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**COMPARING NUTRIENT LEACHING BETWEEN STANDARD AND DIVERSE
PASTURE UNDER SHEEP GRAZING**

A thesis presented in partial fulfilment of the requirements

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ABSTRACT

Current intensive sheep farming in New Zealand has led farmers to focus on improving economic outcomes based on production. Thus, in such an environment, there is a potential risk to contaminate soil and waterways with nutrients, more specifically as nitrate. However, there is lack of knowledge on nitrate leaching in modern sheep farming systems, particularly in the context of using perennial diverse pasture mixes coupled with regenerative pasture management practices. The objective of this study was to compare the nitrate leaching concentrations and quantify nutrient losses in both diverse pasture and standard pasture systems under regenerative pasture management and contemporary pasture management over one year from January to December 2023.

This study was conducted on a poorly-drained, fine-textured Tokomaru silt loam soil at Massey University's Whenua Haumanu sheep farmlet study located at the Pasture Crop Research Unit, near Palmerston North, Manawatū, New Zealand. The study design was a randomised complete block design containing eight drainage paddocks (each approximately 0.25 ha) including two pasture types (standard and diverse) and two management practices (contemporary and regenerative) each with two replicates. Each paddock had an independent mole-pipe drainage system. Standard pasture treatments were sown with perennial ryegrass (*Lolium perenne*), white clover (*Trifolium repens*) and red clover (*Trifolium pratense*) and diverse pasture treatments were sown with a mix of 21 species which resulted in six dominant species including perennial ryegrass, cocksfoot (*Dactylis glomerata*), white clover, red clover, plantain (*Plantago lanceolata*) and chicory (*Cichorium intybus*). Regenerative pasture management treatments were managed with longer grazing intervals, higher post-grazing residuals and low to no mineral fertiliser and chemical use while contemporary pasture management treatments followed the Beef and Lamb New Zealand best practice grazing advice for sheep and used mineral fertiliser and chemicals as required. The drainage volume and concentrations of nitrate-N, nitrite-N, ammonium-N and dissolved reactive phosphorus (DRP) in each drainage paddock were measured to estimate the nutrient loads. In addition, pasture growth rate and accumulated dry matter mass were monitored along with botanical composition.

Due to improper functioning of one of the drainage pipes, the data from one replicate was not usable, so the data were analysed by comparing pasture types and ignored the effect of management type.

The measured total cumulative drainage (mm) was higher ($p < 0.05$) in diverse pasture treatment than the standard pasture treatment. The total loads of nitrate (kg N/ha) were higher ($p > 0.05$) in standard pasture treatments (1.04 kg N/ha) than in diverse pasture treatments (0.73 kg N/ha). The diverse pasture treatment had visually greater pasture growth and accumulated dry matter yield, and greater herb contents than the standard pasture treatments which likely caused the numerically lower nitrate concentrations observed in the diverse pasture treatments than the standard pasture treatments. Overall, the measured loads of nitrate-N, nitrite-N ammonium-N and DRP in both treatments were very small (< 1.0 kg /ha). These low loads in contaminants were likely because all the drainage paddocks were not grazed until late autumn as they were cut for hay and then allowed to recover early in the year. Therefore, the amount of urinary N loading that occurred during late summer, early autumn would have been minimal. Overall, diverse pastures have the potential to reduce nitrate leaching in sheep grazing systems.

Key words: Intensive sheep farming, mole-pipe drain system, perennial diverse pastures, regenerative pasture management, nitrate leaching

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Dedicated to my beloved family....

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COMMON ABBREVIATIONS

The abbreviations are defined at the first use and then without definition throughout this dissertation.

Ca	Calcium
CEC	Cation exchange capacity
CEL	Central Environmental Laboratories
Div-Con	Diverse pasture and contemporary management
Div-Reg	Diverse pasture and regenerative management
DM	Dry matter
DRP	Dissolved reactive phosphorus
K	Potassium
MAF	Ministry for agriculture and fisheries
Mg	Magnesium
N	Nitrogen
Na	Sodium
NIWA	National Institute of Water and Atmospheric Research
P	Phosphorus
PCRU	Pasture Crop Research Unit
RCBD	Randomised complete block design
RGWC	Perennial ryegrass and white clover mix
SIN	Soluble inorganic nitrogen
Std-Con	Standard pasture and contemporary management
Std-Reg	Standard pasture and regenerative management

CHAPTER 1: INTRODUCTION

Sheep farming is a leading industry in New Zealand which contributes to the export market for meat and wool production (McCoard et al., 2023). New Zealand accounts for approximately 47% of the global lamb meat trade and is considered one of the world's largest lamb meat exporters (Morris, 2009). Hence, sheep farming is one of the main drivers of New Zealand's economy. To remain economically viable, present intensive sheep farming has intensified with higher stocking rates and improved efficiency with greater use of fertiliser and irrigation resulting in improved pasture production with the overall aim of maximising animal production per unit area (Morris & Kenyon, 2014; Morris, 2017). Therefore, in such an environment, there is a potential risk to contaminate soil and waterways with nutrients.

At present, there is an increased concern about the contamination of waterways with nutrients, specifically nitrogen (N) and phosphorus (P) (Hoogendoorn et al., 2017; Ministry for the Environment, 2020). Nitrate is the most prevalent type of N in drainage water leached from grazed pastures (Haynes & Williams, 1993) and minor contaminants like nitrite (NO_2^-), ammonium (NH_4^+) and dissolved reactive phosphorus (DRP) can also be present (Di & Cameron, 2002). Livestock urine patches are regarded as the primary source of nitrate leaching from a pastoral system (Williams & Haynes, 1994). The surplus nitrate not taken up by plants easily leaches with drainage water into the soil profile (Haynes & Williams, 1993) and contaminates ground and surface water (Ruz-Jerez et al., 1995; Silva et al., 2000). It has been found that higher nitrate concentrations (>11.3 mg N/L) in water can be harmful to human health and aquatic life (Di & Cameron, 2002; Ministry of Health, 2008). Furthermore, even low nitrate concentrations can stimulate biological growth, leading to eutrophication and water quality degradation in surface water bodies (Di & Cameron, 2002; McDowell et al., 2021). Therefore, the implementation of mitigation practices is critical within the pastoral system.

The most commonly sown standard pasture type in New Zealand sheep farms is a mix of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) (RGWC) (Kemp, 1999; Ledgard et al., 2009), hereon termed standard pastures. Additionally, there is a growing interest in the use of on multi-species pastures or diverse pastures which comprises a mix of herbs and legumes, including plantain (*Plantago lanceolata*), chicory (*Cichorium intybus*), red clover (*Trifolium pratense*) and white clover combined with perennial and annual grass species (Bryant et al., 2017; Daly et al., 1996; Goh & Bruce, 2005; Pembleton et al., 2015; Ruz-Jerez

et al., 1991). Moreover, many current intensive sheep farms utilise standard pastures which are managed under conventional/contemporary management and rely on synthetic inputs to maintain productivity (Distel et al., 2020; Gray, 2023). Regenerative pasture management is a growing concept in New Zealand (Rowarth et al., 2020), which focuses mainly on preserving pasture fertility through less synthetic fertiliser use, extended rest periods for plants, and maintaining wider pasture species diversity (Grelet et al., 2021; Tozer et al., 2022).

The effects of nitrate leaching on water quality under different pasture-soil systems and mitigation practices have been widely documented in the context of dairy farming in New Zealand (Cameron et al., 2013; Christensen et al., 2019; Dalley et al., 2017; Malcolm et al., 2014; Nguyen et al., 2023). In contrast, the understanding of nitrate leaching in current sheep farming systems is very limited in New Zealand. Further, most of the nitrate loss mitigation practices applied in dairy systems do not fit easily into sheep farming systems due to the differences in management and issues with economic viability (Anastasiadis et al., 2012).

A few recent studies have focused on mitigating nitrate leaching under intensive sheep farming systems by utilising alternative forages (Algharibeh, 2024; Maheswaran et al., 2023). These studies have focussed on investigating the benefits of short-term forage mixtures, such as Italian ryegrass (*Lolium multiflorum Lam*) and plantain, compared to RGWC (Algharibeh, 2024; Maheswaran et al., 2023). In New Zealand, no previous studies have looked at the effect of perennial diverse pasture mixtures or regenerative pasture management on nutrient leaching under intensive sheep farming systems.

The research objective of this study is to compare nitrate leaching losses and drainage water quality via nitrite-N, ammonium-N, soluble inorganic N (SIN) and DRP in both diverse and standard pasture systems under regenerative pasture management and contemporary pasture management in sheep grazing.

CHAPTER 2: LITERATURE REVIEW

2.1 Sheep farming in New Zealand

Sheep farming in New Zealand currently produces approximately 341,000 tonnes of sheep meat and 128,800 tonnes of wool annually (Beef+Lamb-NewZealand-EconomicService, 2023) and makes an important contribution to the export market for meat and wool production (McCoard et al., 2023). New Zealand accounts for approximately 47% of the global lamb trade, thus being one of the world's largest exporters of lamb (Morris, 2009). Moreover, New Zealand produces nearly 12% of global wool output on a "clean" basis, making it the third-largest producer in the world (Morris, 2017). Subsequently, sheep farming contributes significantly to the economy of New Zealand through employment along the entire value chain and revenues from product sales locally and internationally (Johnson et al., 2022).

Historically, the total number of sheep in New Zealand peaked at 70 million (in 1982), but it gradually decreased, to 25.7 million in 2021/2022 (Beef+Lamb-NewZealand-EconomicService, 2023). However, overall, the production of lamb has not decreased accordingly (Figure 2.1).

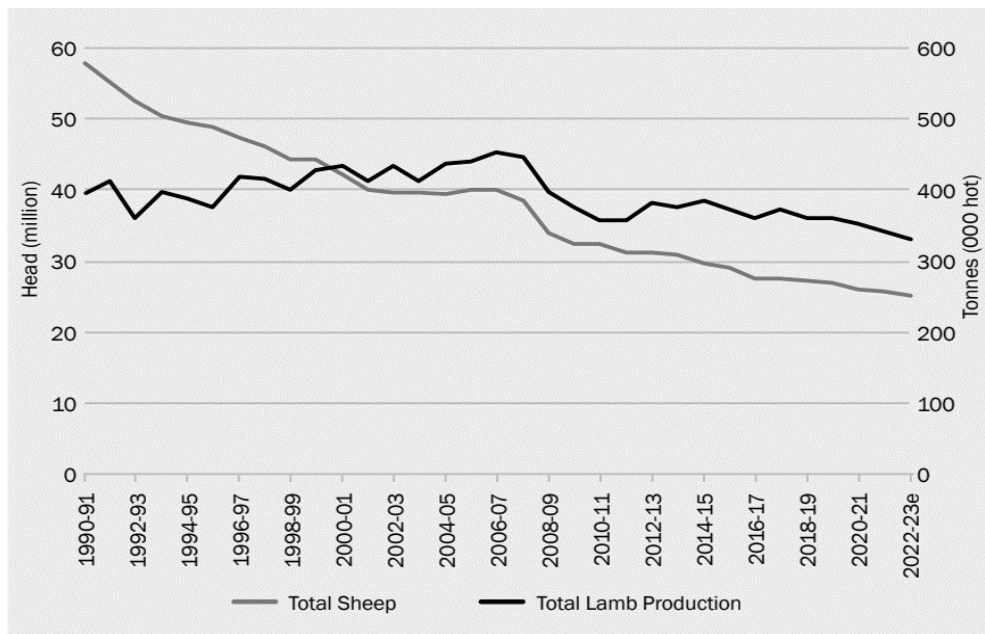


Figure 2.1 Total sheep and lamb production (domestic) in New Zealand between 1990 and 2023 (sourced from Beef+Lamb-NewZealand-EconomicService (2023)).

* Hot- refers to the hot carcass weight at slaughter, 2022-2023e refer to projected values at the time of publication.

This is due to a significant improvement in the lambing performance of ewes and an increase in the carcass weight of lambs over this same period (Table 2.1). This has resulted in an increase in lamb production efficiency (kg carcass weight/ ewe) by 114% from 1991/1992 to 2021/2022 (Table 2.1). This explain that even though the total number of sheep has decreased, the improvement in individual sheep performance has maintained New Zealand’s total lamb production (Morris & Kenyon, 2014).

Table 2.1 New Zealand sheep production: a comparison between 1990–1991 and 2021–2022.

