Can Fertigation Increase Nitrogen Use Efficiency in NZ Dairy Pastures?

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Abstract of a Thesis submitted in partial fulfilment of the requirement for the degree of a Master of Agricultural Science

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From September 22nd 2019 - June 6th 2020, two field experiments were conducted on perennial ryegrass/white clover pastures within Lincoln University. Experiment 1 compared monthly application of urea (25 kgN/ha) in solution (fertigation) against the conventional/ recommended practice method of monthly 25 kgN/ha solid urea application with either immediate irrigation or irrigation applied after two days on production and quality of the pasture. This experiment aimed to determine if fertigation will increase nitrogen use efficiency (dry matter yield and nitrogen off taken relative to nitrogen input) when compared with the standard recommended dairy farm fertilisation methods. Experiment 2 tested the application timing of 25 kgN/ha/month of urea dissolved in water. The 25 kgN/ha was applied once per month or once per week (6.25 kgN/ha/week) to determine if smaller gaps between application timing increased nitrogen use efficiency. The two experiments had a zero-nitrogen control and were repeated across two field sites (autumn renewed pasture and permanent pasture).

In the initial and repeat experiment 1, application of N regardless of treatment gave similar yield and pasture quality (dry matter digestibility, metabolisable energy, crude protein and neutral detergent fibre) at all harvests throughout the growing season. In the initial and repeat experiment 2, application of N in solution once per month or once per week gave similar yield and pasture quality throughout the growing season. In the initial and repeat experiment 1 and the initial and repeat experiment 2, the control gave lower yields to the N application treatments at the first two harvests, but similar yields and quality to the N application treatments at all later harvests. It is concluded that fertigation, as defined here, produces similar yields and quality to the standard/recommended dairy farm fertilisation methods regardless of timing frequency within a month. Areas for further research are discussed.

Keywords: Irrigation, Lolium perrene, nitrogen, NUE, pasture composition, Perennial ryegrass, Trifolium repens, White clover.

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CHAPTER 1:
General Introduction

1.1 Background to Study

New Zealand agriculture is based around productive pasture-based systems for the export of primarily milk and meat products. Meat production contributes 10% of New Zealand's total exports while milk production contributes 30% (3% of global milk production) making dairy farming the largest contributor to New Zealand's export market (DairyNZ, 2018). The value of the dairy export market to the New Zealand economy has increased over the past few years, contributing $13.3 billion in 2016, $14.6 billion in 2017 and $16.7 billion in 2018 (DairyNZ, 2019). Within New Zealand, the main areas for dairy farming are in Taranaki, Waikato and Canterbury. Dairy farms in New Zealand are intensively grazed pasture systems with cows obtaining approximately 80% of their total annual intake from pasture, compared to the rest of the developed world that generally relies more heavily on cultivated crops and feedlots (Keller et al., 2014, Thorrold & Doyle, 2007). This makes high levels of pasture production the keystone of the New Zealand agricultural economy. Within the New Zealand dairy system, the primary species is the highly productive perennial ryegrass (*Lolium perenne)*. Often white clover (*Trifolium repens*) is sown with perennial ryegrass; however, white clover usually comprises <20% of total dry matter production over the growing season (Andrews et al., 2007, Chapman, Parsons & Schwinning, 1995). Other minor pasture species that are sometimes included within a perennial ryegrass dairy pasture sward are chicory (*Cichorium intybus*), narrow-leaf plantain (*Plantago lanceolata*) and lucerne (*Medicago sativa*) (Woodward et al., 2013, McCarthy et al., 2019).

The main limiting factors to dairy pasture production in New Zealand are nitrogen, under the assumption that other macro and micronutrients are already optimal, and water. However, total water and nitrogen requirements are dependent on soil type and climatic conditions/topographical location. Generally, dry matter production of perennial ryegrass based dairy pastures increases with nitrogen application (split application) up to a rate of 350-400 kgN/ha (Andrews et al., 2007, Ledgard et al., 2001). However, the addition of nitrogen fertiliser at rates above 200 kgN/ha linked to the associated higher stocking rate and supplementary irrigation (if required), results in high nitrogen losses to the environment (Cameron, Di & Moir 2013). Nitrogen in the form of nitrate (NO_3^-) in the soil above plant requirements or uptake capacity can have negative impacts on the environment (Cameron et al., 2013).

Nitrate has high soil mobility, making it readily available for plant uptake. However, it is also readily leached below the root zone as the soil becomes saturated, leading to eutrophication of waterways when combined with phosphorus runoff (Cameron et al., 2013). Additionally, increased pasture production is associated with increased nitrous oxide (N_2O) losses to the atmosphere and nitrogen applied to pasture without sufficient water to wash the nitrogen into the soil can be lost to the atmosphere from ammonia volatilisation (Cameron et al., 2013, Freney, 1997). Excessive irrigation can also increase erosion risk due to sediment loss, further contaminating waterways (Stockle, 2001). Because of the nitrogen losses to the environment associated with the addition of nitrogen fertiliser to pasture systems, legislation is being brought in to reduce the total amount of nitrogen lost from the system. Different areas in New Zealand have different limits of the amount of nitrogen lost to catchments and water sources based on water catchment location, annual rainfall and soil type (Glassey et al., 2013). Currently, the limitations on the use of nitrogen fertiliser in both organic (i.e. effluent application) and synthetic (primarily urea) forms are that effluent application on grazed pastures must not exceed the limit of 150 kgN/ha and nitrogen lost from below the root zone must fall within the regions acceptable range as determined by modelled data of Overseer version 6.2.3 (Waikato Regional Council, 2019). Additionally, the application of synthetic nitrogen fertiliser is to be restricted to 190 kgN/ha on grazed pastures from 2021 (MFE, 2020). To continue to have productive dairy farming systems under these nitrogen loss and application restrictions, the application and management of nitrogen on pastures must be adapted.

Cameron et al. (2013) stated that methods for lowering the amount of nitrogen lost from the system include adjusting nitrogen timing for greater plant uptake in anticipation of a feed deficit, adjusting irrigation timing to prevent nitrate loss from drainage, and split nitrogen applications to prevent applied nitrogen from exceeding maximum plant uptake. The current recommended practices for New Zealand dairy farms as practised on the Lincoln University dairy farm are the application of around 25 kgN/ha once per month (totalling 200 kgN/ha/ year) with irrigation of 6mm every 1-2 days as required during the season (September–May). Fertigation is a further possible strategy to reduce nitrogen losses to the environment while maintaining or increasing production. Fertigation is the application of nitrogen fertiliser in a soluble/dissolved form through an irrigation system. However, there is little research conducted on fertigation for dairy pastures around the world let alone in New Zealand.

1.2 Objectives of Study

From September 22nd 2019 - June 6th 2020, two field experiments were conducted on perennial ryegrass/white clover pastures within Lincoln University. Experiment 1 compared the monthly application of urea (25 kgN/ha) in solution (fertigation) against conventional/ recommended practice method of monthly 25 kgN/ha solid urea application with either immediate irrigation or irrigation applied after two days on production and quality of the pasture. This experiment aimed to determine if fertigation will increase nitrogen use efficiency (dry matter yield and nitrogen off taken relative to nitrogen input) when compared with the standard recommended dairy farm fertilisation methods. Experiment 2 tested the application timing of 25 kgN/ha/month of urea dissolved in water. The 25 kgN/ha was applied once per month or once per week (6.25 kgN/ha/week) to determine if smaller gaps between application timing increased nitrogen use efficiency. The two experiments had a zero-nitrogen control and were repeated across two field sites (autumn renewed pasture and permanent pasture).

CHAPTER 2

Review of the Literature

2.1 Plant requirements for growth

Vascular plants require water (H_2O) from the soil, carbon dioxide (CO_2) from the atmosphere, and light to produce carbohydrates (CH_2O), in a process called photosynthesis (Poorter & Nagel, 2000). Additionally, plants require sufficient space, soil/air temperature within a given range that is dependent on genotype, and at least 14 mineral nutrients from the soil to thrive (Marschner, 1995).

Light of wavelength 400-700nm is captured by the photosynthetic pigments (chlorophyll A, B and carotenoids) in the chloroplast to generate high energy compounds such as nicotinamide adenine dinucleotide phosphate and adenosine triphosphate (NADPH and ATP) from the oxidation of water (Zhu, Long & Ort 2008, Messel & Butler 1975). The NADPH and ATP are then used in the Calvin cycle to produce carbohydrates (Messel & Butler 1975). Approximately 90% of plants use the C_3 photosynthesis pathway, while the remainder uses the C_4 pathway or the modified C_4 crassulacean acid metabolism (CAM) pathway (Raghavendra, 2003). C_3 photosynthesis is made up of three phases, carboxylation, reduction and regeneration. Firstly, carbon dioxide is fixed to ribulose-1, 5-bisphosphate (RuBP) using the enzyme/catalyst Ribulose-1, 5-bisphosphate carboxylase/oxygenase (RuBisCO) to form two molecules of the three-carbon compound 3-phosphoglycerate (3-PGA) in the mesophyll cells of plant leaves (Raghavendra, 2003, Raines, 2011). In the second phase (reduction), 3-PGA is reduced to triose phosphate by the high energy compounds ATP and NADPH generated in the light reactions. Thirdly, the ribulose-1, 5-bisphosphate (RuBP) is regenerated from triose phosphate for the cycle to continue. The net cost of CO_2 fixation is two molecules of NADPH and three moles of ATP per CO_2 fixed (Raghavendra, 2003, Raines, 2011).

Water is required for nutrient uptake, maintaining cellular turgor and hence tissue expansion, maintaining stomatal conductance, cooling via evapotranspiration and metabolite transport in both the xylem and phloem (Cosgrove, 1993). Additionally, water is the medium in which almost all plant reactions take place. Generally, the optimum soil water level for crops is field capacity as it allows for oxygen to be present in the soils through macro-pores while providing sufficient water for plant growth (Brouwer, Goffeau & Heibloem, 1985). When soil water is not plant-available (water stress), the stomata close their guard cells to prevent water loss through evapotranspiration at the cost of lowering carbon fixation and increasing temperature stress (Chaves et al., 2002). Temperature directly influences plant growth rate and development, with the ideal temperature range dependent on plant species/genotype (Hatfield & Prueger, 2015). Generally, temperate plants have a lower optimum temperature range for growth and development than plants from tropical and subtropical regions (Hatfield & Prueger, 2015).

In addition to carbon, oxygen, and hydrogen, there are fourteen essential elements/nutrients required for plant growth and development that are obtained from the soil (Marschner, 1995). These elements split into two groups the soil-derived macro-nutrients nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg) and the soil-derived micro-nutrients boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn), with the total requirement of each element determined by plant species (White & Brown, 2010).

Nitrogen is the focus of this thesis and is a significant component of a range of essential plant molecules including amino acids and hence proteins and enzymes (e.g. RuBisCO), Deoxyribonucleic acid (DNA), Ribonucleic acid (RNA), the photosynthetic pigments chlorophyll A and B, the plant hormones (auxins and cytokinins), and multiple high energy metabolic compounds (e.g., ATP and NADPH) (Raven et al., 2004; Andrews et al., 2013). The total amount of nitrogen present within plants tissues ranges from 0.5% nitrogen in woody tissue of trees and around 6% nitrogen in legume leaf tissue (Mahler, 2004). The primary forms of nitrogen taken up by most plants are nitrate (NO_3^-) and ammonium (NH_4^+) which appear in the soil at different rates depending on the climatic conditions, and in nitrogen fertilised agricultural soils, the rate and form of nitrogen applied (Andrews et al., 2013). Around 70% of legumes and all actinorhizal plants can fix atmospheric nitrogen (N_2) via symbiotic bacteria (generally called rhizobia) (Andrews & Andrews, 2017).

2.2 Importance of nitrogen for pasture and milk production

From 1990 to 2015 New Zealand's total yearly application of nitrogen fertiliser increased from 59,000t to 429,000t with the dairy sector utilising 63% of New Zealand's total nitrogen fertiliser (Fertiliser association NZ, 2018, Stats NZ, 2019). Urea (46-0-0-0) is the most commonly applied nitrogen fertiliser to New Zealand pasture systems and contributes 84% (274,855t) of New Zealand's total nitrogen (325,754t) applied in 2017 (Stats NZ, 2019). Pasture production can be determined by total soil nitrogen availability when other nutrients are not limiting.

Data compiled by DairyNZ (2020) showed that pasture production ranged significantly from region to region when supplied with different rates of nitrogen fertiliser but increased substantially with additional nitrogen in all regions. Canterbury on average produced the greatest annual average pasture dry matter yield (16.3-21.7 tDM/ha) in New Zealand followed by Taranaki (14.2-17.1 tDM/ha) and Waikato (13.8-17.7 tDM/ha) (DairyNZ, 2020) when supplied with nitrogen fertiliser. The large increases in pasture production from added nitrogen fertiliser have increased the countrywide production of milk solids. From 1990 -2012, the total production of milk solids increased from 0.572 to 1.685 million tonnes due to the higher stocking rate that can be maintained on the increased levels of pasture production (LIC & DairyNZ, 2018, Harris et al., 1994).

In addition to dry matter produced, quality is also influenced by nitrogen applied. The important measurements for pasture quality are dry matter digestibility (DMD%), crude protein (CP), metabolisable energy (ME), organic matter digestibility (OMD), acid detergent fibre (ADF) and neutral detergent fibre (NDF). Dry matter digestibility is considered the most critical value in plant quality as it determines how much energy can be derived from the food before excretion (Ulyatt, 1981). Food that cannot be digested is classified as neutral detergent fibre content (NDF %), which is primarily made up of plant cell walls containing the slow-digesting complex carbohydrates cellulose, hemicellulose and lignin (Lambert & Litherland, 2000). The application of nitrogen fertiliser increases crude protein and metabolisable energy content of the pasture generally, leading to less dead material present, resulting in less neutral detergent fibre content. Neutral detergent fibre content is unfavourable in high quantities as it has less metabolisable energy content than carbohydrates and proteins (Lambert & Litherland, 2000).

2.3 Nitrogen related environmental impacts from New Zealand dairy pastures.

The addition of nitrogen fertiliser to perennial ryegrass dairy pastures results in increased dry matter production. Increased dry matter production allows a greater stocking rate and as a result, greater annual nitrogen excretion. It is the greater annual nitrogen excretion that is the primary reason for increased nitrogen loss from the pasture with increased nitrogen fertiliser. The amount of nitrogen lost from pasture is closely related to the amount of nitrogen cycling within the system (Andrews et al., 2007, Cameron et al., 2013, Moir, Cameron & Di 2016, Drymond et al., 2013).

The most renowned environmental impact in New Zealand from dairy farms is the eutrophication of the waterways by a combination of nitrogen (nitrate) leaching with phosphorus (phosphate) runoff. Nitrogen excretion and thus leaching is directly proportional to the amount of nitrogen taken in by diet with only 25% of nitrogen ingested by grazing animals used to produce meat or milk. The remaining nitrogen is excreted onto the pasture as primarily urinary urea in concentrated urine patches, but also dung (Calsamiglia et al., 2010, Moir, et al., 2016, Ledgard et al., 2009, Van Vuuren & Meijs, 1987) Cow Urine patches are the leading source of nitrate loss from pasture systems with urine patches having a nitrogen concentration ranging from 700-1400 kgN/ha (Haynes & Williams, 1993; Eckard, 2006; Di & Cameron, 2002) This quantity of nitrogen is far greater than the capacity for plant uptake and assimilation (Clough, 1994) with some leaching rates from irrigated dairy farms in Canterbury reaching 180 kgN/ha (Lilburne et al., 2010).

