryegrass to decrease when regrowth interval was increased from four (3.5%) to six (3.0%) weeks. Results showed a similar trend in all 3 years of the study (Kunelius and Calder 1978).

However, cutting intervals longer than six weeks have been reported to have little or no consistent effect on the total nitrogen yield (Binnie and Chestnutt 1991; Schills *et al*. 1999). For example, nitrogen removal by pasture cut after a six week regrowth interval (319 kg N ha^{-1} yr^{-1}) was not significantly different than with a seven week (311 kg N ha^{-1} yr^{-1}), an eight week (308 kg N ha^{-1} yr^{-1}) or a nine week (327 kg N ha^{-1} yr^{-1}) regrowth interval in Northern Ireland (Binnie *et al*. 1997). Binnie *et al*. (1997) reported that during the growing season and with the application of fertiliser, nitrogen uptake by pasture reaches a maximum at around six weeks.

4.2.6. Summary of literature review

Harvesting frequency influences pasture growth rate, total pasture yield and herbage death. However, there is no clear "best harvesting frequency" identified in the literature. A too frequent or too infrequent harvesting regime can lower pasture production. Within infrequent harvesting regimes, reduced production is caused by asymptotic growth, shading, or death and decay.

With the application of nitrogen fertiliser pasture regrowth interval should be decreased. However, no studies reported pasture production and harvesting frequency with the application of wastewater or effluent.

Harvesting regimes should be altered seasonally. Many studies suggest that during the growing season, in temperate regions, there is little advantage of a harvesting frequency longer than six weeks with the incorporation of a nine week regrowth interval in winter months. However, this was concluded from international studies as minimal New Zealand literature was available. It is hard to conclude a best harvesting regime for the View Road land based disposal site based on literature.

4.3. METHODOLOGY

4.3.1. Overview

An area of pasture at the View Road site was divided into twelve sections and harvested approximately once every five or once every ten weeks from January 2012 (mid-summer) to November 2012 (late-spring). During the trial period 265 kg N ha^{-1} of wastewater nitrogen was applied. Pasture was collected, and the dry matter production and nitrogen component were quantified.

4.3.2. Experimental design

The harvesting frequency experiment was installed on the 26th of January 2012 in an area of pasture underneath pivot F at the View Road site (Figure 4.1).

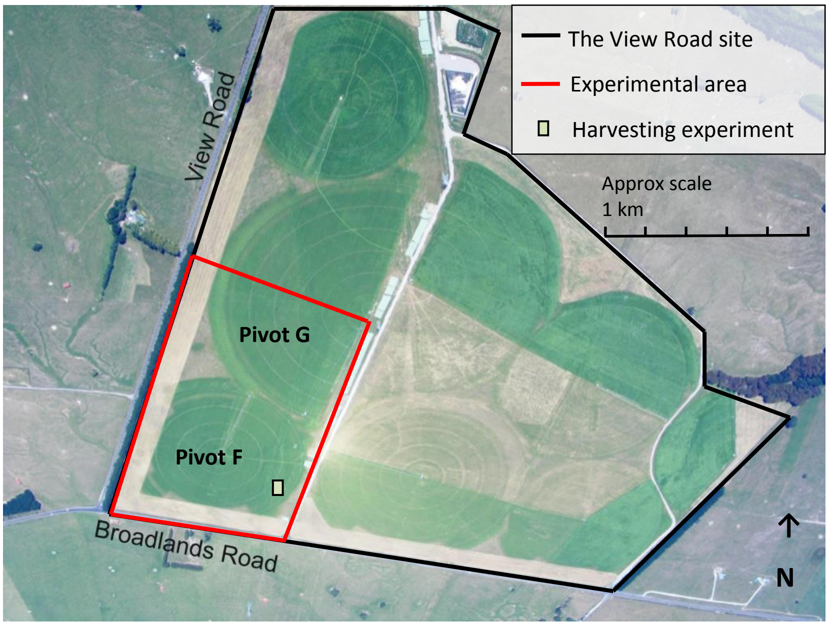

Figure 4.1. Location of the harvesting frequency experiment at the View Road land based wastewater treatment site.

The area of pasture (9 m x 12 m) was divided into twelve sections (Figure 4.2). Wooden pegs were installed to create 1 m x 1 m plots surrounded by a 1 m buffer (Figure 4.3). Two treatments were randomly assigned; nominally a five week and a ten week harvesting frequency.

Figure 4.2. The harvesting frequency experiment installed at the View Road site.

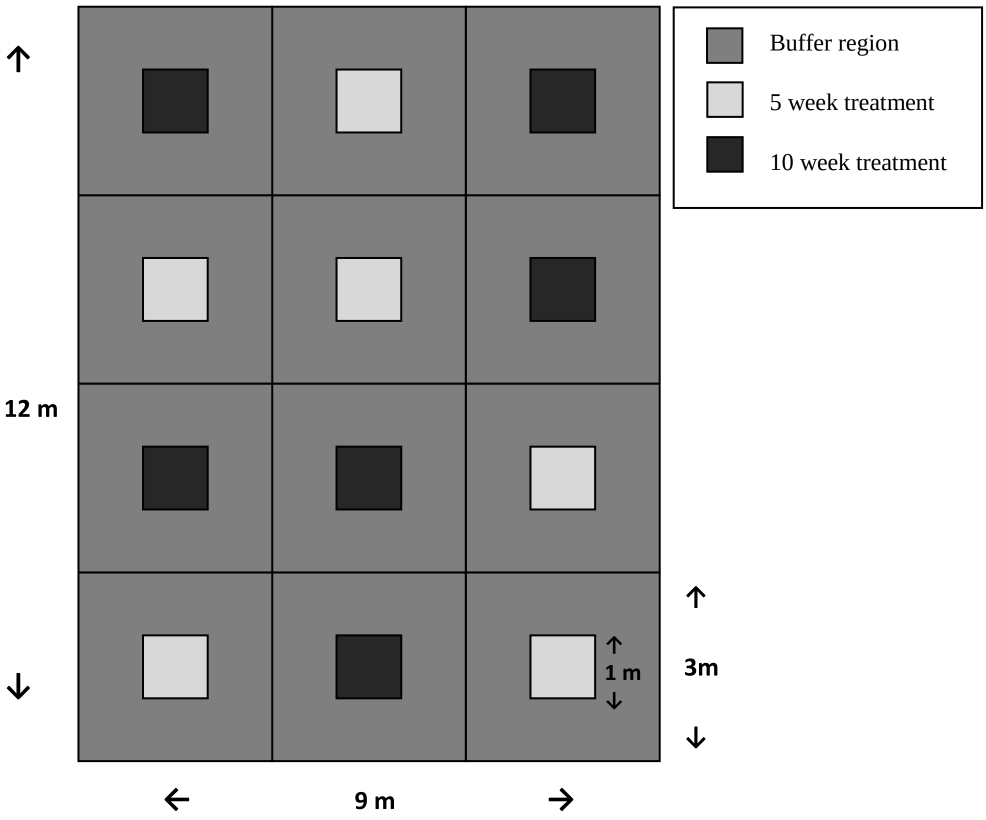

Figure 4.3. **Experimental design of the harvesting frequency experiment.**

4.3.3. Pasture collection

Pasture plots were harvested at either a five or a ten week regrowth interval. Buffers strips were removed when pasture plots were harvested (at either five or ten weeks). Grass growing within buffer strips was removed with a linetrimmer. (Figure 4.4a) and mown to a height of 7 cm with a lawnmower. The lawnmower was used to cut straight lines directly around the pasture plots at a height of 5 cm (Figure 4.4b). Additional grass that had fallen onto pasture plots was removed using a rake (Figure 4.4c).

Wooden stakes surrounding the pasture plot were removed and the area of the pasture plot was measured with a measuring tape (Figure 4.4d). The lawnmower bag was emptied and all extra grass within the bag and underneath the lawnmower was removed.

Pasture growing within each plot was cut to 7 cm — the same height as cut by the harvest machinery (Figure 4.4e) — with the lawnmower and collected in a paper bag (Figure 4.4f). Remaining harvested grass within the lawnmower bag, attached underneath the lawnmower or on the pasture plot was collected by hand or with a rake and added to the sample bag. The wooden stakes were replaced and paper bags were returned to the laboratory for analysis.

Figure 4.4. Steps in pasture harvest. a) A linetrimmer was used to remove grass growing within buffer regions. b) Buffer regions are mowed a height of 7 cm and grass growing directly around the pasture plot mowed to 5 cm, creating the straight lined pasture plot. c) Additional grass that had fallen onto the pasture plots removed with a rake. d) Plot length was measured to give the area of pasture collected. e) Grass growing within the pasture plot was mowed to a height of 7 cm. f) Herbage was collected into a paper bag.

4.3.4. Dry matter and nitrogen analyses

Dry matter weight and the nitrogen concentration of pasture were determined following the method described in section 3.2.3.2.

4.3.5. Statistical analysis

Statistical analysis was undertaken with STATISTICA Version 11. One way ANOVA was performed and post hoc tests (Tukey honest significant difference test) were undertaken. The difference between treatments was considered significant if $P < 0.05$. Means are presented ± 1.96 x standard error.

4.4. RESULTS

4.4.1. Overview

The results examined below include the definition of harvesting treatments, rainfall and temperature values during the trial period and a five year mean, total and seasonal pasture production and nitrogen removal, and a brief nitrogen balance for each of the harvesting frequencies. Full datasets are presented in Appendices 11 to 13.

4.4.2. Harvesting treatments

Treatments were intended to have a five week (35 days) or a ten week (70 days) interval between pasture collections. However, due to weather, cutting intervals were not exactly 35 or 70 days (Table 4.1).

Table 4.1. The date and number of days between pasture collections for the five week and ten week harvesting treatments from the 26th of January 2012 to the 15th of November 2012.

Harvest	Date	Days between harvest	
		"5 week" treatment	"10 week" treatment
Installation	26/01/2012	-	-
1	1/03/2012	35	-
2	13/04/2012	43	78
3	19/05/2012	36	-
4	22/06/2012	34	70
5	2/08/2012	41	-
6	6/09/2012	35	76
7	11/10/2012	35	-
8	15/11/2012	35	70

4.4.3. Rainfall

Rainfall for the period of January to November 2012 (923 mm) was higher than the previous five year mean (843 mm), as a result of the wetter summer months. January 2012 had 40 mm more rainfall and February had 59 mm more rainfall than the five year mean (Figure 4.5). Rainfall during the autumn months (March, April, and May) and the winter months (June, July, and August) fluctuated above and below the five year mean. The spring months (September, October, and November) were similar to the five year mean, with low rainfall during November.

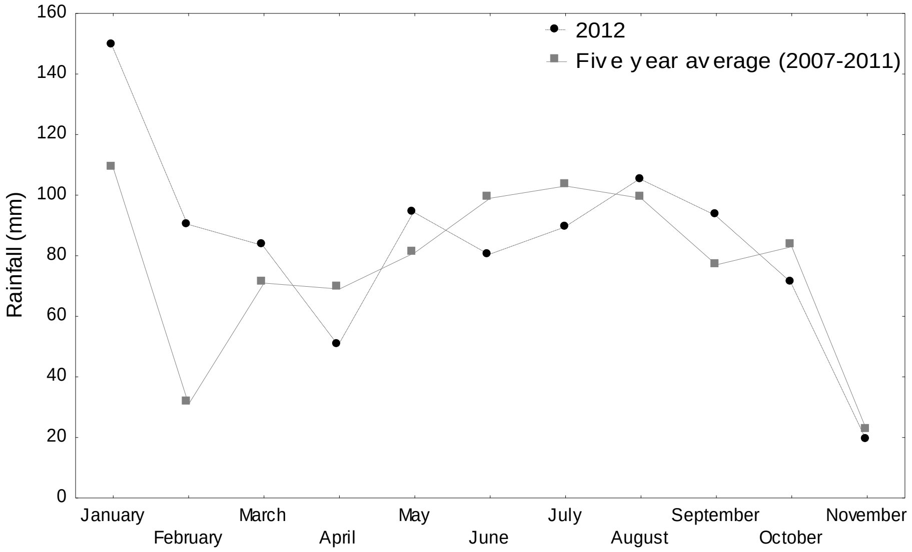

Figure 4.5. Rainfall recorded at the Taupō airport (8 km south-west of the View Road) for 2012 and a mean of rainfall values for the five previous years (2007 – 2012). ***Rainfall data supplied by NIWA (2013).***

4.4.4. Temperature

Temperature during 2012 and the five year mean decreased from February to a minimum in July (Figure 4.6). Temperature increased from July until December. Temperature was lower during January to July and October to November 2012 than the previous five year mean.

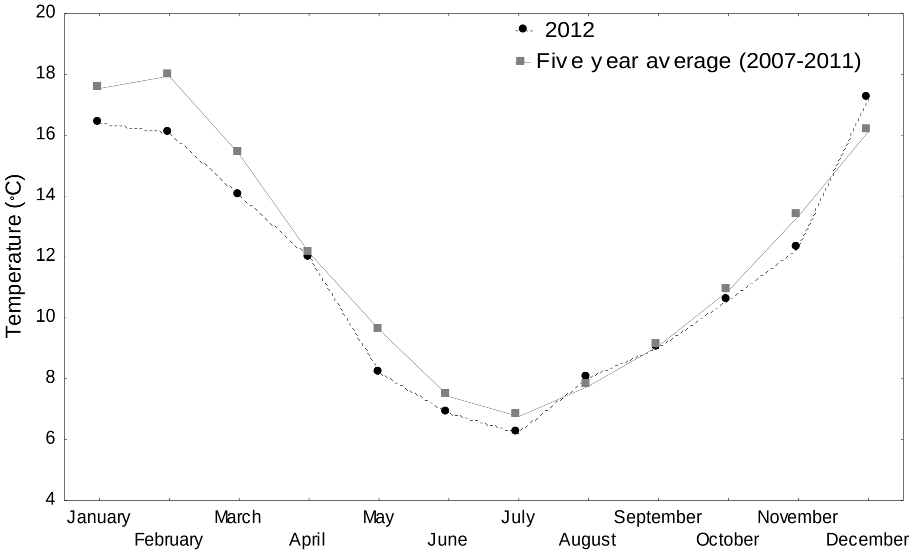

Figure 4.6. Temperature recorded at the Taupō airport (8 km south-west of the View Road) for 2012 and a mean of temperature values for the five previous years (2007 - 2012). ***Temperature data supplied by NIWA (2013).***

4.4.5. Pasture dry matter

Mean pasture dry matter was 877 kg DM ha^{-1} higher ($P < 0.05$) in the five week treatment (8231 ± 186 kg DM ha^{-1}) than in the ten week treatment (7354 ± 67 kg DM ha^{-1}) (Figure 4.7).

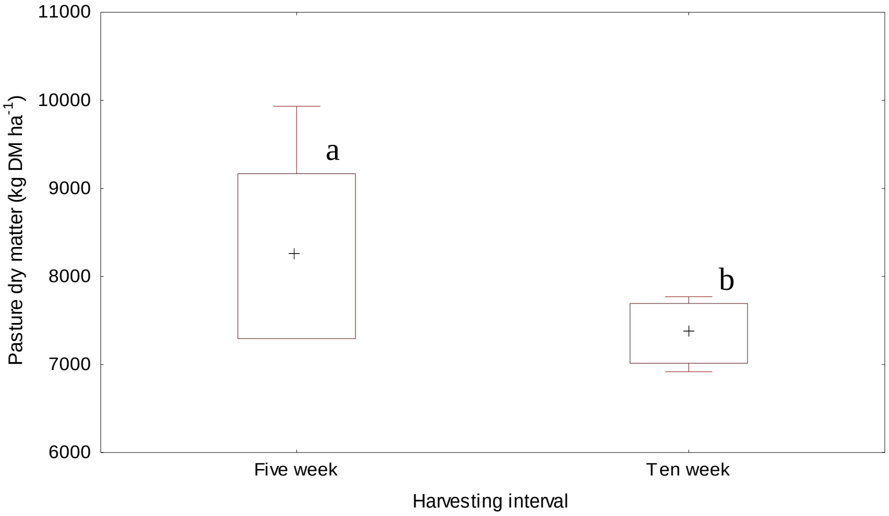

Figure 4.7. Total pasture dry matter produced within a five week and a ten week harvesting frequency treatment from the 26th of January 2012 to the 15th of November 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals, and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments (P < 0.05).***

4.4.6. Nitrogen removal

Over the trial period, the mean nitrogen concentration in pasture was higher ($P < 0.001$) in the five week treatment (3.2%) than in the ten week treatment (2.8%). Mean nitrogen removal was 59 kg N ha^{-1} higher ($P < 0.001$) with the five week harvesting frequency (250 ± 5 kg N ha^{-1}) than in the ten week treatment (191 ± 3 kg N ha^{-1}) (Figure 4.8).

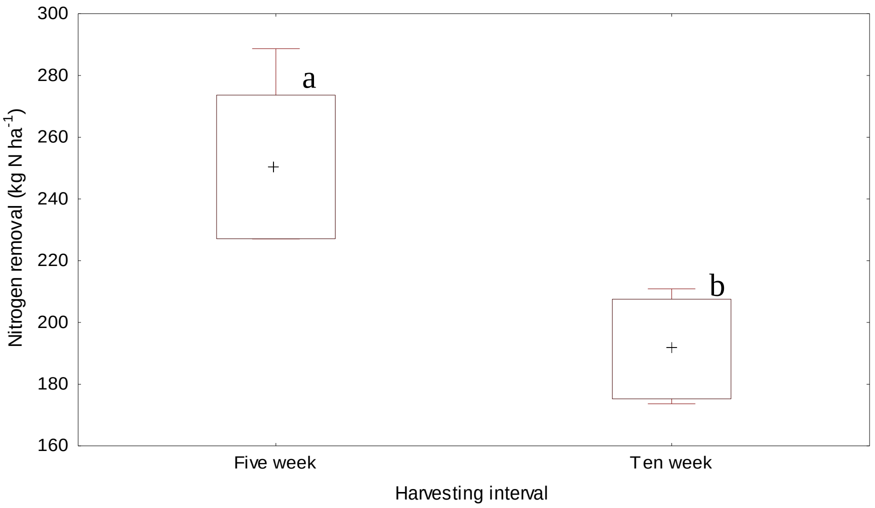

Figure 4.8. Total nitrogen removed by pasture within a five week and a ten week harvesting frequency treatment from the 26th of January 2012 to the 15th of November 2012. ***Crosses represent the mean value, boxes represent 0.95 confidence intervals, and whiskers represent the maximum and minimum values. Letters illustrate significant difference between treatments ($P < 0.05$).***

4.4.7. Seasonal dry matter production and nitrogen removal

From January to April, pasture production was higher under the five week harvesting frequency than in the ten week treatment ($P < 0.05$) (Figure 4.9). From April to July, pasture production was similar between the treatments and from July to September pasture production was observed to be higher under the ten week treatment. Pasture production in the harvesting treatments was similar from late-September until the remainder of the trial. However, pasture production in the five week treatment was observed to increase, relative to the ten week treatment, after October.

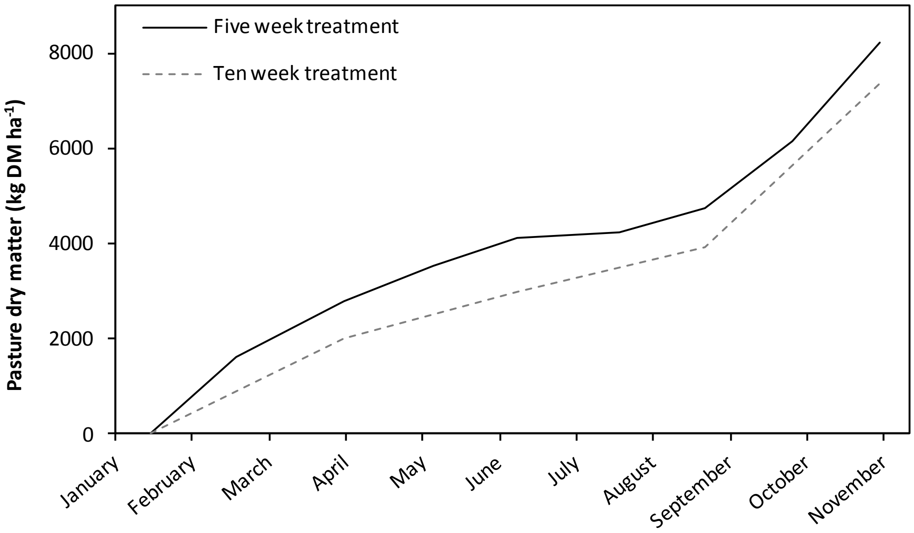

Figure 4.9. Cumulative mean dry matter produced within a five week and a ten week harvesting frequency treatment from the 26th of January 2012 to the 15th of November 2012.

Seasonal nitrogen removal (Figure 4.10) had a similar seasonal pattern to pasture production (Figure 4.9). However, differences in nitrogen removal between the five week and the ten week treatment were larger, relative to the differences in pasture production, from September to November.

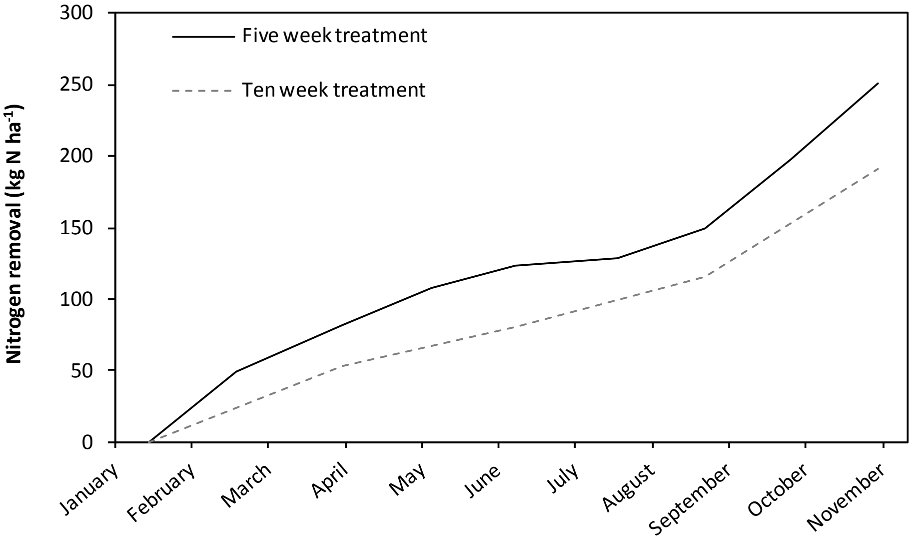

Figure 4.10. Cumulative mean nitrogen removal within a five week and a ten week harvesting frequency treatment from the 26th of January 2012 to the 15th of November 2012.

4.4.8. Nitrogen balance

During the trial period, significantly more nitrogen was removed by plant uptake within the five week treatment (equivalent to 96% of the nitrogen input) than within the ten week treatment (equivalent to 73% of the nitrogen input) (Table 4.2). Therefore, more nitrogen was accounted for, and less nitrogen was available to potentially be leached within the five week treatment.

Table 4.2. Nitrogen input, pasture production, nitrogen removal and the mean proportion of nitrogen input that was removed by pasture for each harvesting frequency treatment from the 26th of January to the 15th of November 2012.

Treatment	Nitrogen input (kg N ha^{-1})	Pasture production (kg DM ha$^{-1)}$	Nitrogen removal (kg N ha^{-1})	Plant removal (% of nitrogen input)
Five week	265	8231 ± 186	250 ± 5	96 ±7
Ten week	265	7354 ± 67	191 ± 3	73 ± 5

4.5. DISCUSSION

4.5.1. Seasonal pasture growth and nitrogen removal

Pasture growth varies between years and seasons within New Zealand (Baars *et al*. 1991). Pasture growth in both the five week and the ten week treatments followed the characteristic seasonal pattern in temperate regions (Whitehead 1995) (Figure 4.9). Seasonal differences in pasture growth were more pronounced in the five week treatment than in the ten week treatment.

Pasture growth within the five week treatment was rapid from the beginning of the trial in January (mid-summer) to June (late-autumn). Rapid pasture growth during late-summer to mid-autumn is characteristic for the Waikato region of New Zealand (Baars *et al*. 1991), especially in pastures that are not limited by nitrogen input (Bartholomew and Chestnutt 1977; Binnie *et al.* 1997). During this time, pasture growth at the View Road site appeared to reach maximum growth at, or before, the end of the five week interval. Bartholomew and Chestnutt (1977) reported ryegrass pastures to reach maximum growth between six weeks and ten weeks growing interval with the application of 600 kg N ha^{-1} fertiliser in Ireland. Binnie *et al.* (1997) also reported maximum pasture growth at a six week interval during the late-summer to early-autumn period under the application of 416 kg N ha yr^{-1} in Northern Ireland. Extending the growing time to ten weeks during late-summer at the View Road site meant pasture entered the asymptotic growth phase, grew a ceiling, and decreased photosynthetic capacity and thus ability to grow. Over a two year trial in Taranaki, New Zealand, Kerrisk and Thomson (1990) reported greater pasture production, during summer and autumn, with a cutting interval less than 30 days. The influence of cutting interval in Kerrisk and Thomson (1990) was more pronounced in the “wet” summer of 1985/86 and the “wet” autumn of 1987, than compared to the “dry” autumn of 1986 and the “dry” summer of 1986/87. With high rainfall in Taupō during the 2012 summer (Figure 4.5) and the application of wastewater during the summer and autumn months, water limitations did not restrict pasture growth at the View Road site. Therefore, pasture could thrive and the effect of cutting interval on pasture production was enhanced.

Pasture production in the five week treatment was steady during autumn and the early-winter months (March to June). However, production within the five week treatment almost halted in the late-winter months (July and August). Pasture growth is slower during winter months with shorter days (less exposure to sunlight) and lower temperatures (Figure 4.6) (Hopkins and Hüner 2009). However, pasture production in the ten week treatment was constant from late-autumn to late-winter (April to September). Dry matter production during the first half of the ten week interval may have compensated for the low production rate that occurred during the second half of the growth interval (mid-July to late-August). The life of a blade of unharvested Italian ryegrass is about eight weeks in winter (Hunt and Brougham 1966), illustrating a longer harvesting frequency is suitable during winter months. Pasture growth during winter in Taranaki, New Zealand was unaffected by harvesting interval (Kerrisk and Thomson 1990). However, Kerrisk and Thomson (1990) reported maximum pasture growth at six weeks during winter.

During the beginning of spring (September to October) pasture production within both the five week and ten week treatments began to accelerate at a similar rate (Figure 4.9). Binnie *et al.* (1997) reported pasture production to continue to increase after a nine week growth interval during spring in Northern Ireland, indicating that maximum yields had not been achieved. Results from Binnie *et al*. (1997) and Wilman *et al*. (1976) suggest that there is an advantage in extending regrowth intervals beyond six weeks during late-spring to early-summer. The advantage of a longer regrowth interval on pasture growth has been attributed to uninterrupted growth during the reproductive growth stage in the early part of the season, therefore, higher growth rates (Binnie *et al*. 1997).

While production was similar in the five week and the ten week treatment during the beginning of spring; dry matter production within the five week treatment continued to increase, relative to the ten week treatment, towards the end of the trial in late-spring. The View Road experiment began in late-January and ended in mid-November. Therefore, the influence of harvesting frequency on pasture yields during late-spring and early- to mid-summer were not monitored. It is expected pasture production within the five week trial will continue to increase, relative to the ten week treatment, and more pasture will be produced in the five week treatment until late-autumn of the following year. While Kerrisk and Thomson (1990) reported no difference between the medium (15 day) and infrequent (30 day) cutting treatment during spring, the more frequent (10 day) harvesting frequency produced more pasture during summer. During the “dry” summer, difference in pasture growth between the medium and infrequent cutting treatment was small. However, during the “wet” summer the difference in pasture production was emphasized (Kerrisk and Thomson 1990). With the irrigation of wastewater at the View Road site there are no water limitations during the summer months, therefore, summer drought will not restrict pasture growth as it did during the “dry” summer reported in Kerrisk and Thomson (1990).

Seasonal nitrogen removal (Figure 4.10) followed a similar pattern to seasonal pasture production (Figure 4.9). The only main difference is that more nitrogen was removed from September onwards relative to the amount of pasture produced. The nitrogen concentration of pasture that was harvested during spring (September and October) (3.7%) was significantly higher ($P < 0.001$) than the nitrogen concentration of pasture during autumn and winter (March to August)

(3.0%). Therefore, even with less pasture production, more nitrogen was removed by pasture during this time. Binnie *et al*. (1991) reported higher nitrogen concentration in pasture harvested during spring in comparison with pasture harvested in late-summer to early-autumn. As pasture reaches maturity, the nitrogen concentration of leaves decrease (Whitehead 1995). With slower pasture growth during the early-spring months it is possible nitrogen decreases are also slowed. Therefore, less nitrogen may have been lost by the slower aging of pasture during late-spring in comparison to a time when pasture thrives and reaches senescence earlier.

Harvesting at shorter intervals during late-November to May (late-spring to late-autumn) and longer intervals from May until early-November (late-autumn to mid-spring) may be the most suitable harvesting regime at the View Road site.

4.5.2. Total pasture dry matter production

Total dry matter production over the ten month trial was, on average, 877 ± 152 kg DM ha^{-1} higher ($P < 0.05$) in the five week harvesting treatment (8231 ± 186 kg DM ha^{-1}) than in the ten week treatment (7354 ± 67 kg DM ha^{-1}). The interaction between harvesting frequency and pasture production confirmed the observation of Kunelius and Calder (1978) and Binnie *et al*. (1997); that there is little advantage in increasing harvesting interval beyond around six weeks, except for during the winter months.

Conversely, Fulkerson and Michell (1978) reported no difference in dry matter yield, in a ryegrass clover sward, between a four week and a sixteen week harvesting interval in north-western Tasmania, Australia. In addition, more dry matter was produced in the twelve week interval than the four week interval (Fulkerson and Michell 1978). There were also minimal pasture losses by death and decay in this study. The mass of dead material collected from the four week treatment was not different to the mass of dead material collected from the sixteen week treatment. However, pastures within Fulkerson and Michell (1978) were not fertilised. Bartholomew and Chestnutt (1977) reported that with the application of fertiliser over the three year trial, a six week harvesting treatment produced more dry matter than the sixteen week treatment. Therefore, applying nitrogen to pastures means more harvesting events are needed.

Pasture at the View Road site thrived under the application of wastewater as there are no water or nitrogen limitations. Once pasture ages and reaches the asymptotic growth phase, herbage has little additional or no photosynthetic capacity. Therefore, growth rate declines and pasture reaches its maximum yield.

Literature suggests that pasture can be lost through death and decay with a long regrowth interval (Tayler and Deriaz 1963; Hunt 1970; Hunt 1971; Wilman and Mares Martin 1977). While no objective assessment of dead material accumulation was made within the View Road study, significant accumulation was not obvious, mirrored in the findings of Bartholomew and Chestnutt (1977). It is unlikely death would have a strong influence on pasture yield under a ten week harvesting frequency at the View Road site under the irrigated conditions. Hunt (1965) suggested that dead matter would decompose rather than accumulate in moist conditions, such as those under effluent irrigation.

At the View Road site, pasture production was greatest within the five week harvesting treatment.