Sheep productivity	Unit	1990/1991	2021/2022	Change
Lamb performance	Lambs/100 ewes	102	127	+24%
Lamb weight	kg/head	13.9	19.0	+37%
Lamb production	kg/ewe	9.8	20.9	+114%
Wool production	kg/head	5.3	5.0	- 6%

Source: Beef+Lamb New Zealand Economic Service (2023).

2.1.1 Management systems of sheep farming

New Zealand grasslands can be categorised into three major groups as, high, hill, and flat to rolling country based on topography and elevation (Hodgson et al., 2019). Typical sheep farming in New Zealand is extensive in nature, where sheep are raised on high or hill topographies at stocking rates of 7–12 sheep per hectare, without housing or additional feed (Morris, 2013). The high country is mostly utilised for sheep farming based on the production of fine wool and is characterised by high topography and low pasture production, particularly during the cold winter months (Morris, 2013). Large numbers of sheep may typically be supported on flat to rolling country with adequate grass production throughout the year (Morris, 2013).

2.1.2 Modern intensive sheep farming

Modern intensive sheep farming In New Zealand is mainly distinguished by genetic improvements and modifications, to widen the production (Rohloff, 1992). Furthermore, these systems commonly involve high fertiliser, irrigation, pasture production, and grazing pressure, aiming for high animal production per unit area. (Morris & Kenyon, 2014). A considerable

part of this intensification has been accomplished by raising soil fertility levels and using improved pasture species and management techniques (Caradus et al., 2023). Hence, in such an environment, sheep farming will likely have a greater influence on the soil nutrient dynamics and the surrounding ecosystem.

Thus, the ecosystems, sustainability, and reputation of agricultural output are all potentially at risk from the ongoing intensification of New Zealand's pastoral systems (Caradus et al., 2023). Therefore, as a remedy, technologies and systems that support and safeguard sustainable land use and ensure resource use have been brought forward (Moller et al., 2008).

2.2 Pasture systems in sheep farming

2.2.1 Standard pasture system

New Zealand's pastoral agricultural systems are simple, with RGWC pasture swards being the most common species planted (Woodward et al., 2013). This RGWC combination is dominant due to high nutritional content, rapid establishment, high productivity, and well-understood grazing management requirements (Fulkerson & Donaghy, 2001).

These RGWC pastures has long formed the foundation of standard pastoral systems in sheep farming in New Zealand (Kemp, 1999). They are very effective on a production basis in pastoral agriculture in Australasia and are typically considered sustainable livestock production systems (Goh & Bruce, 2005). It is generally accepted that white clover gives New Zealand pastoral agriculture its primary competitive edge (Brock & Hay, 1996), by combining the benefits of high-quality forage and biological N fixation, which enhance animal performances (Caradus et al., 1995).

Although this combination has proven to be a very effective production basis for the pastoral sector of New Zealand, its widespread use has resulted in certain drawbacks (Daly et al., 1996). For instance, limited rainfall and high soil temperatures disfavour RGWC, despite their ability to withstand a variety of grazing conditions and environments (MacFarlane, 1990). This means pasture growth and production is limited during dry periods of the year, including summer and autumn (Matthews et al., 1999). Furthermore, these RGWC have been identified by a high solubility crude protein content, usually exceeding 20% of dry matter (DM), which causes considerable quantities of dietary N to be excreted in the urine (Beukes et al., 2014; Litherland & Lambert, 2007).

In this regard, it has been found that more complex mixes or diverse pastures, also known as mixed-herb leys (Woodward & Foster, 1988), have the potential to address some of the problems commonly associated with RGWC (Daly et al., 1996).

2.2.2 Diverse pasture system

The term, multi-species pastures or diverse pasture is commonly used to describe a mix of herb, legume, and grass species, containing a major proportion of grass and minor proportions of other species including herbs and legumes, like plantain, chicory, red clover and white clover (Bryant et al., 2017; Daly et al., 1996; Goh & Bruce, 2005; Pembleton et al., 2015; Ruz-Jerez et al., 1991). This system combines a mix of species with different root architecture and growth patterns (Charlton & Stewart, 1999; Nobilly et al., 2013; Woodward et al., 2013). (Table 2.2).

Diverse pastures have been found to be more advantageous compared to conventional RGWC pastures (Goh & Bruce, 2005). A study in Canterbury, New Zealand, under sheep grazing pastures, with a mix of grasses and herbs (chicory and plantain) yielded significantly higher herbage than standard RGWC pastures (Daly et al., 1996). Especially in dryland areas, sheep and cattle farmers are using herb and clover mixtures of chicory, plantain, red clover, and white clover as specialised summer active perennial swards to obtain higher yields (Cranston et al., 2015; Kemp et al., 2010) and to retain excellent nutrient composition in warm summers (Lee et al., 2015). Somasiri (2014), observed these herb and clover mixes had a high nutritive value with lower fibre content, higher metabolisable energy and organic matter digestibility compared to standard pastures. However, when chicory and plantain are grazed during winter, their persistence decreases considerably (Ayala et al., 2011; Kemp et al., 2015).

Table 2.2 Summarised features of main pasture species sown in standard and diverse pasture systems in New Zealand pastoral farming. Information adopted from (Beukes et al., 2014; Charlton & Stewart, 1999; Nguyen et al., 2022).

Pasture Type	Species	Common name	Important characteristics
Grasses	<i>Lolium perenne</i> L.	Perennial ryegrass	Easy establishment and management, persists well under grazing conditions.
	(bred from perennial ryegrass x Italian ryegrass)	Hybrid ryegrasses	High yield of larger-leaved forages
	<i>Dactylis glomerata</i> L.	Cocksfoot	High productivity, drought tolerance
	<i>Phleum pratense</i> L.	Timothy	Low drought tolerance. High quality palatable pasture
Legumes	<i>Trifolium repens</i> L.	White clover	High quality herbage, classified according to the leaf size (large/medium and small leaved)
	<i>Trifolium pratense</i> L.	Red clover	Excellent performance in mixed pastures
	<i>Trifolium subterraneum</i> L.	Subterranean clover	Grow well in dry summers
	<i>Trifolium fragiferum</i> L.	Strawberry clover	Thrives on saline soils, close to sea or river estuaries
Herbs	<i>Lotus pedunculatus</i>	Lotus	Thrives in wet acidic, infertile situations under lighter grazing pressure.
	<i>Cichorium intybus</i> L.	Chicory	Moderately persistent, leafy herb with a deep taproot. Yields high quality feed in dry weather and has the potential to reduce nitrates leaching.
	<i>Plantago lanceolata</i> L.	Plantain	Performs well in a range of pastures, particularly with less fertile. Rapid establishment, erect growing nature, drought tolerant and reduces urinary-N in animals and resulting in lower nitrate leaching.

2.3 Nutrient transformation processes in grazed pastures

2.3.1 N cycling in pasture swards

The major N dynamics in a grazing system include animal intake of above-ground biomass, nutrient removal via animal products like milk, meat, and wool, nutrient dispersal through unequal excreta deposition, and gaseous and leaching/runoff nutrient losses (Figure 2.2) (Saggar et al., 2013; Williams & Haynes, 1990). In addition to that, N is added to the system via symbiotic N fixation in association with legume-based pastures and N fertilisers, which depend upon the intensity of the production system (Saggar et al., 2013).

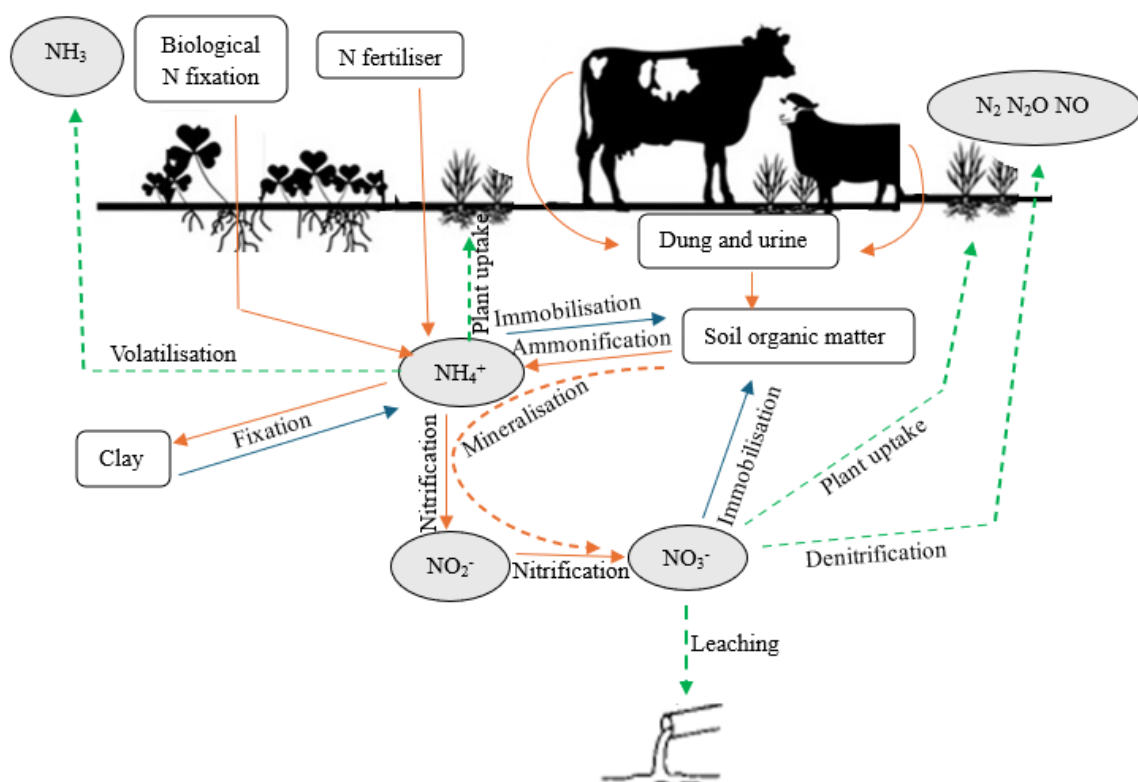


Figure 2.2 Structure of N dynamics in legume-based grazed pastures. Redrawn from Cameron et al. (2013); Saggar et al. (2013).

N fixation

The symbiotic N fixation process occurs only in legume-based pastures, by converting atmospheric N to ammonia (NH_3) and ammonium by the bacteria possessing nitrogenase enzyme, in legume root nodules (Ball & Ryden, 1984; Lazenby, 2019). Additionally, soil free living bacteria like *Asospirillum*, *Azotobactor* also can fix N, by using the nitrogenase enzyme to break down atmospheric N into ammonium (Reid et al., 2024).

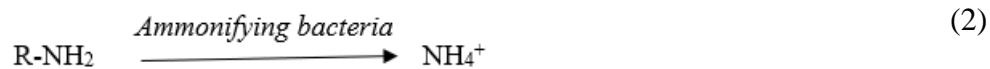


Mineralisation

The process of transforming organic nitrogenous compounds and dead organisms into inorganic N is known as mineralisation. This microbial-mediated process consists of two main steps called ammonification and nitrification, which typically take place under warm and moist soil conditions (Cameron et al., 2013). The inorganic ions formed through mineralisation in pasture soils can undergo several paths including being taken up by plants (as nitrates and ammonium), adsorbed onto colloids, immobilised, oxidised, reduced or leached away (as nitrates). (Carran, 1978).

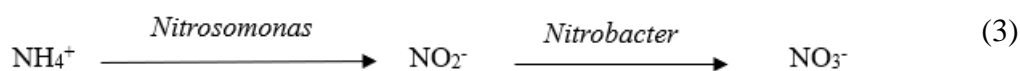
Ammonification

The biological conversion of soil organic N (present in plant residues, dead animals, urine, and dung) into ammonia and ammonium is known as ammonification (Saggar et al., 2004). Ammonium produced in the nitrification process are available to go through different processes including uptake by the plants, denitrification and leaching losses (Cameron et al., 2013).



Nitrification

An oxidation process carried out by nitrifying bacteria, transforms ammonium into nitrites and further into nitrates (Cameron et al., 2013).



Nitrates produced in the nitrification process are available to go through different processes including uptake by the plants, denitrification and leaching losses. Nitrate, being an anion, is weakly adsorbed to soil particles and more vulnerable to leaching from the soil profile compared to ammonium (Bolan et al., 2004; Hoogendoorn et al., 2011).

Immobilisation

Immobilisation is the process of converting inorganic N forms, like nitrate and ammonium into organic N. Here inorganic N, which is taken up by plants and assimilated into plant tissue compounds and after being ingested by animals deposited back as complex N (amino acids and

proteins) (Lazenby, 2019). Also, microorganisms assimilate inorganic N to create proteins and other organic N compounds (Myrold & Bottomley, 2008).