Additional nitrogen loss from pastures includes losses to the atmosphere via denitrification. Denitrification is the process of converting nitrates (NO_3^-) and nitrites (NO_2^-) into nitrous oxide (N_2O) and nitrogen gas (N_2). Nitrous oxide is a greenhouse gas that has a life span of 150 years in the atmosphere and has a potential effect on global warming 300 times greater than carbon dioxide (MFE, 2019). Nitrous oxide emissions contribute to 17% of New Zealand's total greenhouse gas emission compared with the rest of the world (10%) due to the prominence of the agricultural sector (De Klein & Ledgard, 2005). Barton et al.

(1999) reported from other studies (Ryden & Lund, 1980, Lowerance et al., 1998) that nitrogen fertilised irrigated pastures have the highest average denitrification rate of 113 kgN/ha/year (ranging from 49-239 kgN/ha), while unfertilised, non-irrigated pastures had the lowest average denitrification rate of 3.2 kgN/ha/year (range 0-17.4 kgN/ha).

2.4 Legislation related to nitrogen losses

Due to the environmental losses associated with the addition of nitrogen fertiliser to pasture systems, legislation is coming into effect to reduce the total amount of nitrogen lost from the system. Different areas in New Zealand have different limits of the amount of nitrogen lost to catchments and water sources based on water catchment location, annual rainfall and soil type (Glassey et al., 2013). Currently, the limitations on the use of nitrogen fertiliser in both organic (i.e. effluent application) and synthetic (urea, ammonium nitrate etc.) are the use of effluent application on grazed pastures must not exceed the limit of 150 kgN/ha/ year (Waikato Regional Council, 2015) and nitrogen lost from below the root zone must fall within the regions modelled data of Overseer version 6.2.3 found acceptable range.

Concerning human health, there is also legislation related to nitrate. To prevent blue baby syndrome (nitrate poisoning of bottle-fed infants), there is a limit for the amount of nitrate nitrogen (NO_3^--N) found in drinking water. The maximum acceptable value of water nitrate content is 50mg/L and 11.3mg/L for nitrate-nitrogen (ECan, 2020).

Currently, there is a law coming into effect on the Hinds Plains (Mid Canterbury) where nitrogen loss needs to be reduced by 15% by 2025, 25% by 2030 and 36% by 2035 with restrictions no longer applying after nitrogen losses are below 20 kgN/ha (ECan, 2018). To stay within restrictions on the use of nitrogen for pastures, nitrogen application and management must be adapted. Cameron et al. (2005) stated that methods for lowering the amount of nitrogen lost from the system include the alteration of nitrogen timing in anticipation of a feed deficit to have a greater plant uptake, adaptation of irrigation timing to prevent nitrate loss from drainage, and split nitrogen applications to prevent applied nitrogen from exceeding maximum plant uptake. The current recommended practices for a New Zealand dairy farm are the application of 25 kgN/ha once per month (totalling 200 kgN/ha/year) while irrigating 6mm every 1-2 days as required during the season (September–May).

2.5 Fertigation in New Zealand dairy systems

Fertigation is the process of applying liquid/dissolved fertiliser with irrigation water. The primary advantages of fertigation are the ability to maintain or increase the potential dry matter yield by smaller and more frequent fertiliser applications when required, the direct incorporation of nitrogen into the soil profile preventing ammonia volatilisation losses (fertigation lowers nitrogen retention time on the soil surface and prevents microsite alkalisation) and the possibility of maintaining a lower constant nutrient level in the soil solution to reduce nitrate leaching and maintain yield and quality (Black, Sherlock & Smith 1987, Cameron et al., 2013, Incrocci, Massa, & Pardossi, 2017). Fertigation originated in Israel in the 1960s and was developed to maximise nitrogen and water use efficiency in its arid climate. Currently, 80% of Israel's irrigated land uses fertigation (Imas, 2003). Fertigation is used most commonly through placement of drip lines alongside plant root systems as this minimises water loss through evaporation, and the addition of water and nutrients concentrate the roots around the emitter, allowing for greater plant uptake and reduced loss from the system. Currently, fertigation systems around the world are used for a wide variety of crops such as the fruit trees orange (*Citrus X sinensis*), grapefruit (*Citrus × paradise*), apple (*Malus domestica*), and peach (*Prunus persica*) in America, Israel, Canada, and France respectively and the field crops wheat (*Triticum aestivum*), sugarcane (*Saccharum officinarum*), corn (*Zea mays*) and peanuts (*Arachis hypogaea*) in Sweden, America, France and Israel respectively (Bar- Yosef, 1999). Additionally, Bar-Yosef (1999) referred to fertigation use in greenhouse crops like tomato (*Solanum lycopersicum*), lettuce (*Lactuca sativa*) and roses (*Rosa hybrida L.*) in Cyprus, Australia, Israel, the Netherlands and France.

Fertigation has received few trials in New Zealand and is not widely used. Haynes (1988) completed a fertigation study on drip fertigated sweet peppers (*Capsicum annuum L.*) finding low rates of nitrogen application (75 kgN/ha) favoured fertigation for fruit yields but using high nitrogen rates (150 kgN/ha) favoured broadcasted nitrogen application as the high nitrogen rates caused the emitter to block on the fertigation system. Marsh and

Stowell (1993) completed a three-year nitrogen and potassium fertigation trial on kiwifruit, applying 40% (63 kgN/ha & 118 kgK/ha) of the total applied nutrients (158 kgN/ha & 294 kgK/ha) in the form of fertigation while the remaining 60% was applied as solid fertiliser. In the second treatment, 100% of the nitrogen and potassium fertiliser was applied as a solid application. No significant difference in yield or leaf nutrient levels from fertigation was found when compared to conventional (solid) nitrogen applications. No published data were found on the effects of fertigation on yield or quality of New Zealand pastures or loss of nitrogen from the system.

2.6 Objectives of study

High-quality pastures contribute 85-90% of a cow's diet on New Zealand dairy farms allowing dairy production to become the largest contributor to New Zealand's export market. The pasture deficiencies that need to be applied in the greatest quantity are typically water (supplied through irrigation) and nitrogen (supplied through nitrogen fertiliser).

The problem with the addition of nitrogen fertiliser and irrigation is the increase in environmental nitrogen losses in particular into waterways (nitrate leaching) and to the atmosphere (nitrous oxide emission). Strategies are being considered to maintain/increase production by decreasing nitrogen losses. One possible strategy to increase the nitrogen use efficiency of perennial ryegrass/white clover pastures is the application of nitrogen fertiliser in irrigation water in a process called fertigation. However, there is little research conducted on fertigation for dairy pastures around the world let alone in New Zealand.

From September 22nd 2019 - June 6th 2020, two experiments were conducted at two field sites (autumn renewed pasture and permanent pasture) within Lincoln University. Experiment 1 compared the monthly application of urea fertiliser in solution (fertigation) on a perennial ryegrass/white clover pasture against conventional fertilisation methods of solid urea fertiliser broadcast applied then immediately irrigated and solid urea broadcast applied then irrigated two days after fertiliser application to simulate the maximum time duration for a centre pivots rotation. This experiment aimed to see if urea in solution (fertigation) increased nitrogen use efficiency (dry matter yield and nitrogen off taken relative to nitrogen input) when compared with standard dairy farm fertilisation methods (broadcast urea). Experiment 2 compared the application timing/frequency of urea dissolved in water applied once per month and once per week using an even application totalling 25 kgN/ha per month, to determine if smaller gaps between application timing (split application) using the same total nitrogen per month increased nitrogen use efficiency.

CHAPTER 3:

Does Fertigation Increase Nitrogen Use Efficiency of Perennial Ryegrass/White Clover Pastures?

3.1 Introduction

Dairy farms in New Zealand are intensively grazed pasture systems with cows obtaining approximately 80% of their total annual intake from pasture, compared to the rest of the developed world that generally relies more heavily on cultivated crops and feedlots (Keller et al., 2014, Thorrold & Doyle, 2007). Thus, high levels of pasture production are the keystone of the New Zealand agricultural economy. Within the New Zealand dairy system, the primary species is perennial ryegrass. White clover can input nitrogen into the pasture system via nitrogen fixation, but usually comprises <20% of total dry matter production over the growing season (Andrews et al., 2007, Harris & Clark 1996, Ledgard, 2001)

The main limiting factors to dairy pasture production in New Zealand are nitrogen, under the assumption that other macro and micronutrients are already optimal, and water. However, total water and nitrogen requirements are dependent on soil type and climatic conditions/ topographical location. Generally, dry matter production of perennial ryegrass based dairy pastures increases with nitrogen application (split application) up to a rate of 350-400 kgN/ ha (Andrews et al., 2007, Ledgard et al., 2001). However, the addition of nitrogen fertiliser at rates above 200 kgN/ ha linked to the associated higher stocking rate and supplementary irrigation (if required), results in high nitrogen losses to the environment (Andrews et al., 2007, Cameron, Di & Moir 2013).

The primary routes of nitrogen loss to the environment are nitrate leaching, nitrous oxide emissions and ammonia volatilisation. The high soil mobility of nitrate results in it being leached as the soil becomes saturated. When in combination with phosphorus runoff, nitrate leaching causes waterway eutrophication (Cameron et al., 2013). Increased pasture production is associated with increased nitrous oxide production, a potent greenhouse gas which has global warming potential approximately 300 times greater than carbon dioxide losses (MFE, 2019). Additionally, nitrogen can be lost from the soil surface through ammonia volatilisation by lack of irrigation within a short time of nitrogen application (Cameron et al., 2013, Freney, 1997). The current limitations for nitrogen use in grazed dairy pastures in New Zealand are a maximum application limit of 150 kgN/ha applied as effluent, and nitrogen lost below the root zone falling within the acceptable range of the modelled regional nitrogen loss data of Overseer version 6.2.3. A 190 kgN/ha limit of applied synthetic nitrogen fertiliser is also coming into effect in 2020 (MFE, 2020). Consequently, the application and management of nitrogen on pastures must be adapted. The current recommended practice for nitrogen application on New Zealand dairy farms is a monthly split application of nitrogen fertiliser over the eight-month growing season, totalling 200 kgN/ha/ year. Generally, irrigation is supplied within two days of nitrogen application (K. Cameron personal communication August 2nd, 2019). Cameron et al. (2005) listed the methods for lowering nitrogen losses from a pasture system as adjusting nitrogen timing in anticipation of a feed deficit, adjusting irrigation timing to prevent nitrate loss through drainage, and split nitrogen applications to prevent applied nitrogen from exceeding maximum plant uptake. All of these adjustments are possible through the use of fertigation.

From September 22nd 2019 - June 6th 2020, an experiment (experiment 1) was conducted across two field sites (autumn renewed pasture and permanent pasture) within Lincoln University. Experiment 1 compared the monthly application of urea (25 kgN/ha) in solution (fertigation), as solid granules/immediately irrigated and as solid granules irrigated two days after nitrogen application on production and quality of perennial ryegrass/ white clover pasture. The aim of this experiment was to determine if the application of urea in solution (fertigation) would increase nitrogen use efficiency when compared with standard dairy farm fertilisation methods.

3.2 Materials and methods

3.2.1 Trial sites and preparation

Experiment 1 and 2 were run in parallel. Experiment 1 was conducted from the 22nd of September 2019 to the 12th of June 2020 to compare the monthly application of urea fertiliser in solution (fertigation) on a perennial ryegrass/white clover pasture against the recommended dairy farm fertilisation methods of solid urea fertiliser application with either immediate irrigation or irrigation applied after two days. The experiment was conducted across two trial sites, the initial site, Iverson 13(S 43°38'54.42374" E 172°27'49.8191", permanent pasture) and the repeated site, H19 East (S 43°38'58.56212" E 172°27'40.03114", autumn-sown/direct drilled pasture). The soil type at both sites was a Templeton silt loam (immature pallic soil) with an average annual temperature of 11°C and rainfall of 630mm. Both pastures consisted of perennial ryegrass and white clover.

Plate 3-1 Iverson 13 Permanent Perennial Ryegrass/White Clover Pasture

Plate 3-2 H19 east autumn sown perennial ryegrass/white clover pasture.

3.2.2 Preparation and trial design

Before conducting the trial, a complete soil nutrient profile (0-75mm depth) was performed on the 22nd of August 2019 to determine the residual nutrients in the soil. The soil test was completed using a soil corer with a maximum depth of 75mm. Each sample was made up of 10 soil cores taken from the field and mixed together. A total of three samples were taken per field site.

Table 3-1 Results from soil nutrient test at both sites and the medium range nutrient level for the soil.

Soil nutrients tested	Iverson 13	H19 East	Medium range
Nitrogen (total nitrogen %)	0.33	0.2	0.30 - 0.60
Phosphorus (Olsen P)	45.3	9.0	20 -30
Potassium (me/100g)	1.6	0.4	0.30 - 0.60
Sulphur (Extractable Organic Sulphur mg/kg)	6.0	3.0	12- 20
Boron (mg/kg)	0.7	0.5	1.0 - 2.0
Cobalt (mg/kg)	1.5	0.8	2.0 - 4.0

It was determined that boron, cobalt, nitrogen and sulphur were deficient in the Iverson 13 plots while the H19 east plots were deficient in boron, cobalt, nitrogen, phosphorus and sulphur. To remedy these deficiencies fertiliser was applied at equivalent rates of 5kg/ha boron, 1 kg/ha cobalt and 130 kg/ha of Sulphurgain 30S (0-7-0-29.5) to the Iverson 13 site (site A) and 5 kg/ha boron, 1 kg/ha cobalt and 1000kg/ha Single Superphosphate (0-9-0-11) to the H19 east site (site B). These nutrients were mixed and applied through a chest-mounted fertiliser spreader on the 10th of October 2019. No phosphorus fertiliser additions were required for Iverson 13 probably due to its previous history as a pig farm 30 years ago. The recent history of both field sites is displayed in table 3-2.

Table 3-2 Fertiliser additions, pasture renewal and weed control prior to harvest past six years of Iverson 13 and H19 east.

Iverson 13

Date	Action	Rate
27/08/2014	Drilled arrow ryegrass + white clover.	20 kg/ha perennial ryegrass seed + 4 kg/ha white clover seed.
10/03/2015	Sprayed total area with Preside +	65grams/ha.
10/05/2019	Applied 30 units of N/ha.	75 kg/ha of product applied.
10/10/2019	Ballance fertiliser application.	130 kg/ha sulphur gain 30, 5kg/ha boron and 1kg/ha cobalt.

H19 East

Date	Action	Rate
29/09/2014	Drilled with Arrow ryegrass and Tribute white clover.	20 kg/ha perennial ryegrass seed + 5 kg/ha white clover seed.
7/12/2016	Cropmaster fertiliser applied.	200 kg/ha.
11/12/2018	Sprayed with Weedmaster 540.	2 litres/ha.
25/01/2019	Sprayed with Weedmaster 540.	2 litres/ha.
1/04/2019	Ryegrass clover mix drilled with Fiona drill.	25 kg/ha.
30/07/2019	Sprayed with Pulsar mixed with uptake oil.	Pulsar 5L/ha+ uptake oil 1L.
10/10/2019	Ballance fertiliser application.	1000kg/ha sulphur superphosphate, 5kg/ha boron and1kg/ha cobalt.