4.5.3. Total nitrogen uptake and yield

Plants generally contain 1 to 5% nitrogen on a dry weight basis (Haynes 1986; Hopkins and Hüner 2009). The mean nitrogen concentration of pasture over the duration of my study was higher ($P < 0.05$) in the five week treatment (3.2%) than in the ten week treatment (2.9%). The concentration of herbage nitrogen continually declines with advancing maturity and has been attributed to changes in leaf tissue that occur with leaf senescence (Whitehead 1995). As herbage matures, nitrogen proportion gradually increases in cell wall material and decreases in the cytoplasm. The cytoplasm is the substance within cell membrane which contains enzyme proteins, nucleic acids and chlorophyll (Whitehead 1995).

The lower nitrogen concentration of older pastures has also been attributed to a decrease in uptake relative to an increase in losses. Nitrogen has been reported to be lost from senescent leaves with leaching from rainfall and volatilisation of ammonia that occurs with death and decay (Wetselaar and Farquhar 1980; Sutton *et al*. 1993; Whitehead 1995). Increasing cutting interval beyond four weeks generally decreases the nitrogen concentration of pasture (Kunelius and Calder 1978; Zhang *et al*. 1995; Binnie *et al*. 1997).

Pasture harvest within the five week treatment removed, on average, 59 kg N ha^{-1} more nitrogen than within the ten week treatment over the 10 month trial. Nitrogen yield was largely dependent on pasture yield and nitrogen uptake by herbage. The lower nitrogen yields of older pasture have been explained by low uptake that occurs with decreased pasture growth when pasture creates a ceiling level (Colman and Lazenby 1970; Bartholomew and Chestnutt 1977). For example, lower nitrogen yields were reported during an eleven and a sixteen week harvesting frequency than in a six week interval (Bartholomew and Chestnutt 1977).

The rate of nitrogen uptake is greatest during the first phase of growth (exponential growth phase). The total amount of nitrogen that can be taken up by herbage reaches a peak a few days before maximum herbage yield (the linear growth phase) (Brougham 1955; Whitehead 1995). Nitrogen uptake decreases during the later stages of senescence when disintegration of a leaf's membrane tissue occurs, therefore, nitrogen uptake (further translocation of nitrogen in the phloem) is restricted (Whitehead 1995).

Not only does nitrogen uptake decrease in older pasture, but nitrogen can become remobilized within a pasture plant; nitrogen removal from external sources decreases while the nitrogen concentration of a pasture leaf is further reduced (Hunt 1983; Robinson and Deacon 1987). Significantly less ($P < 0.05$) of the applied nitrogen was removed by pasture in the ten week treatment than in the five week treatment (Table 4.2), therefore, more nitrogen is available to potentially be leached. From the 265 kg N ha^{-1} wastewater input, 4% was unrecovered within the five week treatment while 27% was unrecovered within the ten week treatment. However, while more nitrogen was unrecovered within the ten week treatment, it does not necessarily mean it was leached, but instead could be converted to gaseous nitrogen. There was no direct measurement of nitrogen leaching during this experiment.

Studies have found that with high application of nitrogen, the response of nitrogen uptake was greatest under a more frequent cutting regime (Kunelius and Calder 1978; Chestnutt *et al*. 2006). Wilman (1975) observed a decline in nitrogen yield if harvesting intervals exceeded nine weeks. The decline was associated with pasture death and decay or from leaching of nitrogen from the senescent herbage. This theory was accepted in the eleven week and sixteen week harvesting treatments in Bartholomew and Chestnutt (1977). Conversely, Binnie *et al.* (1997) saw no consistent increase in nitrogen yield between a five, six, seven, eight or nine week cutting interval.

At the View Road site, the harvesting frequency which produced the greater nitrogen removal was the five week treatment.

4.5.4. Harvesting frequency at the View Road site

4.5.4.1. Current harvesting regime at the View Road site

During the lysimeter experiment within this thesis (Chapter 3) and a previous lysimeter study at the View Road site (Treweek 2011) the commercial field harvesting events occurred four times a year (Table 4.3). Pasture was harvested in January and March in both studies, with nine and eight weeks between harvesting events. During the autumn and winter months pasture was not harvested, with a harvesting event occurring in September or October (29 and 26 weeks from the March harvest). The five week and the ten week harvesting intervals examined within this experiment are far from the current harvesting regime at the View Road site.

Table 4.3. Date of field harvests and weeks between harvesting events. Note the different starting dates of each experiment.

Harvest number	2009 - 2010 Treweek (2011)		2011 - 2012 Lysimeter experiment (Chapter 3)	
	Date of harvest	Weeks between harvests	Date of harvest	Weeks between harvests
Installation	8/12/2009	-	8/9/2011	-
1	29/1/2010	7	31/10/2011	8
2	30/3/2010	9	21/1/2012	12
3	18/10/2010	29	16/3/2012	8
4	15/12/2010	8	17/09/2012	26

The commercial harvesting contractors charge a flat rate, to the Taupō District Council, of $34 a bale to harvest pasture at the View Road site (B. Mayhill 2013 pers. com). To perform each field harvest comes at a cost to the contractors, therefore, growing time is usually extended to ensure pasture production is maximised, even if more total pasture may be produced from the site if the pasture is harvested more frequently.

4.5.4.2. The five week versus the ten week harvesting frequency

Harvesting pasture at five week intervals removed 96% of the 265 kg N ha^{-1} applied wastewater nitrogen, while harvesting at ten week intervals removed 73%. Therefore, a greater amount of nitrogen was removed with a five week harvesting interval, meaning less nitrogen (23%) was available to potentially be leached. If the consented nitrogen loading limits at the View Road site are increased from 550 to 650 kg N ha^{-1} yr^{-1}, maximising nitrogen removal by pasture is vital to prevent nitrogen leaching from site.

Within the measurement period of late-January to late-November, more pasture was produced in the five week treatment than in the ten week treatment. Therefore, harvesting at five week intervals may profit the Taupō District Council (Table 4.4). The amount of profit depends on pasture quality. During the measurement period, adjusting harvesting frequency from four cuts (ten week treatment) to eight cuts (five week treatment) was predicted to generate, depending on pasture quality, \$23 600 (low grade pasture quality), \$30 300 (high grade pasture quality), or \$ 37 000 (premium grade quality pasture) more profit for the Taupō District Council (Table 4.4).

High quality herbage, in terms of digestibility, was reported when harvesting interval is less than six weeks (Binnie *et al*. 1974; Frame *et al*. 1989; Binnie *et al*. 1997), especially with the application of nitrogen (Bartholomew and Chestnutt 1977). Extending harvesting interval to ten weeks decreases herbage digestibility (Bartholomew and Chestnutt 1977). Pasture quality, herbage grade, and the amount of money that can be made from baylage are likely to be higher when pasture is harvested at five week intervals than at ten week intervals at the View Road site.

However, pasture production did vary seasonally. Pasture production was greater in the five week harvesting treatment from the beginning of the trial (mid-summer) until June (late-autumn). From June to mid-August (late-winter) pasture growth within the five week treatment and the ten week treatment were similar, if not less in the five week treatment. Therefore, a ten week harvesting frequency was more suitable during this time. From mid-August (late-winter) until October (mid-spring) there was no real difference in pasture production. However, pasture production in the five week treatment continued to increase, relative to the ten week treatment, towards the end of the trial in late-spring. Therefore, it is presumed a five week interval will produce more pasture than a ten week interval from late November to mid-January.

4.5.4.3. A seasonally adjusted harvesting regime

A seasonally adjusted harvesting regime is recommended for the View Road site; harvesting at five week intervals during late-November to May (late-spring to late-autumn) and ten week intervals from May until early-November (late-autumn to mid-spring).

Harvesting at shorter intervals during late-November to May is likely to optimise pasture production and nitrogen removal at the View Road site. Results from Wilman *et al*. (1976) and Binnie *et al*. (1997) agree that there is no advantage to be gained by lengthening the regrowth interval beyond six weeks during early-summer to late-autumn.

Harvesting at longer intervals during May until early-November will maximise pasture production during the late-autumn and winter months. A less frequent harvesting regime also decreases the cost to the harvesting contractors for performing the field harvests during this time. Results from Kerrisk and Thomson (1991) and Binnie *et al*. (1997) recommend nine week intervals to be more suitable than shorter intervals during late-autumn, winter and early-spring.

When dry matter production during the four harvests (late-January to late-June) in the five week treatment was combined with the dry matter produced during the last two harvests (late-June to mid-November) in the ten week treatment, pasture dry matter was calculated to be 8483 ± 282 kg DM ha^{-1}. Therefore, pasture dry matter production is predicted to be higher with a seasonally adjusted combination of five and ten week harvesting intervals, than in the primarily five week or ten week harvesting treatments. Nitrogen removal within the seasonally adjusted regime was calculated to be 234 ± 7 kg N ha^{-1}, which was less than within the five week treatment (250 ± 5 kg N ha^{-1}), but higher than the ten week treatment (191 ± 3 kg N ha^{-1}).

The predicted seasonally adjusted harvesting regime was predicted to produce the greatest pasture; therefore, it may produce the most profit for the Taupō District Council (Table 4.4). The amount of profit depends on pasture quality. During the measurement period of late-January to late-November, adjusting harvesting frequency from four cuts (ten week treatment) to six cuts (predicted seasonally adjusted treatment) was predicted to generate, depending on pasture quality, $30 400 (low grade pasture quality), $39 000 (high grade pasture quality), or $47 600 (premium grade quality pasture) more profit for the Taupō District Council (Table 4.4).

Table 4.4. Cost analysis of harvesting treatments from late-January to late-November.

Treatment (number of harvests)	**Dry matter (t DM ha^{-1})**	**Total dry matter (t DM)**	**Number of bales**	**Contractor cost at $34 a bale ($)**	**Total profit (after the cost of the harvest) for Taupō District Council**		
					Low grade baylage	**High grade baylage**	**Premium grade baylage**
Ten week (4)	7.4	875.1	4862	$165 300	$198 120	$254 030	$309 940
Seasonal (6)	8.5	1009.5	5608	$190 690	$228 550	$293 040	$357 540
Five week (8)	8.2	979.5	5442	$185 020	$221 750	$284 320	$346 900

- DM = Dry matter, ME = Metabolisable energy
- Low grade = no guaranteed level of ME and DM, High grade = ME > 9, Premium grade = ME > 10.5
- Costing assumptions (B. Mayhill 2013 pers. com.) are: (1) bales weigh 600 kg, (2) bales contain 30% DM, (3) there are 119 ha of ryegrass pasture at the View Road site, (4) contractors charge $34 a bale, (5) bales cost (bales cost GST exclusive) are $75 ($65) for low grade, $86 ($75) for high grade, $98 ($85) for premium grade.

4.5.5. Discussion of methodology and limitations

In cutting experiments, pasture was grown under normal or fertilised conditions and different cutting intervals were applied. None of the reported studies investigated the effect of harvesting interval on pasture production under the application of wastewater. While fertiliser provided vital nutrients, water could still limit pasture growth, especially during summer. The irrigation of wastewater onto pasture at the View Road site provided vital nutrients and water, allowing pasture to thrive. With the application of wastewater to pasture at the View Road site, production was greatly increased in comparison to unirrigated pastures (refer to section 3.33). Therefore, there is a need to harvest wastewater irrigated pastures often.

In cutting studies, an area of pasture was set aside, divided into pasture plots, and randomly assigned treatments. At the View Road site, pasture plots were also randomly assigned with harvesting treatments (six replicates of each). While six plots is considered a low number of replicates (Utts and Heckard 2006), treatments within literature were commonly only replicated four times (Bartholomew and Chestnutt 1977; Kunelius and Calder 1978; Kerrisk and Thomson 1990; Binnie *et al*. 1997).

Pasture plots within the View Road experiment were about 1 x 1 m. Pasture plots reported in literature were often larger; 4.6 x 1.83 m (Bartholomew and Chestnutt 1977), 3 x 2 m (Fulkerson and Michell 1987), 6 x 1.3 m (Wilman and Mares Martin 1987), 5.0 x 1.5 m (Binnie *et al*. 1997), 6 x 0.7 m (Schills *et al*. 1999) or 2.4 x 1.2 m (Onyeonagu and Asiegbu 2005). While plots in the View Road experiment were smaller than plots reported in literature, only a small area of pasture was allowed for this experiment. The View Road site was harvested as a cut and carry operation; pasture was bailed and sold to farmers, generating a substantial income (Couper *et al*. 2009). As an economic venture, a large area of pasture could not be kept out of production, limiting the experimental area.

During the first two harvesting events of the View Road experiment, the size of pasture plots was not measured but was assumed to be 1 x 1 m. After completion of the first harvesting event, the method was re-evaluated and it was decided not measuring the plot sides was a mistake. The following ten week treatment was also not measured to show consistency between the pair of treatments.

Pasture plots reported in cutting literature were generally rectangular rather than square (see examples above). Rectangular pasture strips can be made by mowing a certain length of pasture by the width of the mower; for example, pasture strips in Schills *et al*. (1999) were 6 m long by the width of the Aria mower (0.7 m). In hindsight, using the combination of a square shaped pasture plot and lawn mower was not the best methodology. However, as the View Road experiment had to take up as little area as possible, strip shaped pasture plots were not viable. Pasture plots were surrounded by a 1 m buffer region to decrease edge effects and create representative treatment conditions within the plot. If plots were rectangular rather than square shaped, a larger area of pasture would have been needed which was not feasible, or replication would have had to be decreased. A possible suggestion to improve methodology was to change the cutting method. A suggestion would be to use a pair of electric hand clippers to cut pasture (as in Fulkerson and Michell 1987), rather than a mower. Electric hand clippers would be more controlled and exact.

The targeted harvesting treatments were five week (35 days) and ten week (70 days) intervals. While treatments were not harvested at exactly 35 or 70 days (Table 4.1), treatments were close with a mean of 37 days and 74 days. The treatment intervals of five and ten weeks differed greatly from the actual harvesting regime at the View Road site in the 2009/2010 period and the 2012/2013 period (Table 4.3). Harvesting events depended on the availability of the contractors who cut the pasture. Harvesting at a five week interval may not be practical or logistically possible. Potentially, a six week harvesting frequency during late-November to May (late-spring to late-autumn) and a twelve week harvesting frequency during May until early-November (late-autumn to mid-spring) may be a suitable compromise.

4.5.6. Suggestions for future research

The influence of harvesting frequency on pasture growth is important at land based wastewater disposal sites both in New Zealand and internationally. Maximising nitrogen removal by pasture, therefore, decreasing the amount of nitrogen available to be leached, can help prevent groundwater contamination and eutrophication of waterways. It is recommended other land based treatment sites identify a best harvesting frequency by setting up similar experiments or monitoring pasture growth. A full year, or multiple years, of monitoring is suggested. If a larger area of pasture is available, pasture strips rather than squares are more suitable. However, if room is limited smaller plots and the use of electric hands clippers, rather than a mower, are adequate.

Another suggestion is to make direct measurements of nitrogen leaching in relation to harvesting frequency with a lysimeter study.

4.6. CONCLUSION

A perennial ryegrass crop has been established at the View Road site to remove wastewater nutrients and to generate income that subsidises operation of the wastewater irrigation scheme. With the potential increase of nitrogen loading limit under resource consent (from 550 to 650 kg N ha^{-1} yr^{-1}), maximising nitrogen removal is important to preventing nitrogen leaching losses from site.

An experiment was undertaken to investigate measures to improve nitrogen removal by pasture, which may reduce nitrogen leaching losses. Nitrogen uptake and pasture growth were examined under two harvesting frequencies in order to find which regime had the greatest pasture production and nitrogen removal. An area of pasture was divided into twelve sections and harvested at either a five week or a ten week interval from the 26th of January 2012 to the 15th of November 2012. During the trial period 265 kg N ha^{-1} of wastewater nitrogen was applied. Pasture was collected and the dry matter production and nitrogen component were quantified.

Over the ten month trial the mean pasture yield was 877 kg DM ha^{-1} higher ($P < 0.05$) in the five week treatment (8231 ± 186 kg DM ha^{-1}) than in the ten week treatment (7354 ± 67 kg DM ha^{-1}). Mean nitrogen concentration of pasture within the five week treatment (3.2%) was higher ($P < 0.001$) than in the ten week treatment (2.8%). Therefore, nitrogen removal was 59 kg N ha^{-1} higher ($P < 0.001$) within the five week treatment (250 ± 5 kg N ha^{-1}) than in the ten week treatment (191 ± 3 kg N ha^{-1}). The five week treatment removed 96% of the 265 kg N ha^{-1} applied wastewater nitrogen while the ten week treatment removed 73%. Consequently, 23% (59 kg N ha^{-1}) more nitrogen was available to possibly be leached in the ten week treatment.

Pasture production and nitrogen removal varied seasonally. Pasture production was greater in the five week harvesting treatment from the beginning of the trial (mid-summer) until June (late-autumn). From June to mid-August (late-winter) pasture growth within the five week and the ten week harvesting frequency was similar, if not less in the five week treatment; therefore, over this period harvesting at a ten week interval was more suitable. From mid-August until October (mid-spring) there was no difference in pasture production. However, pasture production in the five week treatment continued to increase, relative to the ten week treatment, towards the end of the trial in late-spring. It is presumed that a five week treatment will produce most pasture than the ten week treatment from late-November to mid-January. Seasonal nitrogen removal behaved similarly to pasture production.

At the View Road site, a seasonally adjusted harvesting regime is recommended; harvesting at five week intervals during late-November to May (late-spring to late-autumn) and ten week intervals from May until early-November (late autumn to mid-spring).

When dry matter production during the four harvests (late-January to late-June) in the five week treatment was combined with the dry matter produced during the last two harvests (late-June to mid-November) in the ten week treatment, pasture dry matter was calculated to be 8483 ± 282 kg DM ha^{-1}. Therefore, pasture dry matter production is predicted to be higher with a seasonally adjusted combination of five and ten week harvesting intervals, than in the primarily five week or ten week harvesting treatments. Nitrogen removal within the seasonally adjusted regime was calculated to be 234 ± 7 kg N ha^{-1}, which was less than within the five week treatment, but higher than the ten week treatment.

Maximising pasture production should improve economic return on pasture growth. The amount of profit depends on pasture quality. During the measurement period, adjusting harvesting frequency from four cuts (ten week treatment) to eight cuts (five week treatment) was predicted to generate, depending on pasture quality, $23 600 (low grade pasture quality), $30 300 (high grade pasture quality), or $ 37 000 (premium grade quality pasture) more profit. Adjusting harvesting frequency from four cuts (ten week treatment) to six cuts (predicted seasonally adjusted treatment) was predicted to generate, $30 400 (low grade pasture quality), $39 000 (high grade pasture quality), or $47 600 (premium grade quality pasture) more profit for the Taupō District Council (Table 4.4).

In terms of pasture quality, studies indicate the digestibility of a ryegrass pasture decreases when the harvesting interval was extended to more than six weeks (Binnie *et al*. 1974; Frame *et al*. 1989; Binnie *et al*. 1997). Therefore, pasture quality is likely to be higher with frequent harvests at the View Road site.

It is important for other wastewater treatment sites around New Zealand to conduct similar research to determine the best harvesting regime for their site. Finding the best harvesting regime will promote nitrogen removal by maximising pasture productivity, thus minimising the amount of nitrogen available to be leached. Preventing nitrogen leaching protects groundwater resources and aquatic ecosystems, and promotes the sustainability of the wastewater disposal scheme.

CHAPTER FIVE – SUMMARY, DISCUSSION, RECOMMENDATIONS, AND CONCLUSIONS

5.1. INTRODUCTION

The following chapter summarises this study and the findings from the two experiments presented within this thesis. Discussion and recommendations are given in relation to potential for raising wastewater nitrogen application limits at the View Road wastewater irrigation site in Taupō, New Zealand.

5.2. STUDY OVERVIEW

Secondary-treated municipal wastewater is applied to land at the View Road site as a method of disposal and further treatment. Nutrients and water within the effluent are utilised by a perennial ryegrass (predominantly *Lolium perenne*), and pasture is harvested four times a year in a cut and carry scheme, generating income that helps fund the wastewater irrigation scheme.

With a need to increase the wastewater disposal capacity in Taupō, the Taupō District Council requested to increase wastewater nitrogen application limits at the View Road site from 550 to 650 kg N ha^{-1} yr^{-1}. In order to test the impacts of a higher application rate the regulator (Waikato Regional Council) has permitted the application of 650 kg N ha^{-1} yr^{-1} of wastewater on 15% of the irrigated land at the View Road site. A trial was installed to test whether an increase in nitrogen loading from 550 to 650 kg N ha^{-1} yr^{-1} would lead to leaching losses above 30 kg N ha^{-1} yr^{-1}.

With the potential increase in nitrogen loading limit, increasing nitrogen recovery by maximising pasture production is important to prevent nitrogen leaching losses from site. A second experiment was undertaken to determine whether a five week or a ten week harvesting frequency gave the greater pasture production and nitrogen removal at the View Road site, in the hope of reducing nitrogen that was available to potentially be leached.

This thesis had two objectives:

1. Quantify nitrogen movement at the View Road land based treatment site under a range of wastewater application rates. Treatments included a low rate (nominally 450 kg N ha^{-1} yr^{-1}), the consented rate (nominally 550 kg N ha^{-1} yr^{-1}), a high rate (nominally 650 kg N ha^{-1} yr^{-1}), and an unirrigated soil (nominally 0 kg N ha^{-1} yr^{-1}). Specific aims were to determine:
    a. The amount of wastewater nitrogen applied to the land surface within each treatment,
    b. The total amount of nitrogen in leachate that drained through a lysimeter containing an undisturbed soil column within each treatment,
    c. The dry matter production and nitrogen removal by pasture within each treatment,
    d. The amount of unrecovered nitrogen within each treatment.
2. Quantify dry matter production and nitrogen removal by pasture harvested at two different harvesting frequencies to determine which harvesting frequency gave the greater pasture production and nitrogen removal. It was hypothesised that more pasture will be produced and more nitrogen will be removed with a five week harvesting frequency than with a ten week frequency.

5.3. SUMMARY OF THE NITROGEN LEACHING AND PASTURE UPTAKE LYSIMETER EXPERIMENT (CHAPTER THREE)

5.3.1. Experimental design

An experiment was undertaken to quantify nitrogen movement under the irrigation of wastewater at the View Road wastewater treatment site, as follows:

- Forty-eight undisturbed barrel lysimeters (30 cm diameter x 43 cm depth) were installed within 29 hectares of perennial ryegrass pasture;
    - thirty-six lysimeters were installed within the irrigated areas, and
    - twelve lysimeters were installed within unirrigated areas as controls.

- To apply the range of wastewater application rates, the centre pivot travelling irrigators were programmed to vary in speed, thus, applying different, predetermined amounts of wastewater to treatment sectors.
- The amount of wastewater nitrogen applied to each lysimeter was quantified;
    - lysimeters were pumped monthly, and leachate volume and nitrogen concentration were determined, and
    - pasture growing in lysimeters was harvested before each commercial field harvest, and dry matter and nitrogen content were determined.

A nitrogen balance was constructed and the amount of unrecovered nitrogen was quantified.

5.3.2. Nitrogen input

The targeted wastewater nitrogen application loads of 450, 550 and 650 kg N ha^{-1} yr^{-1} were not achieved. Nitrogen application to the land surface ranged from 286 to 567 kg N ha^{-1} yr^{-1}. The following outcomes were obtained:

- Nitrogen loading values were grouped into a low treatment (286 - 380 kg N ha^{-1} yr^{-1}), a medium treatment (380 - 445 kg N ha^{-1} yr^{-1}), and a high treatment (445 - 567 kg N ha^{-1} yr^{-1}).
- Reasons for not achieving the higher application rates were out of the control of the author of this thesis, but involved periods where no wastewater was applied to the study area for reasons of;
    - grass harvest,
    - lack of available wastewater, and
    - other activities such as tree felling adjacent to the irrigation area.
- Nitrogen input within control sectors was assumed to be primarily atmospheric nitrogen that was deposited with rain water, and was expected to be 5 kg N ha^{-1} yr^{-1}. No legumes were observed in the control areas.

5.3.3. Nitrogen leached

A mean of 4% of the applied wastewater nitrogen was leached across all of the irrigated treatments. Applying wastewater to land at the View Road site increased the nitrogen concentration of, and amount of nitrogen within, water that drained through 43 cm of soil.

Applying wastewater to land increased the nitrogen concentration of leachate:

- The mean concentration of nitrogen within;
  - control leachate was 0.7 ± 0.3 mg L^{-1}, and
  - irrigated treatment leachate was 2.4 ± 0.7 mg L^{-1}.

Applying wastewater to land increased the total amount of nitrogen leached:

- The mean amount of nitrogen leached within control treatments was 2.8 ± 0.6 kg N ha^{-1} yr^{-1}.
- The mean amount of nitrogen leached within irrigated treatments was 12.7 ± 4.2 kg N ha^{-1} yr^{-1} in the low treatment, 16.0 ± 7.2 kg N ha^{-1} yr^{-1} in the medium treatment, 28.6 ± 10.1 kg N ha^{-1} yr^{-1} in the high treatment;
  - the mean amount of nitrogen leached from the high treatment was higher ($P < 0.05$) than from the low treatment. The medium treatment was not significantly different to the low treatment or the high treatment.

This experiment was held under field irrigation and harvesting conditions. It was difficult to isolate the drivers of leaching losses due to the number of variables within the field conditions and variability within the site. However, the following conclusions were reached:

- There was a positive correlation between the amount of nitrogen leached and the amount of wastewater applied (R^2= 0.44).
- There was a positive correlation between the amount of nitrogen leached and the amount of water drained through the soil (R^2= 0.54).
- There was no effectively relationship between the amount of nitrogen leached and the amount of nitrogen taken up by pasture (R^2= 0.03).

Types of nitrogen within leachate differed between irrigated and control treatments.

Within control treatments:

- Leachate nitrogen was predominantly organic nitrogen (68%) and nitrate (28%), with a small proportion of ammonium (5%), and nitrite below detection limits.
- The total amount of nitrate leached from control lysimeters ranged from 0.3 to 1.5 kg N ha^{-1} yr^{-1} with a mean of 0.8 ± 0.16 kg N ha^{-1} yr^{-1}.
- The amount of total organic nitrogen leached from control lysimeters ranged from 1.1 to 3.1 kg N ha^{-1} yr^{-1} with a mean of 1.9 ± 0.2 kg N ha^{-1} yr^{-1}.

Within irrigated treatments:

- Leachate nitrogen was predominantly nitrate (mean of all irrigated treatments, 68%) and organic nitrogen (31%), with minimal ammonium (2%), and nitrite below detection limits.
- The total amount of nitrate leached from irrigated treatments ranged from 1.3 to 48.7 kg N $ha^{-1}yr^{-1}$;
    - with an average of 6.8 ± 1.0 kg N ha^{-1} yr^{-1} leached within the low treatment, 10.7 ± 2.0 kg N ha^{-1} yr^{-1} leached within the medium treatment, and 22.1 ± 2.7 kg N ha^{-1} yr^{-1} leached within the high treatment,
    - the mean nitrate concentration of leachate was 1.6 mg L^{-1}. Therefore, nitrate concentrations were well within Ministry of Health guidelines for drinking water (11.3 mg L^{-1}). However, guidelines were exceeded 4 times out of about 520 measurements throughout the trial period, with a maximum nitrate concentration of 19.0 mg L^{-1}.
- The total amount of organic nitrogen leached from irrigated treatments ranged from 1.9 to 13.07 kg N ha^{-1} yr^{-1};
    - with an average of 5.2 ± 0.3 kg N ha^{-1} yr^{-1} leached within the low treatment, 5.9 ± 0.5 kg N ha^{-1} yr^{-1} leached within the medium treatment, and 6.4 ± 0.8 kg N ha^{-1} yr^{-1} leached within the high treatment,
    - the mean organic nitrogen concentration in leachate was 0.8 mg L^{-1}.

- The mean concentration of ammonium in leachate was 0.05 mg L^{-1}.

Within irrigated treatments, a larger proportion of the total annual nitrogen (57%) and nitrate (63%) was leached during the autumn and winter months than in summer and spring.

5.3.4. Pasture production and nitrogen removal

Pasture production was higher ($P < 0.001$) under wastewater irrigation (mean of all irrigated treatments, 14 250 ± 349 kg DM ha^{-1} yr^{-1}) in comparison to unirrigated control pastures (5300 ± 839 kg DM ha^{-1} yr^{-1}), however:

- There were no significant differences in pasture dry matter production between the low (13 922 ± 1196 kg DM ha^{-1} yr^{-1}), medium (13 543 ± 1475 kg DM ha^{-1} yr^{-1}), and high (15 285 ± 1919 kg DM ha^{-1} yr^{-1}) treatments;
    - therefore, under the current harvesting regime at the View Road site, increasing wastewater input past the lower application rate will not lead to further significant increases in pasture production.

A mean of 90% of the applied wastewater nitrogen was removed by pasture across all of the irrigated treatments:

- There were no significant differences in nitrogen removal between the low (341 ± 25 kg N ha^{-1} yr^{-1}), medium (360 ± 51 kg N ha^{-1} yr^{-1}), and high (385 ± 43 kg N ha^{-1} yr^{-1}) treatments;
    - therefore, under the current harvesting regime at the View Road site, increasing wastewater application rates did not lead to further significant increases in nitrogen removal by pasture.
- The mean concentration of nitrogen within pasture was higher ($P < 0.05$) in the irrigated pastures (2.6%) than in the control pastures (1.8%).

5.3.5. Nitrogen balance and unrecovered nitrogen

Within irrigated sectors, nitrogen input ranged from 286 to 567 kg N ha^{-1} yr^{-1}. A large portion (79 to 100%) of the applied nitrogen was removed by pasture, while a small component of the nitrogen input was leached (4 to 6%). The following observations were made:

- The mean proportion of nitrogen removal by pasture ranged from the 100 ± 6% in the low treatment, to 89 ± 13% in the medium treatment, to 79 ± 9% in the high wastewater loading treatment.
- The mean proportion of nitrogen leached was 4 ± 1% in the low treatment, 4 ± 2% in the medium treatment, and 6 ± 2% in the high wastewater loading treatment.
- Therefore, on average, -4 to 16% of the applied wastewater nitrogen remained unrecovered.

Mean unrecovered nitrogen increased with increased wastewater application from; -13 ± 19 kg N ha^{-1} yr^{-1} (-4 ± 6%) in the low treatment, to 30 ± 52 kg N ha^{-1} yr^{-1} (7 ± 13%) in the medium treatment, to 77 ± 39 kg N ha^{-1} yr^{-1} (16 ± 8%) in the high treatment:

- The majority of unrecovered nitrogen was assumed to be volatilised with potential for minor denitrification and soil storage.
- Negative values indicate nitrogen outputs (nitrogen removal by pasture and leaching) were higher than nitrogen inputs;
  - which may represent measurement error or nitrogen released through soil processes, such as net mineralisation.

A previous year of measurement occurred at the View Road site from December 2009 to December 2010 (Treweek 2011), less than two years after the initiation of wastewater application. The second round of measurement, presented within this thesis, was needed to verify equilibration of the soil system and to confirm nitrogen leaching losses had not increased since the first year of monitoring. Results from this experiment and results from the previous year of measurement (Treweek 2011) are compared in Table 3.15, demonstrating:

- Nitrogen leaching values, pasture nitrogen uptake values and unrecovered nitrogen values were similar ($P < 0.05$) between corresponding treatments within the 2009/10 measurement period (Treweek 2011) and the 2011/12 measurement period (reported within this thesis) (Table 3.15).