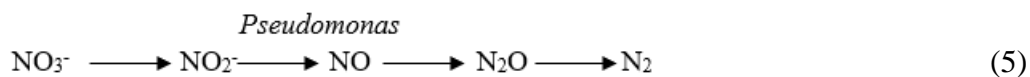
Volatilisation

Ammonium is converted back to ammonia gas and released into the atmosphere. It has been found that, soon after a urination event, significant losses of ammonia occur from a urine patch (Haynes & Williams, 1993).



Denitrification

Reduction of bioavailable N (nitrates or nitrites) by denitrifying bacteria under anaerobic (waterlogged) conditions into gaseous forms (nitrous oxide (NO), dinitrogen oxide (N₂O) and N₂), followed by multiple steps (Phillips et al., 2015).



2.3.2 P cycling in pasture swards

Phosphorus is mainly added to pasture soils via fertilisers or recycled to the soil surface via dung or effluent. In New Zealand, mineral fertiliser is considered the major source of P input to pasture soils (McDowell et al., 2008). Phosphate ions are strongly sorbed to the surfaces of the soil particles, particularly in New Zealand soils (Monaghan et al., 2007). As a result, P is less likely to leach through the soil profile and more prone to exit the system through surface runoff (Monaghan & Smith, 2004). However, some P leaching does occur, particularly in soils which have low P sorption or retention capacities or are artificially drained (McDowell, et al., 2008).

As New Zealand soils are naturally low in P, P fertiliser application is essential to maintain the productivity of the system. Hence, pastoral lands are applied with regular P fertilisers to maintain the optimum plant available P levels in soils (Roberts & Morton, 1999). These soluble P fertilisers increase the , the soluble plant-available forms of P in soil that are prone to loss via surface runoff or leaching in the form of DRP (Hansen et al., 2002).

2.4 Nitrate leaching under sheep farming

Nitrogen losses in drainage and runoff from pastoral grazing systems are a significant environmental concern in many agricultural countries (Di & Cameron, 2002; Ruz-Jerez et al., 1995). Nitrate is the most prevalent type of N in drainage water, and it is considered as a potential water contaminant (Haynes & Williams, 1993). Leaching only occurs when precipitation is more than evapotranspiration and soil moisture level exceeds the soil field capacity (Garwood & Ryden, 1986). Hence, in temperate countries like NZ, leaching is common in winter and spring (drainage season) when high rainfall occurs (Hoogendoorn et al., 2017).

In general, nitrate leaching is generally believed to be significantly less in sheep farming than in dairy cow systems (Hoogendoorn et al., 2010; Williams & Haynes, 1994). However, current sheep production systems in NZ have intensified over time and N fertiliser inputs per unit area are comparatively higher than in the past (Morris & Kenyon, 2014). As a result, sheep farming has the potential to negatively affect NZ water systems.

Therefore, knowledge on adverse impacts, suitable measuring methods, sources, and factors affecting nitrate leaching is important for reducing potential leaching rates in intensive sheep farming under different pasture systems, and mitigation measures will be beneficial.

2.4.1 Impacts of nitrate leaching

Over the past fifty years, agricultural production has intensified, resulting in the application of P and N fertilisers and organic wastes and thereby increased stocking rates, which has led to a serious concern globally about nitrate leaching and water contamination (Di & Cameron, 2002). In developed nations, including New Zealand, where agricultural production has shown to be economically viable through a widespread utilisation of N fertilisers and livestock wastes, the issues of nitrate leaching and surface and groundwater contamination have become particularly critical (Cameron et al., 1997; Morgenstern & Daughney, 2012; Quinn et al., 2009; Spalding & Exner, 1993). It is commonly recognised in New Zealand that the livestock industry generates the most N load per hectare annually compared to other industries (Monaghan et al., 2007). When soil N concentrations are higher than those required by plants, during wet weather, a significant amount of this N leaches into groundwater and subsequently into surface water (Di & Cameron, 2002). Hence, nitrate leaching from pastoral lands is considered an important non-point source of contamination to fresh water (Magesan et al., 1996).

2.4.1.1 Water quality

Eutrophication is a widespread serious environmental concern and occurs when excess nutrients are present in a water body, which causes an overgrowth or bloom of plants, plankton or algae (McDowell & Hamilton, 2013; Payen & Ledgard, 2017), which leads to the depletion of dissolved oxygen in the aquatic system, resulting in an unsuitable habitat for many fish and native organisms (Gibbs et al., 2011). Moreover, the floating mats of growths reduce sunlight penetration and the water turbulence, resulting in the killing of fish and other invertebrates, subsequently developing a bad odour and colour, therefore destroying the aesthetic value of the entire water body. (Abell et al., 2010). Hence, the eutrophication process destroys the balance of natural aquatic ecosystems and biodiversity (Di & Cameron, 2002). This is a serious concern, as poor water quality affects several key economic sectors that depend on this resource, such as drinking water, crop and orchard irrigation, and recreational uses (Holland & Doole, 2014). Nitrate leaching can directly contaminate ground water, which is a serious concern if this water is used for drinking or discharges into sensitive waterways (Baskaran et al., 2009).

2.4.1.2 Human health

Nitrate-contaminated groundwater is considered unsafe for human consumption. A maximum concentration of nitrate in drinking water, 11.3 mg/L is recommended by the World Health Organisation (WHO) and national health organisations to safeguard human health (Ministry of Health, 2008). In New Zealand, 5% of monitoring sites exceeded the 11.3 mg/L, which is higher than the safe drinking water standard (Ministry for Environment, 2007).

Elevated concentrations of nitrate in drinking water are considered detrimental to human health, especially for infants under one year of age, by obstructing the oxygen transport in the blood, leading to methemoglobinemia, commonly referred to, as "blue-baby syndrome" (Di & Cameron, 2002). Moreover, high nitrate levels in the human body have been found to cause, thyroid disease and a range of cancers, particularly colorectal (Tanner, 2024).

Therefore, nitrate loss from agricultural systems is a significant public concern in New Zealand (Larned et al., 2016). As a result, the National Policy Statement for Freshwater Management (NPSFM) has set out objectives, policies and guidelines for managing freshwater resources to conserve water quality (Ministry for the Environment, 2020)

2.4.2 Methods of measuring nitrate leaching

In New Zealand, soil drainage and nutrient loss measurements are vital, as contamination due to nutrient leaching is a growing issue (Dennis, 2020). Since drainage takes place beneath the soil's surface, it is invisible and varies in response to uneven nutrient inputs (e.g., animal urine and faeces) and irregular water distribution (Moir et al., 2011). Also, as it is not practical to record drainage from a whole paddock, particular areas must be sampled for drainage and nutrient loss, which is then used to estimate loss from the paddock or plot. Therefore, the process of collecting and measuring drainage remains complex and expensive (Dennis, 2020).

There are common methods (lysimeters, suction cups, and mole-pipe drains) used to measure nutrient leaching in pastoral drainage water (Wang et al., 2012; Webster et al., 1993; Zotarelli et al., 2007) and the suitability of the method depends on the soil type (Watkins & Shepherd, 2013). According to previous research, the most common methods for assessing nitrate leaching from free-draining soil was using lysimeters (Hoogendoorn et al., 2017; Monaghan et al., 1989) and ceramic suction cup samplers (Wang et al., 2012). Table 2.3 summarises the mechanism of lysimeter and suction cup methods in pastoral farming.

Lysimeter and suction cups

When comparing lysimeters and suction cups, both comprise advantages and drawbacks according to their use and purpose (Wang et al., 2012; Webster et al., 1993). Lysimeters measure a larger volume of leachate, which enables a more representative sample of the ambient soil environment and also, lysimeters collect water from undisturbed soil (Wang et al., 2012). Moreover, the load of nitrate (kg) loss can be measured via lysimeters, as they measure both the nitrate concentration and the drainage volume. Comparatively, the installation and operation of suction cups are easy and have a low capital cost (Webster et al., 1993). Additionally, if required, continuous sampling across the particular soil profile can be done at various depths (Grossmann & Udluft, 1991). However, there is a chance that the soil solution might bypass the porous cups via macropores (Barbee & Brown, 1986), or if a macropore is intercepted, the applied suction could result in a preferential flow in the upward direction of the cup (Fares et al. 2009). Moreover, suction cups only measure the nitrate concentration in the soil solution at specific soil depths and times (Wang et al., 2012). Furthermore, it is uncertain what quantities of cups are required to deal with spatial heterogeneity (Macduff et al., 1990). Consequently, it is challenging to identify the precise composition of the soil

solution in suction cups and therefore the methods present considerable challenges (Barbee & Brown, 1986).

Mole and pipe drains

Measurement of nitrate leaching from poorly or imperfectly drained soils is commonly achieved using, mole and pipe drains (Christensen et al., 2019; Heng et al., 1991; Magesan et al., 1996; Maheswaran et al., 2022). Mole-pipe drains allow the hydrological isolation of plots or paddocks by isolating drainage from designated areas and directing this drainage to a device to measure the volume (Dennis, 2020; Monaghan & Smith, 2004).

Mole channels are pulled through the soil using a mole plough pulled behind a powerful tractor to create a channel which is ~ 45 cm deep and ~5 cm in diameter (Figure 2.3). The moles need to be pulled when the soil conditions are plastic enough to create moles that will be stable when the soil dries out. These moles are located 1.5-2 m apart (Monaghan et al., 2016) and feed in to backfilled gravel pipes to allow all of the water draining through the soil to be collected.

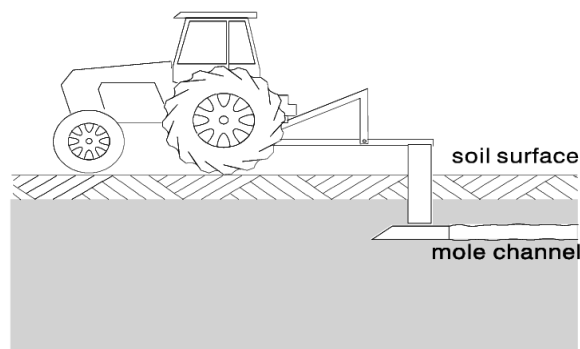


Figure 2.3 Construction of mole channels by a mole plough connected to a tractor. Adopted from (Ritzema, 2014)

Table 2.3 Common methods of measuring drainage in free draining soils using lysimeters and suction cups in pastoral farming.

Method	Principle	Area sampled by a single device	Leachate volume	Reference
Undisturbed soil monolith lysimeter / Intact column lysimeter	A cylinder captures soil water percolating vertically (drainage) in an enclosed soil column. Water moves towards the drainage outlets in the bottom and leachate is collected under of controlled suction.	0.5 m x 0.7 m (diameter x depth) (0.2-0.4) m ² surface area	~200 ml	(Di & Cameron, 2007) (Monaghan et al., 1989) (Cameron et al., 1992)
Trench Lysimeter/ Repacked Lysimeter	A below-ground large lysimeter with a horizontal wick at the lower soil profile, equipped with an autosampler, measures the drainage volume and nutrient concentration.	(10-20) m x (0.3-0.4) m x (0.7-1) m (length x width x depth) (4-10) m ² surface area		(Dennis, 2020) (Norris et al., 2016)
Ceramic cup	Soil water sampling is done manually by creating a vacuum within the ceramic porous cup by and collecting a sample ~24hrs later.	(13.5-22.2) mm x (30-130 cm)	Draws a volume of ~20-30 cm ³	(Grossmann & Udluft, 1991) (Webster et al., 1993) (Wang et al., 2012) (Ledgard, 1991)

These hydrological plots or paddocks collect drainage from a large area with minimal labour requirement and moreover can be automated (Dennis, 2020). Compared to lysimeters and suction cups, the variations in soil solution concentrations and the flow of water through the soil are low in the mole-pipe drainage systems (Heng et al., 1991). Subsequently, once mole and pipe drains are installed, the resulting drainage incorporates the temporal and spatial variability in the soil nitrate concentrations and provides accurate measures of nitrate leaching (Magesan et al., 1996).