The trial area for experiment 1 was broken into 24 6x2m plots in a completely randomised block design. Experiment 1 had 0.5m buffer strips between each of the plots and 0.5 buffer strips on the trial border. Each of the trial plots was mown to give a uniform pasture height (3cm) before the fertiliser treatments application on the 22nd of September 2019. The trial pastures were harvested approximately every 30 days, depending on the weather conditions and technician availability to simulate a monthly grazing pattern.

Plate 3-3 H19 east on the day the trial started (22nd of September 2019).

3.2.3 Irrigation determination

Two different methods determined the irrigation requirements. Primarily the digital output from an Aquaflex probe (Onfarm data) measuring to 400mm soil depth in site 1 (Iverson 13) was used. However, additional climate data from the Lincoln FRC climate station, measuring rainfall and potential evapotranspiration (PET) was used for confirmation. Irrigation was applied when the moisture probe output displayed a soil moisture deficit below field capacity of 6mm or greater. However, irrigation timing was dependent on the current climatic conditions (wind speed) and weather forecast (incoming precipitation). Irrigation was supplied through a lateral pipe irrigation system (plate 3-5).

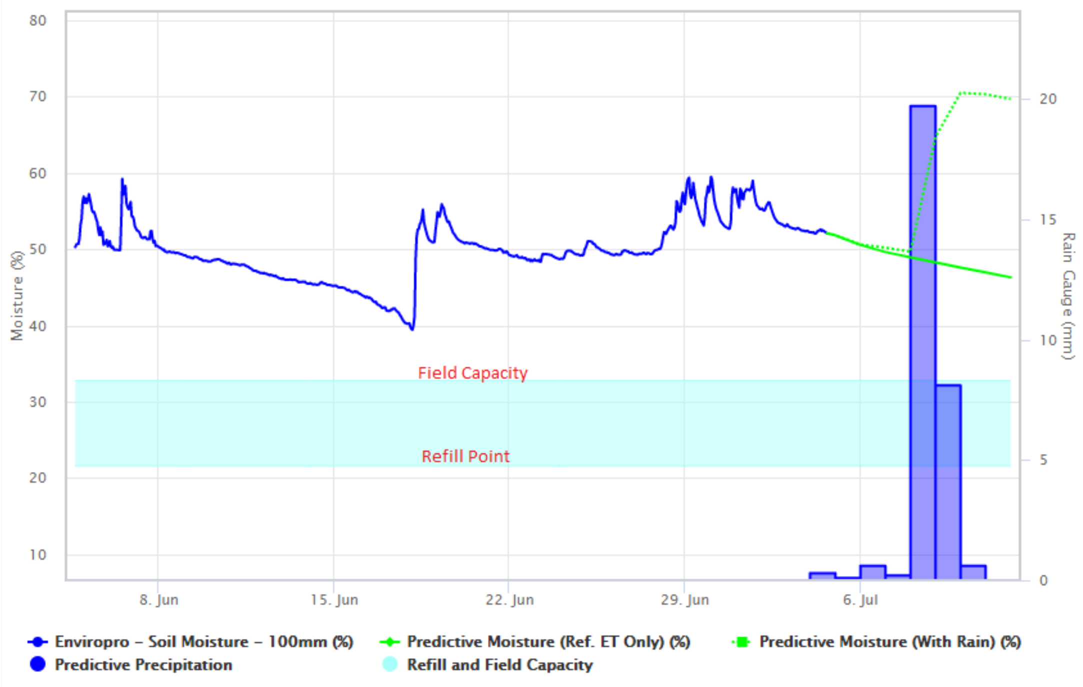

Plate 3-4 An example of the Aquaflex Onfarm data moisture probe's digital output displaying soil moisture, predictive rainfall refill point and field capacity. Field capacity and refill point are written in red for clarification.

Plate 3-5 Lateral irrigation system in the repeated site, H19 East (autumn sown pasture).

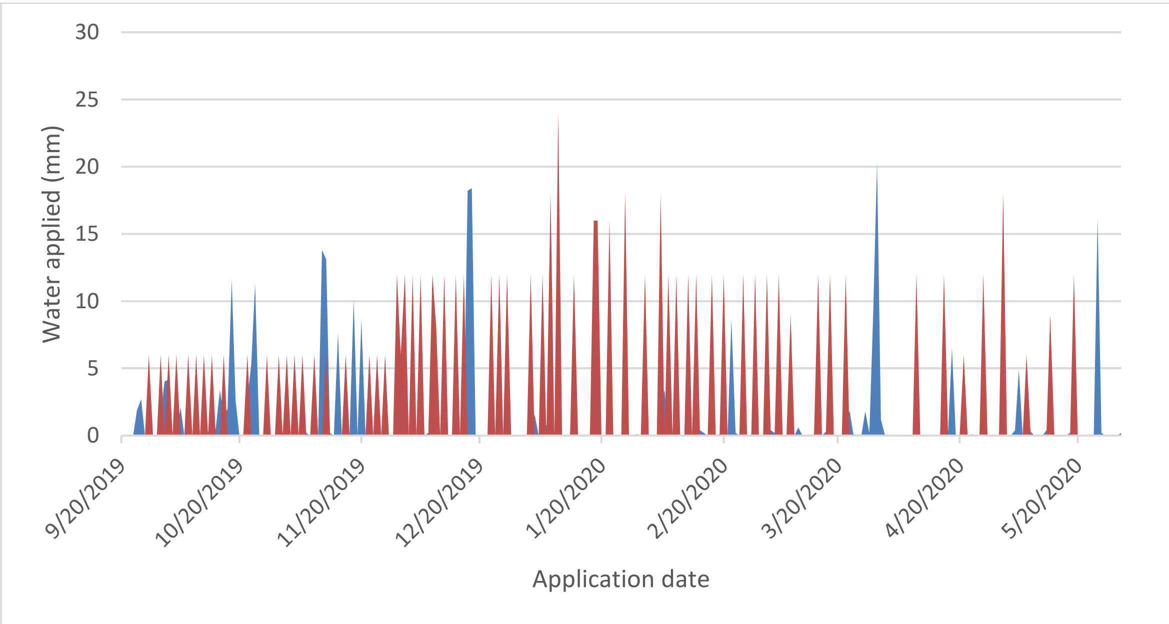

Figure 3-1 Total Rainfall (blue) and Irrigation (red) in millimetres (mm) at both trial sites for the duration of the fertigation trial (22/09/2019- 12/06/2020).

3.2.4 Climatic data

Table 3-3 40-year average rainfall compared to the fertigation trial.

Month	40-year Mean Rainfall (mm)	Fertigation Project Rainfall (mm)
Sep	40.4	31.1
Oct	51.7	52.4
Nov	48.8	54.8
Dec	53.0	37.7
Jan	43.8	6.7
Feb	41.1	17.9
Mar	50.8	36.1
Apr	51.6	6.9
May	56.9	22.8
Total	438.0	266.4

The 40-year rainfall mean was compared with the rainfall mean of the duration of the fertigation project. However, because the use of irrigation corrected moisture deficiency for the trial, it is not applicable unless drought prevented irrigation from occurring from water use restrictions.

Table 3-4 Soil temperature (10cm depth) January 2002 - May 2020 average compared with this fertigation trial (2019-2020). To correspond with the trial finishing on the 12th of June 2020, the average soil temperature for June would be 7.4 °C.

Month	18-year mean soil temperature at 10cm depth (°C)	2019-2020 soil temperature 10cm depth (°C)
Sep	9.7	9.8
Oct	12.4	12.2
Nov	15.9	15.9
Dec	18.2	17.3
Jan	19.8	19.8
Feb	19.0	19.4
Mar	16.3	15.8
Apr	12.5	13.1
May	9.4	9.8
Jun	6.3	7.8

The soil temperature of the fertigation trial was similar to the 18-year mean. Thus, indicating that growing conditions would also be similar.

3.2.5 Trial design and set up

The trial area for experiment 1 was broken into 24 6x2m plots at two field sites in a completely randomised block design. The three nitrogen treatments consisted of 25 kgN/ha of nitrogen (urea, 46-0-0-0) mixed evenly with 6L of water and applied as a solution (*aq*) through a watering can once per month onto the pasture in a single application (Dissolved urea/immediately irrigated, L25 kg), 25 kgN/ha of nitrogen in the form of solid urea granules applied to the pasture once per month and immediately irrigated to wash the nutrients into the root zone (Solid urea/ immediately irrigated, S25 kg) and 25 kgN/ha of nitrogen in the form of solid urea granules applied to pasture once per month after the irrigation water of the dissolved urea / immediately irrigated and Solid urea/ immediately irrigated treatments had soaked into the soil. Irrigation was then supplied after a two-day gap to simulate the maximum amount of time that a high production dairy farm would have between irrigation events (Solid urea/ irrigated two days after application, D25 kg). Additionally, there was a no-nitrogen control treatment receiving only irrigation (Control). Irrigation events occurred simultaneously, with all treatments receiving the same total irrigation at the same time based on the soil water deficit, ensuring there was no plant experiencing a water deficit regardless of treatment.

Table 3-5 The complete randomized block design of Experiment 1a (initial site) and 1b (repeated site). Each plot was 6x2m with 0.5m buffer strips separating the plots.

1a

L25 kg	S25 kg	Control	D25 kg
D25 kg	L25 kg	S25 kg	Control
Control	D25 kg	L25 kg	S25 kg
S25 kg	Control	L25 kg	D25 kg
Control	L25 kg	D25 kg	S25 kg
S25 kg	L25 kg	Control	D25 kg

1b

L25 kg	S25 kg	Control	D25 kg
D25 kg	L25 kg	Control	S25 kg
Control	S25 kg	D25 kg	L25 kg
S25 kg	L25 kg	Control	D25 kg
D25 kg	Control	S25 kg	L25 kg
S25 kg	D25 kg	L25 kg	Control

3.2.6 Pasture composition and quality measurements.

Pasture quality and production were measured at each harvest for both experiments. Fresh weight bulk was determined by mowing a 6-meter central strip with a mower 600mm wide to a residual height of 3cm. The samples were weighed for fresh weight, then a sub-sample of 200g was taken to be dried at 60°C until the sample reached a constant weight to measure dry matter production, quality and change in moisture percentage. The dried sub-sample was ground using a Retsch ZM 200 grinder (Retsch, Germany) complete with a 2mm sieve to allow for uniform small particle size for analysis. The samples were scanned using near-infrared spectroscopy (NIRS; FOSS NIRSystems 5000, FOSS NIRSystems Inc., Laurel, MD, USA) at the Lincoln University Analytical Laboratory to determine crude protein (CP %) dry matter digestibility (DMD %), metabolisable energy (MJME/kgDM) and neutral detergent fibre (NDF). After NIR analysis, the samples were sent away for total pasture nitrogen analysis.

Using an electric shearing handpiece, additional cuts were made as to obtain representative samples from within a 1018cm^2 quadrat (cut to 3cm residual) for harvests one, four, five and six. Each of the samples cut by the handpiece were sorted into the grass, clover and weeds components then dried to a constant weight to determine the clover percentage (%) by weight. Nitrogen and NIR analysis were not conducted on the additional clover percentage cuts.

3.2.7 Statistical analysis

Statistical analysis was carried out on SPSS 26 using a one-way analysis of variance (ANOVA) to determine if the nitrogen treatments (fixed variable) had an effect on the response/dependent variables: dry matter production (kgDM/ha), pasture moisture percentage, crude protein (CP %), neutral detergent fibre content (NDF %), dry matter digestibility (DMD %), metabolisable energy (MJME/kgDM), clover percentage (clover %) and pasture nitrogen (N %). Where appropriate, a Tukey test was used to separate means. The standard error of the mean (SEM) values shown in figures was derived from the ANOVA.

3.3 Results

3.3.1 Experiment 1 site A, permanent pasture.

3.3.1.1 Dry matter production and moisture content

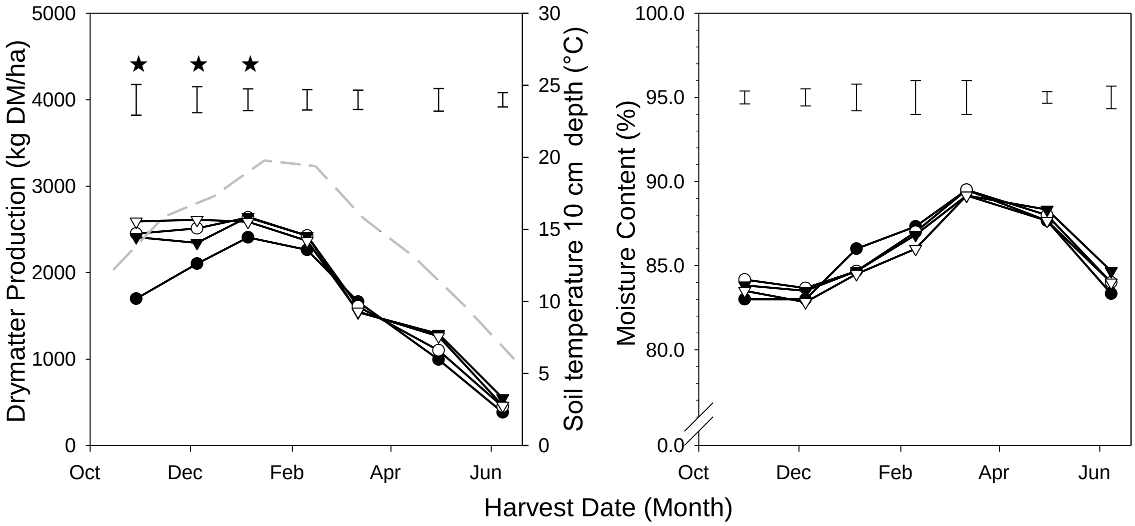

Figure 3-2 Dry matter production and moisture content over seven harvests of perennial ryegrass/white clover pasture at Lincoln University New Zealand with four treatments: no nitrogen control (●), Solid urea applied and irrigated two days after application (○) dissolved urea applied with immediate irrigation (▼), Solid urea applied with immediate irrigation (▽). Error bars are the standard error of the mean from each harvest. The grey dashed line displays the average soil temperature at 10 cm depth each month of the growing season. <u>A star (★) above the error bar signifies a significant difference between the control and all nitrogen treatments.</u>

Dry matter production for the three-plus nitrogen treatments (solid urea/irrigated two days later; dissolved urea/immediate irrigation; solid urea/immediate irrigation) changed little (~2500 kg/ha) for the first four harvests then decreased with each harvest thereafter to around 460 kg/ha at harvest 7 (Figure 3-2). The figure of dry matter production over time showed a similar shape to that of the average soil temperature (10cm depth) over time (Figure 3-2). Dry matter production was similar (not significantly different) for the three-plus nitrogen treatments at all harvests. As shown by the stars above the error bars the control treatment produced significantly less dry matter than the nitrogen treatments at harvest one (p=0.000), two (p=0.17) and three (p=0.034) by 32%, 17% and 8%

respectively, otherwise, there was no significant difference across treatments. For all treatments, moisture percentage was similar for the first two harvests, increased from harvest two to five then decreased from harvest five to seven with values between 84% and 89% for all seven harvests (Figure 3.2). There was no significant difference in moisture percentage found between the treatments.