- Given the lack of difference between the two monitoring years, it is likely that the soil system within the irrigated experimental area at the View Road site had reached equilibrium before the 2009/10 year of measurement of Treweek (2011).
- Therefore, nitrogen leaching losses measured during Treweek (2011) and within this thesis are likely to be representative of future leaching losses when similar nitrogen loads are applied. However, further monitoring would be advised, especially at the higher loading rates.

5.4. SUMMARY OF THE HARVESTING FREQUENCY EXPERIMENT (CHAPTER FOUR)

5.4.1. Experimental design

A second experiment was undertaken to determine whether a five week or a ten week harvesting frequency gave the greater pasture production and nitrogen removal at the View Road site, in the hope of potentially reducing nitrogen that is available to be leached:

- An area of pasture was divided into twelve sections (1m x 1m) and cut at five or ten week intervals from the January 2012 to November 2012.
- During the trial period 265 kg N ha^{-1} of wastewater nitrogen was applied.
- Pasture was collected, and the dry matter content and nitrogen component were quantified.

5.4.2. Pasture dry matter production

Over the ten month trial, mean pasture yield was 877 kg DM ha^{-1} higher ($P < 0.05$) in the five week treatment (8231 ± 186 kg DM ha^{-1}) than in the ten week treatment (7354 ± 67 kg DM ha^{-1}). Pasture production varied seasonally, as follows:

- Pasture production was greater in the five week harvesting treatment from the beginning of the trial (mid-summer) until June (late-autumn).
- Pasture growth within the five week and the ten week harvesting treatment were similar from June to mid-August (late-winter), if not less in the five week treatment;
  - therefore, a ten week harvesting frequency was considered more cost effective during winter.
- From mid-August until October (mid-spring) there was no difference in pasture production between the five and the ten week harvesting frequencies;
  - however, pasture production in the five week treatment continued to increase, relative to the ten week treatment, towards the end of the trial in November (late-spring),
  - thus, it is suggested that from late-November to mid-January (mid-summer) a five week harvesting interval would produce more pasture than a ten week interval.

5.4.3. Nitrogen removal by pasture

The mean nitrogen concentration of pasture within the five week harvesting treatment (3.2%) was higher ($P < 0.001$) than in the ten week treatment (2.8%):

- Nitrogen removal was 59 kg N ha^{-1} higher ($P < 0.001$) within the five week harvesting treatment (250 ± 5 kg N ha^{-1}) than in the ten week treatment (191 ± 3 kg N ha^{-1}).
- On average, 96% of the applied wastewater nitrogen (265 kg N ha^{-1}) was removed within the five week harvesting treatment, while 73% was removed within the ten week harvesting treatment;
  - therefore, 23% more nitrogen was available to potentially be leached in the ten week treatment.
- Nitrogen removal had a similar seasonal pattern to pasture production.

5.4.4. Seasonally adjusted harvesting regime

It is predicted that a seasonally adjusted harvesting regime — harvesting at five week intervals during late-November to May (late-spring to late-autumn) and ten week harvesting intervals from May until early-November (late-autumn to mid-spring) — is best for the View Road site:

- When dry matter production during the first four harvests (late-January to late-June) in the five week treatment was combined with the dry matter produced during the last two harvests (late-June to mid-November) in the ten week treatment, potential pasture dry matter production was calculated to be 8483 ± 282 kg DM ha^{-1};
  - therefore, it is predicted more pasture will be produced with the seasonally adjusted harvesting regime than in the five week or the ten week harvesting treatments.
- Nitrogen removal within the seasonally adjusted harvesting regime was calculated to be 234 ± 7 kg N ha^{-1};
  - therefore, more nitrogen is predicted to be removed within the seasonally adjusted harvesting regime than in the ten week harvesting treatment, but less nitrogen is removed than in the five week harvesting treatment.

5.4.5. Economic return on pasture production at the View Road site

Maximising pasture production should improve economic return on pasture growth, profiting the Taupō District Council. The amount of profit depends on pasture quality. During the measurement period of late-January to late-November, adjusting harvesting frequency from:

- Four cuts (ten week treatment) to eight cuts (five week treatment) was predicted to generate, depending on pasture quality, \$23 600 (low grade pasture quality), \$30 300 (high grade pasture quality), or \$ 37 000 (premium grade quality pasture) more profit.

- Four cuts (ten week treatment) to six cuts (predicted seasonally adjusted treatment) was predicted to generate, \$30 400 (low grade pasture quality), \$39 000 (high grade pasture quality), or \$47 600 (premium grade quality pasture) more profit for the Taupō District Council (Table 4.4).

In terms of pasture quality, literature indicates the digestibility of a ryegrass pasture decreases when harvesting interval is extended to more than six weeks (Binnie *et al*. 1974; Frame *et al*. 1989; Binnie *et al*. 1997). Therefore, pasture quality is likely to be higher with frequent harvests at the View Road site.

5.5. DISCUSSION AND RECOMMENDATIONS FOR THE VIEW ROAD SITE

When the View Road wastewater disposal site was commissioned, a nitrogen application limit of 550 kg N ha^{-1} yr^{-1} was consented. However, there is a need to increase the town's wastewater disposal capacity due to; expected population growth, acquisition of part of the Rakaunui Road disposal site by the New Zealand Transport Agency for the Eastern Taupō Bypass, potential addition of treated wastewater from satellite communities, and a large influx of people during the summer months (Orbell 2007).

With the need to increase disposal capacity in Taupō, the Taupō District Council has requested to increase wastewater application limit at the View Road site. The Waikato Regional Council has agreed to reconsider the application rate, allowing an opportunity to trial a higher input. The application of 650 kg N ha^{-1} yr^{-1} was permitted on 15% of the irrigated land at the View Road site for five years. Conditions of the wastewater irrigation scheme restrict the amount of wastewater nitrogen allowed to be applied to be no more than 120 kg N ha^{-1} yr^{-1} above crop yield, or mean nitrogen leaching losses of up to 30 kg N ha^{-1} yr^{-1}. A trial was installed to test whether an increase in nitrogen loading from 550 to 650 kg N ha^{-1} yr^{-1} would lead to leaching losses above 30 kg N ha^{-1} yr^{-1}.

The application of 650 kg N ha^{-1} yr^{-1} was not achieved during this thesis; the high treatment was defined as 445 - 567 kg N ha^{-1} yr^{-1}. Mean nitrogen leaching losses within the high treatment (28.6 ± 10.1 kg N ha^{-1} yr^{-1}) were below the consented nitrogen leaching limit of 30 kg N ha^{-1} yr^{-1}. However, nitrogen values above the limit were measured from six lysimeters (out of the 46) (Figure 5.1); from four lysimeters within the high treatment and two within the medium treatment. The maximum nitrogen leaching value (61 kg N ha^{-1} yr^{-1}) was measured in one lysimeter under the highest application of 567 kg N ha^{-1} yr^{-1}.

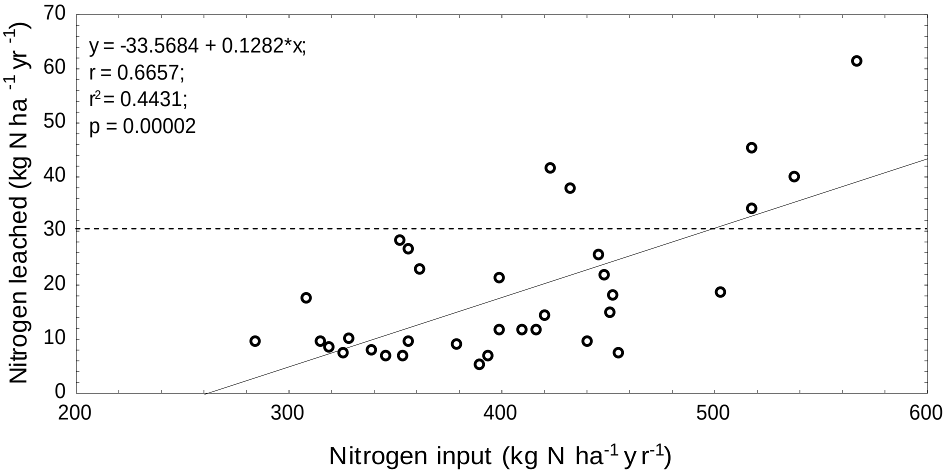

Figure 5.1. The relationship between the amount of nitrogen leached from loading treatments and nitrogen input. ***Dashed line represents the consented nitrogen leaching limit at the View Road site.***

Using the linear relationship between nitrogen leaching and nitrogen input (Figure 5.1), nitrogen leaching values were estimated for a range of wastewater application loads (Table 5.1). The values presented in Table 5.1 are only an indicative estimate of leaching losses as the R^2 value was 0.44.

Table 5.1. Estimated nitrogen leaching losses from a range of nitrogen inputs using the linear regression equation in Figure 5.1.

Nitrogen input ($kg\ N\ ha^{-1}\ yr^{-1}$)	Nitrogen leached ($kg\ N\ ha^{-1}\ yr^{-1}$)
450	24
500	31
550	37
600*	43
650*	50

* Prediction outside of the range of measurements

The application of 650 kg N ha^{-1} yr^{-1} is likely to cause nitrogen leaching losses above 30 kg N ha^{-1} yr^{-1}. Therefore, it is concluded from this experiment that the wastewater application limit should not be increased to 650 kg N ha^{-1} $yr^{-1}$with the current harvesting regime at the View Road site.

However, Chapter 4 has demonstrated that there is an opportunity to remove more nitrogen from the View Road site; therefore, less nitrogen will be available to potentially be leached. If pasture is harvested more often than current harvesting practice (four cuts a year) there is a possible opportunity to prevent nitrogen leaching losses above 30 kg N ha^{-1} yr^{-1} with the application of 650 kg N ha^{-1} yr^{-1}. However, there was no direct measurement of nitrogen removal under the high application of 650 kg N ha^{-1} yr^{-1} and there were no direct measurements of nitrogen leaching in relation to harvesting frequency within this thesis.

It is recommended pasture is cut more often than four times a year, as measured within this thesis and the previous study at the View Road site (Treweek 2011). A more frequent seasonal harvesting regime is suggested with, a five to six week cutting interval during late-November to May (late-spring to late-autumn) and an increased interval of ten to twelve weeks from May until early-November (late-autumn to mid-spring). An increased, seasonally adjusted, harvesting frequency will not only increase nitrogen recovery, but increase pasture production, therefore, increasing profit to the Taupō District Council.

5.6. THESIS CONCLUSIONS

The targeted wastewater nitrogen application rates of 450, 550 and 650 kg N ha^{-1} yr^{-1} were not achieved, with nitrogen application to the land surface ranging from 286 to 567 kg N ha^{-1} yr^{-1}. The nitrogen loading values were grouped into a low treatment (286 - 380 kg N ha^{-1} yr^{-1}), a medium treatment (380 - 445 kg N ha^{-1} yr^{-1}), and a high treatment (445 - 567 kg N ha^{-1} yr^{-1}). Nitrogen input within control sectors was assumed to be primarily atmospheric nitrogen that was deposited with rain water, and was expected to be 5 kg N ha^{-1} yr^{-1}.

On average, 4 to 6% of the applied nitrogen was leached. Applying wastewater to land at the View Road site increased the amount of nitrogen within water that drained through 43 cm of soil. Within control treatments, the mean amount of nitrogen leached was 2.8 ± 0.6 kg N ha^{-1} yr^{-1}. The mean amount of nitrogen leached from the high treatment (28.6 ± 10.1 kg N ha^{-1} yr^{-1}) was higher ($P < 0.05$) than from the low treatment (12.7 ± 4.2 kg N ha^{-1} yr^{-1}). The medium treatment (16.0 ± 7.2 kg N ha^{-1} yr^{-1}) was not significantly different to the low treatment or the high treatment. Mean nitrogen leaching from the high application treatment was below the consented limit of 30 kg N ha^{-1} yr^{-1}. Within irrigated treatments, the mean nitrate concentration of lysimeter leachate was 1.6 mg L^{-1}, the mean concentration of total organic nitrogen was 0.8 mg L^{-1}, and the mean concentration of ammonium was 0.05 mg L^{-1}.

The application of wastewater substantially improved pasture production (mean of all irrigated treatments, 14 250 ± 349 kg DM ha^{-1} yr^{-1}) in comparison to unirrigated control pastures (5300 ± 839 kg DM ha^{-1} yr^{-1}). A large portion (79 to 100%) of the applied nitrogen was removed by pasture. However, there were no significant differences in pasture dry matter production or nitrogen removal between the low treatment (13 922 ± 1196 kg DM ha^{-1} yr^{-1} and 341 ± 25 kg N ha^{-1} yr^{-1}), the medium treatment (13 543 ± 1475 kg DM ha^{-1} yr^{-1} and 360 ± 51 kg N ha^{-1} yr^{-1}), and the high treatment (15 285 ± 1919 kg DM ha^{-1} yr^{-1} and 385 ± 43 kg N ha^{-1} yr^{-1}). Therefore, under the current harvesting regime at the View Road site, increasing wastewater application rates did not lead to further significant increases in pasture production or nitrogen removal by pasture.

On average, -4 to 16% of the applied wastewater nitrogen remained unrecovered. Mean unrecovered nitrogen increased with increased wastewater application from

-13 ± 19 kg N ha^{-1} yr^{-1} (-4 ± 6%) in the low treatment, to 30 ± 52 kg N ha^{-1} yr^{-1} (7 ± 13%) in the medium treatment, to 77 ± 39 kg N ha^{-1} yr^{-1} (16 ± 8%) in the high treatment. The majority of unrecovered nitrogen was assumed to be volatilised with lower potential for denitrification and soil storage.

It is concluded that soil system had reached equilibrium. Thus, leaching losses measured during Treweek (2011) and within this thesis are likely to be representative of future leaching losses when similar nitrogen loads are applied. However, further monitoring would be advised, especially at the higher loading rates.

Over the ten month pasture harvesting frequency trial, mean pasture yield was 877 kg DM ha^{-1} higher ($P < 0.05$) in the five week treatment (8231 ± 186 kg DM ha^{-1}) than in the ten week treatment (7354 ± 67 kg DM ha^{-1}). Nitrogen removal was 59 kg N ha^{-1} higher ($P < 0.001$) within the five week harvesting frequency (250 ± 5 kg N ha^{-1}) than in the ten week treatment (191 ± 3 kg N ha^{-1}). On average, 96% of the applied wastewater nitrogen (265 kg N ha^{-1}) was removed within the five week harvesting treatment, while 73% was removed within the ten week harvesting treatment. Therefore, 23% more nitrogen was available to potentially be leached in the ten week treatment.

It is suggested that harvesting at five week intervals during late-November to May (late-spring to late-autumn) and ten week intervals from May until early-November (late-autumn to mid-spring) will produce the greatest pasture production, with lower harvesting costs. When dry matter production during the first four harvests (late-January to late-June) in the five week treatment was combined with the dry matter produced during the last two harvests (late-June to mid-November) in the ten week treatment, pasture dry matter was calculated to be 8483 ± 282 kg DM ha^{-1}. Nitrogen removal within the predicted seasonally adjusted harvesting regime was calculated to be 234 ± 7 kg N ha^{-1}. Thus, less nitrogen was removed within the predicted seasonally adjusted harvesting regime than within the five week treatment, but more than within the ten week treatment.

The application of 650 kg N ha^{-1} yr^{-1} is likely to cause nitrogen leaching losses above 30 kg N ha^{-1} yr^{-1} (Table 5.1). However, there is an opportunity to remove more nitrogen from the View Road site if harvesting frequency is increased. If pasture is harvested more often than current harvesting practise (four cuts a year) there is a possible opportunity to prevent nitrogen leaching losses above 30 kg N ha^{-1} yr^{-1} with the a higher total wastewater application. An increased seasonally adjusted harvesting frequency is predicted to combine high pasture production and nitrogen removal with best economic return.

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APPENDICES

Appendix 1. Lysimeter experiment- treatment sector labels

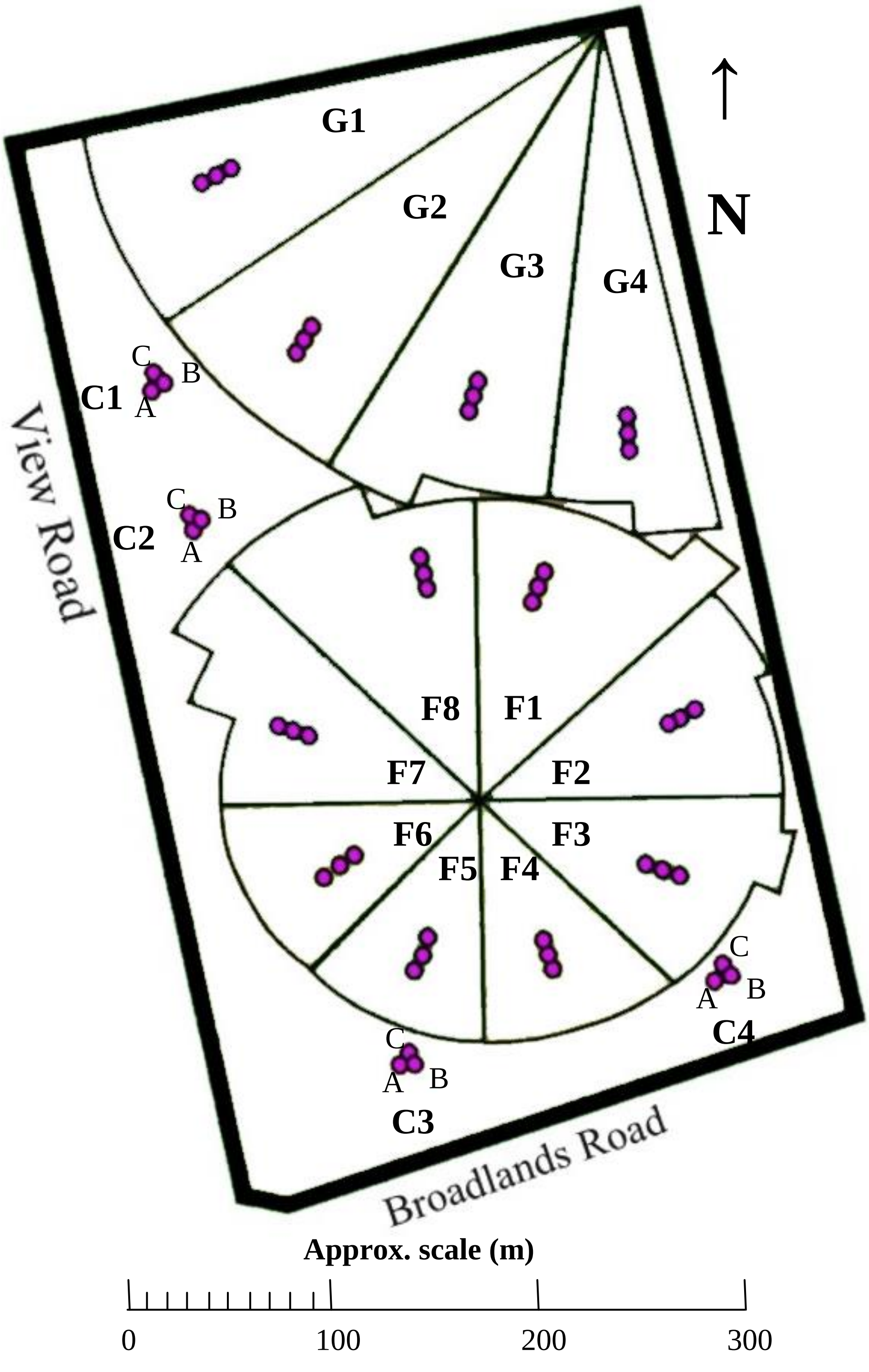

Figure 7.1. Treatment sector labels. Lysimeters within each sector were labelled A, B, or C. Within effluent irrigated sectors (F#s and G#s), lysimeter A is located towards the outside of the pivot circle, lysimeter B is located between A and C, and lysimeter C is located closest to the centre of the pivot circle. Within control sectors (C#s), lysimeters A, B and C are labelled.

Appendix 2. Lysimeter experiment – rainfall, irrigation and wastewater nitrogen data

Table 7.1. Rainfall irrigation and wastewater nitrogen data.

Rain gauge period	Date	Rainfall data		Irrigation data				Wastewater nitrogen data	
		View Road	Airport	Pivot F (Area= 14.02 ha)		Pivot G (Area= 18.39 ha)		Weekly grab sample	Mean of measurement period
		(mm day^{-1})	(mm day^{-1})	(m^3 day^{-1})	(mm day^{-1})	(m^3 day^{-1})	(mm day^{-1})	(g N m^3)	(g N m^3)
1	8/09/2011	0.00	0.00	0.0	0.00	0.0	0.00	54.2	52.31
1	9/09/2011	0.00	0.00	0.0	0.00	0.0	0.00	54.2	
1	10/09/2011	0.00	0.00	584.6	4.17	743.8	4.04	54.2	
1	11/09/2011	17.91	0.00	52.9	0.00	0.0	0.00	54.2	
1	12/09/2011	0.75	12.60	563.8	4.02	757.5	4.12	54.2	
1	13/09/2011	1.92	1.20	613.3	4.37	755.8	4.11	54.2	
1	14/09/2011	7.32	3.60	1311.7	9.36	1518.1	8.26	41.77	
1	15/09/2011	1.89	0.00	613.3	4.37	756.5	4.11	41.77	
1	16/09/2011	4.99	3.60	566.3	4.04	764.6	4.16	41.77	
1	17/09/2011	0.91	0.40	554.2	3.95	748.0	4.07	41.77	
1	18/09/2011	2.70	0.00	111.4	0.00	0.0	0.00	41.77	
1	19/09/2011	0.66	5.40	610.2	4.35	757.0	4.12	41.77	
1	20/09/2011	3.19	2.80	0.0	0.00	0.0	0.00	41.77	
1	21/09/2011	0.00	0.00	5.4	0.00	752.6	4.09	53.75	
1	22/09/2011	0.00	0.00	549.9	3.92	759.5	4.13	53.75	
1	23/09/2011	0.00	0.00	625.0	4.46	755.6	4.11	53.75	
1	24/09/2011	0.06	0.00	68.0	0.00	755.6	4.11	53.75	
1	25/09/2011	0.52	0.00	551.9	3.94	755.6	4.11	53.75	
1	26/09/2011	0.00	2.60	602.8	4.30	753.8	4.10	53.75	
1	27/09/2011	0.00	0.00	0.0	0.00	760.3	4.13	53.75	
1	28/09/2011	0.00	0.00	461.6	3.29	751.2	4.08	60.55	
1	29/09/2011	0.00	0.00	594.7	4.24	748.0	4.07	60.55	
1	30/09/2011	0.06	0.00	0.0	0.00	0.0	0.00	60.55	
1	1/10/2011	0.00	0.00	0.0	0.00	0.0	0.00	60.6	
1	2/10/2011	0.43	0.00	480.8	3.43	744.9	4.05	60.6	
1	3/10/2011	5.81	0.60	91.2	0.00	0.0	0.00	60.6	
1	4/10/2011	6.97	33.00	571.8	4.08	747.1	4.06	60.6	
1	5/10/2011	4.39	0.40	476.0	3.39	741.3	4.03	49.5	
1	6/10/2011	0.00	1.80	587.1	4.19	747.3	4.06	49.5	
2	7/10/2011	0.00	0.00	611.0	4.36	739.0	4.02	49.5	47.57
2	8/10/2011	0.98	0.00	544.2	3.88	748.5	4.07	49.5	
2	9/10/2011	0.00	0.20	628.8	4.49	744.7	4.05	49.5	
2	10/10/2011	3.11	0.00	636.0	4.54	749.9	4.08	49.5	
2	11/10/2011	3.49	6.20	0.0	0.00	0.0	0.00	49.5	
2	12/10/2011	9.96	19.00	5.3	0.00	745.4	4.05	45.4	
2	13/10/2011	2.18	7.60	566.8	4.04	0.0	0.00	45.4	
2	14/10/2011	0.06	0.80	585.7	4.18	740.6	4.03	45.4	
2	15/10/2011	0.74	0.20	577.0	4.12	709.5	3.86	45.4	
2	16/10/2011	1.57	1.80	530.3	3.78	740.6	4.03	45.4	
2	17/10/2011	0.17	0.30	517.2	3.69	734.7	3.99	45.4	
2	18/10/2011	12.80	7.00	5.2	0.00	737.6	4.01	45.4	
2	19/10/2011	5.37	3.00	584.7	4.17	732.3	3.98	50.9	
2	20/10/2011	0.00	5.60	576.5	4.11	732.3	3.98	50.9	
2	21/10/2011	0.00	0.00	573.8	4.09	727.2	3.95	50.9	

2	22/10/2011	0.92	0.00	513.8	3.66	733.1	3.99	50.9	
2	23/10/2011	0.00	6.80	573.3	4.09	639.5	3.48	50.9	
2	24/10/2011	0.00	0.00	444.9	3.17	769.0	4.18	50.9	
2	25/10/2011	0.00	0.00	0.0	0.00	720.8	3.92	50.9	
2	26/10/2011	0.00	0.00	13.8	0.00	361.0	1.96	44.6	
2	27/10/2011	0.06	0.60	498.4	3.56	12.1	0.00	44.6	
2	28/10/2011	0.00	1.60	682.7	4.87	0.0	0.00	44.6	
2	29/10/2011	0.23	0.00	508.3	3.63	626.1	3.40	44.6	
2	30/10/2011	0.00	0.60	83.7	0.00	98.3	0.00	44.6	
2	31/10/2011	0.00	0.00	0.0	0.00	0.0	0.00	44.6	
Harvest	1/11/2011	1.39	0.40	0.0	0.00	0.0	0.00	44.6	56.82
Harvest	2/11/2011	4.21	6.00	0.0	0.00	0.0	0.00	59.8	
Harvest	3/11/2011	0.12	1.20	0.0	0.00	0.0	0.00	59.8	
Harvest	4/11/2011	2.23	2.80	0.0	0.00	0.0	0.00	59.8	
Harvest	5/11/2011	0.12	0.20	0.0	0.00	0.0	0.00	59.8	
Harvest	6/11/2011	0.29	0.00	0.0	0.00	0.0	0.00	59.8	
Harvest	7/11/2011	0.00	0.60	0.0	0.00	0.0	0.00	59.8	
Harvest	8/11/2011	0.00	0.00	0.0	0.00	0.0	0.00	59.8	
Harvest	9/11/2011	0.00	0.00	0.0	0.00	0.0	0.00	48.2	
3	10/11/2011	0.06	0.00	0.0	0.00	0.0	0.00	48.2	48.20
3	11/11/2011	0.00	0.00	537.9	3.84	0.0	0.00	48.2	
3	12/11/2011	0.96	0.00	50.1	0.00	11.0	0.00	48.2	
3	13/11/2011	0.00	0.60	577.2	4.12	1468.1	7.98	48.2	
3.5	14/11/2011	3.05	0.00	5.3	0.00	732.5	3.98	48.2	50.81
3.5	15/11/2011	0.00	3.80	0.0	0.00	726.8	3.95	48.2	
3.5	16/11/2011	0.87	2.80	459.2	3.28	733.5	3.99	54.6	
3.5	17/11/2011	0.00	0.20	480.2	3.42	723.2	3.93	54.6	
3.5	18/11/2011	0.00	0.00	107.6	0.00	731.3	3.98	54.6	
3.5	19/11/2011	0.00	0.00	484.8	3.46	711.4	3.87	54.6	
3.5	20/11/2011	0.00	0.00	99.2	0.00	729.6	3.97	54.6	
3.5	21/11/2011	0.17	0.00	464.6	3.31	727.1	3.95	54.6	
3.5	22/11/2011	0.00	0.20	0.0	0.00	0.0	0.00	54.6	
3.5	23/11/2011	0.00	0.00	0.0	0.00	629.7	3.42	47.3	
3.5	24/11/2011	8.13	3.20	473.8	3.38	625.4	3.40	47.3	
3.5	25/11/2011	0.00	0.80	576.6	4.11	625.4	3.40	47.3	
3.5	26/11/2011	0.00	0.00	560.9	4.00	625.4	3.40	47.3	
3.5	27/11/2011	0.00	0.00	515.4	3.68	631.1	3.43	47.3	
3.5	28/11/2011	0.00	0.00	46.1	0.00	0.0	0.00	47.3	
3.5	29/11/2011	0.00	1.20	496.0	3.54	618.1	3.36	47.3	
3.5	30/11/2011	0.00	0.00	544.6	3.88	626.0	3.40	54	
4	1/12/2011	0.00	0.00	50.9	0.00	0.0	0.00	54	45.92
4	2/12/2011	2.63	0.00	8.2	0.00	624.6	3.40	54	
4	3/12/2011	3.03	5.80	424.8	3.03	561.4	3.05	54	
4	4/12/2011	3.08	0.20	158.8	1.13	64.5	0.35	54	
4	5/12/2011	3.33	8.40	0.0	0.00	618.4	3.36	54	
4	6/12/2011	2.02	0.00	587.1	4.19	622.5	3.39	54	
4	7/12/2011	9.05	0.60	520.3	3.71	611.3	3.32	49.2	
4	8/12/2011	0.00	3.20	59.6	0.00	623.9	3.39	49.2	
4	9/12/2011	0.00	0.00	578.8	4.13	610.4	3.32	49.2	
4	10/12/2011	0.06	0.00	0.0	0.00	0.0	0.00	49.2	
4	11/12/2011	0.00	0.00	119.3	0.85	622.4	3.38	49.2	
4	12/12/2011	2.50	0.20	19.7	0.00	611.5	3.32	49.2	
4	13/12/2011	0.23	10.80	0.0	0.00	518.5	2.82	49.2	
4	14/12/2011	1.18	0.00	0.0	0.00	98.6	0.54	34	