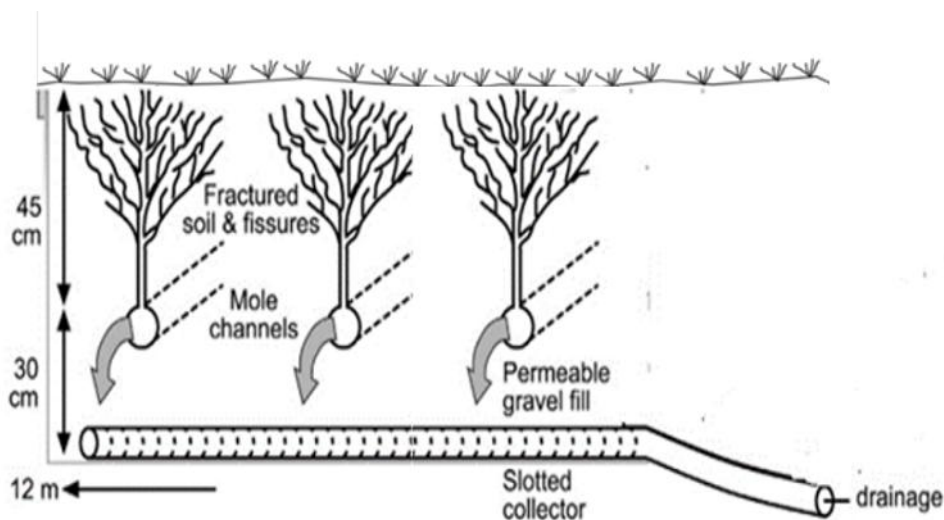


Figure 2.4 Structural view of a mole-pipe drainage system in a subsurface grassland (Monaghan et al., 2016).

Even though mole-pipe drainage is a rather inexpensive way to drain land, the gradual destruction of the mole network related to soil, climate, and management conditions usually necessitates re-moling the soil every five to twenty years (Monaghan et al., 2016).

When comparing the nitrate leaching loads under typical sheep grazing conditions, lysimeters and mole-pipe drains have reported a wide range of loads (Table 2.4) depending on the N sources and grazing management.

Table 2.4 A summary of reported nitrate-N leaching loads under sheep grazing subject to different treatments.

Location	Measurement method	Drainage depth (cm)	Soil type	N source rate and other factors	Leached nitrate amount (kg/ ha)	Reference
New Zealand	Lysimeter (diameter 50cm)	45	Silt loam	Urine application equivalent to 265 kg N/ha	19-37	Monaghan et al., 1989
New Zealand	Mole and pipe drains	45	Silt loam	N fertiliser application at 50 kg/ha 50-60 sheep grazed for a week	14.9-19.7	Heng et al., 1991
New Zealand	Mole and pipe drains	45	Silt loam	N fertiliser application at 50 kg/ha under intensive sheep grazing	43	Magesan et al., 1996
United Kingdom	Lysimeter (0.5 m ² surface area)	100-120	Fine loam	N fertiliser application at 152-197 kg/ha under continuous stocking of ewes and lambs	8-46	Cuttle et al., 1998
New Zealand	Lysimeter (diameter 50cm)	70	Silt loam	Urine application equivalent to 300 kg N/ha	60	Di & Cameron, 2007
New Zealand	Lysimeter (diameter 15cm)	100-200	Silty clay loam to clay loam	N fertiliser application at 0- 750 kg/ha under continuous stocking of ewes and lambs	47-368	Hoogendoorn et al., 2017
New Zealand	Mole and pipe drains	45	Silt loam	N fertiliser application at 30 kg/ha 14 ewes stocked/ha	1.5-9.7	Maheswaran et al., 2023

2.4.3 Sources of nitrate leaching

In New Zealand, livestock are commonly grazed outdoors year-round (Selbie et al., 2015; Wang et al., 2012). Therefore, animals spend most of their time on pastures and much of the N is recycled through grazing animals (Figure 1).

Nitrate leaching in a sheep grazing system mainly depends on the added N levels to the pastures via faeces and urine (Haynes & Williams, 1993). Since urine patches are where nitrate leaching primarily occurs, higher grazing intensities would result in higher herbage N being consumed and excreted in urine (Hoogendoorn et al., 2017). Legume pastures and N fertiliser inputs also contribute to sources of nitrate leaching (Hoogendoorn et al., 2017). In particular, grazing lands in New Zealand contain a legume component, commonly a clover or lotus species, capable of fixing N biologically, which can also contribute to leaching when soil nitrate levels exceed levels required for plant uptake (White & Hodgson, 2000). In New Zealand, there is minimal N fertiliser use in most sheep farms and therefore the impact is likely less compared to dairy farms (Haynes & Williams, 1993). In 2021-2022, across all sheep farms, the average N fertiliser usage accounted for 14.7 kg N/ha/year (Beef+Lamb-NewZealand-EconomicService, 2023).

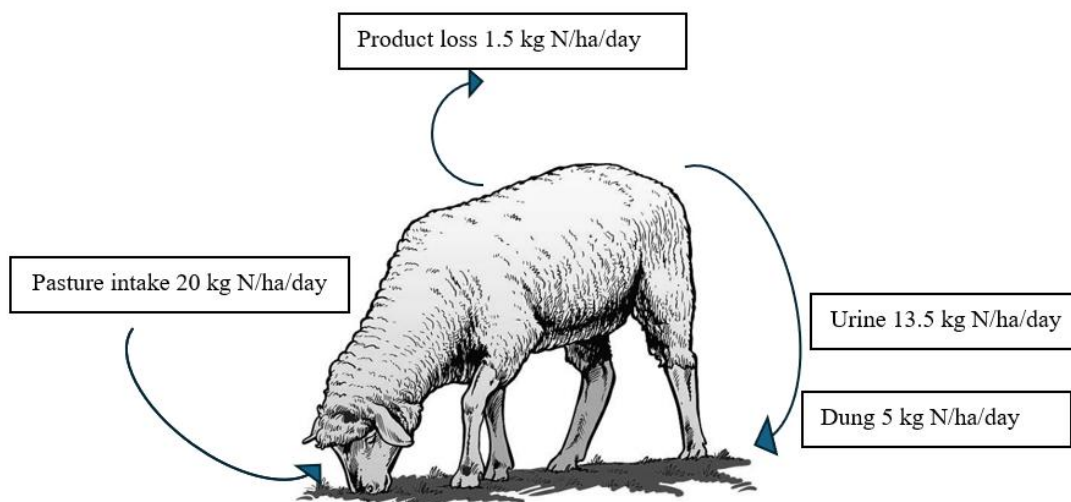


Figure 2.5 N cycling in a sheep grazing system, for a day's grazing assuming 533 sheep /ha grazing a total of 800 kg dry matter pasture/ha at 2.5 % N (20 kg N/ha/day) (Haynes & Williams, 1993). Re-drawn from Maheswaran et al. (2022).

Generally, the type of animal, the amount of dry matter it consumes, and the N concentration of the diet, all determine the proportion of total N intake which is excreted by the animal and how it is divided into urine and dung (Haynes & Williams, 1993). In most high-producing, intensive pasture systems, where animals consume large amounts of N, over half of the N is eliminated as urine (Figure 2.5) (Maheswaran et al., 2022). In fact, most of the organic forms of N in urine are quickly transformed into ammonium or nitrate ions after being added to the soil. These ions are then vulnerable to leaching and other soil processes including volatilisation and denitrification (Monaghan et al., 1989).

It is found that, the amount of N excreted in urine is greater than that in faeces (Whitehead, 1986). For instance, data for New Zealand sheep grazing in RGWC pastures showed approximately 70-80% of excreted N was present in urine (Barrow & Lambourne, 1962), (Hoogendoorn et al., 2010). Despite the amount of N in the feed, sheep usually excrete 0.8 g N/100g of dry matter ingested in their faeces (Barrow & Lambourne, 1962). Also, Barrow and Lambourne (1962), found that the content of the feed does not affect the N content excreted as dung (Figure 2.6). This means, the rest of the N is excreted as urine, and the amount of N in the urine rises in proportion to the amount of N in the diet.

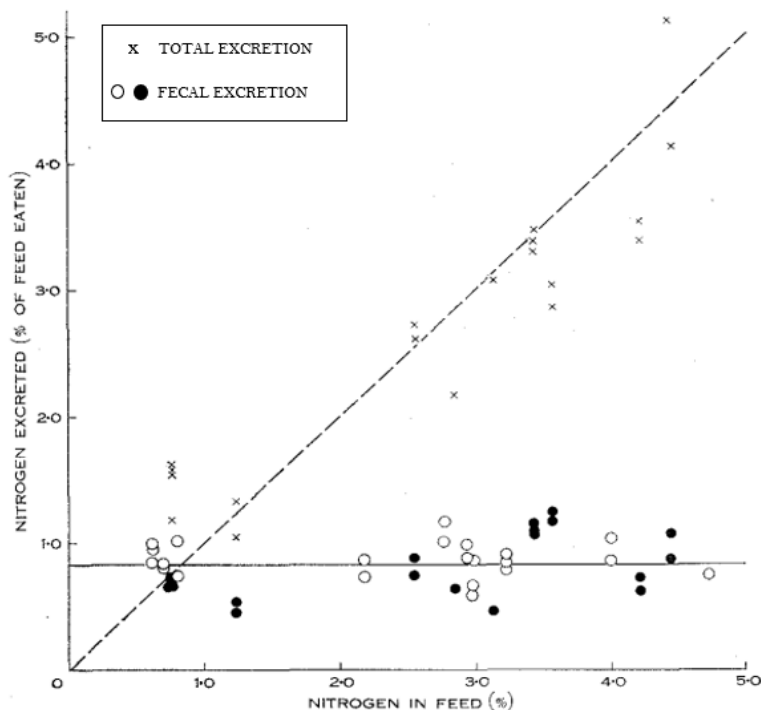


Figure 2.6 Relationship between the N content of the feed and excretion of N (g /100 g of feed eaten) of sheep (Barrow & Lambourne, 1962).

On the other hand, in faeces, most of the N is in organic form and lesser amounts are present as mineral N (Haynes & Williams, 1993). Because the N in faeces is found in more complex organic forms that do not mineralise as quickly (Whitehead, 1986), it does not significantly contribute to nitrate leaching. However, urine contains more readily available forms of N than dung (Selbie et al., 2015). Therefore, animal urine plays a major role in relation to nitrate leaching in grazed pastures.

2.4.3.1 Sheep urine patch

When a sheep urinates it returns a volume of urine to a small area which results in, ‘hot spots’ of potentially leachable nitrate (Magesan et al., 1996). These N returns, are biologically unstable, varied in space and highly concentrated (Ball & Ryden, 1984). The rate of N loading in urine patches frequently surpasses the pasture's N requirements, and the surplus N is susceptible to loss (Selbie et al., 2015). This means that animals spend more time grazing, which increases the amount of N lost through urination.

Generally, sheep urine patches accumulate N over time based on several factors, including the concentration of N in the urine, the frequency of urination, the volume of urine excreted during each urination event, and the size of the urine patch (Haynes & Williams, 1993; Hoogendoorn et al., 2010).

Urine N concentration

Whilst the N concentration in sheep urine varies considerably due to several factors, including the amount of N in the diet and water consumed, it generally ranges between 8-15 g N/L (Whitehead, 1970) and an analysis of published data showed N concentration ranges between 1-18 g N/L (Table 2.5). Usually, water intake helps to dilute the N in urine (Selbie et al., 2015). In addition to that, N concentration in urine, also changes according to the animal's reproductive status, season and time of the day (Hoogendoorn et al., 2010), (Betteridge et al., 1986).

Table 2.5 Characteristics of urine patches deposited by sheep on grazing pasture swards in New Zealand based on range of studies reported by Haynes & Williams (1993) and Selbie et al., (2015).

Reference	Urine N concentration (g N/L)	Urination volume (per event) (L)	Urination frequency (per day)	Urine patch area (wetted) (m ²)
Frame (1971)	7.0	0.10	17.5	
Robertson (1972)		0.15	20.0	
Bristow et al (1992)	3.0-13.7 *8.8			
Haynes & Williams (1993 b)	10.0	0.10-0.18 *0.15		0.03-0.05 *0.03
Hoogendoorn et al (2010)	1.4-17.8 *7.9			
Ledgard et al (2002)		0.5-3.0 *2.0	2.0	
Sherlock & Goh (1984)	5.0-15.0 *10.0			

* median

Among the many N compounds found in urine, urea makes up the majority of urinary N (Selbie et al., 2015). When the digestible N intake of the sheep increases, the N percentage of urea excreted also increases (Topps & Elliott, 1967). Likewise, even with a low-protein (N-25%) sheep diet, the N content of the urine-urea increases (Jarvis et al., 1995).