3.3.1.2 Dry matter digestibility and metabolisable energy

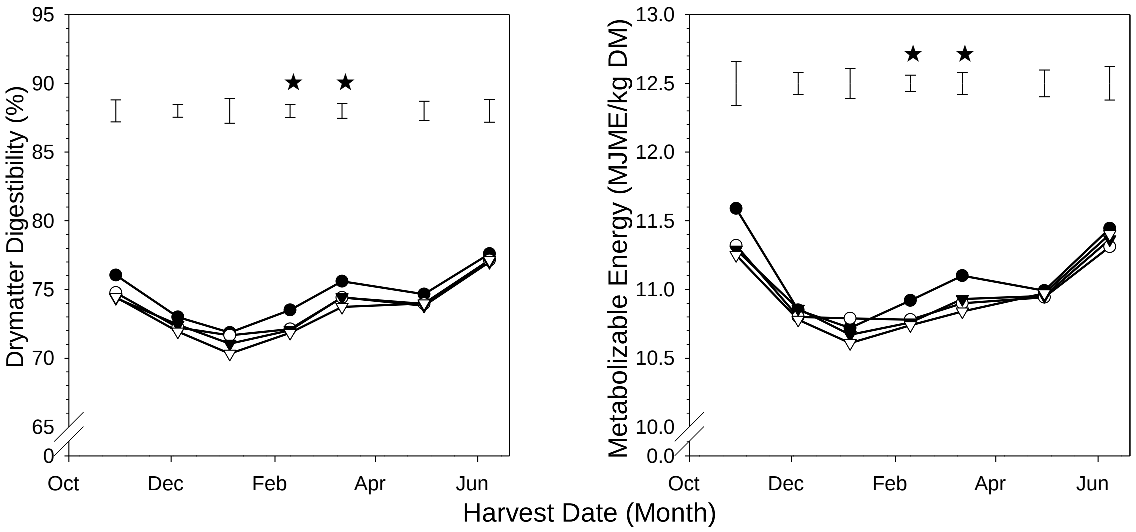

Figure 3-3 Dry matter Digestibility and Metabolisable energy over seven harvests of perennial ryegrass/white clover pasture at Lincoln University, New Zealand with four treatments: no nitrogen control (●), Solid urea applied and irrigated two days after application (○) dissolved urea applied with immediate irrigation (▼), Solid urea applied with immediate irrigation (∇). Error bars are the standard error of the mean from each harvest. <u>A star (★) above the error bar signifies a significant difference between the control and all nitrogen treatments.</u>

For the three-plus nitrogen treatments, dry matter digestibility values were similar at all harvests and decreased from around 75% at harvest one to around 71% at harvest three before increasing steadily to the final value of approximately 77% at harvest seven (Figure 3-3). The control treatments produced significantly greater dry matter digestibility than the nitrogen treatments at harvest four (p=0.009) and five (p=0.19). Otherwise, there was no significant difference in dry matter digestibility between treatments. In harvest one, metabolisable energy for the control treatment (11.6 MJME/kgDM) was not significantly greater than the other nitrogen treatments (11.3 MJME/ kgDM). For the three-plus nitrogen treatments, metabolisable energy values were similar at all harvests and decreased from harvest one (11.4 MJME/ kgDM) to harvest three (10.7 MJME/ kgDM) before increasing steadily to the final harvest (11.4 MJME/ kgDM). Metabolisable energy and dry matter digestibility followed the same trend over the seven harvests with the same harvests showing a significant difference between the control and the nitrogen treatments. The control treatments produced significantly greater metabolisable energy than the nitrogen treatments for harvest four (p=0.029) and harvest five (p=0.019).

3.3.1.3 Crude protein and neutral detergent fibre

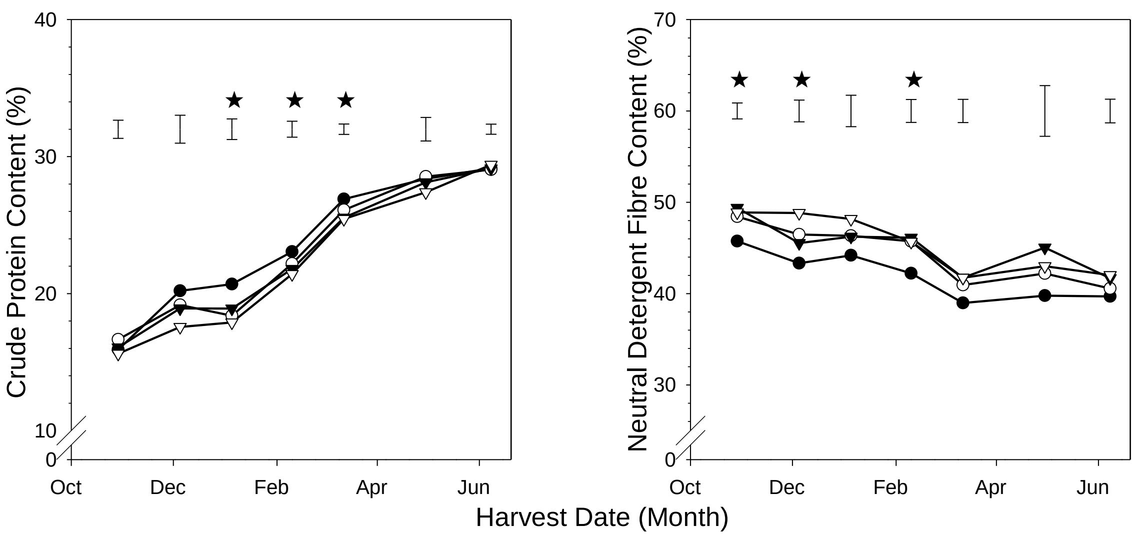

Figure 3-4 Crude protein content and neutral detergent fibre content over seven harvests of perennial ryegrass/white clover pastures at Lincoln University, New Zealand with four treatments: no nitrogen control (●), Solid urea applied and irrigated two days after application (○) dissolved urea applied with immediate irrigation (▼), Solid urea applied with immediate irrigation (▽). Error bars are the standard error of the mean from each harvest. <u>A star (★) above the error bar signifies a significant difference between the control and all nitrogen treatments.</u>

Values for crude protein were similar for all three plus nitrogen treatments at all harvests. For all treatments, crude protein content increased over the seven harvests from an initial value of around 16% to approximately 29% at harvest seven (Figure 3-4). The control treatments produced significantly greater crude protein than the nitrogen treatments in harvest three (p=0.008), four (p=0.006) and five (p=0.004) with the control treatment producing 12.5%, 5.7% and 4.7% greater crude protein than the nitrogen treatments respectively. Generally, the neutral detergent fibre content of the pasture was not significantly different for the three-plus nitrogen treatments and decreased with each subsequent harvest from one to seven (Figure 3-4). Neutral detergent fibre content among the three-plus nitrogen treatments averaged at 49% at harvest one and steadily decreased to around 41% at harvests five to seven. The control treatments produced significantly less neutral detergent fibre content than the three nitrogen treatments at harvest one (p=0.002), two (p=0.002) and four (p=0.018).

3.3.1.4 Pasture nitrogen percentage.

Table 3-6 Nitrogen percentage over three harvests of perennial ryegrass/white clover pasture with three nitrogen treatments (Solid urea applied and irrigated two days after application, dissolved urea applied with immediate irrigation, Solid urea applied with immediate irrigation) and one control treatment. Different letters indicate a significant difference between the two treatments at P <0.05.

Treatment	Harvest 4 (10/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	3.58^{a}	4.18^{a}	4.37^{a}
Solid urea / irrigated two days after application	3.35^{ab}	4.082^{a}	4.33^{a}
Dissolved urea / immediately irrigated	3.28^{b}	3.99^{a}	4.17^{a}
Solid urea/ immediately irrigated	3.20^{b}	3.97^{a}	4.19^{a}
SEM	0.093	0.096	0.17

Nitrogen percentage in the pasture increased with each harvest, averaging around 3.4%N, 4.0%N and 4.3%N in harvests four, five and six, respectively (Table 3.6). At harvest four, the pasture nitrogen percentage was significantly greater in the control treatment (p=0.004) than in the dissolved urea/immediately irrigated and the solid urea/immediately irrigated treatment. There was no significant difference in pasture nitrogen percentage across the treatments in harvests four, five or six.

3.3.1.5 Clover percentage

Table 3-7 Clover percentage (%) over four harvests of perennial ryegrass/white clover pastures with three nitrogen treatments: Solid urea applied and irrigated two days after application dissolved urea applied with immediate irrigation, Solid urea applied with immediate irrigation and one control treatment. Different letters indicate a significant difference between the two treatments at P <0.05.

Treatment	Harvest 1 (29/10/2019)	Harvest 4 (4/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	26.0[a]	74.6[a]	70.3[a]	54.2[a]
Solid urea / irrigated two days after application	9.3[a]			
Dissolved urea / immediately irrigated	13.7[a]	64.9[a]	64.7[a]	35.7[b]
Solid urea/ immediately irrigated	12.8[a]			
SEM	9.9	3.7	5.4	4.9

The clover percentage was lowest in the control and dissolved urea immediately irrigated treatments at harvest one and its maximum at harvest four and five before decreasing in harvest six. The control treatment consistently had a greater clover percentage when compared with the dissolved urea/immediately irrigated treatment. However, it only reached statistical significance (p=0.024) at harvest six.

3.3.2 Experiment 1 site B autumn sown pasture

3.3.2.1 Dry matter production and moisture content

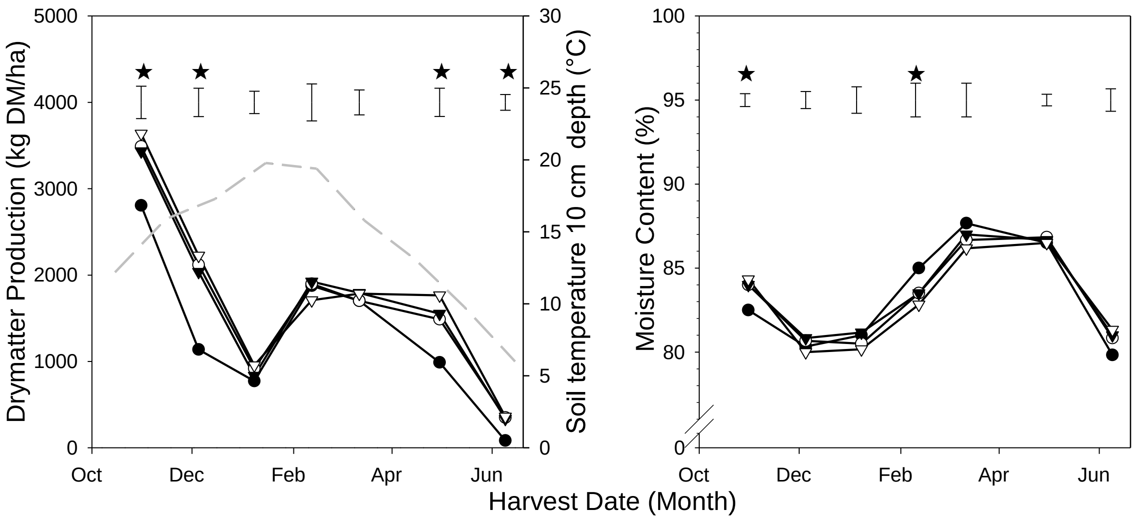

Figure 3-5 Dry matter production and moisture content over seven harvests of perennial ryegrass/white clover pasture at Lincoln University New Zealand with four treatments: no nitrogen control (●), Solid urea applied and irrigated two days after application (○) dissolved urea applied with immediate irrigation (▼), Solid urea applied with immediate irrigation (▽). Error bars are the standard error of the mean from each harvest. The grey dashed line displays the average soil temperature at 10 cm depth each month of the growing season. A star (★) above the error bar signifies a significant difference between the control and all nitrogen treatments.

As in Experiment 1 at site A, dry matter production in Experiment 1 at site B did not differ across the three-plus nitrogen treatments (Figure 3-5). Dry matter production was greatest at harvest one at ~3500 kgDM/ha for the three-plus nitrogen treatments and ~3000 kgDM/ha for the control (Figure 3-5). From harvest one to three, there was a sharp decline in dry matter production to around 870 kg/ha at harvest three (all treatments). Dry matter production (all treatments) then increased to approximately 1850 kgDM/ha at harvest four before decreasing to 350 kgDM/ha at harvest seven (Figure 3-5). The control treatment produced significantly less dry matter than the nitrogen treatments at harvest one (p=0.001), two (p=0.000) six (P=0.001) and seven (p=0.018).

For the three-plus nitrogen treatments, moisture percentage values were similar at all harvests and decreased from 84% at harvest one to around 80% for harvests two and three;

increased to around 87% for harvests five and six then decreased to 80% plant moisture content at harvest seven. The control treatment had a lower moisture content than the nitrogen treatments at harvest one (p=0.001) but a greater moisture percentage than the three-plus nitrogen treatments at harvest four (p=0.056).

3.3.2.2 Dry matter digestibility and metabolisable energy

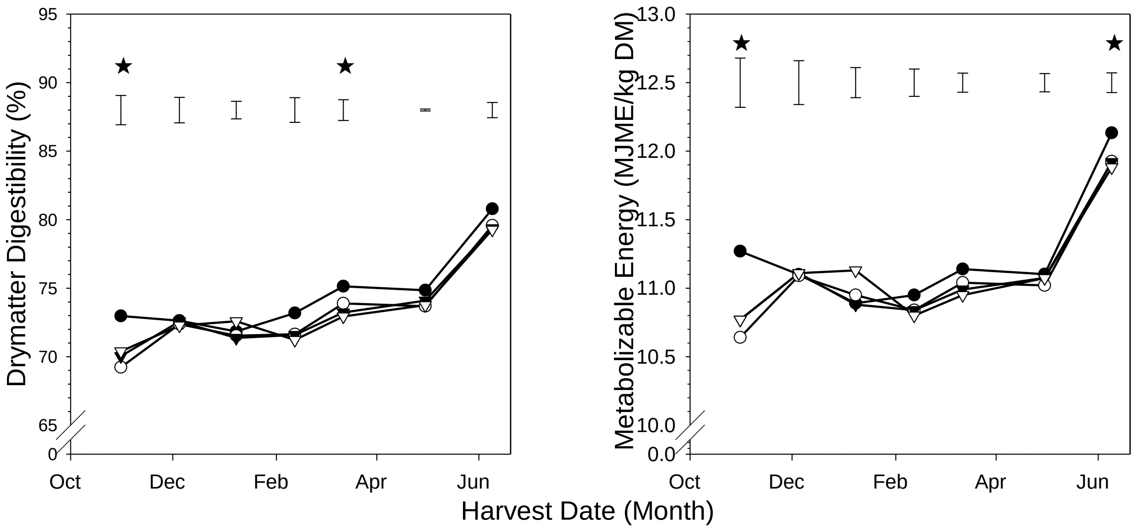

Figure 3-6 Dry matter Digestibility and Metabolisable energy over seven harvests of perennial ryegrass/white clover pasture at Lincoln University, New Zealand with four treatments: no nitrogen control (●), Solid urea applied and irrigated two days after application (○) dissolved urea applied with immediate irrigation (▼), Solid urea applied with immediate irrigation (∇). Error bars are the standard error of the mean from each harvest. <u>A star (★) above the error bar signifies a significant difference between the control and all nitrogen treatments.</u>

As in Experiment 1 at site A, dry matter digestibility and metabolisable energy (Figure 3.6) plus crude protein and neutral detergent fibre (Figure 3.7) in experiment 1 site B were not significantly different across the three-plus nitrogen treatments. Generally, for the three-plus nitrogen treatments, dry matter digestibility, metabolisable energy and crude protein increased with harvest throughout the season while the neutral detergent fibre decreased (Figures 3-6, 3-7). The control treatment gave significantly higher dry matter digestibility than the three-plus nitrogen treatments at harvests one (p=0.013) and five (p=0.042), significantly higher metabolisable energy at harvest one (p=0.01), significantly higher crude protein at harvests five (p=0.047) and six (P=0.025) but lower neutral detergent fibre content at harvest one (P=0.02), four (p=0.016), five (p=0.01) six (p=0.023) (Figures 3-6, 3-7).