4	15/12/2011	5.89	8.20	109.1	0.00	607.2	3.30	34	
4	16/12/2011	2.03	13.60	0.0	0.00	104.3	0.57	34	
4	17/12/2011	7.67	3.40	546.0	3.89	607.5	3.30	34	
4	18/12/2011	75.43	28.60	488.8	3.49	614.3	3.34	34	
4	19/12/2011	0.00	4.80	116.7	0.83	0.0	0.00	34	
5	20/12/2011	0.00	0.00	64.2	0.46	605.2	3.29	34	44.04
5	21/12/2011	0.29	0.00	0.0	0.00	0.0	0.00	47.5	
5	22/12/2011	0.06	0.20	0.0	0.00	0.0	0.00	47.5	
5	23/12/2011	0.00	0.00	515.7	3.68	0.0	0.00	47.5	
5	24/12/2011	0.00	0.00	1107.1	7.90	0.0	0.00	47.5	
5	25/12/2011	0.00	0.00	593.2	4.23	0.0	0.00	47.5	
5	26/12/2011	0.00	0.00	99.7	0.00	0.0	0.00	47.5	
5	27/12/2011	0.00	0.00	0.0	0.00	0.0	0.00	47.5	
5	28/12/2011	0.00	0.00	566.6	4.04	0.0	0.00	41	
5	29/12/2011	0.17	0.00	0.0	0.00	0.0	0.00	41	
5	30/12/2011	10.42	2.20	0.0	0.00	0.0	0.00	41	
5	31/12/2011	46.30	21.40	598.9	4.27	0.0	0.00	41	
5	1/01/2012	15.29	45.40	603.2	4.30	0.0	0.00	41	
5	2/01/2012	0.05	38.80	861.2	6.14	0.0	0.00	41	
5	3/01/2012	0.11	0.00	950.1	6.78	0.0	0.00	41	
5	4/01/2012	1.60	7.80	614.1	4.38	0.0	0.00	51.1	
6	5/01/2012	0.00	0.20	497.6	3.55	0.0	0.00	51.1	51.85
6	6/01/2012	0.00	0.00	736.2	5.25	0.0	0.00	51.1	
6	7/01/2012	9.38	0.00	36.8	0.00	0.0	0.00	51.1	
6	8/01/2012	22.44	24.20	22.8	0.00	0.0	0.00	51.1	
6	9/01/2012	1.64	1.20	0.0	0.00	0.0	0.00	51.1	
6	10/01/2012	10.42	0.40	0.0	0.00	0.0	0.00	53.1	
6	11/01/2012	0.76	6.20	0.0	0.00	0.0	0.00	53.1	
6	12/01/2012	0.00	0.00	0.0	0.00	0.0	0.00	53.1	
Harvest	13/01/2012	12.18	10.00	0.0	0.00	0.0	0.00	53.1	50.49
Harvest	14/01/2012	0.00	10.60	0.0	0.00	0.0	0.00	53.1	
Harvest	15/01/2012	0.00	0.00	0.0	0.00	0.0	0.00	53.1	
Harvest	16/01/2012	0.15	0.60	0.0	0.00	0.0	0.00	53.1	
Harvest	17/01/2012	0.00	0.00	0.0	0.00	0.0	0.00	49	
Harvest	18/01/2012	0.00	0.00	0.0	0.00	0.0	0.00	49	
Harvest	19/01/2012	0.00	0.00	0.0	0.00	0.0	0.00	49	
Harvest	20/01/2012	0.00	0.00	0.0	0.00	0.0	0.00	49	
Harvest	21/01/2012	0.07	0.00	608.5	4.34	649.5	3.53	49	
Harvest	22/01/2012	0.41	0.00	603.5	4.30	658.8	3.58	49	
Harvest	23/01/2012	0.00	0.60	619.5	4.42	661.8	3.60	49	
7	24/01/2012	0.06	0.00	611.2	4.36	662.2	3.60	50.4	49.66
7	25/01/2012	0.00	0.00	610.8	4.36	664.7	3.61	50.4	
7	26/01/2012	0.00	0.00	411.9	2.94	666.2	3.62	50.4	
7	27/01/2012	4.17	0.00	424.1	3.02	658.2	3.58	50.4	
7	28/01/2012	0.00	3.20	232.4	1.66	669.2	3.64	50.4	
7	29/01/2012	0.00	0.00	566.9	4.04	757.0	4.12	50.4	
7	30/01/2012	0.12	0.00	568.8	4.06	764.4	4.16	50.4	
7	31/01/2012	0.00	0.00	591.8	4.22	763.8	4.15	50.1	
7	1/02/2012	0.00	0.00	2.9	0.00	0.0	0.00	50.1	
7	2/02/2012	0.00	0.00	0.0	0.00	0.0	0.00	50.1	
7	3/02/2012	0.00	1.00	530.4	3.78	764.5	4.16	50.1	
7	4/02/2012	0.00	0.00	588.7	4.20	763.0	4.15	50.1	
7	5/02/2012	0.00	0.00	41.7	0.00	0.0	0.00	50.1	
7	6/02/2012	0.00	0.00	1128.2	8.05	760.0	4.13	50.1	

7	7/02/2012	0.00	0.00	602.9	4.30	0.0	0.00	50.1	
7	8/02/2012	0.00	0.00	524.7	3.74	765.5	4.16	49	
7	9/02/2012	0.00	0.00	595.2	4.25	748.7	4.07	49	
7	10/02/2012	0.00	0.00	701.9	5.01	778.5	4.23	49	
7	11/02/2012	0.06	0.40	397.1	2.83	638.1	3.47	49	
7	12/02/2012	0.00	0.00	155.0	1.11	112.7	0.00	49	
7	13/02/2012	0.19	0.60	0.0	0.00	0.0	0.00	49	
7	14/02/2012	0.23	3.00	579.2	4.13	756.8	4.12	49	
7	15/02/2012	13.44	0.60	880.3	6.28	1164.4	6.33	45.6	
8	16/02/2012	42.83	3.00	73.5	0.00	256.4	1.39	45.6	47.20
8	17/02/2012	12.89	22.40	348.2	2.48	759.4	4.13	45.6	
8	18/02/2012	0.00	5.00	445.5	3.18	709.0	3.86	45.6	
8	19/02/2012	0.00	0.00	111.9	0.00	25.7	0.00	45.6	
8	20/02/2012	0.06	0.60	502.0	3.58	751.1	4.08	45.6	
8	21/02/2012	0.16	0.20	675.6	4.82	737.5	4.01	45.6	
8	22/02/2012	5.03	5.00	423.1	3.02	752.8	4.09	47.4	
8	23/02/2012	8.56	9.40	150.1	1.07	747.2	4.06	47.4	
8	24/02/2012	0.00	31.80	565.0	4.03	748.3	4.07	47.4	
8	25/02/2012	0.11	0.20	765.7	5.46	1453.5	7.90	47.4	
8	26/02/2012	0.11	0.00	0.0	0.00	792.9	4.31	47.4	
8	27/02/2012	0.00	0.00	151.5	1.08	756.8	4.12	47.4	
8	28/02/2012	7.32	0.00	201.3	1.44	253.0	1.38	47.4	
8	29/02/2012	0.00	6.80	101.0	0.00	0.0	0.00	51.3	
8	01/03/2012	5.17	7.60	818.1	5.83	504.9	2.75	51.3	
9	02/03/2012	6.11	0.00	610.9	4.36	1007.0	5.48	51.3	49.83
9	03/03/2012	3.51	13.00	663.7	4.73	759.3	4.13	51.3	
9	04/03/2012	0.00	0.00	583.1	4.16	750.8	4.08	51.3	
9	05/03/2012	0.00	0.00	434.6	3.10	750.8	4.08	51.3	
9	06/03/2012	0.00	0.00	357.1	2.55	747.3	4.06	51.3	
9	07/03/2012	0.06	0.00	0.0	0.00	0.0	0.00	48.78	
9	08/03/2012	0.65	0.40	0.0	0.00	0.0	0.00	48.78	
9	09/03/2012	0.00	0.00	508.9	3.63	733.8	3.99	48.78	
9	10/03/2012	0.00	0.00	376.0	2.68	544.9	2.96	48.78	
9	11/03/2012	0.35	0.00	399.5	2.85	763.0	4.15	48.78	
9	12/03/2012	9.45	7.20	732.7	5.23	931.3	5.06	48.78	
9	13/03/2012	0.00	1.80	34.0	0.00	0.0	0.00	48.78	
Harvest	14/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	48.71	48.07
Harvest	15/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	48.71	
Harvest	16/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	48.71	
Harvest	17/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	48.71	
Harvest	18/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	48.71	
Harvest	19/03/2012	55.74	0.20	0.0	0.00	0.0	0.00	48.71	
Harvest	20/03/2012	0.45	23.80	0.0	0.00	0.0	0.00	48.71	
Harvest	21/03/2012	7.53	0.00	0.0	0.00	0.0	0.00	49	
Harvest	22/03/2012	15.65	20.70	0.0	0.00	0.0	0.00	49	
Harvest	23/03/2012	0.16	1.60	0.0	0.00	0.0	0.00	49	
Harvest	24/03/2012	0.60	0.20	0.0	0.00	0.0	0.00	49	
Harvest	25/03/2012	0.17	6.00	0.0	0.00	0.0	0.00	49	
Harvest	26/03/2012	0.39	0.40	0.0	0.00	0.0	0.00	49	
Harvest	27/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	49	
Harvest	28/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	46.5	
Harvest	29/03/2012	0.00	0.00	0.0	0.00	0.0	0.00	46.5	
Harvest	30/03/2012	0.00	0.00	566.6	4.04	753.0	4.09	46.5	
Harvest	30/03/2012	0.00	0.00	57.1	0.00	0.0	0.00	46.5	

Harvest	01/04/2012	0.39	0.00	668.3	4.77	755.5	4.11	46.5	
Harvest	02/04/2012	0.00	0.00	604.1	4.31	760.2	4.13	46.5	
Harvest	03/04/2012	0.00	0.00	601.3	4.29	760.2	4.13	46.5	
10	04/04/2012	0.04	0.00	522.9	3.73	765.5	4.16	43.76	43.76
10	05/04/2012	0.00	0.00	672.7	4.80	2.9	0.00	43.76	
10	06/04/2012	0.00	0.00	631.6	4.50	758.1	4.12	43.76	
10	07/04/2012	0.00	0.00	627.3	4.47	1517.4	8.25	43.76	
10	08/04/2012	0.00	0.00	1188.1	8.47	1511.3	8.22	43.76	
10	09/04/2012	0.00	0.00	369.2	2.63	1509.4	8.21	43.76	
10	10/04/2012	0.00	0.00	556.6	3.97	748.6	4.07	43.76	
11	11/04/2012	13.66	0.00	514.9	3.67	1496.5	8.14	48.81	48.81
11	12/04/2012	37.63	30.60	95.4	0.00	0.0	0.00	48.81	
11	13/04/2012	0.00	9.00	5.7	0.00	739.0	4.02	48.81	
12	14/04/2012	0.00	0.00	496.1	3.54	731.1	3.98	48.81	41.45
12	15/04/2012	0.00	0.00	282.1	2.01	736.1	4.00	48.81	
12	16/04/2012	0.00	0.00	498.1	3.55	736.1	4.00	48.81	
12	17/04/2012	0.00	0.00	567.5	4.05	734.5	3.99	48.81	
12	18/04/2012	0.00	0.00	537.6	3.83	728.6	3.96	39.1	
12	19/04/2012	0.00	0.00	538.9	3.84	716.3	3.90	39.1	
12	20/04/2012	0.00	0.00	492.3	3.51	725.0	3.94	39.1	
12	21/04/2012	0.00	0.00	550.4	3.93	598.7	3.26	39.1	
12	22/04/2012	0.00	0.00	666.7	4.76	821.1	4.47	39.1	
12	23/04/2012	0.00	0.00	554.6	3.96	715.2	3.89	39.1	
12	24/04/2012	0.00	0.00	14.9	0.00	0.0	0.00	39.1	
12	25/04/2012	0.00	0.00	0.0	0.00	0.0	0.00	40.79	
12	26/04/2012	0.00	0.00	0.0	0.00	700.0	3.81	40.79	
12	27/04/2012	2.42	1.80	507.6	3.62	685.4	3.73	40.79	
12	28/04/2012	0.71	7.20	457.1	3.26	708.9	3.85	40.79	
12	29/04/2012	0.00	0.00	88.1	0.63	0.0	0.00	40.79	
12	30/04/2012	0.07	1.20	0.0	0.00	0.0	0.00	40.79	
12	01/05/2012	0.07	0.00	519.2	3.70	0.0	0.00	36.89	
12	02/05/2012	0.00	0.00	495.7	3.54	615.3	3.35	36.89	
13	03/05/2012	0.00	0.00	557.3	3.97	608.5	3.31	36.89	44.83
13	04/05/2012	0.00	0.00	510.3	3.64	607.5	3.30	36.89	
13	05/05/2012	0.00	0.00	512.5	3.66	608.5	3.31	36.89	
13	06/05/2012	0.00	0.00	411.3	2.93	581.8	3.16	36.89	
13	07/05/2012	0.00	0.00	85.5	0.00	606.7	3.30	36.89	
13	08/05/2012	0.37	0.00	0.0	0.00	470.1	2.56	49.82	
13	09/05/2012	62.32	32.60	0.0	0.00	162.7	0.88	49.82	
13	10/05/2012	1.79	9.80	442.8	3.16	699.0	3.80	49.82	
13	11/05/2012	0.82	6.40	0.0	0.00	338.3	1.84	49.82	
13	12/05/2012	0.00	0.20	0.0	0.00	328.3	1.79	49.82	
13	13/05/2012	0.62	0.20	0.0	0.00	332.7	1.81	49.82	
13	14/05/2012	21.07	4.20	0.0	0.00	333.4	1.81	49.82	
13	15/05/2012	2.03	17.20	0.0	0.00	747.9	4.07	46.01	
13	16/05/2012	10.66	8.00	0.0	0.00	332.0	1.81	46.01	
13	17/05/2012	0.00	1.20	0.0	0.00	322.6	1.75	46.01	
13	18/05/2012	2.21	0.00	0.0	0.00	335.6	1.82	46.01	
14	19/05/2012	0.00	0.00	0.0	0.00	0.0	0.00	46.01	51.90
14	20/05/2012	0.00	0.00	0.0	0.00	0.0	0.00	46.01	
14	21/05/2012	0.00	0.00	0.0	0.00	314.9	1.71	46.01	
14	22/05/2012	0.00	0.00	0.0	0.00	317.1	1.72	49.44	
14	23/05/2012	0.00	0.20	0.0	0.00	492.6	2.68	49.44	
14	24/05/2012	0.00	0.00	97.6	0.00	665.0	3.62	49.44	

14	25/05/2012	0.00	0.20	495.6	3.53	698.3	3.80	49.44	
14	26/05/2012	0.00	0.00	416.0	2.97	0.0	0.00	49.44	
14	27/05/2012	2.03	0.60	0.0	0.00	0.0	0.00	49.44	
14	28/05/2012	7.43	12.80	504.9	3.60	0.0	0.00	49.44	
14	29/05/2012	0.00	0.40	68.6	0.00	698.6	3.80	57.31	
14	30/05/2012	0.00	0.00	569.0	4.06	1398.5	7.60	57.31	
14	31/05/2012	0.00	0.00	581.4	4.15	1387.3	7.54	57.31	
14	01/06/2012	0.06	0.00	0.0	0.00	0.0	0.00	57.31	
14	02/06/2012	0.00	0.20	0.0	0.00	691.0	3.76	57.31	
14	03/06/2012	0.00	0.00	0.0	0.00	0.0	0.00	57.31	
14	04/06/2012	0.00	0.00	0.0	0.00	692.9	3.77	57.31	
14	05/06/2012	2.75	0.00	0.0	0.00	689.4	3.75	57.31	
14	06/06/2012	19.67	13.40	0.0	0.00	687.0	3.74	47.74	
14	07/06/2012	3.76	19.40	0.0	0.00	0.0	0.00	47.74	
15	08/06/2012	0.00	0.20	0.0	0.00	683.3	3.72	47.74	48.34
15	09/06/2012	0.00	0.00	0.0	0.00	0.0	0.00	47.74	
15	10/06/2012	0.00	0.00	0.0	0.00	0.0	0.00	47.74	
15	11/06/2012	0.05	0.00	0.0	0.00	665.8	3.62	47.74	
15	12/06/2012	0.05	0.00	0.0	0.00	1361.0	7.40	47.74	
15	13/06/2012	0.00	0.00	0.0	0.00	685.4	3.73	46.64	
15	14/06/2012	0.00	0.00	0.0	0.00	681.1	3.70	46.64	
15	15/06/2012	0.00	0.00	0.0	0.00	679.7	3.70	46.64	
15	16/06/2012	0.00	0.00	0.0	0.00	0.0	0.00	46.64	
15	17/06/2012	0.00	0.00	0.0	0.00	0.0	0.00	46.64	
15	18/06/2012	12.66	0.00	9.3	0.00	684.2	3.72	46.64	
15	19/06/2012	7.85	22.40	57.2	0.00	675.4	3.67	46.64	
15	20/06/2012	0.00	0.60	0.0	0.00	687.5	3.74	53.32	
15	21/06/2012	2.12	0.40	0.0	0.00	681.6	3.71	53.32	
15	22/06/2012	0.00	0.20	12.4	0.09	680.3	3.70	53.32	
16	23/06/2012	0.00	0.00	0.0	0.00	0.0	0.00	53.32	44.55
16	24/06/2012	3.03	7.20	0.0	0.00	0.0	0.00	53.32	
16	25/06/2012	2.51	1.20	71.1	0.00	682.7	3.71	53.32	
16	26/06/2012	6.54	5.00	35.5	0.00	686.9	3.74	53.32	
16	27/06/2012	3.23	7.80	528.3	3.77	684.8	3.72	48.49	
16	28/06/2012	1.25	2.20	66.5	0.00	690.1	3.75	48.49	
16	29/06/2012	0.00	0.00	521.0	3.72	1032.5	5.61	48.49	
16	30/06/2012	0.00	0.00	36.8	0.00	799.1	4.35	48.49	
16	1/07/2012	0.00	0.00	0.0	0.00	325.2	1.77	48.49	
16	2/07/2012	0.00	0.00	494.3	3.53	645.6	3.51	48.49	
16	3/07/2012	8.50	0.00	25.3	0.00	204.3	1.11	48.49	
16	4/07/2012	0.00	6.60	497.7	3.55	589.0	3.20	29.84	
16	5/07/2012	0.00	0.00	585.7	4.18	763.0	4.15	29.84	
16	6/07/2012	0.00	0.00	549.9	3.92	677.8	3.69	29.84	
16	7/07/2012	0.00	0.00	28.5	0.00	0.0	0.00	29.84	
16	8/07/2012	0.00	0.00	0.0	0.00	0.0	0.00	29.84	
16	9/07/2012	0.00	0.20	489.4	3.49	683.6	3.72	29.84	
16	10/07/2012	0.00	0.00	37.4	0.00	0.0	0.00	29.84	
16	11/07/2012	0.00	0.20	484.7	3.46	681.1	3.70	64.67	
16	12/07/2012	0.00	0.00	111.3	0.79	682.7	3.71	64.67	
17	13/07/2012	0.00	0.00	484.3	3.45	682.7	3.71	64.67	49.43
17	14/07/2012	0.00	0.00	37.2	0.00	0.0	0.00	64.67	
17	15/07/2012	1.20	0.00	0.0	0.00	325.2	1.77	64.67	
17	16/07/2012	32.51	13.60	0.0	0.00	337.8	1.84	64.67	
17	17/07/2012	8.14	18.80	0.0	0.00	669.1	3.64	64.67	

17	18/07/2012	0.00	0.00	474.6	3.39	667.1	3.63	43.47	
17	19/07/2012	0.00	0.20	41.2	0.00	0.0	0.00	43.47	
17	20/07/2012	0.00	0.20	117.4	0.84	670.3	3.64	43.47	
17	21/07/2012	0.00	0.20	0.0	0.00	338.1	1.84	43.47	
17	22/07/2012	4.38	0.20	0.0	0.00	320.6	1.74	43.47	
17	23/07/2012	28.38	11.00	24.8	0.00	673.1	3.66	43.47	
17	24/07/2012	6.28	20.00	0.0	0.00	669.4	3.64	43.47	
17	25/07/2012	0.87	1.40	495.6	3.54	669.1	3.64	45.71	
17	26/07/2012	0.83	0.20	35.2	0.00	0.0	0.00	45.71	
17	27/07/2012	0.00	0.00	426.7	3.04	633.6	3.45	45.71	
17	28/07/2012	0.00	0.00	0.0	0.00	336.4	1.83	45.71	
17	29/07/2012	0.11	0.00	0.0	0.00	320.9	1.74	45.71	
17	30/07/2012	11.31	1.60	524.2	3.74	671.9	3.65	45.71	
17	31/07/2012	5.82	14.60	561.6	4.01	669.1	3.64	45.71	
17	1/08/2012	0.00	0.00	561.5	4.00	670.6	3.65	45.3	
17	2/08/2012	0.40	0.00	550.9	3.93	666.3	3.62	45.3	
18	3/08/2012	1.38	0.40	572.6	4.08	666.2	3.62	45.3	46.55
18	4/08/2012	0.78	1.20	32.4	0.00	0.0	0.00	45.3	
18	5/08/2012	0.00	0.00	0.0	0.00	0.0	0.00	45.3	
18	6/08/2012	0.21	0.00	548.8	3.91	666.0	3.62	45.3	
18	7/08/2012	0.11	0.40	559.5	3.99	665.3	3.62	45.3	
18	8/08/2012	4.44	1.80	34.2	0.00	664.2	3.61	46.2	
18	9/08/2012	0.28	7.00	14.7	0.00	660.5	3.59	46.2	
18	10/08/2012	0.00	0.00	1114.2	7.95	665.9	3.62	46.2	
18	11/08/2012	0.00	0.20	29.6	0.00	0.0	0.00	46.2	
18	12/08/2012	48.43	28.20	0.0	0.00	0.0	0.00	46.2	
18	13/08/2012	13.14	26.60	550.6	3.93	661.8	3.60	46.2	
18	14/08/2012	0.67	3.00	484.3	3.45	659.9	3.59	46.2	
18	15/08/2012	2.65	6.60	619.8	4.42	659.0	3.58	48.0	
18	16/08/2012	7.51	10.80	112.1	0.80	661.7	3.60	48.0	
18	17/08/2012	0.00	0.80	916.2	6.53	662.6	3.60	48.0	
18	18/08/2012	0.05	0.00	0.0	0.00	312.1	1.70	48.0	
18	19/08/2012	1.67	0.00	0.0	0.00	0.0	0.00	48.0	
18	20/08/2012	7.98	9.80	479.0	3.42	654.4	3.56	48.0	
19	21/08/2012	0.15	1.2	554.0	3.95	653.8	3.55	48.0	56.72
19	22/08/2012	0	0	47.5	0.00	0.0	0.00	60.4	
19	23/08/2012	1.8	0	464.5	3.31	648.1	3.52	60.4	
19	24/08/2012	1.75	1.4	597.1	4.26	660.7	3.59	60.4	
19	25/08/2012	0	0	27.1	0.00	331.5	1.80	60.4	
19	26/08/2012	0	0	0.0	0.00	315.7	1.72	60.4	
19	27/08/2012	1.81	0	0.0	0.00	661.4	3.60	60.4	
19	28/08/2012	0.18	5.2	529.9	3.78	659.6	3.59	60.4	
19	29/08/2012	0	0	594.1	4.24	1007.4	5.48	53.9	
19	30/08/2012	0	0	575.0	4.10	1018.7	5.54	53.9	
19	31/08/2012	0	0	590.9	4.21	1018.1	5.54	53.9	
19	1/09/2012	0	0	583.5	4.16	1020.9	5.55	53.9	
19	2/09/2012	0	0	41.5	0.00	636.9	3.46	53.9	
19	3/09/2012	14.48	0.8	492.9	3.52	666.4	3.62	53.9	
20	4/09/2012	16.86	21.2	520.5	3.71	669.3	3.64	53.9	41.64
20	5/09/2012	1.63	2.2	571.0	4.07	668.7	3.64	35.5	
20	6/09/2012	0	0	580.4	4.14	661.3	3.60	35.5	
21	7/09/2012	0.15	0	1096.6	7.82	658.1	3.58	35.5	46.04
21	8/09/2012	1.93	1.4	25.8	0.00	316.7	1.72	35.5	
21	9/09/2012	12	6.4	0.0	0.00	331.6	1.80	35.5	

21	10/09/2012	5.45	8.8	17.2	0.00	662.9	3.60	35.5	
21	11/09/2012	8.65	4.6	0.0	0.00	668.8	3.64	35.5	
21	12/09/2012	0	3.4	7.4	0.05	667.0	3.63	54.8	
21	13/09/2012	0	0	544.3	3.88	664.4	3.61	54.8	
21	14/09/2012	0	0	548.5	3.91	659.0	3.58	54.8	
21	15/09/2012	2.73	0	32.3	0.00	0.0	0.00	54.8	
21	16/09/2012	34.63	20	0.0	0.00	0.0	0.00	54.8	
21	17/09/2012	0.16	24.4	0.0	0.00	0.0	0.00	54.8	
Key	▨	Mini irrigator run, removed from data analyses.							

Appendix 3. Lysimeter experiment – rainfall values and the amount of applied wastewater during rain gauge measurement periods

Key	
░	Rain gauge overflow or error - calculated depth*
▒	Mean of surrounding rain gauges
▓	Slightly negative value – changed to 0

Table 7.2. Rainfall values and the amount of applied wastewater during each rain gauge measurement period at Pivot F.

Rain gauge measurement period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**During harvest stand down periods**	**Percentage of the effluent applied that was measured in rain gauges (%) (a)**
Beginning date	**8/09/2011**	**7/10/2012**	**10/11/2012**	**1/12/2012**	**20/12/2012**	**5/01/2012**	**24/01/2012**	**16/02/2012**	**2/03/2012**	**4/04/2012**	**11/04/2012**	**14/04/2012**	**3/05/2012**	**19/05/2012**	**8/06/2012**	**23/06/2012**	**13/07/2012**	**2/08/2012**	**21/08/2012**	**4/09/2012**	**4/09/2012**		
Ending date	**6/10/2011**	**31/10/2011**	**30/11/2011**	**19/12/2011**	**4/01/2012**	**12/01/2012**	**15/02/2012**	**1/03/2012**	**13/03/2012**	**10/04/2012**	**13/04/2012**	**2/05/2012**	**18/05/2012**	**7/06/2012**	**22/06/2012**	**12/07/2012**	**1/08/2012**	**20/08/2012**	**3/09/2012**	**6/09/2012**	**17/09/2012**		
Rainfall (mm)	68	70	13	115	122	54	7	89	42	0	69	9	119	62	30	32	100	110	10	18	93	86	
Calculated effluent irrigated (mm)	74	77	36	28	42**(b)**	9	70	36	39	29	8	48	21	18	0	30	27	43	35	11	20	30	
Lysimeters	**Rain gauge measurement of the irrigated effluent (mm)**																						
F1A	60	46	41	27	43	3	58	41	37	37	0	57	19	27	8	47	38	44	52	4	24	31	101.9
F1B	65	49	40	25	41	3	57	43	46	32	4	59	19	21	6	36	30	42	42	2	23	30	97.6
F1C	60	50	39	23	41	3	60	38	40	35	0	56	21	24	6	45	30	42	49	11	25	30	98.5
F2A	82	71	37	25	47	5	62	49	39	32	3	57	23	38	0	52	40	48	51	11	32	34	111.6
F2B	82	79	54	32	49	5	58	45	39	40	3	58	22	38	1	51	40	51	49	11	35	36	118.1
F2C	82	73	51	29	48	5	56	43	39	37	3	56	16	38	1	50	39	50	49	11	29	35	115.5
F3A	70	54	39	19	44	7	61	39	58	38	0	61	15	24	0	35	28	46	60	11	24	32	105.9

F3B	64	51	36	20	43	7	62	40	46	38	0	57	19	23	1	36	30	44	59	7	26	31	102.1
F3C	75	57	34	21	43	7	60	37	48	40	0	60	24	23	1	40	23	44	50	8	23	31	101.7
F4A	82	65	53	25	50	7	75	54	53	43	0	68	20	27	2	49	22	52	62	12	27	37	120.1
F4B	82	70	50	25	50	6	73	53	45	45	4	70	22	29	2	54	31	51	65	11	16	36	119.2
F4C	82	67	53	19	55	6	71	51	50	45	0	71	27	32	2	55	31	56	69	9	34	40	131.4
F5A	62	47	37	19	34	9	48	26	27	32	0	38	20	21	1	24	22	34	47	2	19	24	80.2
F5B	72	62	43	20	39	9	53	32	33	39	0	39	21	20	0	27	23	40	54	2	25	28	92.5
F5C	64	53	42	19	37	7	53	30	23	36	0	37	20	18	1	39	23	38	63	3	23	27	89.2
F6A	82	55	44	25	45	9	68	43	41	31	0	60	22	27	0	44	25	46	60	5	28	33	108.1
F6B	82	64	57	27	44	9	75	42	43	30	0	63	21	19	0	46	30	45	60	6	20	32	104.2
F6C	82	59	71	22	49	8	75	40	43	33	0	66	21	29	2	49	31	50	61	6	25	36	116.8
F7A	81	72	46	27	36	5	30	18	7	25	0	18	20	23	2	46	36	37	63	8	36	26	86.5
F7B	82	72	45	33	36	6	24	16	6	24	0	19	25	20	0	44	35	37	61	6	23	26	85.3
F7C	82	73	46	32	47	9	61	33	36	36	0	57	26	21	3	48	33	48	61	7	33	34	112.4
F8A	67	78	35	17	42	8	67	37	40	39	0	58	13	20	1	39	24	44	59	5	23	31	101.3
F8B	67	56	42	25	37	8	60	33	35	34	0	53	11	18	1	34	22	39	60	6	18	27	89.5
F8C	82	93	52	34	51	8	77	44	47	48	0	56	18	21	0	42	29	52	61	7	27	37	121.3

***Calculated depth**

On occasion irrigated rain gauges overflowed, for example during the period of intense rainfall that occurred within measurement period #5 (20/12/2012 to 4/01/2012). To determine depth of wastewater that was irrigated during an overflow period, each rain gauge was assigned a value (denoted as ‘a’ in the table above). Values were the proportion of irrigated wastewater depth that was measured during a measurement period in which the rain gauge did not overflow. For the period of overflow, the assigned value was multiplied by the amount of irrigated wastewater, for that same time period (denoted as ‘b’ in the table above).

For example, the rain gauge that was installed at F1A, on average, measured 102% of the wastewater that was calculated to be irrigated from Pivot F. When rain gauges over flowed during measurement period #5 (20/12/2012 to 4/01/2012), the amount of wastewater that was applied during that time period (‘b’) was 42 mm. Therefore, the amount of wastewater applied to FIA was estimated to be 43 mm (102% of 42 mm).

Table 7.3. Rainfall values and the amount of applied wastewater during each rain gauge measurement period at Pivot G.

Rain gauge measurement period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**During harvest stand down periods**	**Percentage of the effluent applied that was measured in rain gauges (%)**
Beginning date	**8/09/2011**	**7/10/2011**	**10/11/2011**	**1/12/2011**	**20/12/2011**	**5/01/2012**	**24/01/2012**	**16/02/2012**	**2/03/2012**	**4/04/2012**	**11/04/2012**	**14/04/2012**	**3/05/2012**	**19/05/2012**	**8/06/2012**	**23/06/2012**	**13/07/2012**	**2/08/2012**	**21/08/2012**	**4/09/2012**	**4/09/2012**		
Ending date	**6/10/2011**	**31/10/2011**	**30/11/2011**	**19/12/2011**	**4/01/2012**	**12/01/2012**	**15/02/2012**	**1/03/2012**	**13/03/2012**	**10/04/2012**	**13/04/2012**	**2/05/2012**	**18/05/2012**	**7/06/2012**	**22/06/2012**	**12/07/2012**	**1/08/2012**	**20/08/2012**	**3/09/2012**	**6/09/2012**	**17/09/2012**		
Rainfall (mm)	68	70	13	115	122	54	7	89	42	0	69	9	119	62	30	32	100	110	10	18	93	86	
Calculated effluent irrigated (mm)	86	78	60	48	3	0	64	48	41	33	16	51	42	49	41	53	54	45	51	11	29	27	
Lysimeters	**Rain gauge measurement of the irrigated effluent (mm)**																						
G1A	82	60	51	46	0	1	53	51	45	47	5	60	41	48	42	52	53	48	88	13	28	27	97.6
G1B	82	68	52	55	6	0	52	61	56	58	7	72	49	57	47	81	63	52	87	13	33	32	116.4
G1C	82	68	56	55	0	0	53	59	47	52	4	64	27	98	58	68	63	52	89	13	40	31	115.8
G2A	59	42	36	39	3	0	64	43	33	34	6	48	24	37	42	51	44	36	54	8	33	22	81.1
G2B	70	49	45	49	4	0	68	46	42	46	6	57	24	37	48	113	46	46	69	11	33	28	103.3
G2C	79	57	54	49	1	0	69	53	43	48	4	61	25	39	55	68	56	46	69	12	38	28	102.1
G3A	80	51	42	46	1	0	55	49	41	48	8	53	41	45	50	64	53	44	69	12	28	26	97.0
G3B	82	62	52	54	1	0	64	54	56	56	7	70	47	52	62	73	56	51	83	14	29	31	113.2
G3C	80	51	44	48	2	0	58	50	46	44	3	58	22	48	51	65	55	45	74	13	54	27	100.5
G4A	72	53	55	47	0	0	63	40	58	43	5	54	25	57	47	62	54	44	92	12	30	27	98.9
G4B	82	71	57	61	0	0	67	61	60	64	8	79	53	57	73	90	61	57	93	19	42	35	127.7
G4C	82	69	73	58	0	0	43	58	57	61	7	80	51	57	74	90	67	55	61	17	42	33	122.2

Appendix 4. Lysimeter experiment – summary of nitrogen application

Table 7.4. Summary of nitrogen application.