Frequency of urination

The concentration of nutrients in excreta alongside the frequency of excretions affects the amount and availability of nutrients returned to pasture in urine. In addition, excreted return

patterns are also important because they indicate how effectively nutrients can be recycled within the pasture system (Haynes & Williams, 1993). In particular, the water intake and the moisture content of pasture can hugely impact daily urinary frequency (Doak, 1952). There is limited data on the sheep urination frequency. However, research on sheep urination frequency under pastoral grazing has reported a range between 18-20 urination events per day (Betteridge et al., 2010; Haynes & Williams, 1993). In contrast, a study on ewes in grazed pasture and place pens (for 6 hours) has indicated a range of 8-12 urinary events per day (Marsden et al., 2020). Accordingly, the change in the grazing method can influence the daily urination events.

Furthermore, rates of sheep urination frequency vary according to the weather (Betteridge et al., 1986) and the season (Marsden et al., 2020). For instance, warmer weather causes animals to drink more water more often, and rain causes more water to stick to the pastures that animals consume (Marsden et al., 2020). Consequently, such environmental conditions can alter the urination frequency of animals. Further to that, Betteridge et al. (2010) mentioned that the time of the day can also influence urination frequency with sheep urination frequency being greater in the daytime than at night (Betteridge et al., 2010). Moreover, this study determined that the urination frequency of sheep increases as the day progresses, as urinary frequency began to rise at around 09:00 hours and peaked at 20:00 hours.

Volume and urine patch area

The volume of urine excreted by sheep is strongly related to the water intake and the temperature conditions (Betteridge et al., 1986; Pontius et al., 1932). On warmer days both water intake and urinary volumes are higher than on cooler days (Betteridge et al., 1986; Marsden et al., 2020). The volumes that are excreted influence the size of the surface area covered by urinations. According to William & Haynes (1994), urine patch volume changes according to surface area, moisture, water repellence, compaction, micro-topography, vegetation cover, slope, and wind.

However, due to the high cost and labour requirements of capturing urine in paddocks or under specific housing, urine volume is rarely monitored, particularly for individual urination events (Clark et al., 2010). The effective area of a urine patch includes the wetted area where urine is directly voided, and the space outside where plants can acquire urinary N through root expansion and soil diffusion (Lantinga et al., 1987; Tinker & Nye, 2000). This effective area is important in determining accurate N-removal processes (Selbie et al., 2015).

The covered surface area from a single urination event for sheep ranges from 0.03-0.05 m² (Table 2.6) and the depth of the urine patch recorded a maximum of 0.15m (Haynes & Williams, 1993; Williams & Haynes, 1994). The study used bromide to determine the shape and the size of the sheep urine patch by tracking the vertical and horizontal paths of urine flow in silt loam soil.

Urine patch N loading rate

The N loading rate (kg N/ha) is the amount of N deposited in a urine patch. It is calculated based on the urine concentration (g N/L), excreted urine volume (L), and the urine surface/patch area (m²) (Haynes & Williams, 1993).

$$\text{Urine N rate} = \text{Urea concentration} \times \frac{\text{Urea volume}}{\text{Surface area}} \times 10$$

According to Haynes and Williams (1993), they found, 500 kg N/ha of N loading rate for sheep, which consisted of urine N concentration of 10 g N/L, urination volume of 0.5 L, and urine patch surface area (wetted) of 0.1 m².

2.4.3.2 N fixing legume pastures

Legumes make major contributions to the entire N cycle and are a vital component of many grasslands. In fact, biological N fixation by white clover served as the foundation for many improved grazing systems in temperate regions, before the development of inexpensive mineral N fertilisers (Jarvis et al., 1995). Likewise, the productivity of much of New Zealand sheep farming is mostly dependent on N supplied initially by white clover (Brock & Hay, 1996; Ledgard, 1991). It is noted that, biological N fixation by clovers provides N to pastures (Ruz-Jerez et al., 1995) and also increases animal production by improving the feed quality of offer (J. Caradus et al., 2023).

Basically, legume pastures fix atmospheric N into ammonium by the *Rhizobium* bacteria that live symbiotically in the root nodules (Figure 2.7) and add N to the below-ground rhizosphere (Brock & Hay, 2001). Additionally, the transfer of fixed N below ground in grazed pastures is accomplished by either the direct excretion of N compounds from legume roots (Ledgard,

1991) or through the decomposition of legume nodules, roots, and senescing root material (Butler et al., 1959).

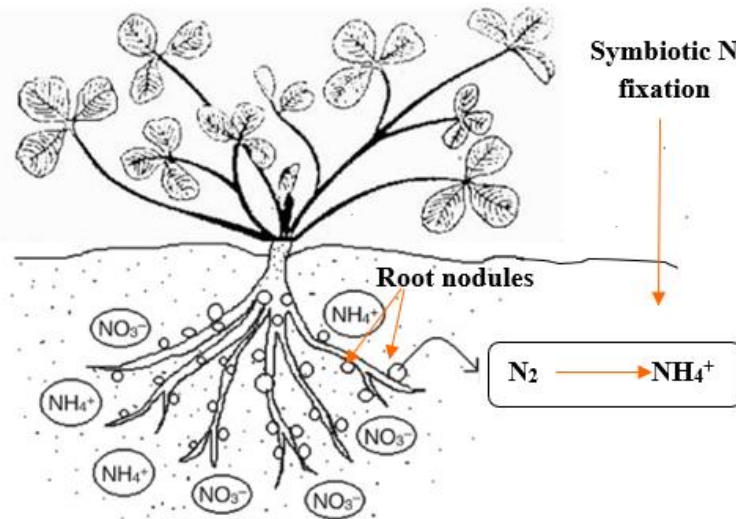


Figure 2.7 N fixation in a legume-Rhizobium symbiosis. Redrawn from Basu and Kumar (2020).

Depending on the pasture type, growth of clovers and climate, N fixation levels of clovers ranging from 70 to 240 kg N/ha/year (Crush et al., 1982). For pasture containing 3-40 % white clover, N fixation has been measured up to 20-250 kg N/ha annually (Crush et al., 1983; Goh et al., 1996). Similarly, another study in New Zealand has determined the N fixation quantities of white clovers ranging from 18-90 kg N/ha/year (Lucas et al., 2010). According to research from the United Kingdom, it was found that unfertilised or ungrazed swards could fix up to 280 kg N/ha annually (Cowling, 1982).

In particular, clover growth and rate of N fixing rely upon seasonal changes in soil and management practices (Caradus, Woodfield, & Stewart, 1995). For instance, there is an impact of mineral N on clover growth and N fixation activity (Hoglund & Brock, 1987). More specifically, with the increased soil fertility and N supply, grasses become more competitive and dominant resulted in declining of white clover growth (Brock & Hay, 1995). It was initially assumed that increased grass growth by mineral fertilisers leads to greater sward height than clover and shading of clover plants could reduce the photosynthesis (Parsons et al., 1991; Pinxterhuis, 2000). On the other hand, another mechanism states that, comparing the growth competition clover leaves remain folded for longer periods compared to grasses resulting in a lower rate of photosynthesis (Pinxterhuis, 2000). Hence, it is important to apply N fertilisers

without affecting the growth and N fixation in clovers (Walker, 1995). It has been reported that during late autumn to early spring clover growth is dormant and grass growth is prominent and that time is most suitable for additional N fertiliser requirements (Walker, 1995). Therefore, in many, New Zealand clover-based pastures additional N fertilisers are often added to increase herbage growth further. (Harris & Clark, 1996).

There are indications that clover-based pastures (Ball, 1982) and pure clover swards (Parsons et al., 1991) have leached significant quantities of N. Conversely, clover-based swards have been found to leach less nitrate than grass-based swards that received N from inorganic fertilisers in a rate of 420 kg N/ha/year (Cuttle & Scholefield, 1995; Ryden et al., 1984). Similarly, evidence from the United Kingdom showed that nitrate leaching from pastures with clover may be lower than from grass pastures receiving N fertilisers (Garwood & Ryden, 1986). In contrast, another study showed that, at least in the early years following pasture establishment, nitrate loss from clover-based pastures is higher than that from grass fertilised at moderate N rates of 120-200 kg N/ha/year (Cuttle et al., 1992).

In a New Zealand study, which compared the sheep-grazing pasture effect on nitrate leaching without using N fertilisers, measured nitrate leaching which was roughly 50% more from an RGWC sward than the perennial ryegrass monoculture (Field et al., 1985). Further to that, grass/clover pastures have been shown to have lower leaching losses when grasslands are excluded from grazed animals (Garwood et al., 1980; Navarrete et al., 2018).

2.4.3.3 N fertiliser applications

N is an essential limiting factor in the potential growth of grass swards, which is only second to water (Jarvis et al., 1995). Research has shown that the application of additional fertiliser N can enhance pasture growth in New Zealand, although white clover provides an average N of 185 Kg N/ha/year naturally to improve pasture growth (Harris & Clark, 1996; Hoglund et al., 1979). Hence, the development of modern pasture management techniques and the extreme productivity gain in pastures are mainly determined by applying additional N fertilisers (Jarvis et al., 1995). In New Zealand, the growth of pasture swards is greatly limited by the availability of N throughout the year and applying N fertilisers is considered a common management tool (Field & Ball, 1982). In addition, to improve the rate of N fixation by legumes in hill country, large quantities of phosphate fertiliser have been applied since the 1950's (Fertiliser Association of New Zealand, 2017; Mackay & Lambert, 2011). Phosphate fertilisers help

enhance the legume component of pastures and thereby, improve the N fixation naturally (Lambert et al., 2014). Further since the 1990's the use of N fertiliser has been increasingly used on sheep and beef farms to increase growth (Gillingham et al., 1998; Hoogendoorn et al., 2017; Lambert et al., 2014; Morton et al., 1993).

Generally, nitrate leaching directly from fertiliser application is less, when fertiliser application rate and timing are managed according to the plant requirement (Cameron et al., 2013). However, it has been shown a high risk of leaching loss of mineral N occurs from an increase in stocking rate brought on by applying additional N fertilisers to improve pasture growth and dry matter production (Ledgard, 2001). More importantly, there is an increased risk of nitrate leaching with the concurrent application of N fertilisers onto urine-affected areas and the effect of reduction in N fertiliser use efficiency (Buckthought, 2013). However, it is obvious that the direct leaching of fertiliser N from grazed pastures is often insignificant compared to nitrate leaching arising from the urine patch (Monaghan et al., 2007).

Previous studies in New Zealand and overseas have shown a positive relationship between applying N fertilisers and subsequent nitrate leaching under sheep grazing. Hoogendoorn et al (2017), studied the effects of N fertiliser applications in the form of urea by using lysimeters, with the presence of increased stocking rates in hill country intensively grazed pastures in an imperfectly drained Pallic soil, in South Island, New Zealand, and reported an increased rate of mineral N leaching over N fertiliser application rates from 0-750 kg N ha/year (Table 2.6). Moreover, the study reported that N leaching increased continuously when fertiliser N application increased above 100 kg N/ha/year. Currently, the maximum regulated application rate for N fertilisers in New Zealand applied to grazed pastures is 190 kg N/ ha/ year (Ministry for the Environment, 2020). In particular, in most sheep farms in New Zealand, except for a few intensively managed farms, N application rates are managed at a lesser rate of 100 kg N / ha/ year (Maheswaran et al., 2022).

Table 2.6 Average concentration of nitrate-N leached in drainage water when increasing rates of N fertiliser (0-750 kg N/ha/year) were applied over a three-year study in New Zealand (Hoogendoorn et al., 2017).

N fertiliser application rate (kg N ha/year)	2005-2006	2006-2007	2007-2008
	Nitrate-N (mg L⁻¹)		
0	13.9	5.7	6.1
100	9.6	7.0	9.6
200	12.1	10.7	13.5
300	14.0	20.2	17.8
400	20.4	18.2	35.1
500	43.3	31.7	28.9
750	52.7	38.2	41.0

*Note: N fertiliser was applied at six different times annually in application rates varying between 50-125 kg N/ha/year at a given time depending on the soil total N.

A recent three-year lysimeter study in sheep-grazed pastures in poorly drained Pallic soil in New Zealand, has shown a positive relationship between nitrate leaching and N fertiliser application rates (Figure 2.8) (Morton & Stevens, 2023). According to the results, when compared with the control, there was no significant difference in the amount of nitrate leached (8–15 kg/ha/year) at 100 and 200 kg N/ha/year fertiliser application rates and in contrast, at 500 kg N/ha/year fertiliser application rate, the amount of nitrate leached was significantly higher at 116 kg/ha/year. Furthermore, the nitrate leaching load increased substantially when N fertiliser application rates increase by 300 kg N/ha/year. Morton & Stevens (2023) noted that during all three years when N fertiliser application rates were at 100 and 200 kg N/ha/year, nitrate concentrations were reported below the WHO standard of 11.3 mg/ L (Ministry of Health, 2008) for drinking water. Moreover, application rates increases of 200 kg N/ha/year exceed the standardised limit.