3.3.2.3 Crude protein and neutral detergent fibre

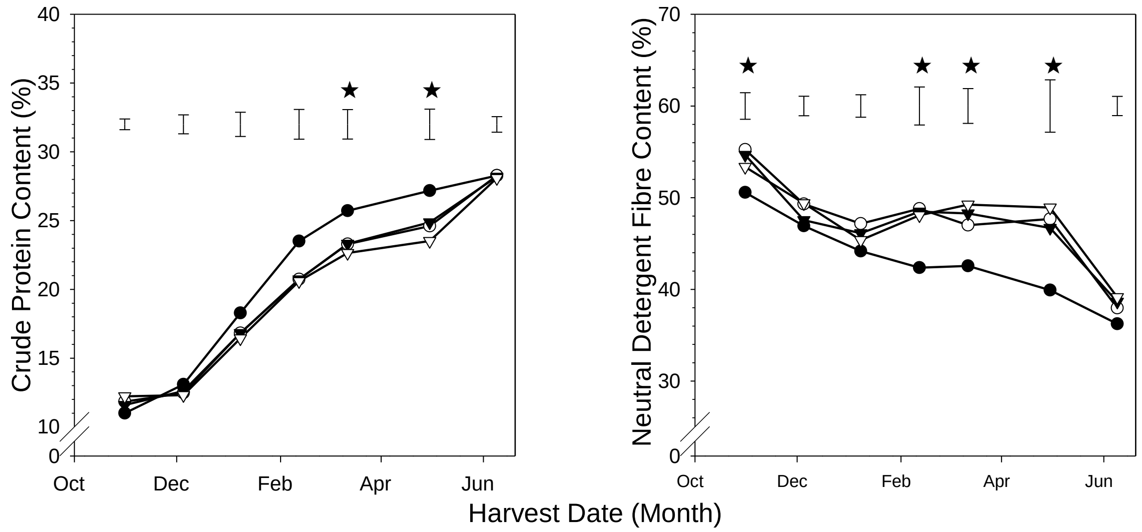

Figure 3-7 Crude protein content and Neutral detergent fibre content over seven harvests of perennial ryegrass/white clover pastures at Lincoln University New Zealand with four treatments: no nitrogen control (●), Solid urea applied and irrigated two days after application (○) dissolved urea applied with immediate irrigation (▼), Solid urea applied with immediate irrigation (▽). Error bars are the standard error of the mean from each harvest. A star (★) above the error bar signifies a significant difference between the control and all nitrogen treatments.

3.3.2.4 *Nitrogen percentage.*

Table 3-8 Nitrogen percentage over three harvests of perennial ryegrass/white clover pasture with three nitrogen treatments (Solid urea applied and irrigated two days after application, dissolved urea applied with immediate irrigation, Solid urea applied with immediate irrigation) and one control treatment. Different letters indicate a significant difference between the two treatments at P <0.05.

Treatment	Harvest 4 (10/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	3.5^{a}	3.86^{a}	4.073^{a}
Solid urea / irrigated two days after application	3.03^{b}	3.43^{a}	3.64^{ab}
Dissolved urea / immediately irrigated	3.0^{b}	3.47^{a}	3.71^{ab}
Solid urea/ immediately irrigated	3.0^{b}	3.31^{a}	3.47^{b}
SEM	0.17	0.2	0.19

Pasture nitrogen percentage was not significantly different for the three-plus nitrogen treatments at all harvests and increased from around 3%N at harvest four to around 3.6% at harvest six. The control treatment had significantly greater pasture nitrogen percentage than the nitrogen treatments at harvest four (p=0.011).

3.3.2.5 *Clover percentage*

Table 3-9 Clover percentage over four harvests of perennial ryegrass/white clover pastures with three nitrogen treatments (Solid urea applied and irrigated two days after application, dissolved urea applied with immediate irrigation, Solid urea applied with immediate irrigation) and one control treatment. Different letters indicate a significant difference between the two treatments at P <0.05.

Treatments	Harvest 1 (31/10/2019)	Harvest 4 (10/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	2.2^{a}	66.4^{a}	65.0^{a}	73.9^{a}
Solid urea / irrigated two days after application	1.2^{a}			
Dissolved urea / immediately irrigated	0.7^{a}	39.1^{b}	31.2^{b}	42.0^{b}
Solid urea/ immediately irrigated	2.0^{a}			
SEM	1.4	5.4	5.6	12.4

The clover percentage was lowest for the control and dissolved urea/immediately irrigated treatments at harvest one and increased with each subsequent harvest to harvest six. The control treatment consistently had a greater clover percentage when compared with the dissolved urea/immediately irrigated treatment either significantly (harvest four, p=0.007, five, p=0.008, and six, p=0.002) or non-significantly (harvest 1).

3.4 Discussion

Generally, dairy farms in New Zealand are intensively grazed perennial ryegrass/white clover pasture systems with cows obtaining approximately 80% of their total annual intake from pasture. White clover can input nitrogen into the pasture system via nitrogen fixation, but it usually comprises <20% of total dry matter production over the growing season and perennial ryegrass/white clover swards are nitrogen-limited (Andrews et al., 2007, Harris & Clark 1996, Ledgard, 2001). Nitrogen and water are the main limiting factors to dairy pasture production in New Zealand under the assumption that other macro and micronutrients are already optimal. Generally, dry matter production of perennial ryegrass based dairy pastures increases with nitrogen application (split application) up to a rate of 350-400 kgN/ ha. However, the addition of nitrogen fertiliser at rates above 200 kgN/ha linked to the associated higher stocking rate and supplementary irrigation (if required), results in high nitrogen losses to the environment through nitrate leaching, nitrous oxide emissions and ammonia volatilisation (Andrews et al., 2007, Cameron et al., 2013). Because of this, limitations on nitrogen input into perennial ryegrass have been set.

As of 2021 grazed pastures will be limited to a total application of 190kgN/ha/year of synthetic fertiliser and a maximum effluent application limit of 150kgN/ha/year, but this is region dependent as nitrogen lost below the root zone cannot exceed the regional limit as determined by Overseer version 6.2.3 (Glassey et al., 2013, MFE, 2020 Waikato regional council, 2015). The current recommended practice for nitrogen application on New Zealand dairy farms is a monthly split application of nitrogen fertiliser over the eight-month growing season, totalling 200 kgN/ha/year. Generally, irrigation is supplied within two days of nitrogen application. Thus, the application and management of nitrogen on pastures must be adapted to fit within nitrogen usage limitations.

Here an experiment was conducted from September 22nd 2019 - June 6th 2020 across two field sites (site A permanent pasture and site B, autumn renewed pasture) within Lincoln University. The experiment compared the monthly application of urea (25 kgN/ha) in solution (fertigation) or as solid granules/immediately irrigated or as solid granules irrigated two days after nitrogen application on production and quality of perennial ryegrass/ white clover pasture. The aim of this experiment was to determine if the application of urea in solution (fertigation) will increase nitrogen use efficiency when compared with the recommended dairy farm fertilisation methods. Here nitrogen use efficiency is defined as dry matter and nitrogen taken off the pasture relative to nitrogen input.

The findings of Experiment one showed no consistent significant difference between the nitrogen treatments at both sites in dry matter production, pasture moisture content, pasture quality (crude protein, neutral detergent fibre, dry matter digestibility, and metabolisable energy), nitrogen content or clover percentage. Thus, in relation to the first objective of the thesis, fertigation, as defined here, did not increase nitrogen use efficiency when compared with recommended dairy farm fertilisation methods.

Despite no significant difference found between the nitrogen treatments at both sites, the dry matter production over the season followed different trends at the field sites A and B (Figure 3-2 and 3-5). For the majority of the growing season (harvest three onwards) yield was similar for the control and the three-plus nitrogen treatments. The likeliest reason for this is an increase in the proportion of total plant biomass as clover (See Table 3-7 and 3-9) in some cases increased clover is linked to increased crude protein and pasture nitrogen (and decreased neutral detergent fibre). The trend in dry matter production at the initial site (Figure 3-2) followed the soil temperature with production decreasing proportionately from harvest three until the final harvest with dropping soil temperature. This indicates that temperature may have been the main factor determining production under the conditions of the experiment.

However, at site B, dry matter production was greatest at harvest one (~3500 kgDM/ha for the three-plus nitrogen treatments) but sharply decreased from harvest one to three (870 kgDM/ha in all treatments) despite increasing soil temperature. The initial high spike in production was due to harvest being a week later at site B than site A, whereas the most likely cause of the decrease in dry matter production was from insufficient irrigation. The initial site was fitted with a moisture probe measuring the soil water content to 400mm, and the site was a permanent pasture. Since the harvest with the greatest drop in dry matter production occurred during the months (December and January) with the greatest average air temperature (15.1, 16.6 °C) and potential evapotranspiration (Penman PET 40-year mean of 141.6mm and 149.7mm respectively), it is likely that the pasture was not receiving enough water. This can be seen in Figure 3-2 as the moisture percentage of harvest two (80%) and three (81%) were lower than harvest one (84%), and four (83%) in which there was a greater dry matter. Additionally, due to the pastures recent sowing (May 2019), the root system would be less developed at the repeated site compared to the initial site. Since both pastures received the same total irrigation based on the irrigation determination of moisture probe at the initial permanent pasture site, it is likely the repeated site received insufficient irrigation during harvest three. After harvest three of site B, dry matter production increased to ~1850 kgDM/ha at harvest four before decreasing to 350 kgDM/ha at harvest seven with decreasing soil temperature (Figure 3-6).

CHAPTER 4

Does multiple fertigation applications increase nitrogen use efficiency compared to single application with same total nitrogen?

4.1 Introduction

In Chapter 3, a repeated (across two sites) experiment (Experiment 1) was carried out at Lincoln University that compared the monthly application of urea (25 kgN/ha) in solution (fertigation) or as solid granules/immediately irrigated or solid granules irrigated two days after nitrogen application on the production and quality of perennial ryegrass/white clover pasture over a seven-harvest irrigation season. The aim of the experiment was to determine if the application of urea in solution (fertigation) will increase nitrogen use efficiency (dry matter yield and nitrogen off taken relative to nitrogen input) when compared with the current recommended dairy farm fertilisation methods. The findings of the first experiment showed no consistent significant difference between the nitrogen treatments at both sites in dry matter production, pasture moisture content, pasture quality (crude protein, neutral detergent fibre, dry matter digestibility, and metabolisable energy), nitrogen content or clover percentage. It was concluded that fertigation, as defined here, did not increase nitrogen use efficiency when compared with the currently recommended dairy farm fertilisation methods. At some harvests, the control had as great a dry matter production as the plus nitrogen treatments. Also, at some harvests, crude protein, clover percentage and nitrogen percentage were greater for the control.

In this Chapter, another method of possibly improving the nitrogen use efficiency of a perennial ryegrass/white clover pasture was tested. Experiment 2 compared the application timing/frequency of urea dissolved in water applied once per month and once per week using an even application totalling 25kgN/ha per month, to determine if smaller gaps between application timing (split application) using the same total nitrogen per month increased nitrogen use efficiency.

By splitting the application of nitrogen into smaller amounts and increasing the application frequency, nitrogen can be applied at rates that are possibly closer to plant uptake capacity while maintaining a lower nitrogen concentration in the soil. This could decrease nitrogen losses to the environment while maintaining or possibly increasing pasture production and preserving nitrogen fixation (white clover).

The second experiment was carried out as for Experiment 1, with a 7-harvest cycle from 22nd September 2019 to the 12th June 2020 at two different field sites (the autumn renewed pasture and a permanent pasture of Experiment 1) within Lincoln University. This experiment aimed to see if smaller gaps between application timing (approximately weekly split application) of nitrogen in solution increased nitrogen use efficiency compared to a single (nitrogen monthly) nitrogen application in solution when both treatments use the same total applied nitrogen.

4.2 Materials and Methods

Experiment 1 and 2 were run in parallel. Refer to Chapter 3.2 Materials and Methods for site preparation (Chapters 3.2.1 and 3.2.2), irrigation determination (Chapter 3.2.3), climatic data (Chapter 3.2.4), pasture composition (Chapter 3.2.6) and quality measurement methods (Chapter 3.2.6).

4.2.1 Experiment 2: Trial design and set up.

Experiment 2 ran from the 22nd of September 2019 to the 12th of June 2020 across two sites comparing the application timing of urea dissolved in water and applied once per month (Dissolved urea/monthly) against urea dissolved in water and applied once per week (Dissolved urea/weekly).

The trial area for experiment 2 was broken into 18 6x2m plots with 0.5m buffer strips between the plots at two field sites in a completely randomised block design (Table 4-1). Each of the treatments was supplied with 6mm of irrigation after fertiliser application with each subsequent irrigation occurring when required depending on the soil moisture content. The treatments consisted of 25 kgN/ha in the form of urea dissolved in 6L of water applied by watering can once per month over the trial period (L25 kg) and 25 kgN/ha in the form of urea dissolved in 6mm water applied in four even solutions per month by watering can over the trial period (L6.25 kg). Additionally, there was a no-nitrogen control treatment receiving only irrigation applied to the perennial ryegrass/white clover pasture with no nitrogen fertiliser (Control). All treatments received the same total irrigation.

Table 4-1 Complete randomized block design of Experiment 2a (permanent pasture) and 2b (autumn-sown pasture)

2a

L25 kg	Control	L6.25 kg
Control	L25 kg	L6.25 kg
L6.25 kg	Control	L25 kg
L6.25 kg	L25 kg	Control
L25 kg	Control	L6.25 kg
Control	L6.25 kg	L25 kg

2b

L6.25 kg	L25 kg	Control
Control	L6.25 kg	L25 kg
L25 kg	Control	L6.25 kg
Control	L6.25 kg	L25 kg
L6.25 kg	L25 kg	Control
L25 kg	Control	L6.25 kg

4.2.2 Statistical analysis

Statistical analysis was carried out on SPSS 26 using a one-way analysis of variance (ANOVA) to determine if the nitrogen treatments (fixed variable) had an effect on the response/dependent variables: dry matter production (kgDM/ha), pasture moisture percentage, crude protein (CP %), neutral detergent fibre content (NDF %), dry matter digestibility (DMD %), metabolisable energy (MJME/kgDM), clover percentage (clover %) and pasture nitrogen (N %). Where appropriate, a Tukey test was used to separate means. The standard error of the mean (SEM) values shown in figures was derived from the ANOVA. A one-way ANOVA was carried out between the control and L25 treatments in harvests four-six for clover percentage while the standard error of the mean was generated from the replicates of each of the treatments.