Lysimeter	Effluent nitrogen applied	Nitrogen applied (Effluent and atmospheric nitrogen)	Treatment
	(kg N ha^{-1} yr^{-1})	(kg N ha^{-1} yr^{-1})	
C1A	0	5	Control
C1B	0	5	Control
C1C	0	5	Control
C2A	0	5	Control
C2B	0	5	Control
C2C	0	5	Control
F1A	350	355	Low
F1B	335	340	Low
F1C	342	347	Low
F2A	395	400	Medium
F2B	413	418	Medium
F2C	395	400	Medium
F3A	361	366	Low
F3B	349	354	Low
F3C	352	357	Low
F4A	417	422	Medium
F4B	419	424	Medium
F4C	436	441	Medium
F5A	281	286	Low
F5B	322	327	Low
F5C	311	316	Low
F6A	375	380	Medium
F6B	386	391	Medium
F6C	406	411	Medium
F7A	315	320	Low
F7B	304	309	Low
F7C	390	395	Medium
F8A	352	357	Low
F8B	325	330	Low
F8C	419	424	Medium
G1A	448	453	High
G1B	513	518	High
G1C	514	519	High
G2A	358	363	Low
G2B	442	447	High
G2C	451	456	High
G3A	429	434	Medium
G3B	500	505	High
G3C	444	449	High
G4A	449	454	High
G4B	562	567	High
G4C	534	539	High

Key	
Treatment	Nitrogen application
	(kg N ha^{-1} yr$^{-1)}$
Control	5
Low	286 - 380
Medium	380 - 445
High	445 - 567

Appendix 5. Lysimeter experiment – leachate mass

Table 7.5. Leachate mass.

Lysimeter	Leachate mass (kg)											
	6/10/2011	7/11/2011	19/12/2011	24/01/2012	15/02/2012	13/03/2012	13/04/2012	18/05/2012	22/06/2012	1/08/2012	3/09/2012	25/09/2012
C1A	0.72	3.10	2.69	3.56	0.07	6.17	5.04	5.56	4.03	6.04	4.37	4.77
C1B	1.68	3.75	1.72	9.62	0.05	4.14	5.61	2.43	3.85	7.48	4.99	5.68
C1C	0.71	2.66	0.65	9.12	0.54	3.21	6.48	5.17	3.95	7.61	5.31	5.38
C2A	0.39	1.57	0.61	4.13	0.12	2.10	3.28	3.98	2.87	4.66	3.72	3.42
C2B	1.58	3.60	1.73	7.19	0.11	9.81	5.16	6.29	4.76	6.42	5.81	5.46
C2C	1.07	2.85	1.30	6.36	0.30	5.73	3.87	4.71	3.63	7.67	4.71	4.70
C3A	12.69	3.19	1.33	9.04	0.40	5.32	6.33	5.80	3.08	6.68	11.94	5.80
C3B	0.77	2.77	1.85	7.51	0.30	2.63	6.14	5.97	4.17	7.28	6.45	6.39
C3C	ND	0.92	0.58	8.54	0.12	1.48	4.35	3.41	2.36	6.13	5.76	5.89
C4A	0.94	4.14	1.72	10.55	0.17	13.70	6.22	8.69	3.96	6.69	8.53	5.25
C4B	0.16	2.34	0.39	11.37	0.68	14.98	6.68	10.63	5.99	8.25	11.01	8.40
C4C	0.22	0.50	0.36	7.66	0.68	4.60	8.47	9.48	2.63	4.84	12.37	7.26
FIA	3.64	4.81	3.28	5.19	0.18	1.92	3.06	5.11	2.77	7.65	3.22	4.46
FIB	4.88	6.37	2.86	2.55	0.10	4.09	5.61	9.10	4.42	11.99	10.55	7.18
FIC	3.31	4.67	2.09	3.44	ND	5.72	2.63	4.07	1.61	5.57	7.25	2.53
F2A	6.80	9.42	3.93	8.15	2.16	7.89	9.23	10.58	5.11	12.76	ND	7.70
F2B	6.00	7.50	4.66	10.68	0.38	5.48	3.31	4.44	2.35	6.54	8.39	3.79
F2C	7.21	7.81	6.19	7.87	1.64	7.01	4.60	7.23	3.01	7.38	6.68	4.50
F3A	7.10	ND	ND	ND	ND	ND	ND	ND	ND	ND	5.60	ND
F3B	7.26	8.50	5.99	9.31	0.33	13.14	6.51	3.20	1.05	2.69	12.36	3.13
F3C	7.81	10.91	3.67	9.67	1.64	7.02	8.24	11.47	5.99	11.33	11.96	9.55
F4A	13.98	11.60	5.17	7.16	1.01	7.19	1.88	9.02	3.75	7.85	8.358	5.19
F4B	ND	ND	ND	ND	ND	ND	ND	ND	12.38	ND	ND	ND
F4C	4.37	4.32	1.55	2.88	0.37	2.76	7.20	3.05	1.64	3.99	2.644	3.14
F5A	4.95	6.56	3.09	3.95	0.18	4.32	3.13	4.60	2.89	6.11	6.971	4.62
F5B	6.00	8.00	2.12	2.40	0.26	2.54	2.32	2.81	1.72	4.33	3.881	2.31
F5C	6.86	7.53	3.00	6.41	0.14	3.05	4.39	6.70	3.81	8.62	8.51	6.13
F6A	4.27	4.49	3.72	6.02	0.48	3.87	2.39	3.85	2.47	6.10	5.804	2.63
F6B	3.39	4.67	3.15	2.86	0.79	1.96	1.73	0.96	ND	ND	1.449	1.25
F6C	8.40	9.27	5.47	8.93	0.34	6.19	5.64	4.81	7.15	8.47	9.215	4.92
F7A	7.57	8.69	3.42	4.52	0.37	3.00	3.56	7.13	4.93	11.85	12.75	7.94
F7B	7.33	10.45	4.74	6.39	0.23	3.37	3.64	6.41	3.97	8.85	8.899	5.94
F7C	2.20	ND	6.94	3.83	0.21	2.41	0.66	ND	ND	ND	3.809	ND
F8A	6.45	8.62	4.01	8.53	0.16	4.51	4.24	6.65	4.68	6.82	9.384	6.84
F8B	2.80	6.58	1.90	4.01	0.67	ND	2.96	6.17	3.08	7.80	8.08	5.59
F8C	9.37	10.86	5.71	7.95	0.34	3.90	3.39	4.56	2.76	8.57	7.40	3.64
G1A	8.03	8.55	6.81	3.39	0.21	8.02	8.53	11.00	8.36	11.25	9.99	6.50
G1B	8.18	9.09	7.01	3.74	0.28	6.03	7.34	10.86	11.13	10.68	11.119	10.39
G1C	6.39	6.32	7.92	6.75	0.54	9.48	8.84	8.82	4.82	11.62	11.676	11.23
G2A	7.62	9.41	7.50	6.28	0.70	6.86	6.92	8.81	7.20	11.79	11.40	3.48
G2B	6.95	6.87	5.26	3.06	5.30	4.69	7.11	10.11	5.67	10.07	7.94	6.43

G2C	4.36	6.95	4.01	3.80	2.28	4.29	3.23	4.54	4.10	8.55	8.24	4.94
G3A	5.06	4.63	4.34	8.58	0.40	5.55	6.16	8.00	10.36	12.93	12.83	7.13
G3B	10.55	9.76	9.25	6.13	0.86	8.97	9.13	11.05	7.17	12.50	12.63	8.80
G3C	5.75	6.48	5.87	5.92	0.27	4.48	7.83	4.70	5.60	12.73	12.94	7.93
G4A	7.35	7.59	9.42	6.42	0.72	7.55	5.72	8.67	7.80	12.82	11.19	6.79
G4B	12.31	12.63	12.95	11.23	1.25	12.17	13.08	11.16	12.66	12.54	12.48	11.28
G4C	6.43	8.72	7.28	5.53	0.81	7.39	14.43	11.37	12.61	14.39	9.59	9.46

Appendix 6. Lysimeter experiment – filtered total nitrogen correction

Leachate samples taken in September 2011 and October 2011 were accidentally filtered. Only half of each sample was supposed to be filtered for inorganic analysis with an unfiltered sample needed for TN analysis. To obtain TN concentration from the filtered samples, the relationship between the filtered TN and the actual TN was investigated using twenty six replicates from June 2012. A filtered and a non-filtered sample were analysed for TN. The actual TN and the filtered TN concentrations were plotted against each other and the regression equation was used to calculate the actual TN concentration for the filtered September 2011 and October 2011 leachate samples.

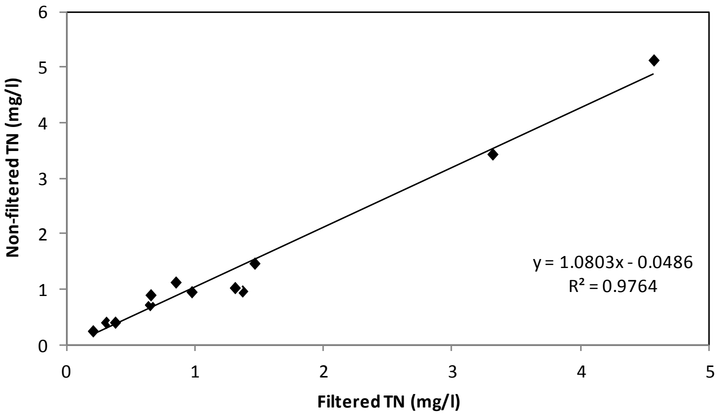

Figure 7.2. Filtered TN plotted against the non-filtered TN.

Appendix 7. Lysimeter experiment – leachate nitrogen

Table 7.6. Leachate nitrogen.

Date	Sampling number	Lysimeter	Treatment	TN	NH_4	NO_2	Nox	NO_3^-	ToN
				(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})
6/10/2011	1	C1A	Control	1.063	0.054	0.001	0.306	0.305	0.702
6/10/2011	1	C1B	Control	0.621	0.055	0.001	0.042	0.041	0.523
6/10/2011	1	C1C	Control	1.452	0.055	0.001	0.278	0.277	1.118
6/10/2011	1	C2A	Control	1.286	0.058	0.001	0.259	0.258	0.968
6/10/2011	1	C2B	Control	1.522	0.058	0.001	0.046	0.045	1.417
6/10/2011	1	C2C	Control	1.079	0.055	0.001	0.168	0.167	0.855
6/10/2011	1	C3A	Control	0.778	0.047	0.001	0.032	0.031	0.698
6/10/2011	1	C3B	Control	0.923	0.050	0.001	0.073	0.072	0.799
6/10/2011	1	C3C	Control	ND	ND	ND	ND	ND	ND
6/10/2011	1	C4A	Control	1.736	0.053	0.001	0.902	0.901	0.780
6/10/2011	1	C4B	Control	4.749	0.071	0.002	3.302	3.300	1.374
6/10/2011	1	C4C	Control	3.160	0.135	0.002	2.041	2.038	0.982
6/10/2011	1	F1A	Low	2.046	0.056	0.001	0.527	0.525	1.462
6/10/2011	1	F1B	Low	1.308	0.045	0.001	0.167	0.165	1.095
6/10/2011	1	F1C	Low	1.497	0.052	0.001	0.431	0.430	1.013
6/10/2011	1	F2A	Medium	0.949	ND	ND	ND	0.508	ND
6/10/2011	1	F2B	Medium	1.533	0.040	0.001	0.739	0.738	0.753
6/10/2011	1	F2C	Medium	3.156	0.049	0.001	1.647	1.645	1.459
6/10/2011	1	F3A	Low	1.383	0.070	0.001	0.456	0.455	0.000
6/10/2011	1	F3B	Low	1.928	0.046	0.001	0.809	0.807	1.072
6/10/2011	1	F3C	Low	1.574	0.037	0.001	0.713	0.712	0.823
6/10/2011	1	F4A	Medium	2.249	0.048	0.001	1.057	1.056	1.143
6/10/2011	1	F4B	Medium	ND	ND	ND	ND	ND	ND
6/10/2011	1	F4C	Medium	1.560	0.045	0.001	0.653	0.652	0.861
6/10/2011	1	F5A	Low	2.619	0.048	0.001	0.844	0.843	1.726
6/10/2011	1	F5B	Low	2.013	0.038	0.001	0.555	0.554	1.419
6/10/2011	1	F5C	Low	1.522	0.041	0.001	0.600	0.599	0.880
6/10/2011	1	F6A	Medium	1.920	0.050	0.001	0.468	0.467	1.401
6/10/2011	1	F6B	Medium	2.198	0.043	0.001	0.827	0.826	1.327
6/10/2011	1	F6C	Medium	1.612	0.045	0.001	0.670	0.669	0.896
6/10/2011	1	F7A	Low	1.410	0.034	0.001	0.522	0.521	0.853
6/10/2011	1	F7B	Low	2.611	0.056	0.001	1.760	1.758	0.794
6/10/2011	1	F7C	Medium	2.513	0.060	0.001	1.498	1.497	0.954
6/10/2011	1	F8A	Low	0.617	0.015	0.000	0.488	0.488	0.114
6/10/2011	1	F8B	Low	1.747	0.031	0.001	0.802	0.801	0.913
6/10/2011	1	F8C	Medium	2.873	ND	ND	ND	2.430	ND
6/10/2011	1	G1A	High	2.381	0.043	0.002	1.798	1.796	0.538
6/10/2011	1	G1B	High	2.123	0.035	0.001	1.001	1.000	1.086
6/10/2011	1	G1C	High	4.387	ND	ND	ND	1.774	ND
6/10/2011	1	G2A	Low	0.567	0.018	0.003	0.476	0.473	0.070
6/10/2011	1	G2B	High	1.757	0.011	0.002	0.964	0.962	0.780
6/10/2011	1	G2C	High	1.426	0.022	0.002	0.955	0.953	0.447
6/10/2011	1	G3A	Medium	10.244	0.036	0.003	12.078	12.066	0.000
6/10/2011	1	G3B	High	1.644	0.010	0.001	1.201	1.200	0.432

6/10/2011	1	G3C	High	5.446	0.033	0.003	5.935	5.931	0.000
6/10/2011	1	G4A	High	1.433	0.036	0.000	0.621	0.621	0.776
6/10/2011	1	G4B	High	3.091	0.021	0.001	2.988	2.987	0.081
6/10/2011	1	G4C	High	2.142	0.038	0.001	1.584	1.583	0.519
Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH_4**	**NO_2**	**Nox**	**NO_3^-**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
7/11/2011	2	C1A	Control	1.382	0.041	0.001	0.072	0.071	1.268
7/11/2011	2	C1B	Control	0.725	0.082	0.001	0.109	0.108	0.533
7/11/2011	2	C1C	Control	0.628	0.049	0.005	1.673	1.668	0.000
7/11/2011	2	C2A	Control	0.909	0.075	0.001	0.042	0.041	0.791
7/11/2011	2	C2B	Control	0.900	0.053	0.001	0.030	0.029	0.816
7/11/2011	2	C2C	Control	0.911	0.043	0.001	0.240	0.240	0.627
7/11/2011	2	C3A	Control	0.378	0.033	0.001	0.007	0.006	0.337
7/11/2011	2	C3B	Control	0.661	0.034	0.001	0.013	0.013	0.613
7/11/2011	2	C3C	Control	0.619	0.072	0.001	0.051	0.050	0.495
7/11/2011	2	C4A	Control	1.200	0.037	0.002	0.380	0.375	0.781
7/11/2011	2	C4B	Control	1.241	0.042	0.001	0.319	0.318	0.879
7/11/2011	2	C4C	Control	2.386	0.072	0.001	0.721	0.721	1.592
7/11/2011	2	F1A	Low	2.259	0.052	0.001	0.980	0.979	1.226
7/11/2011	2	F1B	Low	1.033	0.000	0.000	0.000	0.142	0.859
7/11/2011	2	F1C	Low	1.259	0.000	0.000	0.000	0.400	0.816
7/11/2011	2	F2A	Medium	1.223	0.064	0.002	0.668	0.666	0.489
7/11/2011	2	F2B	Medium	1.470	0.061	0.001	0.723	0.722	0.685
7/11/2011	2	F2C	Medium	3.852	0.054	0.002	3.530	3.528	0.266
7/11/2011	2	F3A	Low	ND	ND	ND	ND	ND	ND
7/11/2011	2	F3B	Low	1.663	0.057	0.001	0.842	0.841	0.763
7/11/2011	2	F3C	Low	2.631	0.062	0.001	0.723	0.722	1.845
7/11/2011	2	F4A	Medium	2.114	0.061	0.001	0.589	0.589	1.463
7/11/2011	2	F4B	Medium	ND	ND	ND	ND	ND	ND
7/11/2011	2	F4C	Medium	2.785	0.118	0.003	2.216	2.212	0.448
7/11/2011	2	F5A	Low	0.938	0.076	0.001	0.628	0.627	0.233
7/11/2011	2	F5B	Low	1.535	0.050	0.001	0.555	0.554	0.929
7/11/2011	2	F5C	Low	1.672	0.058	0.002	0.619	0.618	0.993
7/11/2011	2	F6A	Medium	2.316	0.053	0.001	1.722	1.721	0.540
7/11/2011	2	F6B	Medium	1.729	0.054	0.001	0.698	0.697	0.976
7/11/2011	2	F6C	Medium	1.588	0.050	0.001	0.459	0.458	1.078
7/11/2011	2	F7A	Low	1.327	0.049	0.001	0.371	0.370	0.906
7/11/2011	2	F7B	Low	3.779	0.065	0.001	1.888	1.887	1.825
7/11/2011	2	F7C	Medium	ND	0.067	0.002	0.939	0.937	0.926
7/11/2011	2	F8A	Low	0.720	0.012	0.001	0.483	0.482	0.224
7/11/2011	2	F8B	Low	2.224	0.055	0.001	0.961	0.960	1.207
7/11/2011	2	F8C	Medium	2.416	0.014	0.004	0.000	4.082	2.398
7/11/2011	2	G1A	High	1.875	0.048	0.002	1.327	1.325	0.498
7/11/2011	2	G1B	High	1.196	0.044	0.001	0.639	0.638	0.512
7/11/2011	2	G1C	High	1.563	0.067	0.001	0.559	0.558	0.936
7/11/2011	2	G2A	Low	0.435	0.011	0.002	0.441	0.439	0.000
7/11/2011	2	G2B	High	1.116	0.018	0.003	1.367	1.364	0.000
7/11/2011	2	G2C	High	0.973	0.012	0.004	0.729	0.725	0.228
7/11/2011	2	G3A	Medium	10.804	0.046	0.004	14.346	14.342	0.000

7/11/2011	2	G3B	High	0.655	0.032	0.003	0.343	0.340	0.277
7/11/2011	2	G3C	High	2.518	0.051	0.002	2.522	2.521	0.000
7/11/2011	2	G4A	High	0.903	0.072	0.006	0.214	0.208	0.611
7/11/2011	2	G4B	High	2.510	0.109	0.005	2.067	2.061	0.329
7/11/2011	2	G4C	High	1.978	0.089	0.003	1.585	1.583	0.301

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH_4**	**NO_2**	**Nox**	**NO_3^-**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
19/12/2011	3	C1A	Control	0.948	0.042	0.000	0.190	0.190	0.716
19/12/2011	3	C1B	Control	0.479	0.007	0.000	0.049	0.049	0.423
19/12/2011	3	C1C	Control	0.497	0.003	0.000	0.035	0.035	0.459
19/12/2011	3	C2A	Control	1.268	0.032	0.000	0.263	0.263	0.973
19/12/2011	3	C2B	Control	0.656	0.010	0.000	0.007	0.007	0.639
19/12/2011	3	C2C	Control	0.842	0.031	0.000	0.118	0.118	0.694
19/12/2011	3	C3A	Control	0.903	0.026	0.000	0.089	0.089	0.789
19/12/2011	3	C3B	Control	0.557	0.011	0.000	0.012	0.012	0.535
19/12/2011	3	C3C	Control	1.007	0.009	0.000	0.087	0.086	0.910
19/12/2011	3	C4A	Control	2.061	0.196	0.001	0.313	0.312	1.551
19/12/2011	3	C4B	Control	3.290	0.769	0.001	0.563	0.562	1.956
19/12/2011	3	C4C	Control	1.682	0.010	0.000	0.339	0.339	1.333
19/12/2011	3	F1A	Low	1.395	0.029	0.000	0.809	0.809	0.557
19/12/2011	3	F1B	Low	0.759	0.017	0.000	0.120	0.120	0.622
19/12/2011	3	F1C	Low	1.021	0.034	0.000	0.369	0.369	0.618
19/12/2011	3	F2A	Medium	0.883	0.024	0.001	0.218	0.217	0.639
19/12/2011	3	F2B	Medium	1.287	0.019	0.000	0.654	0.654	0.614
19/12/2011	3	F2C	Medium	2.632	0.029	0.003	2.100	2.097	0.499
19/12/2011	3	F3A	Low	ND	ND	ND	ND	ND	ND
19/12/2011	3	F3B	Low	1.737	0.012	0.000	1.203	1.203	0.522
19/12/2011	3	F3C	Low	1.014	0.018	0.001	0.469	0.468	0.526
19/12/2011	3	F4A	Medium	1.517	0.024	0.000	0.624	0.624	0.868
19/12/2011	3	F4B	Medium	ND	ND	ND	ND	ND	ND
19/12/2011	3	F4C	Medium	2.777	0.015	0.001	2.245	2.244	0.515
19/12/2011	3	F5A	Low	2.092	0.015	0.000	1.615	1.614	0.462
19/12/2011	3	F5B	Low	1.603	0.073	0.000	0.798	0.797	0.732
19/12/2011	3	F5C	Low	2.099	0.006	0.001	1.952	1.951	0.140
19/12/2011	3	F6A	Medium	2.288	0.025	0.001	1.721	1.720	0.541
19/12/2011	3	F6B	Medium	2.004	0.022	0.000	1.396	1.396	0.586
19/12/2011	3	F6C	Medium	1.816	0.023	0.000	1.278	1.278	0.515
19/12/2011	3	F7A	Low	0.996	0.024	0.001	0.395	0.394	0.578
19/12/2011	3	F7B	Low	2.318	0.030	0.000	1.615	1.615	0.673
19/12/2011	3	F7C	Medium	2.155	0.045	0.002	1.660	1.657	0.448
19/12/2011	3	F8A	Low	1.064	0.013	0.000	0.570	0.570	0.481
19/12/2011	3	F8B	Low	1.946	0.016	0.000	0.836	0.836	1.094
19/12/2011	3	F8C	Medium	8.301	0.019	0.004	7.388	7.384	0.890
19/12/2011	3	G1A	High	2.693	0.018	0.000	2.387	2.387	0.287
19/12/2011	3	G1B	High	3.725	0.011	0.002	3.276	3.274	0.436
19/12/2011	3	G1C	High	1.688	0.009	0.000	1.064	1.064	0.615
19/12/2011	3	G2A	Low	1.361	0.010	0.000	0.469	0.469	0.883
19/12/2011	3	G2B	High	1.367	0.020	0.000	1.106	1.106	0.241
19/12/2011	3	G2C	High	1.078	0.054	0.000	0.572	0.572	0.452

19/12/2011	3	G3A	Medium	3.150	0.018	0.002	2.632	2.631	0.499
19/12/2011	3	G3B	High	1.534	0.032	0.002	1.288	1.286	0.211
19/12/2011	3	G3C	High	2.365	0.011	0.000	2.219	2.219	0.136
19/12/2011	3	G4A	High	1.067	0.003	0.001	0.726	0.725	0.338
19/12/2011	3	G4B	High	2.246	0.018	0.009	1.460	1.450	0.758
19/12/2011	3	G4C	High	3.326	0.028	0.000	2.965	2.965	0.332

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN** (mg l^{-1})	**NH$_4$** (mg l^{-1})	**NO$_2$** (mg l^{-1})	**Nox** (mg l^{-1})	**NO$_3^-$** (mg l^{-1})	**ToN** (mg l^{-1})
24/01/2012	4	C1A	Control	0.488	0.027	0.000	0.082	0.082	0.379
24/01/2012	4	C1B	Control	0.411	0.018	0.000	0.068	0.068	0.326
24/01/2012	4	C1C	Control	0.519	0.017	0.000	0.137	0.137	0.366
24/01/2012	4	C2A	Control	0.637	0.026	0.000	0.101	0.101	0.510
24/01/2012	4	C2B	Control	0.687	0.034	0.000	0.083	0.083	0.570
24/01/2012	4	C2C	Control	1.034	0.019	0.000	0.115	0.115	0.899
24/01/2012	4	C3A	Control	0.602	0.264	0.000	0.119	0.119	0.219
24/01/2012	4	C3B	Control	0.449	0.029	0.000	0.067	0.067	0.353
24/01/2012	4	C3C	Control	0.603	0.032	0.000	0.124	0.124	0.447
24/01/2012	4	C4A	Control	7.349	3.971	0.011	0.116	0.105	3.251
24/01/2012	4	C4B	Control	0.753	0.071	0.001	0.145	0.144	0.538
24/01/2012	4	C4C	Control	0.597	0.026	0.001	0.105	0.104	0.466
24/01/2012	4	F1A	Low	1.147	0.025	0.000	0.557	0.557	0.565
24/01/2012	4	F1B	Low	2.145	0.025	0.000	0.001	0.001	2.119
24/01/2012	4	F1C	Low	2.625	0.031	0.000	0.678	0.678	1.916
24/01/2012	4	F2A	Medium	2.477	0.056	0.003	0.339	0.336	2.079
24/01/2012	4	F2B	Medium	3.279	0.017	0.000	0.330	0.330	2.933
24/01/2012	4	F2C	Medium	1.880	0.021	0.002	1.646	1.643	0.211
24/01/2012	4	F3A	Low	ND	ND	ND	ND	ND	ND
24/01/2012	4	F3B	Low	4.488	0.071	0.001	2.143	2.142	2.272
24/01/2012	4	F3C	Low	2.939	0.085	0.000	1.510	1.510	1.344
24/01/2012	4	F4A	Medium	3.144	0.071	0.000	0.680	0.680	2.393
24/01/2012	4	F4B	Medium	ND	ND	ND	ND	ND	ND
24/01/2012	4	F4C	Medium	3.570	0.047	0.000	2.187	2.186	1.336
24/01/2012	4	F5A	Low	4.222	0.161	0.006	0.622	0.616	3.433
24/01/2012	4	F5B	Low	2.615	0.012	0.000	0.188	0.188	2.415
24/01/2012	4	F5C	Low	2.508	0.043	0.000	0.788	0.788	1.677
24/01/2012	4	F6A	Medium	4.616	0.020	0.001	1.269	1.268	3.325
24/01/2012	4	F6B	Medium	3.722	0.178	0.001	0.458	0.457	3.085
24/01/2012	4	F6C	Medium	3.395	0.018	0.001	0.369	0.368	3.007
24/01/2012	4	F7A	Low	2.507	0.029	0.001	0.742	0.742	1.736
24/01/2012	4	F7B	Low	5.110	0.061	0.003	1.495	1.492	3.551
24/01/2012	4	F7C	Medium	6.519	0.101	0.002	3.172	3.171	3.244
24/01/2012	4	F8A	Low	3.009	0.040	0.002	1.319	1.317	1.647
24/01/2012	4	F8B	Low	3.016	0.076	0.001	1.198	1.197	1.741
24/01/2012	4	F8C	Medium	26.719	0.044	0.011	18.987	18.976	7.676
24/01/2012	4	G1A	High	1.452	0.031	0.000	0.808	0.808	0.613
24/01/2012	4	G1B	High	4.885	0.026	0.001	2.185	2.184	2.673
24/01/2012	4	G1C	High	1.265	0.040	0.000	0.719	0.719	0.506
24/01/2012	4	G2A	Low	0.924	0.023	0.000	0.128	0.128	0.773
24/01/2012	4	G2B	High	2.877	0.045	0.004	1.933	1.930	0.895

24/01/2012	4	G2C	High	0.881	0.042	0.000	0.493	0.493	0.346
24/01/2012	4	G3A	Medium	10.018	0.042	0.010	6.642	6.632	3.324
24/01/2012	4	G3B	High	1.108	0.017	0.000	0.338	0.338	0.753
24/01/2012	4	G3C	High	2.249	0.038	0.000	1.657	1.657	0.554
24/01/2012	4	G4A	High	0.888	0.061	0.000	0.440	0.440	0.386
24/01/2012	4	G4B	High	1.626	0.271	0.005	0.554	0.549	0.796
24/01/2012	4	G4C	High	2.469	0.117	0.002	1.592	1.590	0.758