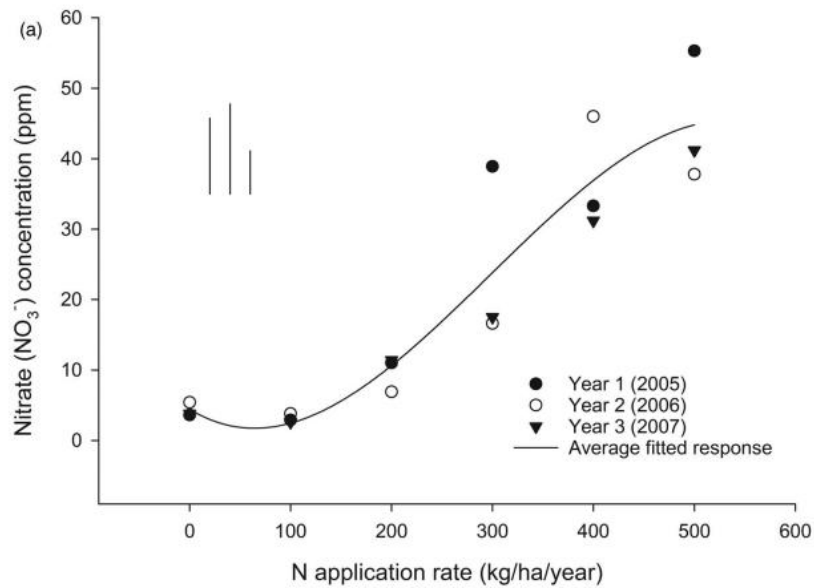


Figure 2.8 Nitrate concentration in leachate for three years from pastures receiving increasing rates of N (Standard error difference bars represent years 1, 2 and 3 from left to right (Morton & Stevens, 2023).

2.4.4 Factors affecting nitrate leaching

Even in situations where N inputs and sources are similar, there may be considerable differences in the amounts of nitrate leached at different places and in years due to the relative importance of the various processes that determine nitrate contents in the soil and the subsequent process of leaching (Cuttle & Scholefield, 1995). Therefore, it has been found that factors like climate, soil, pasture and grazing management are the key factors effect on nitrate leaching.

2.4.4.1 Season and climate

The climate and season determine the total N losses from a grazing system (Williams & Haynes, 1994) and the interactions in the N cycle, which are influenced by weather, in turn, affect the nitrate concentrations in the soil (Haynes & Williams, 1993).

In temperate regions, leaching commonly occurs during winter and early spring, when precipitation exceeds evapotranspiration (Brock et al., 1990). Similarly, during winter and early spring periods, nitrate leaching is high, as plant uptake is low due to cold environmental

conditions and high drainage (Wild & Cameron, 1981). For instance, a New Zealand study reported a higher leaching potential in pasture land (15-19%) with autumn-applied N fertiliser (NH_4Cl - Ammonium chloride) compared to late spring-applied (8-11%) under the same application rates (Di et al., 1999). This means fertilisers applied in late autumn have the potential for higher losses due to higher drainage in the following winter.

In summer, soil nitrate concentrations on the surface increase due to poor pasture growth followed by low soil mineral N uptake (Scholefield et al., 1993). Consequently, this condition exceeds mineral N levels in pasture soils due to the accumulation of mineralised soil organic matter during summer (Wild & Cameron, 1981). Finally, following a dry summer, rewetting soils in the winter washes excess minerals and causes greater nitrate leaching (Cameron et al., 2013).

2.4.4.2 Soil type

The N concentration and volume of drainage water, alongside the efficiency with which the leaching water reaches the pore volume, are the primary factors that determine the nitrate leaching load from a soil profile (White & Magesan, 1991). Similarly, research shows that peak concentrations for the quantity of nitrate leached may vary depending on soil type (Scholefield et al., 1993). Generally, increased nitrate concentrations can be observed with decreased clay content in soils, and it has been found that reduced soil water capacity and degree of preferential flow are likely the causes (Cameron et al., 2013). On the other hand, increased drainage in coarse-textured soils will cause the pore to flush more frequently than in fine-textured soils (Cameron et al., 2013).

In addition, the rate at which nitrate leaching occurs can be greatly influenced by macropores formed by earthworms, plant roots, or wetting and drying cycles, which allow nitrate to enter the soil profile rapidly (Silva et al., 2000). Moreover, conditions such as temperature and moisture levels in the soil can also play a role in nitrification rates and subsequent leaching of nitrates (White & Magesan, 1991).

2.4.4.3 Pasture root architecture

The physical properties of plant roots, such as their density and depth, can influence nitrate leaching losses in a grazed pasture system (Thorup-Kristensen, 2001). In particular, pasture species that exhibit superior root architecture, characterized by factors like root distribution into deeper layers, high rooting density and diameter in the top layers can absorb nutrients on the surface and reduce the downward movement (Crush et al., 2007; Crush et al., 2005; Dunbabin et al., 2003).

2.4.4.4 Livestock and grazing management

Nutrient cycling in a grazing ecosystem depends on livestock type and its grazing management (Cameron et al., 2013). Whereas, the proportion of total N intake that is excreted and partitioned between urine and faeces depends on the type of animal, the intake of dry matter, and the N concentration of the diet (Whitehead, 1986; Whitehead, 1970). More importantly, grazing frequency, timing and intensity are the key management tools in livestock grazing which affect nutrient losses from a pastureland (Cameron et al., 2013).

Grazing intensity may affect the cycling of N through fixation, immobilisation and the quantity of N taken up by pastures (Hoogendoorn et al., 2016; Ryden et al., 1984). For instance, in extensively grazed grassland systems nitrate leaching losses are low (Di & Cameron, 2002) as there is less N cycling in the system and therefore animal N intake via grazing and then return to soil is lower, resulting in lower nitrate concentrations in the soil solution (Moir et al., 2006; Woodmansee et al., 1981).

Conversely, higher stocking rates result in more herbage consumption per hectare, which in turn causes more N to be deposited as urine patches (Hoogendoorn et al., 2017). For instance, research conducted in a sheep-grazing system in the United Kingdom, which compared the nitrate leaching with stocking rates, has shown a positive relationship irrespective of the fertilised or non-fertilised pasture swards (Figure 2.9).

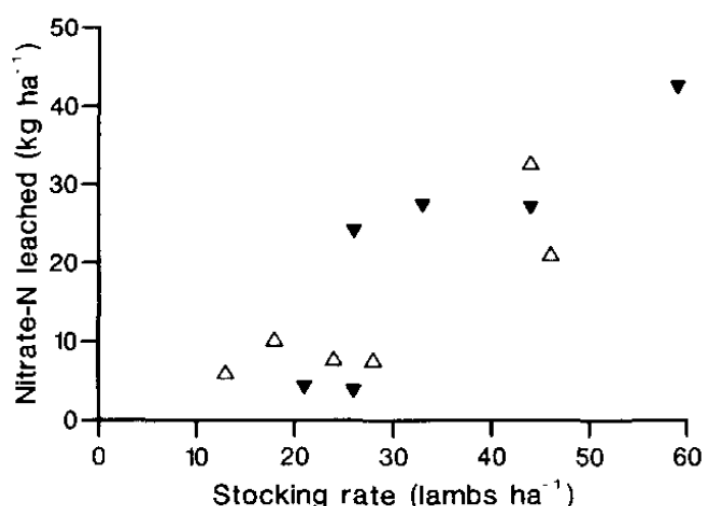


Figure 2.9 Relationship between quantities of annual nitrate leached and mean stocking rates (post –weaning) in a ryegrass sward receiving 150-200 kg/ ha fertiliser-N (solid symbols) and unfertilized grass/ clover (open symbols) : 1987-1993 (Cuttle et al., 1992) ; Adopted from (Cuttle & Scholefield, 1995).

A study carried out in New Zealand, which compared rotational grazing (all year with 10-12 grazings/year at rotations lengths varying from 24 days in spring to 60 plus days in winter) and set-stocking (all year) in sheep grazeland has shown a 2.5 times higher leaching losses under set-stocking compared to rotational grazing (Brock et al., 1990). Furthermore, the study has shown an increased amount of nitrate leached from the fertilised grass/clover sward according to the increase in the number of grazing days (July- December).

2.5 Mitigating nitrate leaching with pasture management

Diverse pasture species

As pressure mounts to improve efficiency and reduce the environmental effects of intensive pastoral systems, more attention has been focused on pasture swards that exhibit characteristics which reduce N leaching (Vogeler et al., 2017). Hence, there is a growing awareness by farming communities, government and other industrial bodies of the potential of diverse pasture systems and eco-friendly pasture management practices to reduce environmental impact.

Therefore, as a potential mitigating technique, researchers have started looking into the effects of diverse grass species, especially on N uptake, focussing on root length, density, structure, distribution and N absorbing nature (Crush et al., 2005; Moir et al., 2013). For instance, research studying the relationships between root systems and nitrate uptake in different forage mixes indicates that expanding root densities at greater soil depths and increasing the uptake of N from the root zone can reduce nitrate leaching losses (Crush et al., 2005; Maxwell et al., 2019; Woods et al., 2018). This means, pastures with larger root densities in lower soil layers can potentially capture nitrate before it is leached (Dunbabin et al., 2003). Whereas, perennial ryegrass typically has shallow roots, with up to 80% of them are found in the top 15 cm of the soil (Haynes & Williams, 1993). Hence, using suitable deep-rooted perennial species could improve the efficiency of N cycling and lessen variability in N inputs and losses (Ledgard, 2001).

On the other hand, it has been found that winter active pastures absorb more soil nitrate reducing loss to leaching (Selbie et al., 2015), with, Italian ryegrass/ white clover swards showing 24-54% less nitrate leaching than RGWC swards (Malcolm et al., 2014). Furthermore, the study argues that winter growth rates are more important than the root architecture of the pasture. Therefore, a strategy to reduce nitrate leaching would be to create a pasture sward formed from multiple plant species that possess various functional traits, such as growth activity throughout the season, rooting depth, and a profile of bioactive components (Al-Marashdeh et al., 2020).

In addition, there are several studies conducted in New Zealand under dairy farming in that have measured significantly less nitrate leaching under plantain monoculture and plantain clover mixtures compared to ryegrass monocultures and RGWC pastures (Box et al., 2023; Cheng et al., 2017; Navarrete et al., 2018). However, there is a lack of similar research on New Zealand sheep grassland. Therefore, it is important to study the potential advantage of utilising diverse pastures in terms of reducing nitrate leaching under sheep grazing.

Grazing management

Under dairy production systems, reducing the stocking rate and limiting grazing time in pastures have been found to be important strategies to reduce N leaching by minimising the N recycling back to pasture soils via urine (Monaghan et al., 2008). More specifically, during autumn (March and April), in late lactation, cows are kept on a loafing pad 12 hours a day away

from pasture (stand-off pasture) (Beukes et al., 2017). However, it is not practicable or cost effective for sheep management systems due to low economic margin associated with these systems (Anastasiadis et al., 2012).

2.5.1 Contemporary pasture management

In New Zealand, the conventional/traditional pasture management practices rely on maintaining a tight control over lambing dates to align with seasonal fluctuations in pasture supply and demand and to use rotational grazing on standard pastures at high stocking rates to ensure effective pasture utilisation (Matthews et al., 1999). Furthermore, these pasture-based management systems mainly focus on higher production followed by increased pasture utilisation with a high emphasis on fertiliser inputs (Gray, 2023).

2.5.2 Regenerative pasture management

As a result of growing dissatisfaction with the social and environmental impacts of contemporary industrialised agriculture, alternative food production models have emerged (Gosnell, 2022). Many alternative agricultural methods are being practiced (such as sustainable and organic agriculture), and more recently, regenerative agriculture (Grelet et al., 2021).

Regenerative agriculture is being identified as a sustainable food production method with minimum environmental impact that increases soil carbon under high residual rotational grazing (Rowarth et al., 2020).

The key principles of regenerative pasture management include a longer grazing round, wider plant diversity, less synthetic fertiliser use, and a focus on higher pasture covers prior to grazing and more residuals following grazing (Table 2.7) (Grelet et al., 2021; Tozer et al., 2022).

Table 2.7 Key principles in regenerative pastoral farming. Adopted from (Grelet et al., 2021).