4.3 Results

4.3.1 Experiment 2 site A

4.3.1.1 Dry matter production and moisture content

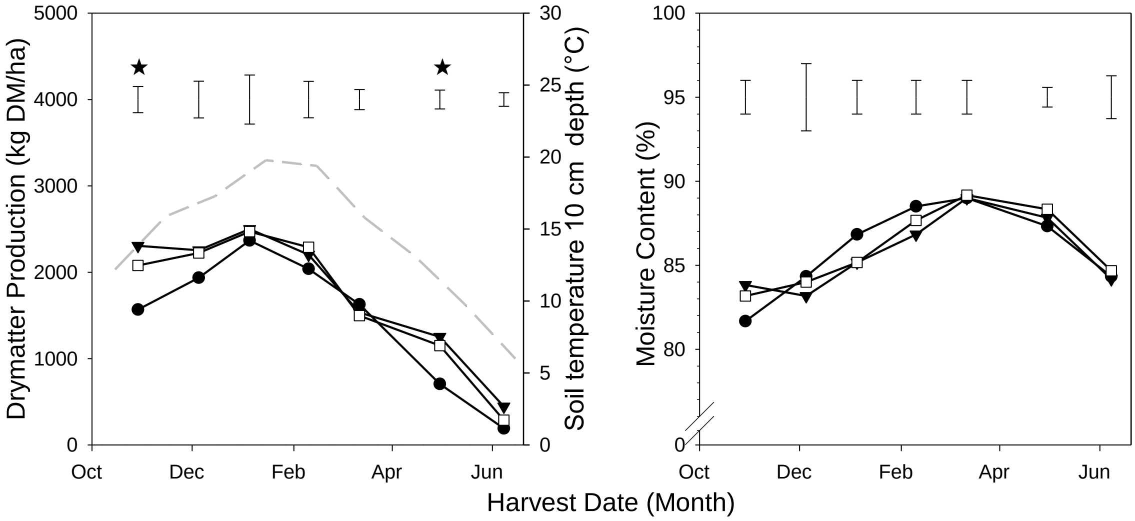

Figure 4-1 Dry matter production and moisture content over seven harvests of perennial ryegrass/white clover pastures at Lincoln University, New Zealand with three treatments: no nitrogen control (●), urea dissolved in water and applied with immediate irrigation once per month (▼), and urea dissolved in water and applied with immediate irrigation once per week (□). Error bars are the standard error of the mean for each harvest. The dashed line displays the monthly average soil temperature at 10cm depth. A star (★) above the error bar signifies a significant difference between the control and both plus nitrogen treatments.

Dry matter production for the two-plus nitrogen treatments (dissolved urea/applied monthly and dissolved urea/applied weekly) were similar and changed little (~2200 kg/ha) for the first four harvests then decreased with each harvest thereafter to around 365 kgDM/ha at harvest seven (Figure 4-1). Dry matter production and average soil temperature (10cm depth) displayed a similar trend over the season (Figure 4-1). The control treatment produced significantly less dry matter than the nitrogen treatments at harvest one (p=0.001) and six (P=0.009). Generally, for all treatments, the moisture percentage increased from harvest one/two to five then decreased from harvest five to seven. Moisture percentage was always between 84 to 89% for all seven harvests with the only significant difference being that the dissolved urea/monthly treatment had a significantly greater moisture percentage than the control at harvest one (p=0.038).

4.3.1.2 Dry matter digestibility and metabolisable energy

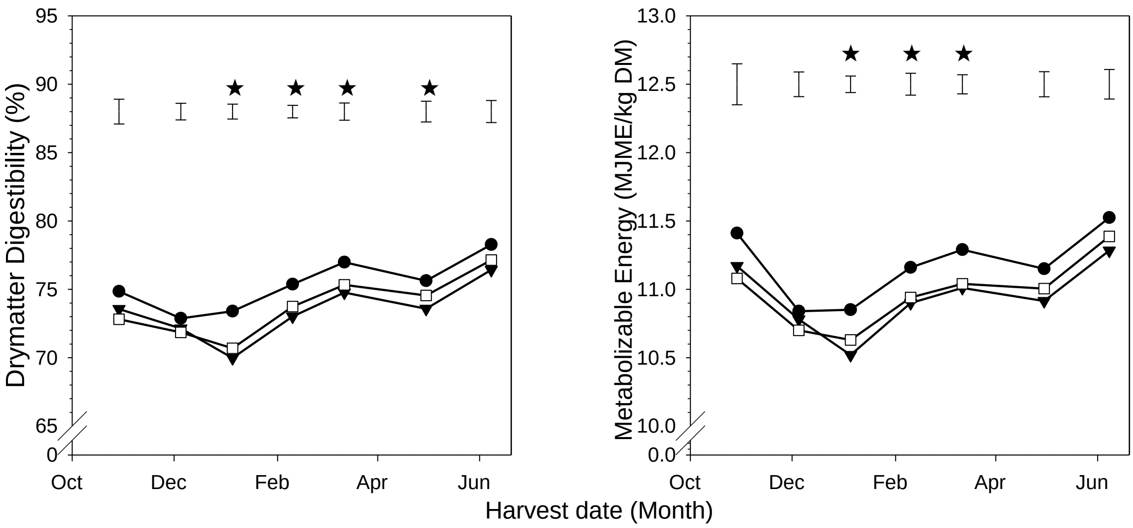

Figure 4-2 Dry matter Digestibility and Metabolisable energy over seven harvests of perennial ryegrass/white clover pastures at Lincoln University, New Zealand with three treatments: no nitrogen control (●), urea dissolved in water and applied with immediate irrigation once per month (▼), and urea dissolved in water and applied with immediate irrigation once per week (□). Error bars are the standard error of the mean for each harvest. A star (★) above the error bar signifies a significant difference between the control and both plus nitrogen treatments.

Dry matter digestibility was similar for the two-plus nitrogen treatments at all harvests. For the two treatments, dry matter digestibility (DMD) decreased from around 73% at harvest one to around 70% DMD at harvest three then generally increased with subsequent harvest to the final value of around 77% at harvest seven (Figure 4-2). The control treatment produced significantly greater dry matter digestibility than the nitrogen treatments for harvest three (p=0.000), four (p=0.000), five (p=0.009) and six (p=0.052).

Metabolisable energy was similar for the two-plus nitrogen treatments at all harvests. For the two treatments, metabolisable energy decreased from harvest one (11.2 MJME/

kgDM) to harvest three (10.6 MJME/ kgDM) then generally increased with harvest to the final value of around 11.4 MJME/kgDM at harvest seven (Figure 4-2). The control treatment produced significantly greater metabolisable energy than the nitrogen treatments for harvest three (p=0.000), four (p=0.014) and harvest five (p=0.001). Metabolisable energy and dry matter digestibility followed similar trends over the seven harvests (Figure 4-2).

4.3.1.3 Crude protein and neutral detergent fibre content

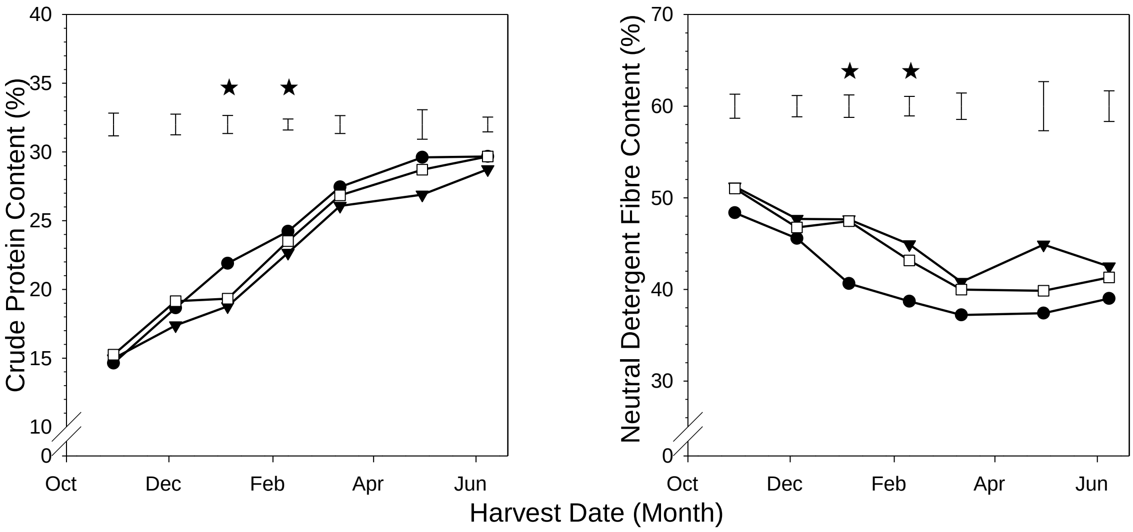

Figure 4-3 Crude protein content and Neutral detergent fibre content over seven harvests of perennial ryegrass/white clover pastures at Lincoln University New Zealand with three treatments: no nitrogen control (●), urea dissolved in water and applied with immediate irrigation once per month (▼), and urea dissolved in water and applied with immediate irrigation once per week (□). Error bars are the standard error of the mean for each harvest. <u>A star (★) above the error bar signifies a significant difference between the control and both nitrogen treatments.</u>

Crude protein was similar for the two-plus nitrogen treatments at all harvests. Crude protein increased over the seven harvests from initial crude protein content of around 15% to approximately 29% at harvest seven (Figure 4-3). The control treatment produced significantly greater crude protein than the nitrogen treatments during harvest three (p=0.028) and four (p=0.05).

Neutral detergent fibre was similar for the two-plus nitrogen treatments at all harvests. For the two treatments, neutral detergent fibre (NDF) decreased from around 50% at harvest one to around 41% NDF at harvest five (Figure 4-3). The control treatment produced significantly less neutral detergent fibre than the nitrogen treatments for harvest three (p= 0.000) and four (P=0.000).

4.3.1.4 Nitrogen Percentage

Table 4-2 Nitrogen percentage over three harvests of perennial ryegrass/white clover pastures with two nitrogen treatments (urea dissolved in water and applied with immediate irrigation once per month and urea dissolved in water and applied with immediate irrigation once per week) and one no nitrogen control treatment (control). Different letters indicate a significant difference between the treatments at P < 0.05.

Treatments	Harvest 4 (10/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	3.71^{a}	4.34^{a}	4.46^{a}
Dissolved urea/monthly	3.31^{b}	4.088^{ab}	4.15^{a}
Dissolved urea/weekly	3.58^{a}	3.89^{b}	4.41^{a}
SEM	0.055	0.11	0.19

For all treatments pasture nitrogen percentage increased from harvest four to six (Table 4-2), averaging around 3.44%N, 3.99%N and 4.29%N in harvests four, five and six respectively. There was no consistent effect of treatment on pasture nitrogen percentage (Table 4-2).

4.3.1.5 Clover percentage

Table 4-3 Clover percentage over four harvests of perennial ryegrass/white clover pastures with two nitrogen treatments (urea dissolved in water and applied with immediate irrigation once per month, and urea dissolved in water and applied with immediate irrigation once per week) and one no nitrogen control treatment (control). Different letters indicate a significant difference between the treatments at P < 0.05.

Treatment	Harvest 1 (29/10/2019)	Harvest 4 (4/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	10.3[a]	91.5[a]	95.7[a]	67.7[a]
Dissolved urea /monthly	4.8[a]	68.1[b]	61.2[b]	41.7[b]
Dissolved urea /weekly	8.3[a]			
SEM	2.6	6.2	3.6	8.2

For the dissolved urea/monthly application and the control, clover percentage increased from harvest one to harvest four and five then decreased at harvest six. The control treatment had a greater clover percentage when compared with the dissolved urea/monthly treatment at harvest four (p=0.005), harvest five (p=0.000) and harvest six (p=0.049).

4.3.2 Experiment 2 site B

4.3.2.1 Dry matter production and moisture content

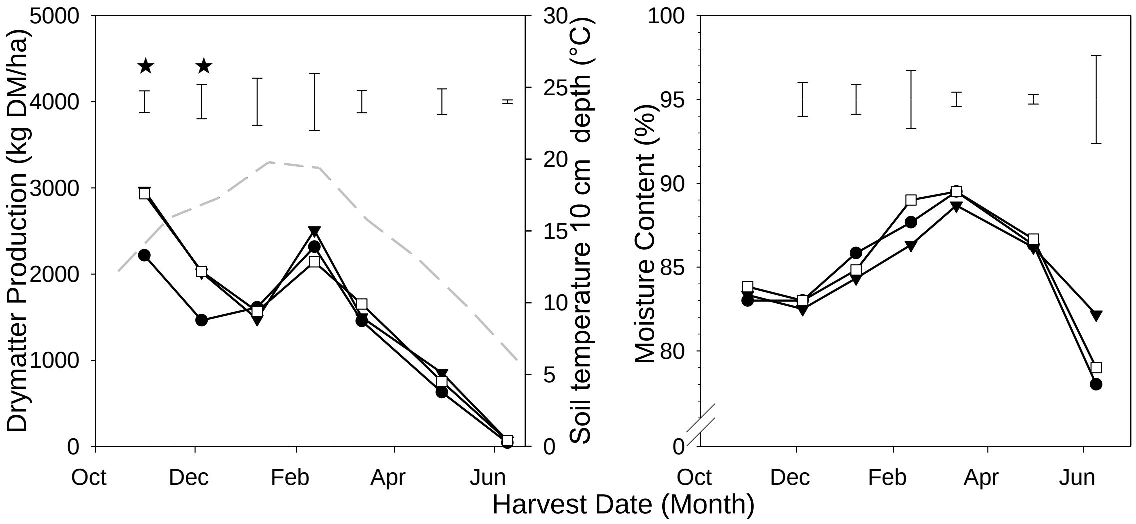

Figure 4-4 Dry matter production (kgDM/ha) and moisture content (%) over seven harvests of perennial ryegrass/white clover pastures at Lincoln University New Zealand with three treatments: no nitrogen control (●), urea dissolved in water and applied with immediate irrigation once per month (▼), and urea dissolved in water and applied with immediate irrigation once per week (□). Error bars are the standard error of the mean for each harvest. The dashed line displays the monthly average soil temperature at 10cm depth. <u>A star (★) above the error bar signifies a significant difference between the control and both nitrogen treatments.</u>

As in Experiment 2 at site A, dry matter production in Experiment 2 at site B did not differ across the two-plus nitrogen treatments. Dry matter production was greatest at harvest one at ~3000 kgDM/ha for the two-plus nitrogen treatments and ~2200 kgDM/ha for the control (Figure 4-4). From harvest one to three, there was a sharp decline in dry matter production to around 1500 kg/ha at harvest three (all treatments). Dry matter production (all treatments) then increased to approximately 2300 kgDM/ha at harvest four before decreasing to 250 kgDM/ha at harvest seven (Figure 4-4). The control treatment produced significantly less dry matter than the nitrogen treatments at harvest one (p=0.000) and two (p=0.017).

For all treatments, moisture percentage was similar for the first two harvests, increased from 83% at harvests one/two to around 89% for harvests five, and then decreased to around 79% for harvests seven). There was no significant difference in the moisture percentage found between the treatments.