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH$_4$**	**NO$_2$**	**Nox**	**NO$_3^-$**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
24/01/2012	5	C1A	Control	1.500	0.111	0.000	0.332	0.332	1.057
15/02/2012	5	C1B	Control	1.433	0.087	0.001	0.521	0.520	0.825
15/02/2012	5	C1C	Control	0.460	0.025	0.000	0.219	0.219	0.216
15/02/2012	5	C2A	Control	0.687	0.064	0.000	0.317	0.317	0.306
15/02/2012	5	C2B	Control	0.986	0.049	0.000	0.214	0.214	0.723
15/02/2012	5	C2C	Control	0.821	0.020	0.000	0.284	0.284	0.517
15/02/2012	5	C3A	Control	2.679	0.072	0.005	1.800	1.795	0.802
15/02/2012	5	C3B	Control	1.219	0.121	0.004	0.528	0.525	0.566
15/02/2012	5	C3C	Control	1.180	0.039	0.000	0.507	0.506	0.634
15/02/2012	5	C4A	Control	5.840	0.053	0.003	4.107	4.105	1.678
15/02/2012	5	C4B	Control	1.412	0.055	0.000	0.459	0.458	0.898
15/02/2012	5	C4C	Control	1.245	0.075	0.000	0.254	0.254	0.916
15/02/2012	5	F1A	Low	1.358	0.042	0.000	0.327	0.326	0.988
15/02/2012	5	F1B	Low	2.139	0.081	0.000	0.695	0.695	1.363
15/02/2012	5	F1C	Low	ND	ND	ND	ND	ND	ND
15/02/2012	5	F2A	Medium	0.645	0.025	0.000	0.312	0.312	0.308
15/02/2012	5	F2B	Medium	1.213	0.025	0.001	1.058	1.057	0.129
15/02/2012	5	F2C	Medium	1.137	0.027	0.001	0.706	0.706	0.403
15/02/2012	5	F3A	Low	ND	ND	ND	ND	ND	ND
15/02/2012	5	F3B	Low	4.518	0.403	0.004	1.909	1.905	2.202
15/02/2012	5	F3C	Low	1.496	0.027	0.002	1.126	1.124	0.341
15/02/2012	5	F4A	Medium	1.819	0.027	0.000	1.102	1.102	0.690
15/02/2012	5	F4B	Medium	ND	ND	ND	ND	ND	ND
15/02/2012	5	F4C	Medium	2.035	0.066	0.001	1.475	1.474	0.493
15/02/2012	5	F5A	Low	1.798	0.000	0.074	0.519	0.445	1.205
15/02/2012	5	F5B	Low	0.837	0.014	0.003	1.682	1.679	0.000
15/02/2012	5	F5C	Low	2.503	0.042	0.001	1.988	1.987	0.472
15/02/2012	5	F6A	Medium	1.558	0.059	0.004	1.214	1.209	0.282
15/02/2012	5	F6B	Medium	2.168	0.033	0.000	1.433	1.433	0.701
15/02/2012	5	F6C	Medium	1.298	0.032	0.001	0.696	0.696	0.569
15/02/2012	5	F7A	Low	6.346	0.056	0.001	5.669	5.668	0.620
15/02/2012	5	F7B	Low	3.619	0.014	0.004	2.286	2.283	1.315
15/02/2012	5	F7C	Medium	2.642	0.091	0.001	0.624	0.624	1.926
15/02/2012	5	F8A	Low	1.514	0.034	0.000	0.525	0.524	0.955
15/02/2012	5	F8B	Low	3.128	0.037	0.001	1.655	1.654	1.435
15/02/2012	5	F8C	Medium	14.032	0.334	0.042	14.790	14.748	0.000
15/02/2012	5	G1A	High	1.396	0.037	0.000	0.178	0.178	1.181
15/02/2012	5	G1B	High	2.415	0.013	0.001	2.101	2.100	0.301
15/02/2012	5	G1C	High	1.105	0.020	0.000	0.490	0.490	0.596
15/02/2012	5	G2A	Low	0.368	0.200	0.000	0.300	0.300	0.000

15/02/2012	5	G2B	High	3.136	0.092	0.019	2.209	2.190	0.816
15/02/2012	5	G2C	High	1.484	0.082	0.001	0.829	0.828	0.572
15/02/2012	5	G3A	Medium	2.911	0.007	0.004	2.322	2.319	0.578
15/02/2012	5	G3B	High	1.221	0.025	0.000	0.771	0.771	0.426
15/02/2012	5	G3C	High	1.157	0.023	0.000	0.793	0.793	0.340
15/02/2012	5	G4A	High	3.317	0.240	0.001	1.854	1.853	1.222
15/02/2012	5	G4B	High	1.342	0.014	0.000	0.546	0.546	0.781
15/02/2012	5	G4C	High	0.794	0.087	0.001	0.241	0.240	0.466

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH$_4$**	**NO$_2$**	**Nox**	**NO$_3^-$**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
13/03/2012	6	C1A	Control	1.448	0.028	0.029	0.997	0.968	0.394
13/03/2012	6	C1B	Control	0.760	0.025	0.026	0.311	0.285	0.399
13/03/2012	6	C1C	Control	0.435	0.018	0.019	0.000	0.138	0.399
13/03/2012	6	C2A	Control	0.616	0.023	0.024	0.000	0.040	0.569
13/03/2012	6	C2B	Control	0.732	0.038	0.039	0.000	0.014	0.654
13/03/2012	6	C2C	Control	0.741	0.023	0.024	0.185	0.160	0.508
13/03/2012	6	C3A	Control	1.221	0.033	0.034	0.798	0.764	0.355
13/03/2012	6	C3B	Control	0.397	0.021	0.022	0.000	0.000	0.355
13/03/2012	6	C3C	Control	0.526	0.036	0.037	0.000	0.000	0.453
13/03/2012	6	C4A	Control	4.751	0.039	0.040	0.828	0.788	3.845
13/03/2012	6	C4B	Control	2.310	0.059	0.060	2.127	2.067	0.065
13/03/2012	6	C4C	Control	0.495	0.020	0.021	0.000	0.000	0.454
13/03/2012	6	F1A	Low	0.701	0.030	0.031	0.141	0.110	0.498
13/03/2012	6	F1B	Low	0.972	0.020	0.021	0.000	0.000	0.932
13/03/2012	6	F1C	Low	1.374	0.025	0.026	0.949	0.923	0.374
13/03/2012	6	F2A	Medium	1.626	0.029	0.030	1.197	1.167	0.371
13/03/2012	6	F2B	Medium	1.171	0.022	0.023	0.928	0.905	0.198
13/03/2012	6	F2C	Medium	5.843	0.020	0.021	3.637	3.616	2.165
13/03/2012	6	F3A	Low	ND	ND	ND	ND	ND	ND
13/03/2012	6	F3B	Low	1.666	0.027	0.028	1.386	1.358	0.226
13/03/2012	6	F3C	Low	ND	ND	ND	ND	ND	ND
13/03/2012	6	F4A	Medium	1.487	0.037	0.038	0.703	0.666	0.710
13/03/2012	6	F4B	Medium	ND	ND	ND	ND	ND	ND
13/03/2012	6	F4C	Medium	1.972	0.024	0.025	1.681	1.656	0.242
13/03/2012	6	F5A	Low	1.469	0.019	0.020	1.092	1.072	0.338
13/03/2012	6	F5B	Low	1.138	0.035	0.036	0.343	0.307	0.724
13/03/2012	6	F5C	Low	0.986	0.031	0.032	0.261	0.229	0.662
13/03/2012	6	F6A	Medium	1.643	0.029	0.030	1.148	1.117	0.436
13/03/2012	6	F6B	Medium	2.185	0.068	0.069	1.187	1.118	0.862
13/03/2012	6	F6C	Medium	1.045	0.020	0.021	0.421	0.400	0.583
13/03/2012	6	F7A	Low	0.907	0.014	0.015	0.266	0.251	0.612
13/03/2012	6	F7B	Low	2.273	0.031	0.032	1.443	1.411	0.767
13/03/2012	6	F7C	Medium	2.770	0.017	0.018	2.397	2.379	0.338
13/03/2012	6	F8A	Low	1.005	0.028	0.029	0.382	0.352	0.566
13/03/2012	6	F8B	Low	ND	ND	ND	ND	ND	ND
13/03/2012	6	F8C	Medium	3.086	0.024	0.025	2.475	2.450	0.562
13/03/2012	6	G1A	High	0.861	0.020	0.021	0.000	0.051	0.820
13/03/2012	6	G1B	High	1.588	0.020	0.021	1.178	1.158	0.369
13/03/2012	6	G1C	High	5.423	0.031	0.032	3.411	3.379	1.949

13/03/2012	6	G2A	Low	0.915	0.021	0.022	0.176	0.154	0.695
13/03/2012	6	G2B	High	2.145	0.025	0.026	1.993	1.966	0.101
13/03/2012	6	G2C	High	0.657	0.027	0.028	0.387	0.359	0.214
13/03/2012	6	G3A	Medium	5.390	0.021	0.022	3.526	3.503	1.822
13/03/2012	6	G3B	High	1.475	0.025	0.027	1.181	1.155	0.242
13/03/2012	6	G3C	High	1.988	0.030	0.032	1.822	1.791	0.103
13/03/2012	6	G4A	High	1.774	0.056	0.057	1.100	1.043	0.561
13/03/2012	6	G4B	High	1.735	0.024	0.025	1.228	1.203	0.458
13/03/2012	6	G4C	High	1.977	0.035	0.036	1.236	1.200	0.669
Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH$_4$**	**NO$_2$**	**Nox**	**NO$_3^-$**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
13/04/2012	7	C1A	Control	0.902	0.032	0.005	0.468	0.464	0.397
13/04/2012	7	C1B	Control	0.684	0.028	0.003	0.331	0.328	0.322
13/04/2012	7	C1C	Control	0.577	0.012	0.002	0.162	0.160	0.401
13/04/2012	7	C2A	Control	0.615	0.007	0.002	0.059	0.057	0.547
13/04/2012	7	C2B	Control	0.728	0.005	0.001	0.047	0.046	0.675
13/04/2012	7	C2C	Control	0.742	0.005	0.002	0.260	0.258	0.475
13/04/2012	7	C3A	Control	1.430	0.267	0.009	0.520	0.511	0.634
13/04/2012	7	C3B	Control	0.200	0.075	0.003	0.104	0.101	0.018
13/04/2012	7	C3C	Control	0.059	0.028	0.002	0.040	0.038	0.000
13/04/2012	7	C4A	Control	1.607	0.027	0.002	1.048	1.046	0.530
13/04/2012	7	C4B	Control	0.562	0.018	0.002	0.867	0.865	0.000
13/04/2012	7	C4C	Control	0.789	0.007	0.002	0.280	0.278	0.500
13/04/2012	7	F1A	Low	3.581	0.015	0.003	2.226	2.223	1.337
13/04/2012	7	F1B	Low	2.240	0.012	0.002	0.645	0.643	1.581
13/04/2012	7	F1C	Low	1.611	0.023	0.002	0.521	0.519	1.065
13/04/2012	7	F2A	Medium	2.651	0.023	0.002	0.798	0.795	1.828
13/04/2012	7	F2B	Medium	4.797	0.016	0.003	3.046	3.043	1.732
13/04/2012	7	F2C	Medium	2.355	0.000	0.004	2.722	2.718	0.000
13/04/2012	7	F3A	Low	ND	ND	ND	ND	ND	ND
13/04/2012	7	F3B	Low	2.418	0.092	0.010	2.091	2.081	0.225
13/04/2012	7	F3C	Low	10.766	0.056	0.015	8.521	8.506	2.174
13/04/2012	7	F4A	Medium	1.813	0.029	0.002	1.024	1.022	0.758
13/04/2012	7	F4B	Medium	ND	ND	ND	ND	ND	ND
13/04/2012	7	F4C	Medium	3.169	0.022	0.003	2.813	2.810	0.331
13/04/2012	7	F5A	Low	3.659	0.014	0.002	2.493	2.491	1.150
13/04/2012	7	F5B	Low	2.857	0.021	0.002	0.966	0.964	1.868
13/04/2012	7	F5C	Low	3.057	0.017	0.002	0.854	0.852	2.184
13/04/2012	7	F6A	Medium	1.154	0.018	0.002	0.738	0.736	0.396
13/04/2012	7	F6B	Medium	3.904	0.011	0.002	0.991	0.989	2.900
13/04/2012	7	F6C	Medium	1.838	0.011	0.002	0.764	0.762	1.061
13/04/2012	7	F7A	Low	1.738	0.020	0.002	0.714	0.712	1.002
13/04/2012	7	F7B	Low	5.453	0.016	0.002	2.691	2.689	2.744
13/04/2012	7	F7C	Medium	7.070	0.017	0.010	6.019	6.010	1.024
13/04/2012	7	F8A	Low	1.601	0.004	0.001	1.448	1.447	0.148
13/04/2012	7	F8B	Low	2.796	0.011	0.003	2.383	2.381	0.399
13/04/2012	7	F8C	Medium	1.831	0.012	0.002	1.674	1.672	0.143
13/04/2012	7	G1A	High	2.780	0.011	0.002	1.675	1.672	1.092
13/04/2012	7	G1B	High	5.889	0.607	0.015	4.162	4.147	1.105

13/04/2012	7	G1C	High	8.025	0.308	0.010	6.096	6.086	1.611
13/04/2012	7	G2A	Low	2.201	0.058	0.004	2.394	2.390	0.000
13/04/2012	7	G2B	High	3.448	0.535	0.012	1.822	1.810	1.079
13/04/2012	7	G2C	High	2.387	0.333	0.007	1.620	1.613	0.427
13/04/2012	7	G3A	Medium	3.474	0.041	0.003	2.510	2.507	0.920
13/04/2012	7	G3B	High	1.978	0.020	0.002	2.021	2.019	0.000
13/04/2012	7	G3C	High	4.801	0.024	0.002	4.220	4.218	0.555
13/04/2012	7	G4A	High	2.521	0.024	0.002	2.640	2.637	0.000
13/04/2012	7	G4B	High	7.942	0.021	0.005	6.317	6.312	1.599
13/04/2012	7	G4C	High	5.445	0.100	0.010	5.968	5.958	0.000

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH_4**	**NO_2**	**Nox**	**NO_3^-**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
18/05/2012	8	C1A	Control	0.535	0.017	0.000	0.110	0.110	0.408
18/05/2012	8	C1B	Control	0.499	0.013	0.000	0.174	0.175	0.312
18/05/2012	8	C1C	Control	0.527	0.014	0.000	0.169	0.170	0.344
18/05/2012	8	C2A	Control	0.540	0.019	0.000	0.014	0.014	0.507
18/05/2012	8	C2B	Control	0.679	0.017	0.000	0.006	0.006	0.656
18/05/2012	8	C2C	Control	0.565	0.019	0.000	0.057	0.057	0.489
18/05/2012	8	C3A	Control	0.580	0.017	0.000	0.288	0.289	0.275
18/05/2012	8	C3B	Control	0.326	0.018	0.000	0.140	0.140	0.168
18/05/2012	8	C3C	Control	0.513	0.012	0.000	0.010	0.010	0.491
18/05/2012	8	C4A	Control	0.483	0.015	0.000	0.163	0.163	0.305
18/05/2012	8	C4B	Control	0.581	0.014	0.000	0.174	0.173	0.393
18/05/2012	8	C4C	Control	0.541	0.036	0.002	0.147	0.145	0.356
18/05/2012	8	F1A	Low	1.218	0.011	0.000	0.602	0.603	0.605
18/05/2012	8	F1B	Low	1.345	0.012	0.000	0.234	0.234	1.099
18/05/2012	8	F1C	Low	1.685	0.011	0.000	0.830	0.831	0.844
18/05/2012	8	F2A	Medium	1.484	0.011	0.000	0.843	0.843	0.630
18/05/2012	8	F2B	Medium	1.537	0.017	0.000	0.956	0.956	0.564
18/05/2012	8	F2C	Medium	5.416	0.018	0.002	5.088	5.086	0.308
18/05/2012	8	F3A	Low	ND	ND	ND	ND	ND	ND
18/05/2012	8	F3B	Low	2.074	0.015	0.000	1.430	1.430	0.629
18/05/2012	8	F3C	Low	4.569	0.013	0.001	4.336	4.334	0.219
18/05/2012	8	F4A	Medium	1.411	0.015	0.000	0.706	0.706	0.690
18/05/2012	8	F4B	Medium	ND	ND	ND	ND	ND	ND
18/05/2012	8	F4C	Medium	2.355	0.017	0.000	1.731	1.731	0.607
18/05/2012	8	F5A	Low	1.945	0.011	0.000	0.774	0.774	1.160
18/05/2012	8	F5B	Low	1.848	0.015	0.000	0.675	0.675	1.158
18/05/2012	8	F5C	Low	1.453	0.017	0.000	0.393	0.393	1.043
18/05/2012	8	F6A	Medium	1.228	0.017	0.000	0.605	0.605	0.606
18/05/2012	8	F6B	Medium	2.015	0.024	0.000	0.767	0.767	1.224
18/05/2012	8	F6C	Medium	1.264	0.019	0.000	0.578	0.578	0.667
18/05/2012	8	F7A	Low	1.114	0.020	0.000	0.222	0.222	0.872
18/05/2012	8	F7B	Low	2.363	0.019	0.000	1.094	1.094	1.250
18/05/2012	8	F7C	Medium	ND	ND	ND	ND	ND	ND
18/05/2012	8	F8A	Low	1.681	0.018	0.000	0.873	0.873	0.790
18/05/2012	8	F8B	Low	1.721	0.019	0.000	0.666	0.666	1.036
18/05/2012	8	F8C	Medium	2.945	0.023	0.001	2.567	2.566	0.354
18/05/2012	8	G1A	High	1.553	0.020	0.000	0.829	0.828	0.704

18/05/2012	8	G1B	High	1.683	0.102	0.001	0.703	0.702	0.877
18/05/2012	8	G1C	High	6.954	0.015	0.003	6.461	6.458	0.475
18/05/2012	8	G2A	Low	1.140	0.016	0.000	0.277	0.277	0.847
18/05/2012	8	G2B	High	4.423	0.028	0.000	3.997	3.997	0.398
18/05/2012	8	G2C	High	1.390	0.018	0.000	0.668	0.668	0.704
18/05/2012	8	G3A	Medium	1.449	0.018	0.000	0.785	0.785	0.646
18/05/2012	8	G3B	High	3.708	0.029	0.002	3.190	3.188	0.487
18/05/2012	8	G3C	High	2.561	0.065	0.003	1.432	1.430	1.061
18/05/2012	8	G4A	High	1.820	0.014	0.000	0.867	0.866	0.939
18/05/2012	8	G4B	High	8.816	0.003	0.002	8.500	8.499	0.311
18/05/2012	8	G4C	High	3.090	0.017	0.000	2.505	2.504	0.568

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH_4**	**NO_2**	**Nox**	**NO_3^-**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
22/06/2012	9	C1A	Control	0.394	0.028	0.000	0.048	0.049	0.318
22/06/2012	9	C1B	Control	0.278	0.034	0.000	0.074	0.074	0.170
22/06/2012	9	C1C	Control	0.795	0.045	0.000	0.256	0.256	0.494
22/06/2012	9	C2A	Control	0.315	0.025	0.000	0.033	0.034	0.257
22/06/2012	9	C2B	Control	0.396	0.026	0.000	0.041	0.041	0.329
22/06/2012	9	C2C	Control	0.330	0.024	0.000	0.059	0.059	0.247
22/06/2012	9	C3A	Control	0.338	0.027	0.000	0.151	0.152	0.160
22/06/2012	9	C3B	Control	0.240	0.026	0.000	0.010	0.011	0.204
22/06/2012	9	C3C	Control	0.335	0.027	0.000	0.006	0.007	0.302
22/06/2012	9	C4A	Control	0.392	0.029	0.000	0.031	0.032	0.332
22/06/2012	9	C4B	Control	0.505	0.027	0.000	0.093	0.094	0.385
22/06/2012	9	C4C	Control	0.440	0.037	0.000	0.086	0.086	0.317
22/06/2012	9	F1A	Low	0.945	0.027	0.000	0.504	0.504	0.414
22/06/2012	9	F1B	Low	1.030	0.029	0.000	0.121	0.122	0.880
22/06/2012	9	F1C	Low	0.959	0.028	0.000	0.618	0.618	0.313
22/06/2012	9	F2A	Medium	0.937	0.033	0.000	0.407	0.408	0.497
22/06/2012	9	F2B	Medium	1.229	0.031	0.000	0.811	0.812	0.387
22/06/2012	9	F2C	Medium	2.849	0.029	0.001	2.472	2.471	0.347
22/06/2012	9	F3A	Low	ND	ND	ND	ND	ND	ND
22/06/2012	9	F3B	Low	1.615	0.033	0.001	0.925	0.824	0.656
22/06/2012	9	F3C	Low	0.859	0.030	0.001	0.880	0.880	0.000
22/06/2012	9	F4A	Medium	1.056	0.031	0.000	0.409	0.410	0.616
22/06/2012	9	F4B	Medium	1.186	0.193	0.004	0.177	0.173	0.000
22/06/2012	9	F4C	Medium	2.092	0.038	0.001	1.472	1.471	0.581
22/06/2012	9	F5A	Low	1.365	0.065	0.003	0.491	0.488	0.806
22/06/2012	9	F5B	Low	1.445	0.031	0.000	0.423	0.423	0.991
22/06/2012	9	F5C	Low	1.120	0.030	0.000	0.081	0.081	1.009
22/06/2012	9	F6A	Medium	0.871	0.029	0.001	0.348	0.347	0.493
22/06/2012	9	F6B	Medium	ND	ND	ND	ND	ND	ND
22/06/2012	9	F6C	Medium	1.030	0.030	0.000	0.402	0.402	0.598
22/06/2012	9	F7A	Low	0.890	0.032	0.000	0.143	0.143	0.715
22/06/2012	9	F7B	Low	1.276	0.030	0.000	0.560	0.560	0.686
22/06/2012	9	F7C	Medium	ND	ND	ND	ND	ND	ND
22/06/2012	9	F8A	Low	1.460	0.029	0.000	0.960	0.961	0.471
22/06/2012	9	F8B	Low	1.020	0.029	0.000	0.234	0.235	0.757
22/06/2012	9	F8C	Medium	2.968	0.028	0.001	2.668	2.667	0.271

22/06/2012	9	G1A	High	0.713	0.034	0.000	0.085	0.086	0.594
22/06/2012	9	G1B	High	2.586	0.434	0.127	1.877	1.750	0.148
22/06/2012	9	G1C	High	3.148	0.038	0.005	2.724	2.718	0.381
22/06/2012	9	G2A	Low	0.965	0.058	0.009	0.230	0.221	0.668
22/06/2012	9	G2B	High	3.063	0.050	0.018	2.808	2.791	0.187
22/06/2012	9	G2C	High	1.442	0.040	0.002	0.606	0.604	0.794
22/06/2012	9	G3A	Medium	1.194	0.051	0.008	0.612	0.604	0.523
22/06/2012	9	G3B	High	1.747	0.042	0.001	0.910	0.909	0.794
22/06/2012	9	G3C	High	2.407	0.038	0.003	1.740	1.736	0.626
22/06/2012	9	G4A	High	1.504	0.086	0.006	0.591	0.585	0.821
22/06/2012	9	G4B	High	3.429	0.032	0.000	3.408	3.408	0.000
22/06/2012	9	G4C	High	5.125	0.291	0.000	3.690	3.679	1.144

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH$_4$**	**NO$_2$**	**Nox**	**NO$_3^-$**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
1/08/2012	10	C1A	Control	0.276	0.016	0.005	0.051	0.047	0.204
1/08/2012	10	C1B	Control	0.163	0.023	0.003	0.062	0.059	0.075
1/08/2012	10	C1C	Control	0.503	0.018	0.001	0.183	0.182	0.301
1/08/2012	10	C2A	Control	0.222	0.014	0.001	0.200	0.199	0.007
1/08/2012	10	C2B	Control	0.348	0.012	0.001	0.080	0.079	0.255
1/08/2012	10	C2C	Control	0.323	0.019	0.001	0.067	0.066	0.236
1/08/2012	10	C3A	Control	0.273	0.017	0.000	0.043	0.043	0.213
1/08/2012	10	C3B	Control	0.297	0.016	0.000	0.010	0.010	0.271
1/08/2012	10	C3C	Control	0.351	0.015	0.000	0.004	0.004	0.332
1/08/2012	10	C4A	Control	0.608	0.021	0.000	0.112	0.112	0.475
1/08/2012	10	C4B	Control	0.503	0.020	0.000	0.296	0.295	0.187
1/08/2012	10	C4C	Control	0.445	0.017	0.000	0.218	0.218	0.210
1/08/2012	10	F1A	Low	0.944	0.013	0.000	0.336	0.335	0.595
1/08/2012	10	F1B	Low	0.628	0.011	0.000	0.194	0.194	0.423
1/08/2012	10	F1C	Low	1.158	0.012	0.000	0.675	0.685	0.471
1/08/2012	10	F2A	Medium	0.834	0.026	0.001	0.508	0.507	0.299
1/08/2012	10	F2B	Medium	0.895	0.016	0.006	0.520	0.513	0.353
1/08/2012	10	F2C	Medium	1.573	0.021	0.001	0.994	0.994	0.557
1/08/2012	10	F3A	Low	ND	ND	ND	ND	ND	ND
1/08/2012	10	F3B	Low	0.952	0.016	0.000	0.606	0.605	0.330
1/08/2012	10	F3C	Low	1.376	0.020	0.001	0.696	0.695	0.659
1/08/2012	10	F4A	Medium	1.058	0.019	0.001	0.539	0.538	0.499
1/08/2012	10	F4B	Medium	ND	ND	ND	ND	ND	ND
1/08/2012	10	F4C	Medium	1.074	0.013	0.001	0.697	0.696	0.363
1/08/2012	10	F5A	Low	1.297	0.013	0.000	0.545	0.545	0.739
1/08/2012	10	F5B	Low	1.472	0.021	0.001	0.893	0.892	0.557
1/08/2012	10	F5C	Low	0.647	0.017	0.000	0.687	0.686	0.000
1/08/2012	10	F6A	Medium	0.916	0.023	0.001	0.549	0.548	0.343
1/08/2012	10	F6B	Medium	ND	ND	ND	ND	ND	ND
1/08/2012	10	F6C	Medium	0.863	0.019	0.001	0.518	0.517	0.325
1/08/2012	10	F7A	Low	0.802	0.016	0.000	0.284	0.283	0.502
1/08/2012	10	F7B	Low	1.065	0.022	0.000	0.564	0.564	0.479
1/08/2012	10	F7C	Medium	ND	ND	ND	ND	ND	ND
1/08/2012	10	F8A	Low	0.851	0.009	0.000	0.567	0.567	0.275
1/08/2012	10	F8B	Low	1.444	0.018	0.000	0.344	0.344	1.082

1/08/2012	10	F8C	Medium	3.495	0.009	0.001	3.470	3.468	0.015
1/08/2012	10	G1A	High	0.815	0.016	0.000	0.687	0.687	0.112
1/08/2012	10	G1B	High	3.058	0.019	0.001	3.028	3.028	0.010
1/08/2012	10	G1C	High	4.645	0.013	0.004	4.955	4.952	0.000
1/08/2012	10	G2A	Low	3.695	0.012	0.001	4.247	4.246	0.000
1/08/2012	10	G2B	High	3.637	0.013	0.001	3.772	3.772	0.000
1/08/2012	10	G2C	High	0.804	0.012	0.000	0.572	0.572	0.220
1/08/2012	10	G3A	Medium	1.807	0.015	0.001	1.947	1.947	0.000
1/08/2012	10	G3B	High	1.101	0.013	0.000	1.030	1.030	0.058
1/08/2012	10	G3C	High	3.285	0.013	0.001	3.266	3.266	0.005
1/08/2012	10	G4A	High	0.959	0.010	0.000	0.717	0.717	0.232
1/08/2012	10	G4B	High	7.019	0.020	0.001	5.646	5.646	1.352
1/08/2012	10	G4C	High	5.485	0.180	0.008	5.584	5.757	0.000

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH_4**	**NO_2**	**Nox**	**NO3**	**ToN**
				(mg/l)	**(mg/l)**	**(mg/l)**	**(mg/l)**	**(mg/l)**	**(mg/l)**
3/09/2012	11	C1A	Control	0.642	0.016	0.001	0.664	0.663	0.000
3/09/2012	11	C1B	Control	0.586	0.013	0.001	0.163	0.162	0.409
3/09/2012	11	C1C	Control	0.664	0.122	0.008	0.591	0.583	0.000
3/09/2012	11	C2A	Control	0.304	0.088	0.002	0.201	0.199	0.013
3/09/2012	11	C2B	Control	0.454	0.019	0.000	0.095	0.095	0.340
3/09/2012	11	C2C	Control	0.336	0.014	0.000	0.093	0.093	0.229
3/09/2012	11	C3A	Control	0.553	0.026	0.000	0.217	0.217	0.310
3/09/2012	11	C3B	Control	0.350	0.019	0.000	0.081	0.081	0.250
3/09/2012	11	C3C	Control	0.495	0.019	0.000	0.008	0.008	0.468
3/09/2012	11	C4A	Control	0.707	0.020	0.000	0.264	0.264	0.423
3/09/2012	11	C4B	Control	1.302	0.043	0.000	0.947	0.947	0.312
3/09/2012	11	C4C	Control	0.820	0.106	0.002	0.441	0.438	0.271
3/09/2012	11	F1A	Low	1.389	0.059	0.001	0.736	0.735	0.593
3/09/2012	11	F1B	Low	0.816	0.051	0.002	0.128	0.126	0.635
3/09/2012	11	F1C	Low	2.077	0.050	0.001	0.392	0.391	1.634
3/09/2012	11	F2A	Medium	1.777	0.052	0.002	0.498	0.497	1.225
3/09/2012	11	F2B	Medium	1.061	0.058	0.002	0.488	0.487	0.513
3/09/2012	11	F2C	Medium	1.634	0.139	0.002	0.970	0.968	0.523
3/09/2012	11	F3A	Low	ND	ND	ND	ND	ND	ND
3/09/2012	11	F3B	Low	10.509	0.064	0.008	2.808	2.800	0.025
3/09/2012	11	F3C	Low	1.235	0.351	0.002	0.638	0.636	0.244
3/09/2012	11	F4A	Medium	1.299	0.315	0.001	0.474	0.472	0.509
3/09/2012	11	F4B	Medium	ND	ND	ND	ND	ND	ND
3/09/2012	11	F4C	Medium	1.883	0.255	0.001	0.778	0.777	0.849
3/09/2012	11	F5A	Low	1.269	0.127	0.002	0.521	0.519	0.619
3/09/2012	11	F5B	Low	2.096	0.091	0.002	0.426	0.425	1.577
3/09/2012	11	F5C	Low	0.836	0.078	0.001	0.089	0.088	0.668
3/09/2012	11	F6A	Medium	1.155	0.107	0.002	0.502	0.500	0.544
3/09/2012	11	F6B	Medium	1.164	0.063	0.003	0.530	0.526	0.568
3/09/2012	11	F6C	Medium	0.788	0.066	0.006	0.400	0.392	0.316
3/09/2012	11	F7A	Low	0.671	0.065	0.003	0.273	0.270	0.330
3/09/2012	11	F7B	Low	1.031	0.040	0.008	0.447	0.439	0.536
3/09/2012	11	F7C	Medium	1.629	0.248	0.009	0.635	0.625	0.737
3/09/2012	11	F8A	Low	1.070	0.063	0.002	1.909	1.907	0.000

3/09/2012	11	F8B	Low	1.609	0.026	0.001	0.725	0.724	0.857
3/09/2012	11	F8C	Medium	2.151	0.019	0.001	1.038	1.307	1.093
3/09/2012	11	G1A	High	1.386	0.042	0.002	1.052	1.050	0.290
3/09/2012	11	G1B	High	5.471	0.152	0.010	6.117	6.106	0.000
3/09/2012	11	G1C	High	5.134	0.072	0.004	5.958	5.954	0.000
3/09/2012	11	G2A	Low	9.073	0.021	0.002	10.828	10.827	0.000
3/09/2012	11	G2B	High	7.553	0.021	0.002	6.669	6.666	0.861
3/09/2012	11	G2C	High	1.057	0.020	0.001	0.924	0.924	0.112
3/09/2012	11	G3A	Medium	5.216	0.018	0.001	4.210	4.209	0.987
3/09/2012	11	G3B	High	1.378	0.032	0.000	0.895	0.895	0.451
3/09/2012	11	G3C	High	1.149	0.014	0.000	0.854	0.854	0.281
3/09/2012	11	G4A	High	6.035	0.142	0.007	4.838	4.832	1.048
3/09/2012	11	G4B	High	4.888	0.069	0.003	5.857	5.854	0.000
3/09/2012	11	G4C	High	0.783	0.052	0.000	0.934	0.934	0.000