Management practice	Key strategy	Description
Pasture composition	<ul style="list-style-type: none"> • Pastures species richness 	<ul style="list-style-type: none"> • Includes planting various species (16–40+ species) to establish perennial plant communities. • Over time, this high functional diversity improves ecosystem productivity and resilience in many ways, including increasing resilience to variable climates (including extremes), Improving nutritional quality of forage, improving soil health and reducing leaching.
Grazing management	<ul style="list-style-type: none"> • Rotational grazing systems • Longer grazing interval • Adaptive multi-paddock grazing 	<ul style="list-style-type: none"> • Rotational grazing systems promote the growth of pasture for the whole year. • Grazing interval is maintaining with a longer rotational period, by letting the pasture to grow longer before grazing and leaving more residue in the soil. This allows more plant litter to be absorbed into the soil, raising the amount of organic matter in the soil. • Extended grazing intervals may stimulate the development of diverse perennial pastures, which often exhibit higher growth rates all year round. • Allows grazed areas to recover and encourages healthier pasture development by rotating livestock between several paddocks.
Fertiliser application	<ul style="list-style-type: none"> • Minimising synthetic inputs 	<ul style="list-style-type: none"> • Reduce expenses and maintain or increase profitability, focusses on effective nutrient uptake by reducing fertiliser usage. • Help to mitigate the risk of nutrient runoff into waterways, maintaining water quality and protecting aquatic life.

CHAPTER 3: METHODOLOGY

The study was carried out from January to December 2023, with the approval of Massey University animal ethics (MU22/17).

3.1 Experimental site and treatments

This study was conducted at Massey University's Whenua Haumanu sheep farmlet study located at the Pasture Crop Research Unit (PCRU), 5.3 km southeast of Palmerston North, Manawatū, New Zealand (40°23'24.3" S 175°36'24.5" E). The average annual rainfall (2002-2023) is ca. 1007 mm (NIWA, 2024). Average monthly soil temperatures at 10 cm depth are 9.7 °C in July and 20.1 °C in January (NIWA, 2024). The site was located in a flat landscape. The study site's soil type is Tokomaru silt loam soil, classified as a Argillic-fragic Perch-gley Pallic soil (Hewitt, 1998). Soil depth class is moderately deep and drainage class is classified as poorly drained (S-Map Online).

This research site includes four farmlets (each 3ha) with a total farmlet area of 12ha (Table 3.1)

Table 3.1 Whenua Haumanu farmlet treatment description.

Treatment	Pasture management system	Number of ewes/ ha
A (Std-Con)	Standard pasture under contemporary management	14
B (Std-Reg)	Standard pasture under regenerative management	12
C (Div-Con)	Diverse pasture under contemporary management	13
D (Div-Reg)	Diverse pasture under regenerative management	12

*Average stock rates under standard pastures were 13 ewes/ha and under diverse pastures 12.5 ewes/ha.



Figure 3.1 Layout of the Whenua Haumanu sheep farmlets treatments (paddock numbers with pasture and management type).

3.2 Experimental design and treatments

The sheep were managed within their self-contained farmlet according to their treatment criteria. Each farmlet contained twelve paddocks and within each farmlet. Two paddocks of each treatment contained hydrologically isolated mole and pipe drainage systems (Bowler, 1980). Only these two paddocks (8 paddocks total) will be considered in the experimental design hereafter (Figure 3.2). Specific drainage area of the eight drained paddocks is listed in Table 3.2.

Mole channels were ploughed at 2 m intervals at a depth of 0.45 m at the commencement of the study during the summer of 2022. The mole channels intercept (perpendicularly) a gravel backfilled trench above a perforated pipe drain (0.11 m diameter, installed at a depth of 0.60 m) (Christensen et al., 2019).

The experimental design was a randomised complete block design (RCBD) under field conditions with two pasture types (standard and diverse) and two management practices (contemporary and regenerative) each with two replicates.

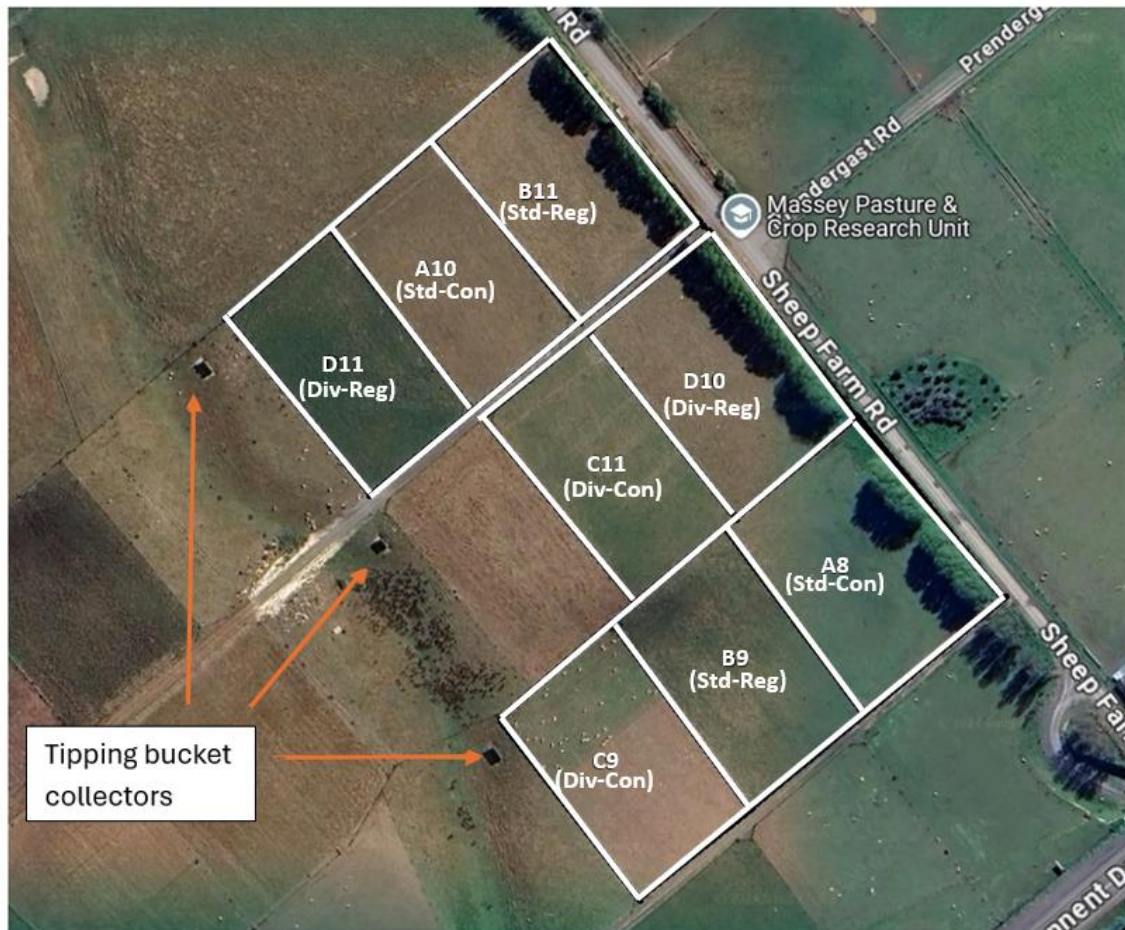


Figure 3.2 Layout of the eight drained paddocks (four treatments by two replicates; A8 and A10 (Std-Con) - standard pasture and contemporary management; B9 and B11 (Std-Reg) - standard pasture and regenerative management; C9 and C11 (Div-Con) - diverse pasture and contemporary management and D10 and D11 (Div-Reg) - diverse pasture and regenerative management).

Table 3.2 Specific drainage area of each hydrologically isolated paddocks (A8 and A10 - (Std-Con) standard pasture and contemporary management; B9 and B11 - (Std-Reg) standard pasture and regenerative management; C9 and C11 - (Div-Con) diverse pasture and contemporary management and D10 and D11 - (Div-Reg) diverse pasture and regenerative management).

Paddock/treatment	Drainage plot area (ha)
A8 (Std-Con)	0.25
A10 (Std-Con)	0.24
B9 (Std-Reg)	0.25
B11(Std-Reg)	0.216
C9 (Div-Con)	0.25
C11 (Div-Con)	0.23
D10 (Div-Reg)	0.23
D11(Div-Reg)	0.23

3.3 Pasture management

Contemporary management is described as following the Beef and Lamb New Zealand best practice grazing advice for sheep and the use of mineral fertiliser and chemicals as required. Regenerative management is described as having longer grazing intervals, higher post-grazing residuals and low to no mineral fertiliser and chemical use.

3.4 Pasture systems

All pasture was established in April 2022 and the pastures sown are listed in Table 3.3.

Table 3.3 Pasture system and pastures species sown under different treatments in April 2022.

Pasture treatment	Pastures species sown
Standard pasture	Diploid perennial ryegrass, Tetraploid hybrid ryegrass, Red clover, White clover small leaved, White clover medium/ large leaved
Diverse pasture	Diploid perennial ryegrass, Tetraploid hybrid ryegrass, Red clover, White clover small leaved, White clover medium/ large leaved, Meadow fescue, Cocksfoot, Timothy, Chicory, Plantain, Lotus corniculatus, Sainfoin, Sheep's Burnett, Balansa clover, Persian clover, Arrowleaf clover, Subterranean clover, Strawberry clover, Vetch

3.5 Pasture measurements

3.5.1 Pasture dry matter mass

Pasture mass was measured weekly in all farmlot paddocks (excluding those currently being grazed) using a rising plate method (Ashgrove Pastoral Productions, New Zealand). Pasture growth was then calculated as the difference in pasture mass between week 1 and week 0 and this was used to calculate monthly average rate and accumulated DM yield.

3.5.2 Botanical composition

Herbage samples (four to five samples per treatment) for botanical composition were randomly collected within paddocks within each farmlot treatment at approximately two-month interval (including summer and autumn). Each sample was collected by walking across a paddock and collecting one handful to ground level every few steps (10 sampling points). The samples were dissected into species (grasses, legumes, herbes) being further sorted into unsown species (weeds) and dead materials. Each sample was washed and oven dried at 70°C to a constant weight (for approximately 48 hours). The material dry matter weight was measured and botanical composition percentages of each were calculated based on dry weight basis.

3.6 Grazing management

Romney breeding ewes were allocated to each treatment farmlet at a variable stocking rate for each treatment (Table 3.1).

First phase - At the beginning of the year, the paddocks were shut up to make hay. The hay was cut in early February and paddocks were allowed to regrow for the following ~2 months, as dry conditions meant that regrowth was slow.

Second phase - Rotational grazing was resumed and the hydrologically isolated paddocks were grazed during late April/ early May and continued through winter. Each paddock was grazed for 6-9 days, depending on pasture growth and treatment, and the regenerative treatment paddocks were grazed less frequently (every 11-12 weeks) than the contemporary treatment paddocks (every 9-10 weeks).

Third phase - All the paddocks were set stocked for lambing for a six-week period (15 August to 5 October).

Fourth Phase - Rotational grazing resumed in early October and continued until the end of December. Each paddock was grazed for 2-5 days and in each grazing event, the regenerative treatment paddocks every 4-6 weeks, and the contemporary treatment paddocks every 3-4 weeks.

3.7 Soil fertility and fertiliser application

Each hydrologically isolated paddock was soil sampled on 23 May 2023 to a depth of 7.5cm. The samples were analysed tested for pH (based on H₂O in 1:2 soil: water(v/v)), Olsen P (mg P/L soil), sulphate (SO₄²⁻) sulphur (S) (mg S/L soil), soil quick tests for potassium (K MAF), calcium (Ca MAF), magnesium (Mg MAF), sodium (Na MAF), and cation exchange capacity (CEC) (me/ 100g) at RJ Hill laboratory, Hamilton, New Zealand (Table 3.4). These soil fertility data were used to determine the annual fertiliser application rates (if required). The timing and rates of fertiliser applied during the study period are shown in Table 3.5.

P fertiliser was applied to selected paddocks towards the end of the drainage season in 2023 to even up Olsen P concentrations across the farmlets.

Table 3.4 Soil test results (0-7.5 cm) measured in May 2023 for the drainage paddocks (A8 and A10 - (Std-Con) standard pasture and contemporary management; B9 and B11 - (Std-Reg) standard pasture and regenerative management; C9 and C11 - (Div-Con) diverse pasture and contemporary management and D10 and D11 - (Div-Reg) diverse pasture and regenerative management).