4.3.2.2 Dry matter digestibility and metabolisable energy

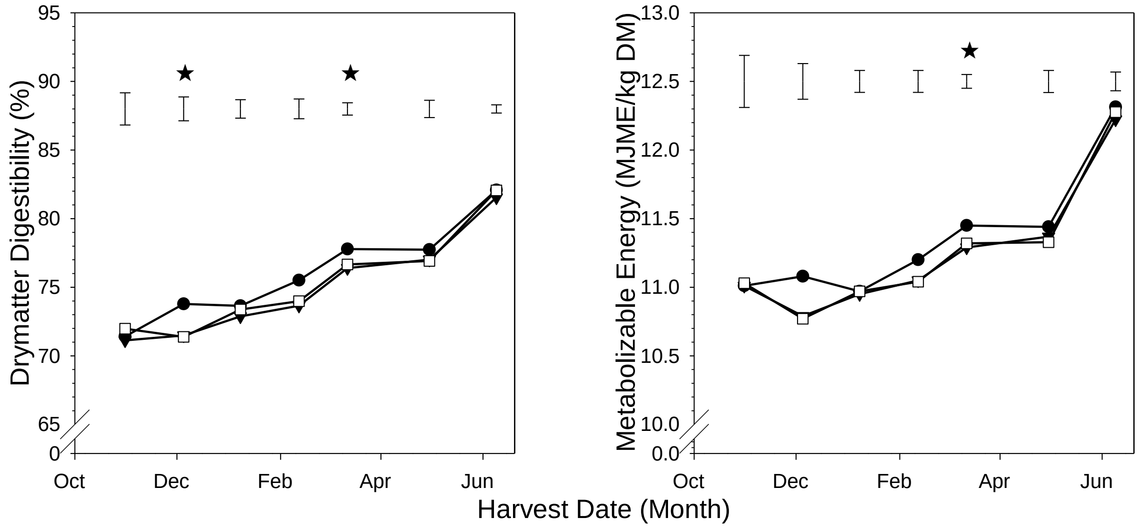

Figure 4-5 Dry matter Digestibility and Metabolisable energy over seven harvests of perennial ryegrass/white clover pastures at Lincoln University, New Zealand with three treatments: no nitrogen control (●), urea dissolved in water and applied with immediate irrigation once per month (▼), and urea dissolved in water and applied with immediate irrigation once per week (□). Error bars are the standard error of the mean for each harvest. <u>A star (★) above the error bar signifies a significant difference between the control and both nitrogen treatments,</u>

As in Experiment 2 at site A, dry matter digestibility and metabolisable energy (Figure 4.5) and crude protein and neutral detergent fibre (Figure 4.6) in experiment 2 site B were not significantly different across the two-plus nitrogen treatments. Generally, for the two-plus nitrogen treatments, dry matter digestibility, metabolisable energy and crude protein increased with harvest throughout the season while the neutral detergent fibre decreased (Figures 4.5 and 4.6). The control treatment gave significantly higher dry matter digestibility than the two-plus nitrogen treatments at harvest two (p=0.023) and five (0.018), significantly higher metabolisable energy at harvest five (p=0.019), significantly higher crude protein at harvest four (p=0.031) but lower neutral detergent fibre content at harvest two (P=0.005), four (p=0.017), five (p=0.025) and six (p=0.039) (Figures 4.5, 4.6).

4.3.2.3 Crude protein and neutral detergent fibre content

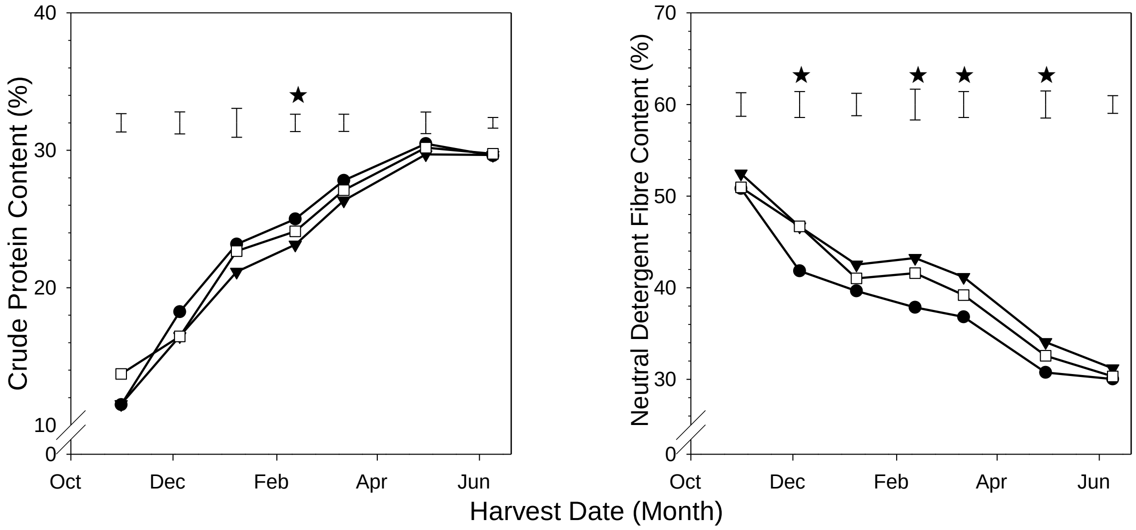

Figure 4-6 Crude protein content and neutral detergent fibre content over seven harvests of perennial ryegrass/white clover pastures at Lincoln University New Zealand with three treatments: no nitrogen control (●), urea dissolved in water and applied with immediate irrigation once per month (▼), and urea dissolved in water and applied with immediate irrigation once per week (□). Error bars are the standard error of the mean for each harvest. A star (★) above the error bar signifies a significant difference between the control and both nitrogen treatments.

4.3.2.4 Nitrogen percentage

Table 4-4 Nitrogen percentage over three harvests of perennial ryegrass/white clover pastures with two nitrogen treatments (urea dissolved in water and applied with immediate irrigation once per month, and urea dissolved in water and applied with immediate irrigation once per week) and one no nitrogen control treatment (control). Different letters indicate a significant difference between the treatments at $P < 0.05$.

Treatment	Harvest 4 (12/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	3.71[a]	4.35 [a]	4.56[a]
Dissolved urea /monthly	3.44[a]	4.026[b]	4.49[a]
Dissolved urea /weekly	3.56[a]	4.093[b]	4.59[a]
SEM	0.11	0.089	0.13

For all treatments, pasture nitrogen percentage increased with each subsequent harvest. Pasture nitrogen percentage was not significantly different for the two-plus nitrogen treatments at all harvests and increased from around 3.5%N at harvest four to around 4.54% at harvest six. The control treatment had significantly greater pasture nitrogen percentage than the nitrogen treatments at harvest five (P=0.005).

4.3.2.5 Clover percentage

Table 4-5 Clover percentage over four harvests of perennial ryegrass/white clover pastures with two nitrogen treatments (urea dissolved in water and applied with immediate irrigation once per month, and urea dissolved in water and applied with immediate irrigation once per week) and one no nitrogen control treatment (Control). Different letters indicate a significant difference between the treatments at P < 0.05.

Treatments	Harvest 1 (31/10/2019)	Harvest 4 (10/02/2020)	Harvest 5 (12/03/2020)	Harvest 6 (30/04/2020)
Control	8.8^{a}	91.1^{a}	95.2^{a}	86.8^{a}
Dissolved urea /monthly	4.3^{a}	75.6^{a}	77.8^{b}	66.1^{a}
Dissolved urea /weekly	4.3^{a}			
SEM	3.5	6.3	5.2	8.5

For the dissolved urea/monthly application and the control, clover percentage increased from harvest one to harvest four and five then decreased at harvest six. The control treatment consistently had greater clover percentage when compared with the dissolved urea/monthly treatment, but it only reached statistical significance (p=0.021) at harvest five.

4.4 Discussion

The current recommended practice for nitrogen application on New Zealand dairy farms is eight monthly applications of nitrogen during the irrigation/growing season, totalling 200 kgN/ha/year. Generally, nitrogen is applied as solid urea and irrigation is supplied within two days of nitrogen application. But due to the current and incoming limitations to the application of nitrogen fertiliser (190kgN/ha/year) and effluent (150kgN/ha/year) on grazed pastures in 2021, the application and management of nitrogen fertiliser must be adapted (Glassey et al., 2013, MFE, 2020 Waikato regional council, 2015).

In experiment 1 (Chapter 3) from 22nd September 2019 to the 12th June 2020 at two different field sites (site A, a permanent pasture and site B, an autumn renewed pasture) within Lincoln University, an experiment was carried out to test if fertigation (nitrogen applied in solution) could increase nitrogen use efficiency in New Zealand perennial ryegrass/white clover pastures. This experiment concluded that fertigation did not increase nitrogen use efficiency when compared with recommended dairy farm fertilisation methods. Running parallel to the first experiment, the experiment described in this Chapter (Experiment 2) was conducted testing the effect of increased application frequency of fertigation (single monthly application versus weekly split application) using a total of 25 kgN/ha each harvest. This experiment aimed to see if smaller gaps between application timing (split application) of nitrogen in solution increased nitrogen use efficiency compared to a single nitrogen application in solution when both treatments use the same total applied nitrogen. As for experiment 1 pasture production and quality were measured in experiment 2.

The findings of the second experiment showed no consistent significant difference between the two-plus nitrogen treatments (dissolved urea/monthly and dissolved urea/weekly) at both sites in dry matter production, pasture moisture content, pasture quality (crude protein, neutral detergent fibre, dry matter digestibility, and metabolisable energy), nitrogen content or clover percentage, following the same trends in production and quality as experiment one in each of their respective sites. Thus, in relation to the second objective of the thesis, fertigation, as defined here, did not increase nitrogen use efficiency when applied as weekly split applications when compared with once per month fertigation applications using the same total monthly applied nitrogen.

As in experiment one, for the majority of the growing season (harvest two onwards) yield was similar for the control and the two-plus nitrogen treatments in experiment two. The likeliest reason for this here as in experiment 1 is an increase in the proportion of total plant biomass as clover (See Table 4-3 and 4-5). In some cases, increased clover is linked to increased crude protein and pasture nitrogen and the decrease in neutral detergent fibre (clover percentage Tables 4-3 and 4-5, nitrogen percentage Tables 4-2 and 4-4, crude protein and NDF Figures 4-3 and 4-6). This is likely to be due to increased N_2 fixation of white clover in the control relative to the plus nitrogen treatments. Results here indicate that as previously reported (Andrews et al., 2007) white clover has potential as a nitrogen input into grass dominant pastures when fertiliser nitrogen use is constrained.

CHAPTER 5: Final Discussion

Over the past 30 years, the application of nitrogen fertiliser to New Zealand dairy pastures has increased sevenfold with urea the most commonly applied form of nitrogen (Chapter 2; Fertiliser association NZ, 2018, Stats NZ, 2019). This has resulted in increased dairy pasture production in all regions (DairyNZ, 2020). Fertiliser nitrogen can also affect pasture quality (dry matter digestibility and crude protein) but non – fertilised perennial ryegrass/ white clover swards can have a high-quality pasture, although yields may be lower (Andrews et al., 2007). The large increases in pasture production from added nitrogen fertiliser have increased the country-wide production of milk solids. From 1990-2012, the total production of milk solids increased from 0.572 to 1.685 million tonnes due to the higher stocking rate that can be maintained or increased on the levels of pasture production (LIC & DairyNZ 2018, Harris et al., 1994)

Application of nitrogen fertiliser to New Zealand dairy pastures has contributed to nitrogen related environmental impacts from New Zealand dairy pastures. Increased dry matter production allows a greater stocking rate and as a result, greater annual nitrogen excretion. It is the greater annual nitrogen excretion that is the primary reason for increased nitrogen loss from the pasture with increased nitrogen fertiliser. The amount of nitrogen lost from pasture is closely related to the amount of nitrogen cycling within the system (Andrews et al., 2007, Cameron et al., 2013, Moir et al., 2016, Drymond et al., 2013). The main nitrogen loss from New Zealand dairy pastures is via nitrogen (mainly nitrate) leaching. Nitrate leaching with phosphorus (phosphate) runoff results in eutrophication of waterways (Andrews et al., 2007, Cameron et al., 2013). Additional nitrogen loss from pastures includes losses to the atmosphere via denitrification. Nitrous oxide emissions contribute to 17% of New Zealand's total greenhouse gas emission compared with the rest of the world (10%) (De Klein & Ledgard, 2005). Nitrogen fertilised irrigated pastures have a higher average denitrification rate (113 kgN/ha/year) compared with non-irrigated pastures (3.2 kgN/ha/year) (Barton et al., 1999). Legislation has been put in place to reduce nitrogen losses from perennial ryegrass/white clover dairy pastures (Chapter 2; MFE, 2020).

Fertigation is the process of applying liquid/dissolved fertiliser with irrigation water. Potential advantages of fertigation are the ability to maintain or increase the potential dry matter yield by smaller more frequent fertiliser application when required, the direct incorporation of nitrogen into the soil profile preventing ammonia volatilisation losses and the possibility of maintaining a lower constant nutrient level in the soil solution to reduce nitrate leaching and maintain yield and quality (Black, Sherlock & Smith, 1987, Cameron et al., 2013, Incrocci, Massa & Pardossi, 2017). No published data were found on the effects of fertigation on yield or quality of New Zealand pastures or losses of nitrogen from the system.

From September 22nd 2019 - June 6th 2020, two field experiments were conducted on perennial ryegrass/white clover pastures within Lincoln University. Experiment 1 compared monthly application of urea (25 kgN/ha) in solution (fertigation) against conventional/ recommended practice method of monthly 25 kgN/ha urea application with either immediate irrigation or irrigation applied after two days on production and quality of the pasture. This experiment aimed to determine if fertigation will increase nitrogen use efficiency (dry matter yield and nitrogen off taken relative to nitrogen input) when compared with the standard recommended dairy farm fertilisation methods. Experiment 2 tested the application timing of 25 kgN/ha/month of urea dissolved in water. The 25 kgN/ha was applied once per month or once per week (6.25 kgN/ha/week) to determine if smaller gaps between application timing increased nitrogen use efficiency. The two experiments had a zero-nitrogen control and were repeated across two field sites (autumn renewed pasture and permanent pasture).

In the initial and repeat experiment 1, application of N regardless of treatment gave similar yield and pasture quality (dry matter digestibility, metabolisable energy, crude protein and neutral detergent fibre) at all harvests throughout the growing season. It was concluded that fertigation as defined here (low volume concentrated urea solution followed by irrigation) does not increase nitrogen use efficiency when compared with current recommended dairy farm fertilisation methods.

In the initial and repeat experiment 2, application of N in solution once per month or once per week gave similar yield and pasture quality throughout the growing season. It was concluded that fertigation did not increase nitrogen use efficiency when applied as weekly split applications when compared with once per month fertigation applications using the same total monthly applied nitrogen.

In the initial and repeat experiment 1 and the initial and repeat experiment 2, the control gave lower yields to the N application treatments at the first two harvests, but similar yields and quality to the N application treatments at almost all later harvests. This is likely to be due to increased N_2 fixation of white clover in the control relative to the plus nitrogen treatments. The results here indicate that as previously reported (Andrews et al., 2007), white clover has potential as a nitrogen input in grass-dominated pastures when fertiliser nitrogen is constrained. A weakness of white clover nitrogen fixation as a nitrogen input into pasture is that N_2 fixation rates are limited at low temperatures. Further work could test if strategic nitrogen application early in the season impact on white clover growth and N_2 fixation during the growing period where white clover N_2 fixation can match nitrogen fertiliser input on split application constrained at 200 (now 190) kgN/ha.

It is concluded that:

- Fertigation (as defined here) did not increase nitrogen use efficiency when compared with currently recommended dairy farm fertilisation methods.
- Fertigation applied as weekly split applications did not increase nitrogen use efficiency when compared with once per month fertigation applications using the same total applied nitrogen.
- The control treatment had similar mid-season dry matter yields as the plus nitrogen treatments and, in some cases, had greater crude protein, pasture nitrogen and clover percentage.
- Further research into strategic nitrogen applications to minimise nitrogen applied while maximising clover percentage should be conducted.

REFERENCES

Andrews, M., Scholefield, D., Abberton, M., McKenzie, B., Hodge, S., & Raven, J. (2007). Use of white clover as an alternative to nitrogen fertiliser for dairy pastures in nitrate vulnerable zones in the UK: Productivity, environmental impact and economic considerations. *Annals of Applied Biology*, *151*, 11–23.

Andrews, M., Raven, J. A., & Lea, P. J. (2013). Do plants need nitrate? The mechanisms by which nitrogen form affects plants. *Annals of applied biolog*y, *163*(2), 174–199.