Date	**Sampling number**	**Lysimeter**	**Treatment**	**TN**	**NH$_4$**	**NO$_2$**	**Nox**	**NO$_3^-$**	**ToN**
				(mg l^{-1})	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**	**(mg l^{-1})**
25/09/2012	12	C1A	Control	0.326	0.113	0.003	0.064	0.061	0.146
25/09/2012	12	C1B	Control	0.209	0.042	0.003	0.039	0.037	0.125
25/09/2012	12	C1C	Control	0.487	0.023	0.002	0.219	0.217	0.243
25/09/2012	12	C2A	Control	0.395	0.034	0.002	0.137	0.136	0.222
25/09/2012	12	C2B	Control	0.543	0.036	0.002	0.118	0.116	0.387
25/09/2012	12	C2C	Control	0.573	0.022	0.002	0.098	0.096	0.451
25/09/2012	12	C3A	Control	0.495	0.022	0.003	0.127	0.124	0.343
25/09/2012	12	C3B	Control	0.472	0.029	0.003	0.060	0.058	0.380
25/09/2012	12	C3C	Control	0.317	0.027	0.002	0.018	0.016	0.270
25/09/2012	12	C4A	Control	0.701	0.036	0.002	0.194	0.191	0.469
25/09/2012	12	C4B	Control	1.204	0.030	0.002	0.742	0.739	0.430
25/09/2012	12	C4C	Control	0.822	0.028	0.002	0.557	0.555	0.235
25/09/2012	12	F1A	Low	0.704	0.023	0.001	0.350	0.349	0.330
25/09/2012	12	F1B	Low	0.508	0.018	0.002	0.166	0.164	0.322
25/09/2012	12	F1C	Low	1.157	0.020	0.002	0.268	0.266	0.867
25/09/2012	12	F2A	Medium	0.676	0.017	0.002	0.352	0.350	0.305
25/09/2012	12	F2B	Medium	1.426	0.129	0.002	0.315	0.313	0.980
25/09/2012	12	F2C	Medium	1.067	0.043	0.002	0.506	0.504	0.516
25/09/2012	12	F3A	Low	ND	ND	ND	ND	ND	ND
25/09/2012	12	F3B	Low	7.212	0.111	0.002	1.432	1.430	5.667
25/09/2012	12	F3C	Low	1.235	0.047	0.002	0.819	0.817	0.367
25/09/2012	12	F4A	Medium	0.850	0.040	0.002	0.430	0.428	0.378
25/09/2012	12	F4B	Medium	ND	ND	ND	ND	ND	ND
25/09/2012	12	F4C	Medium	4.184	0.038	0.002	0.466	0.465	3.678
25/09/2012	12	F5A	Low	1.147	0.042	0.001	0.428	0.427	0.676
25/09/2012	12	F5B	Low	1.191	0.041	0.001	0.329	0.328	0.820
25/09/2012	12	F6C	Medium	0.511	0.035	0.001	0.327	0.326	0.148
25/09/2012	12	F7A	Low	0.463	0.024	0.001	0.175	0.174	0.263
25/09/2012	12	F7B	Low	0.847	0.033	0.002	0.119	0.118	0.693
25/09/2012	12	F7C	Medium	ND	ND	ND	ND	ND	ND
25/09/2012	12	F8A	Low	0.649	0.019	0.001	0.143	0.142	0.486
25/09/2012	12	F8B	Low	2.916	0.028	0.001	0.557	0.556	2.33
25/09/2012	12	F8C	Medium	3.331	0.033	0.002	0.781	0.779	2.515

25/09/2012	12	G1A	High	1.646	0.032	0.002	0.696	0.695	0.916
25/09/2012	12	G1B	High	7.613	0.182	0.004	1.898	1.893	5.529
25/09/2012	12	G1C	High	7.21	0.201	0.006	2.996	2.99	4.007
25/09/2012	12	G2A	Low	4.664	0.082	0.004	4.436	4.432	0.142
25/09/2012	12	G2B	High	1.786	0.027	0.005	4.785	4.781	-3.031
25/09/2012	12	G2C	High	1.984	0.043	0.003	2.952	2.949	-1.014
25/09/2012	12	G3A	Medium	1.579	0.021	0.001	1.075	1.074	0.482
25/09/2012	12	G3B	High	2.714	0.019	0.001	0.672	0.671	2.022
25/09/2012	12	G3C	High	1.696	0.016	0.001	0.694	0.692	0.985
25/09/2012	12	G4A	High	1.33	0.024	0.001	0.59	0.589	0.715
25/09/2012	12	G4B	High	7.502	0.023	0.002	2.35	2.349	5.127
25/09/2012	12	G4C	High	5.534	0.082	0.003	3.721	3.718	1.728

Appendix 8. Lysimeter experiment – summary of applied nitrogen and total nitrogen leached

Table 7.7. Summary of applied nitrogen and nitrogen leached

Lysimeter	Nitrogen applied	Treatment	Nitrogen leached
	(kg N ha^{-1} yr^{-1})		(kg N ha^{-1} yr^{-1})
C1A	5	Control	3.3
C1B	5	Control	2.3
C1C	5	Control	2.9
C2A	5	Control	1.5
C2B	5	Control	3.6
C2C	5	Control	2.9
F1A	355	Low	6.4
F1B	340	Low	7.3
F1C	347	Low	6.6
F2A	400	Medium	11.5
F2B	418	Medium	11.2
F2C	400	Medium	21.0
F3A	366	Low	ND
F3B	354	Low	27.9
F3C	357	Low	26.0
F4A	422	Medium	14.0
F4B	424	Medium	ND
F4C	441	Medium	9.4
F5A	286	Low	9.4
F5B	327	Low	6.7
F5C	316	Low	9.0
F6A	380	Medium	8.5
F6B	391	Medium	5.1
F6C	411	Medium	11.4
F7A	320	Low	8.1
F7B	309	Low	17.2
F7C	395	Medium	6.2
F8A	357	Low	8.8
F8B	330	Low	9.9
F8C	424	Medium	41.0
G1A	453	High	14.4
G1B	518	High	33.9
G1C	519	High	44.6
G2A	363	Low	22.3
G2B	447	High	25.4
G2C	456	High	7.1
G3A	434	Medium	37.4
G3B	505	High	18.3
G3C	449	High	21.4
G4A	454	High	17.7
G4B	567	High	61.1
G4C	539	High	39.6

Key

Treatment	Nitrogen application
	(kg N ha^{-1} yr$^{-1)}$
Control	5
Low	286 - 380
Medium	380 - 445
High	445 - 567

Appendix 9. Lysimeter experiment – replication of nitrogen analyses

Table 7.8. Replication of nitrogen analyses at the University of Waikato and Taupō District Council.

Sampling number	Analysis at the University of Waikato laboratory							Analysis at the Taupō District Council laboratory						
	Lysimeter	NH_4 (mg l^{-1})	NO_2 (mg l^{-1})	Nox (mg l^{-1})	NO3 (mg l^{-1})	TN (mg l^{-1})	ToN (mg l^{-1})	Lysimeter	NH_4 (mg l^{-1})	NO_2 (mg l^{-1})	NOx (mg l^{-1})	NO3 (mg l^{-1})	TN (mg l^{-1})	ToN (mg l^{-1})
6	C1A	0.028	0.029	0.997	0.968	1.448	0.394	C1A	0.035	0.006	3.134	3.128	1.988	-1.181
6	C1B	0.025	0.026	0.311	0.285	0.760	0.399	C1B	0.012	0.001	0.487	0.486	0.703	0.204
6	C1C	0.018	0.019	0.000	0.182	0.435	0.399	C1C	0.009	0.000	0.139	0.138	0.469	0.321
6	C2A	0.023	0.024	0.000	0.199	0.616	0.569	C2A	0.009	0.000	0.040	0.040	0.798	0.749
6	C2B	0.038	0.039	0.000	0.079	0.732	0.654	C2B	0.009	0.000	0.014	0.014	0.655	0.632
6	C2C	0.023	0.024	0.185	0.160	0.741	0.508	C2C	0.014	0.001	0.346	0.345	0.775	0.415
6	FIA	0.030	0.031	0.141	0.110	0.701	0.498	FIA	0.028	0.001	0.287	0.286	0.959	0.644
6	FIB	0.020	0.021	0.000	0.000	0.972	0.932	FIB	0.014	0.001	0.249	0.248	1.030	0.767
6	FIC	0.025	0.026	0.949	0.923	1.374	0.374	FIC	0.071	0.002	1.542	1.540	2.127	0.514
6	F2A	0.029	0.030	1.197	1.167	1.626	0.371	F2A	0.009	0.001	1.989	1.988	2.246	0.248
6	F2B	0.022	0.023	0.928	0.905	1.171	0.198	F2B	0.013	0.001	1.195	1.194	1.603	0.395
6	F2C	0.020	0.021	3.637	3.616	5.843	2.165	F2C	0.010	0.004	9.570	9.566	10.060	0.480
6	F3A	N/A	N/A	N/A	N/A	N/A	N/A	F3A	N/A	N/A	N/A	N/A	N/A	N/A
6	F3B	0.027	0.028	1.386	1.358	1.666	0.226	F3B	0.012	0.001	1.270	1.269	1.264	-0.018
6	F3C	N/A	N/A	N/A	N/A	N/A	N/A	F3C	N/A	N/A	N/A	N/A	N/A	N/A
6	F4A	0.037	0.038	0.703	0.666	1.487	0.710	F4A	0.027	0.001	1.009	1.008	2.591	1.555
6	F4B	N/A	N/A	N/A	N/A	N/A	N/A	F4B	N/A	N/A	N/A	N/A	N/A	N/A
6	F4C	0.024	0.025	1.681	1.656	1.972	0.242	F4C	0.010	0.001	2.309	2.309	3.090	0.771
6	F5A	0.019	0.020	1.092	1.072	1.469	0.338	F5A	0.011	0.001	2.657	2.655	3.458	0.790
6	F5B	0.035	0.036	0.343	0.307	1.138	0.724	F5B	0.014	0.001	0.585	0.584	1.655	1.056
6	F5C	0.031	0.032	0.261	0.229	0.986	0.662	F5C	0.012	0.000	0.496	0.496	1.352	0.844

6	F6A	0.029	0.030	1.148	1.117	1.643	0.436	F6A	0.013	0.001	1.536	1.535	2.270	0.721
6	F6B	0.068	0.069	1.187	1.118	2.185	0.862	F6B	0.013	0.001	1.801	1.800	2.920	1.106
6	F6C	0.020	0.021	0.421	0.400	1.045	0.583	F6C	0.011	0.000	0.795	0.795	1.969	1.163
6	F7A	0.014	0.015	0.266	0.251	0.907	0.612	F7A	0.013	0.000	0.711	0.710	1.369	0.645
6	F7B	0.031	0.032	1.443	1.411	2.273	0.767	F7B	0.012	0.000	1.264	1.264	2.057	0.781
6	F7C	0.017	0.018	2.397	2.379	2.770	0.338	F7C	0.011	0.001	6.887	6.886	6.924	0.026
6	F8A	0.028	0.029	0.382	0.352	1.005	0.566	F8A	0.013	0.001	0.528	0.527	1.137	0.596
6	F8B	N/A	N/A	N/A	N/A	N/A	N/A	F8B	N/A	N/A	N/A	N/A	N/A	N/A
6	F8C	0.024	0.025	2.475	2.450	3.086	0.562	F8C	0.013	0.003	3.442	3.439	3.959	0.504
6	G1A	0.020	0.021	0.000	0.687	0.861	0.820	G1A	0.015	0.000	0.051	0.051	1.049	0.983
6	G1B	N/A	N/A	N/A	N/A	N/A	N/A	G1B	N/A	N/A	N/A	N/A	N/A	N/A
6	G1C	0.031	0.032	3.411	3.379	5.423	1.949	G1C	0.015	0.006	7.875	7.869	7.977	0.087
6	G2A	0.021	0.022	0.176	0.154	0.915	0.695	G2A	0.010	0.000	0.387	0.387	1.762	1.365
6	G2B	0.025	0.026	1.993	1.966	2.145	0.101	G2B	0.010	0.003	3.144	3.141	3.538	0.384
6	G2C	0.027	0.028	0.387	0.359	0.657	0.214	G2C	0.012	0.001	0.687	0.687	1.227	0.528
6	G3A	0.021	0.022	3.526	3.503	5.390	1.822	G3A	0.013	0.001	8.056	8.054	7.650	-0.419
6	G3B	0.025	0.027	1.181	1.155	1.475	0.242	G3B	0.012	0.000	1.405	1.405	1.912	0.495
6	G3C	0.030	0.032	1.822	1.791	1.988	0.103	G3C	0.016	0.001	4.340	4.339	4.737	0.381
6	G4A	0.056	0.057	1.100	1.043	1.774	0.561	G4A	0.049	0.001	1.610	1.608	2.458	0.799
6	G4B	0.024	0.025	1.228	1.203	1.735	0.458	G4B	0.016	0.000	1.761	1.761	2.509	0.732
6	G4C	0.035	0.036	1.236	1.200	1.977	0.669	G4C	0.021	0.001	1.752	1.752	2.788	1.015

Table 7.9. Replication of nitrogen analyses at Hills laboratory and Taupō District Council.

Sampling number	Analysis at Hills laboratory						Analysis at the Taupō District Council laboratory						
	Lysimeter	NH_4	Nox	TKN	TN	ToN	Lysimeter	NH_4	NO_2	NOx	NO3	TN	ToN
		(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})		(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})
10	C1A	0.010	0.045	0.230	0.280	0.230	C1A	0.016	0.005	0.051	0.047	0.276	0.204
10	C1B	0.000	0.011	0.260	0.270	0.260	C1B	0.023	0.003	0.062	0.059	0.163	0.075
10	C1C	0.000	0.220	0.310	0.530	0.310	C1C	0.018	0.001	0.183	0.182	0.503	0.301
10	C2A	0.000	0.023	0.220	0.250	0.220	C2A	0.014	0.001	0.200	0.199	0.222	0.007
10	C2B	0.000	0.028	0.340	0.370	0.340	C2B	0.012	0.001	0.080	0.079	0.348	0.255
10	C2C	0.000	0.045	0.340	0.390	0.340	C2C	0.019	0.001	0.067	0.066	0.323	0.236
10	F1A	0.000	0.350	0.540	0.900	0.540	FIA	0.013	0.000	0.336	0.335	0.944	0.595
10	F1B	0.000	0.055	0.640	0.690	0.640	FIB	0.011	0.000	0.194	0.194	0.628	0.423
10	F1C	0.000	0.570	0.700	1.270	0.700	FIC	0.012	0.000	0.675	0.685	1.158	0.471
10	F2A	0.000	0.340	0.560	0.910	0.560	F2A	0.026	0.001	0.508	0.507	0.834	0.299
10	F2B	0.000	0.380	0.890	1.270	0.890	F2B	0.016	0.006	0.520	0.513	0.895	0.353
10	F2C	0.000	1.010	0.920	1.920	0.920	F2C	0.021	0.001	0.994	0.994	1.573	0.557
10	F3A	N/A	N/A	N/A	N/A	N/A	F3A	N/A	N/A	N/A	N/A	N/A	N/A
10	F3B	0.000	0.460	0.540	1.000	0.540	F3B	0.016	0.000	0.606	0.605	0.952	0.330
10	F3C	0.000	0.600	0.540	1.140	0.540	F3C	0.020	0.001	0.696	0.695	1.376	0.659
10	F4A	0.000	0.290	0.480	0.770	0.480	F4A	0.019	0.001	0.539	0.538	1.058	0.499
10	F4B	N/A	N/A	N/A	N/A	N/A	F4B	N/A	N/A	N/A	N/A	N/A	N/A
10	F4C	0.000	0.900	0.790	1.690	0.790	F4C	0.013	0.001	0.697	0.696	1.074	0.363
10	F5A	0.000	0.430	0.830	1.260	0.830	F5A	0.013	0.000	0.545	0.545	1.297	0.739
10	F5B	0.000	0.440	1.090	1.530	1.090	F5B	0.021	0.001	0.893	0.892	1.472	0.557
10	F5C	0.000	0.063	0.670	0.730	0.670	F5C	0.017	0.000	0.687	0.686	0.647	0.000

10	F6A	0.000	0.420	0.510	0.930	0.510	F6A	0.023	0.001	0.549	0.548	0.916	0.343
10	F6B	N/A	N/A	N/A	N/A	N/A	F6B	N/A	N/A	N/A	N/A	N/A	N/A
10	F6C	0.000	0.340	0.600	0.940	0.600	F6C	0.019	0.001	0.518	0.517	0.863	0.325
10	F7A	0.000	0.072	0.420	0.490	0.420	F7A	0.016	0.000	0.284	0.283	0.802	0.502
10	F7B	0.000	0.480	0.930	1.410	0.930	F7B	0.022	0.000	0.564	0.564	1.065	0.479
10	F7C	N/A	N/A	N/A	N/A	N/A	F7C	N/A	N/A	N/A	N/A	N/A	N/A
10	F8A	0.000	0.450	0.520	0.970	0.520	F8A	0.009	0.000	0.567	0.567	0.851	0.275
10	F8B	0.000	0.290	1.110	1.400	1.110	F8B	0.018	0.000	0.344	0.344	1.444	1.082
10	F8C	0.000	2.600	0.710	3.300	0.710	F8C	0.009	0.001	3.470	3.468	3.495	0.015
10	G1A	0.000	0.370	0.260	0.630	0.260	G1A	0.016	0.000	0.687	0.687	0.815	0.112
10	G1B	0.012	2.400	0.580	3.000	0.568	G1B	0.019	0.001	3.028	3.028	3.058	0.010
10	G1C	0.000	3.700	0.210	3.900	0.210	G1C	0.013	0.004	4.955	4.952	4.645	0.000
10	G2A	0.000	3.200	0.360	3.600	0.360	G2A	0.012	0.001	4.247	4.246	3.695	0.000
10	G2B	0.000	2.800	0.780	3.600	0.780	G2B	0.013	0.001	3.772	3.772	3.637	0.000
10	G2C	0.000	0.310	0.510	0.820	0.510	G2C	0.012	0.000	0.572	0.572	0.804	0.220
10	G3A	0.000	1.480	0.460	1.940	0.460	G3A	0.015	0.001	1.947	1.947	1.807	0.000
10	G3B	0.000	0.450	0.440	0.890	0.440	G3B	0.013	0.000	1.030	1.030	1.101	0.058
10	G3C	0.000	2.600	0.750	3.400	0.750	G3C	0.013	0.001	3.266	3.266	3.285	0.005
10	G4A	0.000	0.460	0.490	0.950	0.490	G4A	0.010	0.000	0.717	0.717	0.959	0.232
10	G4B	0.000	6.400	0.061	7.000	0.061	G4B	0.020	0.001	5.646	5.646	7.019	1.352
10	G4C	0.199	4.000	1.440	5.400	1.241	G4C	0.180	0.008	5.584	5.757	5.485	0.000

Appendix 10. Lysimeter experiment – dry matter, nitrogen concentration of pasture, and nitrogen removal

Table 7.10. Dry matter, nitrogen concentration of pasture and the amount of nitrogen removed with pasture harvest.

Harvest number	Date of pasture collection	Lysimeter	Treatment	Weight of bag and pasture	Weight of bag	Weight of pasture	Weight of pasture	Weight of pasture per area of lysimeter	Pasture dry matter	Pasture nitrogen	Nitrogen removal by pasture
				(g)	(g)	(g)	(kg)	(kg cm^2)	(kg DM ha^{-1})	(%)	(kg DM ha^{-1})
1	31/10/2011	C1A	Control	42.94	35	7.94	0.008	1.12271E-05	1122.7	1.46	16.4
1	31/10/2011	C1B	Control	43.78	35	8.78	0.009	1.24183E-05	1241.8	1.93	23.9
1	31/10/2011	C1C	Control	44.62	35	9.62	0.010	1.36095E-05	1360.9	2.39	32.6
1	31/10/2011	C2A	Control	49.42	35	14.42	0.014	2.03972E-05	2039.7	1.29	26.4
1	31/10/2011	C2B	Control	40.11	35	5.11	0.005	7.2334E-06	723.3	1.99	14.4
1	31/10/2011	C2C	Control	41.88	35	6.88	0.007	9.73036E-06	973.0	1.56	15.2
1	31/10/2011	C3A	Control	43.75	35	8.75	0.009	1.23716E-05	1237.2	1.67	20.7
1	31/10/2011	C3B	Control	44.41	35	9.41	0.009	1.33096E-05	1331.0	1.72	22.9
1	31/10/2011	C3C	Control	47.79	35	12.79	0.013	1.80941E-05	1809.4	1.95	35.2
1	31/10/2011	C4A	Control	41.01	35	6.01	0.006	8.49815E-06	849.8	1.67	14.1
1	31/10/2011	C4B	Control	47.57	35	12.57	0.013	1.77815E-05	1778.1	1.81	32.2
1	31/10/2011	C4C	Control	40.81	35	5.81	0.006	8.22228E-06	822.2	1.88	15.4
1	31/10/2011	F1A	Low	68.96	35	33.96	0.034	4.80392E-05	4803.9	2.28	109.4
1	31/10/2011	F1B	Low	74.01	35	39.01	0.039	5.5192E-05	5519.2	2.50	138.1
1	31/10/2011	F1C	Low	75.96	35	40.96	0.041	5.79408E-05	5794.1	2.35	135.9
1	31/10/2011	F2A	Medium	72.36	35	37.36	0.037	5.28535E-05	5285.3	2.58	136.1
1	31/10/2011	F2B	Medium	89.55	35	54.55	0.055	7.71737E-05	7717.4	2.64	203.7
1	31/10/2011	F2C	Medium	70.13	35	35.13	0.035	4.96973E-05	4969.7	3.06	152.1
1	31/10/2011	F3A	Low	69.97	35	34.97	0.035	4.94723E-05	4947.2	2.56	126.4
1	31/10/2011	F3B	Low	72.86	35	37.86	0.038	5.35537E-05	5355.4	2.92	156.4
1	31/10/2011	F3C	Low	70.13	35	35.13	0.035	4.97001E-05	4970.0	2.62	130.1

1	31/10/2011	F4A	Medium	90.38	35	55.38	0.055	7.83394E-05	7833.9	2.49	194.8
1	31/10/2011	F4B	Medium	74.52	35	39.52	0.040	5.59022E-05	5590.2	2.31	129.2
1	31/10/2011	F4C	Medium	64.90	35	29.90	0.030	4.22969E-05	4229.7	2.84	120.3
1	31/10/2011	F5A	Low	64.08	35	29.08	0.029	4.11369E-05	4113.7	2.88	118.6
1	31/10/2011	F5B	Low	72.63	35	37.63	0.038	5.32369E-05	5323.7	2.77	147.2
1	31/10/2011	F5C	Low	67.93	35	32.93	0.033	4.65906E-05	4659.1	2.49	115.8
1	31/10/2011	F6A	Medium	62.29	35	27.29	0.027	3.86059E-05	3860.6	2.74	105.6
1	31/10/2011	F6B	Medium	62.78	35	27.78	0.028	3.92949E-05	3929.5	2.76	108.5
1	31/10/2011	F6C	Medium	78.24	35	43.24	0.043	6.11734E-05	6117.3	2.83	173.4
1	31/10/2011	F7A	Low	65.08	35	30.08	0.030	4.2553E-05	4255.3	3.01	127.9
1	31/10/2011	F7B	Low	73.04	35	38.04	0.038	5.38084E-05	5380.8	2.41	129.8
1	31/10/2011	F7C	Medium	61.20	35	26.20	0.026	3.70639E-05	3706.4	2.58	95.7
1	31/10/2011	F8A	Low	84.81	35	49.81	0.050	7.04623E-05	7046.2	2.76	194.3
1	31/10/2011	F8B	Low	81.69	35	46.69	0.047	6.6047E-05	6604.7	2.52	166.2
1	31/10/2011	F8C	Medium	81.44	35	46.44	0.046	6.56919E-05	6569.2	2.65	174.0
1	31/10/2011	G1A	High	61.05	35	26.05	0.026	3.68475E-05	3684.7	3.13	115.4
1	31/10/2011	G1B	High	79.01	35	44.01	0.044	6.22613E-05	6226.1	3.08	191.8
1	31/10/2011	G1C	High	83.13	35	48.13	0.048	6.80828E-05	6808.3	2.53	172.0
1	31/10/2011	G2A	Low	61.02	35	26.02	0.026	3.68107E-05	3681.1	2.60	95.6
1	31/10/2011	G2B	High	63.87	35	28.87	0.029	4.08454E-05	4084.5	2.29	93.5
1	31/10/2011	G2C	High	74.86	35	39.86	0.040	5.63959E-05	5639.6	2.36	133.2
1	31/10/2011	G3A	Medium	52.09	35	17.09	0.017	2.41717E-05	2417.2	3.04	73.5
1	31/10/2011	G3B	High	88.74	35	53.74	0.054	7.60306E-05	7603.1	2.43	184.7
1	31/10/2011	G3C	High	64.76	35	29.76	0.030	4.2096E-05	4209.6	2.52	106.2
1	31/10/2011	G4A	High	70.38	35	35.38	0.035	5.00538E-05	5005.4	2.46	123.1
1	31/10/2011	G4B	High	76.57	35	41.57	0.042	5.8808E-05	5880.8	2.73	160.4
1	31/10/2011	G4C	High	72.05	35	37.05	0.037	5.24206E-05	5242.1	3.14	164.3

Harvest number	Date of pasture collection	Lysimeter	Treatment	Weight of bag and pasture	Weight of bag	Weight of pasture	Weight of pasture	Weight of pasture per area of lysimeter	Pasture dry matter	Pasture nitrogen	Nitrogen removal by pasture
				(g)	(g)	(g)	(kg)	(kg cm^2)	(kg DM ha^{-1})	(%)	(kg DM ha^{-1})
2	21/01/2012	C1A	Control	30.61	14	16.61	0.016606	2.34926E-05	2349.3	2.01	47.3
2	21/01/2012	C1B	Control	26.39	14	12.39	0.0123925	1.75318E-05	1753.2	1.86	32.5
2	21/01/2012	C1C	Control	22.18	14	8.18	0.008179	1.15709E-05	1157.1	1.70	19.7
2	21/01/2012	C2A	Control	29.56	14	15.56	0.015562	2.20157E-05	2201.6	1.21	26.6
2	21/01/2012	C2B	Control	20.75	14	6.75	0.00675	9.54927E-06	954.9	1.46	13.9
2	21/01/2012	C2C	Control	26.17	14	12.17	0.012174	1.72226E-05	1722.3	1.10	18.9
2	21/01/2012	C3A	Control	24.06	14	10.06	0.010062	1.42348E-05	1423.5	1.68	23.9
2	21/01/2012	C3B	Control	28.00	14	14.00	0.013997	1.98017E-05	1980.2	1.59	31.6
2	21/01/2012	C3C	Control	34.98	14	20.98	0.020979	2.96791E-05	2967.9	1.19	35.3
2	21/01/2012	C4A	Control	21.58	14	7.58	0.007584	1.07291E-05	1072.9	1.56	16.7
2	21/01/2012	C4B	Control	45.17	14	31.17	0.031172	4.40993E-05	4409.9	1.30	57.3
2	21/01/2012	C4C	Control	26.58	14	12.58	0.012579	1.77956E-05	1779.6	1.86	33.0
2	21/01/2012	F1A	Low	41.57	14	27.57	0.027567	3.89992E-05	3899.9	1.92	74.7
2	21/01/2012	F1B	Low	39.96	14	25.96	0.025957	3.67216E-05	3672.2	1.83	67.4
2	21/01/2012	F1C	Low	55.25	14	41.25	0.041248	5.83538E-05	5835.4	1.83	107.0
2	21/01/2012	F2A	Medium	28.40	14	14.40	0.014399	2.03704E-05	2037.0	2.91	59.3
2	21/01/2012	F2B	Medium	37.44	14	23.44	0.023444	3.31664E-05	3316.6	4.40	145.8
2	21/01/2012	F2C	Medium	44.27	14	30.27	0.03027	4.28232E-05	4282.3	4.85	207.9
2	21/01/2012	F3A	Low	46.18	14	32.18	0.032182	4.55281E-05	4552.8	2.92	133.1
2	21/01/2012	F3B	Low	28.22	14	14.22	0.01422	2.01171E-05	2011.7	2.33	47.0
2	21/01/2012	F3C	Low	39.99	14	25.99	0.025994	3.67739E-05	3677.4	2.63	96.6
2	21/01/2012	F4A	Medium	40.07	14	26.07	0.026067	3.68772E-05	3687.7	2.65	97.6
2	21/01/2012	F4B	Medium	35.20	14	21.20	0.021195	2.99847E-05	2998.5	1.73	51.8
2	21/01/2012	F4C	Medium	29.74	14	15.74	0.015736	2.22618E-05	2226.2	4.24	94.4

2	21/01/2012	F5A	Low	32.93	14	18.93	0.018925	2.67733E-05	2677.3	2.85	76.3
2	21/01/2012	F5B	Low	35.65	14	21.65	0.021645	3.06213E-05	3062.1	2.94	90.0
2	21/01/2012	F5C	Low	47.96	14	33.96	0.033958	4.80406E-05	4804.1	3.30	158.4
2	21/01/2012	F6A	Medium	41.28	14	27.28	0.027281	3.85946E-05	3859.5	1.44	55.7
2	21/01/2012	F6B	Medium	29.81	14	15.81	0.015809	2.23651E-05	2236.5	2.26	50.5
2	21/01/2012	F6C	Medium	32.18	14	18.18	0.018178	2.57165E-05	2571.7	1.89	48.7
2	21/01/2012	F7A	Low	32.90	14	18.90	0.018902	2.67408E-05	2674.1	1.87	50.1
2	21/01/2012	F7B	Low	30.71	14	16.71	0.01671	2.36398E-05	2364.0	2.14	50.5
2	21/01/2012	F7C	Medium	27.81	14	13.81	0.013811	1.95385E-05	1953.9	1.59	31.1
2	21/01/2012	F8A	Low	52.02	14	38.02	0.038018	5.37843E-05	5378.4	1.73	92.8
2	21/01/2012	F8B	Low	40.31	14	26.31	0.026312	3.72238E-05	3722.4	1.87	69.6
2	21/01/2012	F8C	Medium	33.05	14	19.05	0.019049	2.69488E-05	2694.9	2.12	57.1
2	21/01/2012	G1A	High	39.91	14	25.91	0.0259125	3.66586E-05	3665.9	2.02	74.0
2	21/01/2012	G1B	High	40.58	14	26.58	0.026576	3.75973E-05	3759.7	2.21	83.1
2	21/01/2012	G1C	High	39.25	14	25.25	0.025249	3.57199E-05	3572.0	1.83	65.3
2	21/01/2012	G2A	Low	49.29	14	35.29	0.035293	4.99293E-05	4992.9	1.75	87.5
2	21/01/2012	G2B	High	29.79	14	15.79	0.015792	2.23411E-05	2234.1	1.48	33.1
2	21/01/2012	G2C	High	40.70	14	26.70	0.026699	3.77713E-05	3777.1	1.79	67.7
2	21/01/2012	G3A	Medium	49.24	14	35.24	0.035242	4.98571E-05	4985.7	1.38	69.0
2	21/01/2012	G3B	High	49.24	14	35.24	0.035242	4.98571E-05	4985.7	1.38	69.0
2	21/01/2012	G3C	High	49.24	14	35.24	0.035242	4.98571E-05	4985.7	1.38	69.0
2	21/01/2012	G4A	High	43.95	14	29.95	0.029952	4.23733E-05	4237.3	1.56	66.3
2	21/01/2012	G4B	High	62.70	14	48.70	0.0487	6.88962E-05	6889.6	1.56	107.8
2	21/01/2012	G4C	High	31.56	14	17.56	0.017558	2.48394E-05	2483.9	2.14	53.0