Andrews, M., & Andrews, M. E. (2017). Specificity in legume-rhizobia symbioses. *International Journal of Molecular Sciences*, *18*(4), 705.

Barton, L., McLay, C. D. A., Schipper, L. A., & Smith, C. T. (1999). Annual denitrification rates in agricultural and forest soils: A review. *Soil Research, 37*(6), 1073–1094.

Bar-Yosef, B. (1999). Advances in fertigation. *Advances in Agronomy*, *65*, 6–8.

Black A.S., Sherlock R.R., & Smith N.P. (1987) Effect of timing of simulated rainfall on ammonia volatilization from urea, applied to soil of varying moisture content. *Journal of Soil Science*, *38*, 679–687.

Calsamiglia, S., Ferret, A., Reynolds, C. K., Kristensen, N. B., & Van Vuuren, A. M. (2010). Strategies for optimizing nitrogen use by ruminants. *Animal*, *4*(7), 1184–1196.

Cameron, K. C., Di, H. J., Moir, J. L., Christie, R. & Pellow, R. (2005). Using nitrogen: What is best practice? *South Island Dairy Event (SIDE) Proceedings*, 1–17. http://hdl.handle.net/10182/576.

Cameron, K. C., Di, H. J., & Moir, J. L. (2013). Nitrogen losses from the soil/plant system: A review. *Annals of Applied Biology, 162*(2), 145–173.

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., Carvalho, I., Faria, T., & Pinheiro C. (2002). How plants cope with water stress in the field? Photosynthesis and growth. *Annals of Botany*, *89*(7), 907–916.

Clark, D. A., & Harris, S. L. (1996). White clover or nitrogen fertiliser for dairying? *New Zealand Grasslands association: Grassland Research and Practice Series 6*, 107–114.

Chapman, D. F., Parsons, A. J., & Schwinning, S. (1995). Management of clover in grazed pastures: Expectations, limitations and opportunities. *New Zealand Grasslands association: Grassland Research and Practice Series 6*, 55–64.

Clough T. J. (1994). *Fate of urine nitrogen applied to peat and mineral soils from grazed pastures* [Doctoral thesis, Lincoln University]. Lincoln University Research Archive. https://hdl.handle.net/10182/1030

DairyNZ (2018). *Quickstats about dairying - New Zealand*. DairyNZ. https://www.dairynz.co.nz/publications/dairy-industry/new-zealand-dairy-statistics-2018-19/

DairyNZ (2019). *Dairy plays a key role in latest economic success*. DairyNZ. https://www.dairynz.co.nz/news/dairy-plays-a-key-role-in-latest-economic-success/

DairyNZ (2020). *Pasture growth data*. DairyNZ. https://www.dairynz.co.nz/feed/pasture-management/pasture-growth-data/

DairyNZ (2020). *Average pasture growth data by region (kgDM/ha/day)*. DairyNZ. https://www.dairynz.co.nz/feed/pasture-management/pasture-growth-data/

De Klein, C. A. M., & Ledgard, S. F. (2005). Nitrous oxide emissions from New Zealand agriculture - key sources and mitigation strategies. *Nutrient Cycling in Agroecosystems, 72*, 77–85.

Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, *64*(3), 237–256.

Dymond, J. R., Ausseil, A. G. E., Parfitt, R. L., Herzig, A., & McDowell, R. W. (2013). Nitrate and phosphorus leaching in New Zealand: A national perspective. *New Zealand Journal of Agricultural Research*, *56*(1), 49–59.

ECan (2018). *Hinds water plan to be made operative*. Environment Canterbury. https://www.ecan.govt.nz/get-involved/news-and-events/zone news/ashburton/hinds-water-plan-to-be-made-operative/

Ecan (2020). *Risk maps of nitrate in Canterbury groundwater*. Environment Canterbury. http://ecan.govt.nz/document/download?uri3820508

Eckard, R. J. (2006). Are there win-win strategies for minimizing greenhouse gas emissions from agriculture? In R. J. Eckard (Ed.) *ABARE Outlook Conference* (pp. 1–8).

Brouwer, C. Goffeau, A., & Heibloem, M. (1985*) Irrigation water management: Training manual No. 1 - introduction to irrigation, chapter 2 - soil and water*. Rome: FAO. http://www.fao.org/3/r4082e/r4082e03.htm#:~:text=2.3.,-3%20Field%20capacity&text=After%20the%20drainage%20has%20stopped,for%20crop%20growth%20(see%20Fig.

Fertiliser association of New Zealand (2018). *Fertiliser use in NZ*. Fertiliser association of New Zealand. http://www.fertiliser.org.nz/Site/about/fertiliser_use_in_nz.aspx

Freney, J. R. (1997). Emission of nitrous oxide from soils used for agriculture. *Nutrient Cycling in Agroecosystems*, *49*, 1–6.

Glassey, C. B., Roach, C. G., Lee, J. M., & Clark, D. A. (2013). The impact of farming without nitrogen fertiliser for ten years on pasture yield and composition, milksolids production and profitability; a research farmlet comparison. *Proceedings of the New Zealand Grassland Association, 75*, 71–77.

Harris, S. L., Penno, J. W., & Bryant, A. M. (1994). Effects of high rates of nitrogen fertiliser on dairy pastures and production. *Proceedings of the New Zealand Grassland Association, 56*, 27–31.

Harris, S. L., & Clark, D. A. (1996). Effect of high rates of nitrogen fertiliser on white clover growth, morphology, and nitrogen fixation activity in grazed dairy pasture in northern New Zealand. *New Zealand Journal of Agricultural Research*, *39*(1), 149–158.

Haynes, R. J. (1988). Comparison of fertigation with broadcast applications of urea-N on levels of available soil nutrients and on growth and yield of trickle-irrigated peppers. *Scientia Horticulturae*, *35*(3–4), 189–198.

Haynes, R. J., & Williams, P. H. (1993). Nutrient cycling and soil fertility in the grazed pasture ecosystem. In D. L Sparks (ed.), *Advances in agronomy* (Vol. 49, pp.119–199). Academic Press.

Incrocci, L., Massa, D., & Pardossi, A. (2017). New trends in the fertigation management of irrigated vegetable crops. *Horticultur*e, *3*(37), 1–20.

Keller, E. D., Baisden, W.T., Timar, L., Mullan, B., & Clark, A. (2014). Grassland production under global change scenarios for New Zealand pastoral agriculture. *Geoscientific Model Development*, *7*(5), 2359–2391.

Lambert, M. G., & Litherland, A. J. (2000). A practitioner's guide to pasture quality. *Proceedings of the New Zealand Grassland Association*, *62,* 111–115.

Ledgard, S. F. (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, *228*(1), 43–59.

Ledgard, S., Schills, R., Eriksen, J., & Luo, J. (2009). Environmental impacts of grazed clover/grass pastures. *Irish Journal of Agricultural and Food Research*, *48*, 209–226.

Ledgard, S. F., Sprosen, M. S., Penno, J. W., & Rajendram, G. S. (2001). Nitrogen fixation by white clover in pastures grazed by dairy cows: Temporal variation and effects of nitrogen fertilisation. *Plant and Soil*, *229*(2), 177–187.

LIC & DairyNZ (2018). *New Zealand Dairy Statistics 2017-18*. Livestock Improvement Corporation Limited & DairyNZ Limited. https://d1r5hvvxe7dolz.cloudfront.net/media/documents/NZ_DAIRY_STATISTICS_2017-18-WEB-10_OCT.pdf

Lilburne, L., Webb, T., Ford, R., & Bidwell, V. (2010). Estimating nitrate-nitrogen leaching rates under rural land uses in Canterbury (Report No. R10/127). Environment Canterbury Regional Council. https://hdl.handle.net/10182/3547

Lowerance, R., Johnson, Jr. J. C., Newton, G. L., & Williams, R. G. (1998). Denitrification from soils of a year-round forage production system fertilised with liquid dairy manure. *Journal of Environmental Quality, 27*, 1504–11.

Marschner, H. (1995). Introduction, definition, and classification of mineral nutrients. In H. Marschner (Ed.), *Mineral Nutrition of Higher Plants* (2nd ed., pp. 3–5). Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Marsh, K. B., & Stowell, B. M. (1993). Effect of fertigation and hydrogen cyanamide on fruit production, nutrient uptake, and fruit quality in kiwifruit. *New Zealand Journal of Crop and Horticultural Science*, *21*(3), 247–252.

McCarthy, K. M., McAloon, C. G., Lynch, M. B., Pierce, K. M., & Mulligan, F. J. (2020). Herb species inclusion in grazing swards for dairy cows - a systematic review and meta-analysis. *Journal of Dairy Science*, *103*(2), 1416–1430.

Messel, H., & Butler, S. T. (1975). Chapter 2 – solar energy conversion in photosynthesis, In H. Messel & S.T Butler (Eds.), *Solar energy* (pp.145–166). Pergamon Press. https://doi.org/10.1016/B978-0-08-019817-0.50017-3

Ministry for Environment (2019). *Measuring emissions: a guide for organisations – 2019 detailed guide*. Ministry for Primary Industries. https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/2019-detailed-guide.pdf

Ministry for Environment (2020*). Action for healthy waterways 2020 – information for dairy farmers*. Ministry for Primary Industries. https://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/action-for-healthy-waterways-information-for-dairy-farmers.pdf

Moir, J., Cameron, K., & Di, H. (2016). Potential pasture nitrogen concentrations and uptake from autumn or spring applied cow urine and DCD under field conditions. *Plants*, *5*(2), 133–147.

Stats NZ, (2019). *Nitrogen and phosphorus in fertilisers*. Statistics New Zealand. https://www.stats.govt.nz/indicators/nitrogen-and-phosphorus-in-fertilisers

Stockle, C. O. (2001). *Environmental impact of irrigation: A review*. Washington State University. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.488.4861&rep=rep1&type=pdf

Thorrold, B. S. & Doyle, P. T. (2007). Nature or nurture – forces shaping the current and future state of dairy farming in New Zealand and Australia. In D. F. Chapman, D. A. Clark, K. L. Macmillan & D. P. Nation (Eds.), Meeting the challenges for pasture based dairying. *Proceedings of the 3rd Australasian Dairy Science Symposium* (pp. 450–460).

Ulyatt, M. J. (1981). The feeding value of herbage: Can it be improved. *New Zealand journal of agricultural research, 15*, 200–205.

Van Vuuren, A. M. & Meijs J. A. C. (1987). Effects of herbage composition and supplement feeding on the excretion of nitrogen in dung and urine by grazing dairy cows. *In* H. G.van der Meer, T. A. van Dijk & G.C. Ennik (Eds.), *Animal Manure on Grassland and Fodder Crops* (pp. 17–25). Martinus Nijhof Publishers.

Raghavendra, A. S. (2003). Photosynthesis and partitioning/ C3 plants. *Encyclopedia of Applied Plant Sciences, 673–680.*

Raines, C. A. (2011). Increasing photosynthetic carbon assimilation in C3 plants to improve crop yield: Current and future strategies*. Plant Physiology, 155(1), 36–42.*

Raven, J. A., Handley, L. L., & Andrews, M. (2004). Global aspects of C/N interactions determining plant-environment interactions. *Journal of Experimental Botany*, *55*, 11–25.

Ryden, J. C., & Lund, L. J. (1980). Nature and extent of directly measured denitrification losses from some irrigated vegetable crop productions units. *Soil Science Society of America Journal, 44*(3), 505–511.

Waikato regional council (2015). *Nitrogen Fertiliser and effluent*. Waikato Regional Council.https://www.waikatoregion.govt.nz/assets/PageFiles/30016/factsheets/CNM%20factsheet%20get_most_fertiliser_effluent_nitrogen_8.pdf

Woodward, S. L., Waugh, C. D., Roach, C. G., Fynn, D., & Phillips, J. (2013). Are diverse species mixtures better pastures for dairy farming? *Proceedings of the New Zealand Grassland Association*, *75*, 79–84.

White, P.J., & Brown, P.H. (2010). Plant nutrition for sustainable development and global health. *Annals of Botany, 105*, 1073–1080.

Zhu, X. G., Long, S. P., & Ort, D. R. (2008). What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Current Opinion in Biotechnology*, *19*(2), 153–159.

APPENDICES

Table 1 Total drymatter production (tDM/ha) from seven harvests of experiment one.

Treatment	Initial site (1a)	Repeat site (1b)
Control	11.5	10.6
Solid urea / irrigated two days after application	13.2	12.0
Dissolved urea / immediately irrigated	13.2	11.9
Solid urea/ immediately irrigated	13.4	12.4

Table 2 Total drymatter production (tDM/ha) from seven harvests of experiment two.

Treatment	Initial site (2a)	Repeat site (2b)
Control	10.4	9.7
Dissolved urea /monthly	12.5	11.4
Dissolved urea/weekly	12.0	11.1

Table 3 Soil tests measured down to 75mm depth over the two field sites, initial (site 1) and repeated (site 2).

Soil Analysis Results							
	Sample Name:	Site 1 1/3 75	Site 1 2/3 75	Site 1 3/3 75	Site 2 1/3 75	Site 2 2/3 75	Site 2 3/3 75
	Lab Number:	2235992.1	2235992.2	2235992.3	2235992.4	2235992.5	2235992.6
	Sample Type:	SOIL Arable	SOIL Arable	SOIL Arable	SOIL Arable	SOIL Arable	SOIL Arable
	Sample Type Code:	S56	S56	S56	S56	S56	S56
pH	pH Units	6.2	6.2	6.2	6.3	6.1	6.3
Olsen Phosphorus	mg/L	49	40	47	10	8	9
Anion Storage Capacity*	%	20	21	22	14	16	14
Potassium	me/100g	1.70	1.33	1.63	0.39	0.38	0.35
Potassium	%BS	11.9	10.3	11.5	3.4	3.4	3.3
Potassium	MAF units	32	25	32	9	9	8
Calcium	me/100g	6.6	6.0	6.3	6.7	6.3	6.3
Calcium	%BS	46	47	44	59	56	59
Calcium	MAF units	8	7	7	9	9	9
Magnesium	me/100g	1.66	1.67	1.82	0.62	0.62	0.59
Magnesium	%BS	11.6	13.0	12.8	5.5	5.5	5.4
Magnesium	MAF units	34	35	39	16	16	15
Sodium	me/100g	0.11	0.11	0.12	0.14	0.13	0.14
Sodium	%BS	0.7	0.8	0.8	1.2	1.1	1.3
Sodium	MAF units	5	5	5	7	7	7
CEC	me/100g	14	13	14	11	11	11
Total Base Saturation	%	70	71	69	69	66	69
Volume Weight	g/mL	0.92	0.93	0.95	1.14	1.11	1.13
Sulphate Sulphur	mg/kg	5	3	4	3	4	6
Extractable Organic Sulphur*	mg/kg	6	6	6	3	3	3
Aluminium ($CaCl_2$ Extractable)	mg/kg	0.5	0.5	0.5	0.6	0.9	0.7
Boron	mg/kg	0.8	0.7	0.7	0.5	0.5	0.4
Ammonium-N*	mg/kg	16	15	61	11	10	12
Nitrate-N*	mg/kg	6	4	16	4	4	3
Mineral N (sum)*	mg/kg	22	19	78	15	14	16
Total Nitrogen*	%	0.33	0.32	0.33	0.22	0.24	0.21
Dry Matter*	%	74.3	76.6	74.7	78.4	78.7	78.7
Moisture*	%	25.7	23.4	25.3	21.6	21.3	21.3