Harvest number	Date of pasture collection	Lysimeter	Treatment	Weight of bag and pasture	Weight of bag	Weight of pasture	Weight of pasture	Weight of pasture per area of lysimeter	Pasture dry matter	Pasture nitrogen	Nitrogen removal by pasture
				(g)	(g)	(g)	(kg)	(kg cm^2)	(kg DM ha^{-1})	(%)	(kg DM ha^{-1})
3	16/03/2012	C1A	Control	48.51	35	13.51	0.013507	1.91085E-05	1910.8	1.61	30.8
3	16/03/2012	C1B	Control	50.56	35	15.56	0.015559	2.20114E-05	2201.1	1.62	35.6
3	16/03/2012	C1C	Control	47.76	35	12.76	0.012757	1.80474E-05	1804.7	1.61	29.0
3	16/03/2012	C2A	Control	46.48	35	11.48	0.011478	1.6238E-05	1623.8	1.58	25.6
3	16/03/2012	C2B	Control	44.73	35	9.73	0.009727	1.37609E-05	1376.1	1.68	23.1
3	16/03/2012	C2C	Control	46.20	35	11.20	0.0112	1.58447E-05	1584.5	1.49	23.6
3	16/03/2012	C3A	Control	47.45	35	12.45	0.01245	1.76131E-05	1761.3	2.05	36.1
3	16/03/2012	C3B	Control	51.62	35	16.62	0.016617	2.35082E-05	2350.8	2.09	49.2
3	16/03/2012	C3C	Control	59.26	35	24.26	0.024262	3.43236E-05	3432.4	1.59	54.7
3	16/03/2012	C4A	Control	54.03	35	19.03	0.019026	2.69162E-05	2691.6	2.10	56.4
3	16/03/2012	C4B	Control	57.88	35	22.88	0.022878	3.23657E-05	3236.6	2.33	75.3
3	16/03/2012	C4C	Control	56.83	35	21.83	0.021833	3.08873E-05	3088.7	2.12	65.5
3	16/03/2012	F1A	Low	54.04	35	19.04	0.019038	2.69332E-05	2693.3	2.26	60.9
3	16/03/2012	F1B	Low	52.46	35	17.46	0.017455	2.46937E-05	2469.4	2.46	60.7
3	16/03/2012	F1C	Low	59.78	35	24.78	0.024777	3.50522E-05	3505.2	2.22	77.8
3	16/03/2012	F2A	Medium	57.30	35	22.30	0.0223	3.1548E-05	3154.8	2.04	64.4
3	16/03/2012	F2B	Medium	59.51	35	24.51	0.02451	3.46745E-05	3467.4	2.24	77.7
3	16/03/2012	F2C	Medium	62.13	35	27.13	0.027133	3.83853E-05	3838.5	2.19	84.0
3	16/03/2012	F3A	Low	55.97	35	20.97	0.020969	2.9665E-05	2966.5	2.31	68.4
3	16/03/2012	F3B	Low	60.37	35	25.37	0.025367	3.58869E-05	3588.7	1.82	65.3
3	16/03/2012	F3C	Low	56.36	35	21.36	0.021356	3.02125E-05	3021.2	2.13	64.4
3	16/03/2012	F4A	Medium	55.04	35	20.04	0.020037	2.83465E-05	2834.6	2.19	62.1
3	16/03/2012	F4B	Medium	57.14	35	22.14	0.022136	3.1316E-05	3131.6	2.03	63.6
3	16/03/2012	F4C	Medium	47.30	35	12.30	0.012302	1.74037E-05	1740.4	2.57	44.8

3	16/03/2012	F5A	Low	49.46	35	14.46	0.014462	2.04595E-05	2045.9	1.93	39.5
3	16/03/2012	F5B	Low	49.47	35	14.47	0.014468	2.0468E-05	2046.8	2.30	47.0
3	16/03/2012	F5C	Low	56.93	35	21.93	0.021934	3.10302E-05	3103.0	2.07	64.3
3	16/03/2012	F6A	Medium	54.92	35	19.92	0.019919	2.81796E-05	2818.0	1.88	53.0
3	16/03/2012	F6B	Medium	53.16	35	18.16	0.018163	2.56953E-05	2569.5	2.39	61.3
3	16/03/2012	F6C	Medium	57.22	35	22.22	0.022222	3.14376E-05	3143.8	2.11	66.2
3	16/03/2012	F7A	Low	54.09	35	19.09	0.01909	2.70068E-05	2700.7	1.78	48.0
3	16/03/2012	F7B	Low	47.24	35	12.24	0.012235	1.73089E-05	1730.9	1.84	31.8
3	16/03/2012	F7C	Medium	49.55	35	14.55	0.014546	2.05783E-05	2057.8	2.78	57.3
3	16/03/2012	F8A	Low	60.09	35	25.09	0.02509	3.5495E-05	3549.5	1.63	58.0
3	16/03/2012	F8B	Low	63.24	35	28.24	0.028235	3.99443E-05	3994.4	1.92	76.8
3	16/03/2012	F8C	Medium	55.06	35	20.06	0.020062	2.83819E-05	2838.2	2.39	67.8
3	16/03/2012	G1A	High	59.76	35	24.76	0.024756	3.50225E-05	3502.2	3.04	106.3
3	16/03/2012	G1B	High	52.71	35	17.71	0.017706	2.50488E-05	2504.9	2.27	56.8
3	16/03/2012	G1C	High	52.57	35	17.57	0.017574	2.48621E-05	2486.2	2.25	55.9
3	16/03/2012	G2A	Low	62.49	35	27.49	0.027486	3.88846E-05	3888.5	2.07	80.4
3	16/03/2012	G2B	High	53.65	35	18.65	0.018648	2.63815E-05	2638.1	2.56	67.4
3	16/03/2012	G2C	High	54.69	35	19.69	0.019691	2.7857E-05	2785.7	2.37	66.1
3	16/03/2012	G3A	Medium	52.56	35	17.56	0.017556	2.48366E-05	2483.7	2.57	63.9
3	16/03/2012	G3B	High	59.12	35	24.12	0.02412	3.41227E-05	3412.3	2.10	71.6
3	16/03/2012	G3C	High	64.16	35	29.16	0.029159	4.12515E-05	4125.1	2.47	101.8
3	16/03/2012	G4A	High	67.03	35	32.03	0.03203	4.53131E-05	4531.3	2.56	115.8
3	16/03/2012	G4B	High	60.19	35	25.19	0.025192	3.56393E-05	3563.9	2.55	90.9
3	16/03/2012	G4C	High	51.46	35	16.46	0.016462	2.32889E-05	2328.9	2.76	64.3

Harvest number	Date of pasture collection	Lysimeter	Treatment	Weight of bag and pasture	Weight of bag	Weight of pasture	Weight of pasture	Weight of pasture per area of lysimeter	Pasture dry matter	Pasture nitrogen	Nitrogen removal by pasture
				(g)	**(g)**	**(g)**	**(kg)**	**(kg cm^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg DM ha^{-1})**
4	17/09/2012	C1A	Control	40.23	35	5.23	0.00523	7.39892E-06	739.9	2.23	16.5
4	17/09/2012	C1B	Control	39.89	35	4.89	0.004892	6.92075E-06	692.1	2.33	16.1
4	17/09/2012	C1C	Control	40.08	35	5.08	0.005077	7.18247E-06	718.2	1.97	14.1
4	17/09/2012	C2A	Control	40.13	35	5.13	0.005128	7.25462E-06	725.5	1.71	12.4
4	17/09/2012	C2B	Control	39.01	35	4.01	0.00401	5.67298E-06	567.3	2.78	15.7
4	17/09/2012	C2C	Control	39.90	35	4.90	0.0049	6.93207E-06	693.2	2.84	19.7
4	17/09/2012	C3A	Control	46.70	35	11.70	0.011704	1.65577E-05	1655.8	2.51	41.5
4	17/09/2012	C3B	Control	51.19	35	16.19	0.016192	2.29069E-05	2290.7	2.35	53.9
4	17/09/2012	C3C	Control	47.94	35	12.94	0.012941	1.83077E-05	1830.8	2.12	38.9
4	17/09/2012	C4A	Control	50.84	35	15.84	0.01584	2.2409E-05	2240.9	2.78	62.2
4	17/09/2012	C4B	Control	46.41	35	11.41	0.011406	1.61362E-05	1613.6	3.38	54.6
4	17/09/2012	C4C	Control	55.27	35	20.27	0.020274	2.86818E-05	2868.2	2.50	71.7
4	17/09/2012	F1A	Low	51.45	35	16.45	0.0164545	2.32783E-05	2327.8	2.81	65.4
4	17/09/2012	F1B	Low	55.59	35	20.59	0.020594	2.91345E-05	2913.4	2.87	83.7
4	17/09/2012	F1C	Low	47.32	35	12.32	0.012315	1.74221E-05	1742.2	2.65	46.1
4	17/09/2012	F2A	Medium	61.87	35	26.87	0.026869	3.80118E-05	3801.2	3.00	114.2
4	17/09/2012	F2B	Medium	59.85	35	24.85	0.024853	3.51597E-05	3516.0	2.93	103.2
4	17/09/2012	F2C	Medium	49.68	35	14.68	0.014683	2.07721E-05	2077.2	3.47	72.2
4	17/09/2012	F3A	Low	57.27	35	22.27	0.02227	3.15055E-05	3150.6	2.84	89.5
4	17/09/2012	F3B	Low	46.91	35	11.91	0.011907	1.68449E-05	1684.5	3.26	54.9
4	17/09/2012	F3C	Low	58.33	35	23.33	0.023328	3.30023E-05	3300.2	2.75	90.6
4	17/09/2012	F4A	Medium	61.13	35	26.13	0.026133	3.69705E-05	3697.1	3.01	111.3
4	17/09/2012	F4B	Medium	51.74	35	16.74	0.016737	2.3678E-05	2367.8	2.93	69.3
4	17/09/2012	F4C	Medium	50.32	35	15.32	0.01532	2.16733E-05	2167.3	3.58	77.6

4	17/09/2012	F5A	Low	43.88	35	8.88	0.008881	1.2564E-05	1256.4	2.84	35.6
4	17/09/2012	F5B	Low	45.63	35	10.63	0.010625	1.50313E-05	1503.1	2.93	44.1
4	17/09/2012	F5C	Low	48.71	35	13.71	0.013706	1.939E-05	1939.0	3.06	59.2
4	17/09/2012	F6A	Medium	54.03	35	19.03	0.019025	2.69148E-05	2691.5	2.87	77.1
4	17/09/2012	F6B	Medium	45.81	35	10.81	0.010812	1.52958E-05	1529.6	3.09	47.3
4	17/09/2012	F6C	Medium	49.13	35	14.13	0.014134	1.99955E-05	1999.5	3.37	67.3
4	17/09/2012	F7A	Low	53.02	35	18.02	0.018023	2.54973E-05	2549.7	3.61	92.0
4	17/09/2012	F7B	Low	49.18	35	14.18	0.014184	2.00662E-05	2006.6	2.62	52.6
4	17/09/2012	F7C	Medium	51.42	35	16.42	0.016418	2.32267E-05	2322.7	2.91	67.5
4	17/09/2012	F8A	Low	54.76	35	19.76	0.01976	2.79546E-05	2795.5	2.76	77.2
4	17/09/2012	F8B	Low	45.78	35	10.78	0.010784	1.52562E-05	1525.6	2.94	44.8
4	17/09/2012	F8C	Medium	45.32	35	10.32	0.010321	1.46012E-05	1460.1	3.62	52.9
4	17/09/2012	G1A	High	57.02	35	22.02	0.022021	3.11533E-05	3115.3	3.37	105.0
4	17/09/2012	G1B	High	60.48	35	25.48	0.025482	3.60496E-05	3605.0	3.42	123.2
4	17/09/2012	G1C	High	41.18	35	6.18	0.006177	8.73865E-06	873.9	3.76	32.8
4	17/09/2012	G2A	Low	47.73	35	12.73	0.012728	1.80064E-05	1800.6	4.04	72.7
4	17/09/2012	G2B	High	49.67	35	14.67	0.014673	2.0758E-05	2075.8	3.38	70.2
4	17/09/2012	G2C	High	49.55	35	14.55	0.014551	2.05854E-05	2058.5	3.48	71.7
4	17/09/2012	G3A	Medium	62.97	35	27.97	0.02797	3.95694E-05	3956.9	3.05	120.5
4	17/09/2012	G3B	High	73.09	35	38.09	0.038087	5.3882E-05	5388.2	3.36	180.9
4	17/09/2012	G3C	High	56.59	35	21.59	0.021589	3.05421E-05	3054.2	3.62	110.5
4	17/09/2012	G4A	High	63.15	35	28.15	0.028149	3.98226E-05	3982.3	3.29	131.0
4	17/09/2012	G4B	High	49.39	35	14.39	0.014392	2.03605E-05	2036.0	3.36	68.3
4	17/09/2012	G4C	High	48.44	35	13.44	0.013439	1.90123E-05	1901.2	4.15	78.9
Key	▨	Herbage data missing- average of data within treatment sector									

Appendix 11. Pasture harvesting frequency experiment – experimental set up

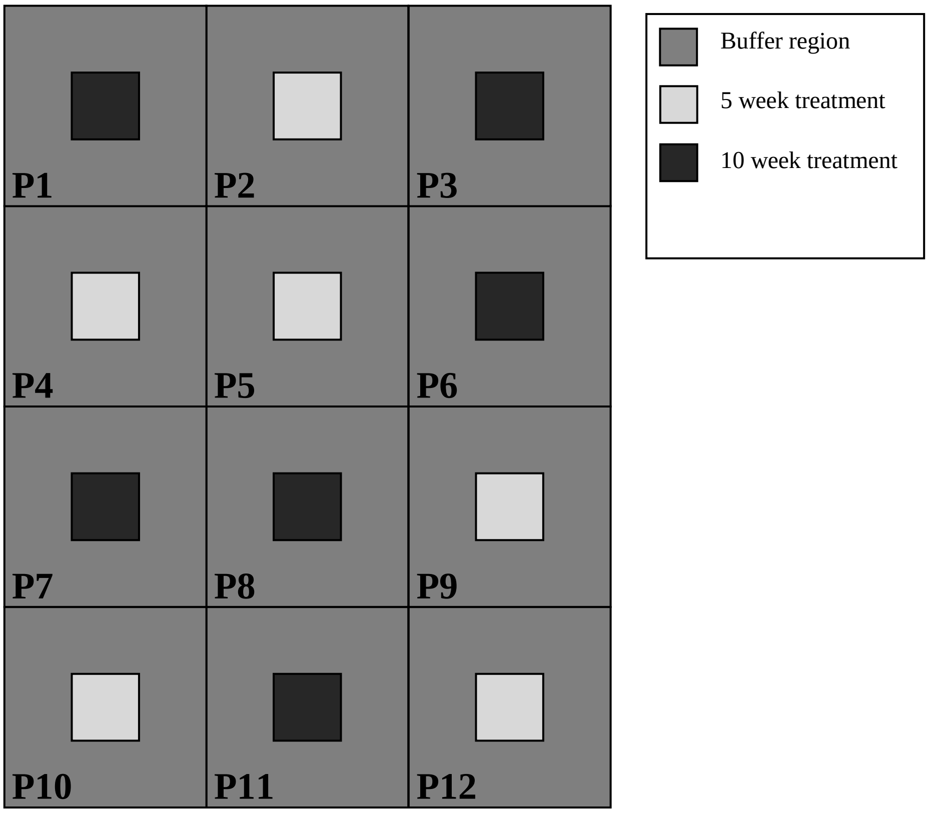

Figure 7.3. Harvesting frequency experiment with plot labels.

Appendix 12. Pasture harvesting frequency experiment – rainfall and temperature data

Table 7.11. Temperature and Rainfall Values measured at the Taupō Airport.

Month	**Temperature**		**Rainfall**	
	Five year mean (2007-2011)	**2012**	**Five year mean (2007-2011)**	**2012**
	(°C)	**(°C)**	**(mm)**	**(mm)**
January	18	16	109	149
February	18	16	31	90
March	15	14	71	83
April	12	12	69	50
May	10	8	81	94
June	7	7	99	80
July	7	6	103	89
August	8	8	99	105
September	9	9	77	93
October	11	11	83	71
November	13	12	22	19

Appendix 13. Pasture harvesting frequency experiment – dry matter, nitrogen concentration of pasture, and nitrogen removal

Table 7.12. Dry matter, nitrogen concentration of pasture and the amount of nitrogen removed with pasture harvest.

Harvest date	Plot #	Treatment	Weight of dry matter + bag	Weight of bag	Weight of dry matter	Weight of dry matter	Length of pasture plot				Area of pasture plot	Area of pasture plot	Dry matter per area of pasture plot	Dry matter per hectare	Pasture nitrogen content	Pasture nitrogen yield
							Left	Top	Right	Bottom						
			(g)	(g)	(g)	(kg)	(cm)	(cm)	(cm)	(cm)	(cm^2)	(m^2)	(kg DM m^2)	(kg DM ha^{-1})	(%)	(kg N ha$^{-1)}$
1/03/2012	P2	5 week	195.8	35	160.8	0.161	100	100	100	100	10000	1.00	0.161	1608	3.01	48.44
1/03/2012	P4	5 week	215.3	35	180.3	0.180	100	100	100	100	10000	1.00	0.180	1803	3.07	55.36
1/03/2012	P5	5 week	178.1	35	143.1	0.143	100	100	100	100	10000	1.00	0.143	1431	2.96	42.34
1/03/2012	P9	5 week	211.1	35	176.1	0.176	100	100	100	100	10000	1.00	0.176	1761	3.10	54.65
1/03/2012	P10	5 week	204.3	35	169.3	0.169	100	100	100	100	10000	1.00	0.169	1693	2.91	49.25
1/03/2012	P12	5 week	173.5	35	138.5	0.138	100	100	100	100	10000	1.00	0.138	1385	3.02	41.77
Harvest date	Plot #	Treatment	Weight of dry matter + bag	Weight of bag	Weight of dry matter	Weight of dry matter	Length of pasture plot				Area of pasture plot	Area of pasture plot	Dry matter per area of pasture plot	Dry matter per hectare	Pasture nitrogen content	Pasture nitrogen yield
							Left	Top	Right	Bottom						
			(g)	(g)	(g)	(kg)	(cm)	(cm)	(cm)	(cm)	(cm^2)	(m^2)	(kg DM m^2)	(kg DM ha^{-1})	(%)	(kg N ha$^{-1)}$
13/04/2012	P1	10 week	259.6	35	224.6	0.225	100	100	100	100	10000	1.00	0.225	2246	2.58	57.88
13/04/2012	P2	5 week	156.7	35	121.7	0.122	100	100	100	100	10000	1.00	0.122	1217	2.82	34.36
13/04/2012	P3	10 week	242.1	35	207.1	0.207	100	100	100	100	10000	1.00	0.207	2071	2.91	60.18
13/04/2012	P4	5 week	160.8	35	125.8	0.126	100	100	100	100	10000	1.00	0.126	1258	2.76	34.72
13/04/2012	P5	5 week	162.6	35	127.6	0.128	100	100	100	100	10000	1.00	0.128	1276	2.80	35.74
13/04/2012	P6	10 week	193.0	35	158.0	0.158	100	100	100	100	10000	1.00	0.158	1580	2.59	41.01
13/04/2012	P7	10 week	223.2	35	188.2	0.188	100	100	100	100	10000	1.00	0.188	1882	2.66	49.99
13/04/2012	P8	10 week	222.2	35	187.2	0.187	100	100	100	100	10000	1.00	0.187	1872	2.68	50.22
13/04/2012	P9	5 week	152.6	35	117.6	0.118	100	100	100	100	10000	1.00	0.118	1176	3.05	35.90

13/04/2012	P10	5 week	137.4	35	102.4	0.102	100	100	100	100	10000	1.00	0.102	1024	2.80	28.64
13/04/2012	P11	10 week	265.4	35	230.4	0.230	100	100	100	100	10000	1.00	0.230	2304	2.69	62.00
13/04/2012	P12	5 week	143.1	35	108.1	0.108	100	100	100	100	10000	1.00	0.108	1081	2.89	31.25
Harvest date	**Plot #**	**Treatment**	**Weight of dry matter + bag**	**Weight of bag**	**Weight of dry matter**	**Weight of dry matter**	**Length of pasture plot**				**Area of pasture plot**	**Area of pasture plot**	**Dry matter per area of pasture plot**	**Dry matter per hectare**	**Pasture nitrogen content**	**Pasture nitrogen yield**
							Left	**Top**	**Right**	**Bottom**						
			(g)	**(g)**	**(g)**	**(kg)**	**(cm)**	**(cm)**	**(cm)**	**(cm)**	**(cm^2)**	**(m^2)**	**(kg DM m^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg N ha$^{-1)}$**
19/05/2012	P2	5 week	96.8	35	61.8	0.062	115	114	103	110	12208	1.22	0.051	506	3.43	17.35
19/05/2012	P4	5 week	128.6	35	93.6	0.094	112	110	106	113	12154	1.22	0.077	770	3.07	23.66
19/05/2012	P5	5 week	107.3	35	72.3	0.072	101	104	110	111	11341	1.13	0.064	637	3.30	21.02
19/05/2012	P9	5 week	132.4	35	97.4	0.097	100	117	116	110	12258	1.23	0.079	795	3.49	27.74
19/05/2012	P10	5 week	118.3	35	83.3	0.083	108	113	102	108	11603	1.16	0.072	718	3.48	24.99
19/05/2012	P12	5 week	155.9	35	120.9	0.121	105	107	111	103	11340	1.13	0.107	1066	3.38	36.09
Harvest date	**Plot #**	**Treatment**	**Weight of dry matter + bag**	**Weight of bag**	**Weight of dry matter**	**Weight of dry matter**	**Length of pasture plot**				**Area of pasture plot**	**Area of pasture plot**	**Dry matter per area of pasture plot**	**Dry matter per hectare**	**Pasture nitrogen content**	**Pasture nitrogen yield**
							Left	**Top**	**Right**	**Bottom**						
			(g)	**(g)**	**(g)**	**(kg)**	**(cm)**	**(cm)**	**(cm)**	**(cm)**	**(cm^2)**	**(m^2)**	**(kg DM m^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg N ha$^{-1)}$**
22/06/2012	P1	10 week	110.7	35	75.7	0.076	113	108	102	111	11771	1.18	0.089	891	2.68	23.85
22/06/2012	P2	5 week	69.6	35	34.6	0.035	101	108	103	104	10812	1.08	0.037	374	2.81	10.49
22/06/2012	P3	10 week	53.6	35	18.6	0.019	108	113	110	118	12590	1.26	0.023	234	2.67	6.26
22/06/2012	P4	5 week	181.2	35	146.2	0.146	111	116	112	118	13046	1.30	0.191	1908	2.93	55.95
22/06/2012	P5	5 week	59.9	35	24.9	0.025	109	103	111	103	11330	1.13	0.028	283	2.75	7.78
22/06/2012	P6	10 week	163.8	35	128.8	0.129	104	111	115	111	12155	1.22	0.157	1565	2.73	42.69
22/06/2012	P7	10 week	114.8	35	79.8	0.080	115	113	109	113	12656	1.27	0.101	1009	2.73	27.52
22/06/2012	P8	10 week	138.4	35	103.4	0.103	115	108	115	114	12765	1.28	0.132	1320	2.91	38.42
22/06/2012	P9	5 week	69.8	35	34.8	0.035	103	101	105	104	10660	1.07	0.037	370	3.05	11.31
22/06/2012	P10	5 week	65.8	35	30.8	0.031	100	105	105	106	10814	1.08	0.033	333	2.97	9.90

22/06/2012	P11	10 week	106.4	35	71.4	0.071	111	103	112	113	12042	1.20	0.086	860	2.97	25.58
22/06/2012	P12	5 week	48.0	35	13.0	0.013	103	106	102	106	10865	1.09	0.014	141	3.16	4.47
Harvest date	**Plot #**	**Treatment**	**Weight of dry matter + bag**	**Weight of bag**	**Weight of dry matter**	**Weight of dry matter**	**Length of pasture plot**				**Area of pasture plot**	**Area of pasture plot**	**Dry matter per area of pasture plot**	**Dry matter per hectare**	**Pasture nitrogen content**	**Pasture nitrogen yield**
							Left	**Top**	**Right**	**Bottom**						
			(g)	**(g)**	**(g)**	**(kg)**	**(cm)**	**(cm)**	**(cm)**	**(cm)**	**(cm^2)**	**(m^2)**	**(kg DM m^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg N ha$^{-1)}$**
2/08/2012	P2	5 week	52.5	35	17.5	0.017	107	108	110	106	11610	1.16	0.020	203	3.61	7.33
2/08/2012	P4	5 week	52.8	35	17.8	0.018	110	106	107	103	11338	1.13	0.020	202	3.60	7.29
2/08/2012	P5	5 week	51.0	35	16.0	0.016	107	104	108	104	11180	1.12	0.018	179	3.66	6.56
2/08/2012	P9	5 week	50.4	35	15.4	0.015	104	107	104	106	11076	1.11	0.017	171	3.66	6.26
2/08/2012	P10	5 week	46.9	35	11.9	0.012	111	104	110	103	11437	1.14	0.014	136	4.09	5.55
2/08/2012	P12	5 week	47.5	35	12.5	0.013	107	102	107	102	10914	1.09	0.014	137	3.72	5.08
Harvest date	**Plot #**	**Treatment**	**Weight of dry matter + bag**	**Weight of bag**	**Weight of dry matter**	**Weight of dry matter**	**Length of pasture plot**				**Area of pasture plot**	**Area of pasture plot**	**Dry matter per area of pasture plot**	**Dry matter per hectare**	**Pasture nitrogen content**	**Pasture nitrogen yield**
							Left	**Top**	**Right**	**Bottom**						
			(g)	**(g)**	**(g)**	**(kg)**	**(cm)**	**(cm)**	**(cm)**	**(cm)**	**(cm^2)**	**(m^2)**	**(kg DM m^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg N ha$^{-1)}$**
6/09/2012	P1	10 week	119.8	35	84.8	0.085	109	109	109	114	12154	1.22	0.070	698	3.66	25.56
6/09/2012	P2	5 week	92.8	35	57.8	0.058	105	102	111	109	11394	1.14	0.051	507	3.98	20.16
6/09/2012	P3	10 week	175.4	35	140.4	0.140	114	104	106	108	11660	1.17	0.120	1204	3.50	42.11
6/09/2012	P4	5 week	68.9	35	33.9	0.034	108	102	107	107	11234	1.12	0.030	302	3.87	11.67
6/09/2012	P5	5 week	87.2	35	52.2	0.052	111	111	112	110	12321	1.23	0.042	424	3.91	16.60
6/09/2012	P6	10 week	159.2	35	124.2	0.124	113	105	113	106	11922	1.19	0.104	1042	3.63	37.86
6/09/2012	P7	10 week	140.8	35	105.8	0.106	107	116	111	110	12317	1.23	0.086	859	3.54	30.42
6/09/2012	P8	10 week	132.0	35	97.0	0.097	106	100	105	104	10761	1.08	0.090	901	3.96	35.69
6/09/2012	P9	5 week	98.4	35	63.4	0.063	107	104	107	107	11289	1.13	0.056	562	3.89	21.89
6/09/2012	P10	5 week	97.4	35	62.4	0.062	104	107	106	107	11235	1.12	0.056	555	3.80	21.11
6/09/2012	P11	10 week	131.6	35	96.6	0.097	103	104	103	102	10609	1.06	0.091	910	3.92	35.67

6/09/2012	P12	5 week	121.0	35	86.0	0.086	105	106	109	108	11449	1.14	0.075	751	3.96	29.77

Harvest date	**Plot #**	**Treatment**	**Weight of dry matter + bag**	**Weight of bag**	**Weight of dry matter**	**Weight of dry matter**	**Length of pasture plot**				**Area of pasture plot**	**Area of pasture plot**	**Dry matter per area of pasture plot**	**Dry matter per hectare**	**Pasture nitrogen content**	**Pasture nitrogen yield**
							Left	**Top**	**Right**	**Bottom**						
			(g)	**(g)**	**(g)**	**(kg)**	**(cm)**	**(cm)**	**(cm)**	**(cm)**	**(cm^2)**	**(m^2)**	**(kg DM m^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg N $ha^{-1)}$**
11/10/2012	P2	5 week	190.9	35	155.9	0.156	108	108	110	104	11554	1.16	0.135	1349	3.64	49.07
11/10/2012	P4	5 week	227.1	35	192.1	0.192	106	102	110	104	11124	1.11	0.173	1727	3.13	54.01
11/10/2012	P5	5 week	192.0	35	157.0	0.157	106	118	113	109	12428	1.24	0.126	1263	3.46	43.71
11/10/2012	P9	5 week	162.3	35	127.3	0.127	103	111	105	112	11596	1.16	0.110	1097	3.47	38.04
11/10/2012	P10	5 week	197.8	35	162.8	0.163	110	109	108	107	11772	1.18	0.138	1383	3.33	46.12
11/10/2012	P12	5 week	226.4	35	191.4	0.191	109	116	106	110	12148	1.21	0.158	1576	3.51	55.35

Harvest date	**Plot #**	**Treatment**	**Weight of dry matter + bag**	**Weight of bag**	**Weight of dry matter**	**Weight of dry matter**	**Length of pasture plot**				**Area of pasture plot**	**Area of pasture plot**	**Dry matter per area of pasture plot**	**Dry matter per hectare**	**Pasture nitrogen content**	**Pasture nitrogen yield**
							Left	**Top**	**Right**	**Bottom**						
			(g)	**(g)**	**(g)**	**(kg)**	**(cm)**	**(cm)**	**(cm)**	**(cm)**	**(cm^2)**	**(m^2)**	**(kg DM m^2)**	**(kg DM ha^{-1})**	**(%)**	**(kg N $ha^{-1)}$**
15/11/2012	P1	10 week	384.4	35	349.4	0.349	111	101	109	105	11330	1.13	0.308	3084	2.17	66.85
15/11/2012	P2	5 week	298.5	70	228.5	0.228	103	111	109	104	11395	1.14	0.201	2005	2.64	52.92
15/11/2012	P3	10 week	531.4	35	496.4	0.496	104	109	104	115	11648	1.16	0.426	4262	1.93	82.33
15/11/2012	P4	5 week	247.4	35	212.4	0.212	97	108	98	110	10628	1.06	0.200	1999	2.36	47.25
15/11/2012	P5	5 week	286.3	35	251.3	0.251	108	105	109	103	11284	1.13	0.223	2227	2.94	65.37
15/11/2012	P6	10 week	428.5	35	393.5	0.393	103	107	112	115	11933	1.19	0.330	3297	2.19	72.34
15/11/2012	P7	10 week	402.9	35	367.9	0.368	111	104	110	100	11271	1.13	0.326	3264	2.01	65.74
15/11/2012	P8	10 week	391.8	35	356.8	0.357	103	96	107	107	10658	1.07	0.335	3348	2.59	86.58
15/11/2012	P9	5 week	274.2	35	239.2	0.239	105	109	109	107	11556	1.16	0.207	2070	2.52	52.12
15/11/2012	P10	5 week	200.3	35	165.3	0.165	91	96	97	103	9353	0.94	0.177	1767	2.41	42.53
15/11/2012	P11	10 week	424.3	35	389.3	0.389	106	104	110	107	11394	1.14	0.342	3417	2.39	81.77
15/11/2012	P12	5 week	254.7	35	219.7	0.220	94	99	94	100	9353	0.94	0.235	2349	2.54	59.56