Paddock/ Treatment	Soil test									
	pH	Olsen P (mg/L)	SO ₄ ²⁻ -S (S/kg)	Soil Quick Test (MAF)*				Potentially available N (kg/ha)	Anaerobically mineralisable N (µg/g)	CEC* (me/100 g)
				K	Ca	Mg	Na			
A8 (Std-Con)	5.9	27	7	5	8	20	6	296	217	14
A10 (Std-Con)	5.8	21	7	6	7	14	7	268	179	11
B9 (Std-Reg)	5.7	28	10	8	8	20	5	322	235	14
B11 (Std-Reg)	5.6	16	7	5	7	16	7	273	194	12
C9 (Div-Con)	5.8	26	11	7	8	21	5	275	183	13
C11(Div-Con)	5.8	24	12	8	9	17	10	321	220	12
D10 (Div-Reg)	5.6	18	8	6	7	16	9	198	139	12
D11 (Div-Reg)	5.8	19	8	6	7	14	8	289	192	11

*MAF-(Ministry for Agriculture and Fisheries) in New Zealand laboratories me/100g unit converts to MAF unit by using a formula (HillLabs, 2024) ; CEC-Cation Exchange Capacity

Table 3.5 Fertiliser application (kg/ha) to drainage paddocks (A8 and A10 - (Std-Con) standard pasture and contemporary management; B9 and B11 - (Std-Reg) standard pasture and regenerative management; C9 and C11 - (Div-Con) diverse pasture and contemporary management and D10 and D11 - (Div-Reg) diverse pasture and regenerative management) in the 2023 (Jan-Dec) drainage year.

Drainage/ paddock	Fertiliser application rate and date	
	N (kg N/ ha)	P (kg P/ ha)
A8 (Std-Con)	24.6 (21/11/2023)	-
A10 (Std-Con)	24.6 (20/12/2023)	38.9 (13/10/2023)
B9 (Std-Reg)	6.2 (21/11/2023)	-
B11 (Std-Reg)	6.2 (21/11/2023)	15.4 (7/11/2023)
C9 (Div-Con)	24.6 (21/11/2023)	-
C11 (Div-Con)	24.6 (21/11/2023)	20.5 (7/11/2023)
D10 (Div-Reg)	6.2 (21/11/2023)	12.9 (7/11/2023)
D11 (Div-Reg)	6.2 (21/11/2023)	11.6 (7/11/2023)

* N applied in the form of Granular Ammonium Sulphate (N-20.5%) and P applied in the form of Triple Super Phosphate (P-20.5%)

3.8 Drainage measurement and analysis

A soil water balance, as described by Scotter et al. (1979), was used to predict when drainage would occur. Climate data (rainfall, evaporation and soil temperature at 10 cm depth) were sourced from the National Institute of Water and Atmospheric Research (NIWA) site (site number 21963), located approximately 1.5 km from the research site. Drainage water was collected from individual tipping bucket devices connected to mole drainage pipes located at sampling points nearby each paddock (Figure 3.3).

Following a rainfall event, drainage water from each paddock was channelled through drainage pipes into individual tipping buckets. The number of tips were recorded by a connected digital meter when drainage water was flowing through the tipping bucket. The volume of a single tip was calibrated for each bucket and was measured (~5L), and the total volume per event was

calculated by multiplying the total number of tips recorded from each pipe (Christensen et al., 2019). A consistent subsample of water (ca. 0.1%) was automatically collected in a black plastic storage can from every second tip of the tipping bucket to generate a mean event sample.



Figure 3.3 Example of tipping bucket devices at the end of each mole-pipe

After completion of each drainage event, water samples (~100 ml) were collected manually from the storage container for water quality analysis (Figure 3.4). Collected samples were sent to Central Environmental Laboratories (CEL) Palmerston North within 24 hours to be analysed for nitrate-N, nitrite-N ammonium-N, soluble inorganic N (SIN) and DRP concentration. The nitrate-N and nitrite-N samples were analysed using ion chromatography (APHA 24th Ed. 4110B). The ammonium-N and DRP samples were analysed using spectrophotometry (APHA 24th Ed. 4500 NH₃-F) and (APHA 24th Ed. 4500-P E) respectively (American Public Health Association, 2023). SIN concentration was calculated by summing the concentrations of nitrate-N, nitrite-N and ammonium-N. The load of nitrate-N, nitrite-N ammonium-N, SIN and DRP lost in drainage was calculated as the product of the measured drainage volume and their concentrations (Christensen et al., 2019).



Figure 3.4 Manual collection of water from the storage container for water quality analysis

3.9 Statistical analysis

The number of tips recorded from paddock/ treatment C9 (Div-Con) was comparatively very much less than the average of other pipes and indicated that it was not functioning correctly. Therefore, the statistical study design was emended to focus on the most important parameter of pasture type and ignoring the effect of management type. This ensured standard pasture treatment had four replicates (A8 and A10 (Std-Con), B9 and B11 (Std-Reg)) and diverse pasture treatment had three replicates (C11 (Div-Con), D10 and D11 (Div-Reg)) respectively.

Data were statistically analysed using SAS version 9.4 (Statistical Analysis System, version 9.4; SAS Institute Inc, Cary, USA). All data were subjected to an analysis of variance using the MIXED or GLM procedure. The nitrate-N, nitrite-N ammonium-N, SIN and DRP concentrations and total load (kg/ha) of drainage water samples were analysed for the drainage season, using a model containing the fixed effects of pasture treatment (diverse and standard), cumulative drainage volume in drainage buckets and sampling date and their two-way interaction. The models also included replicates (drainage plots) nested within the respective pasture treatment.

Effect of pasture treatment (diverse and standard) on cumulative drainage (mm) and cumulative losses of nitrate-N, nitrite-N ammonium-N, SIN and DRP in drainage were analysed using a mixed model that contained pasture treatment and the two-way interaction with sampling date. The model included replicates (drainage plots) nested within the treatment as a random effect.

CHAPTER 4: RESULTS

4.1 Rainfall and drainage

The actual annual rainfall in 2023 was 927mm, while the ten-year average annual was 967 mm. When comparing actual rainfall to the average, January, February and October experienced higher rainfall than usual (Figure 4.1). However, the rainfall during the June, July, September and November periods were below the ten-year average (Figure 4.1).

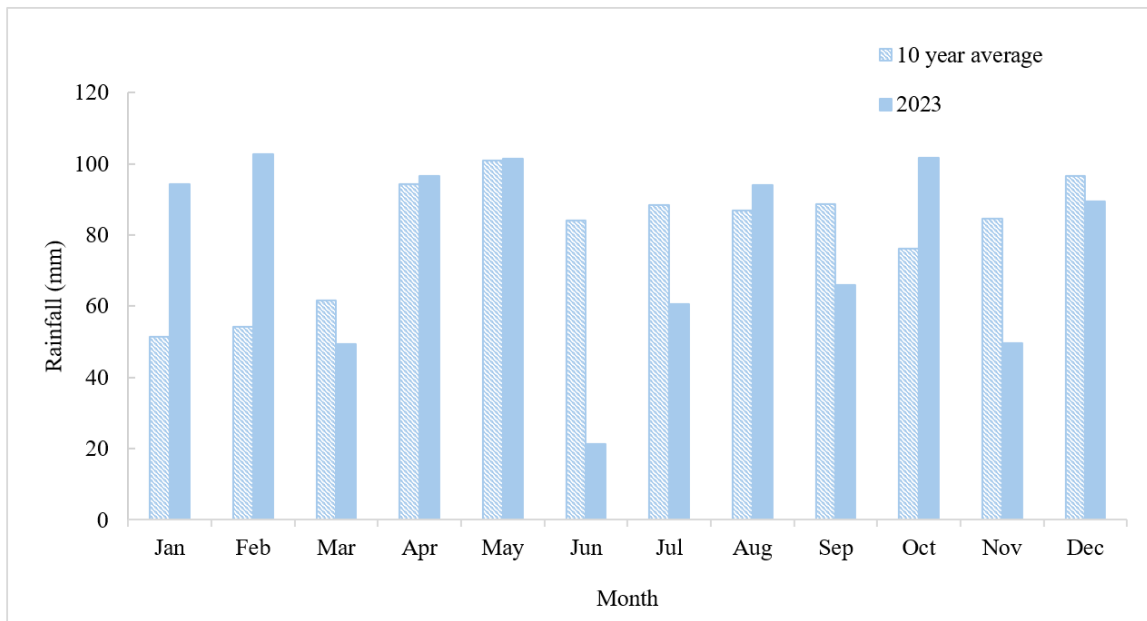


Figure 4.1 Ten-year average monthly rainfall and actual monthly rainfall in 2023 (sourced from NIWA/AgResearch, Palmerston North meteorological station, 1.5 km from study site).

The soil temperature at 10 cm depth ranged between 6.7 to 25.5 °C throughout the year (Figure 4.2). The measured drainage events typically aligned (Figure 4.2) with periods of soil water surplus, as predicted by the soil water deficit of Scotter et al. (1979).

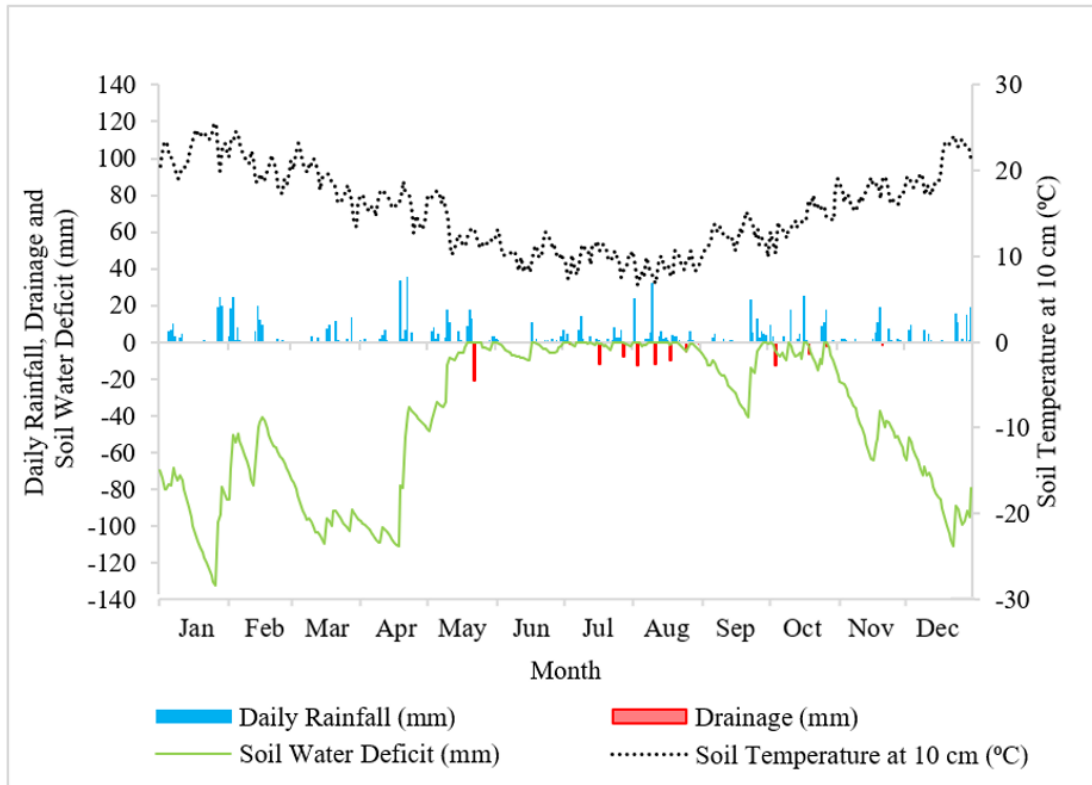


Figure 4.2 Mean drainage (mm), rainfall (mm), soil temperature (°C) and modelled soil water deficit (mm) in 2023. Soil water deficit and drainage are absolute values but are displayed as negative values to add clarity to the figure.

The drainage season began in late May and ended in late November 2023. The late winter-early spring period was wet, with a dry period in September, again followed by high rainfall at the beginning of October (Figure 4.3). A total of 107mm of measured drainage occurred across all drainage plots on average, over the year (Figure 4.3). There was a significant interaction between pasture type and date for cumulative drainage ($p=0.01$). The total cumulative drainage of diverse pastures was higher ($p<0.05$) compared to standard pastures (Table 4.1; Figure 4.3). The size of drainage events between May and August was relatively consistent across both treatments but, towards the end of the drainage season, a considerable difference between the treatments developed, such that, diverse pasture treatment had greater overall drainage than standard pasture treatment. Although only three drainage events (on August 3; $p<0.01$, August 11; $p<0.01$ and October 4; $p<0.05$) were different between the treatments.

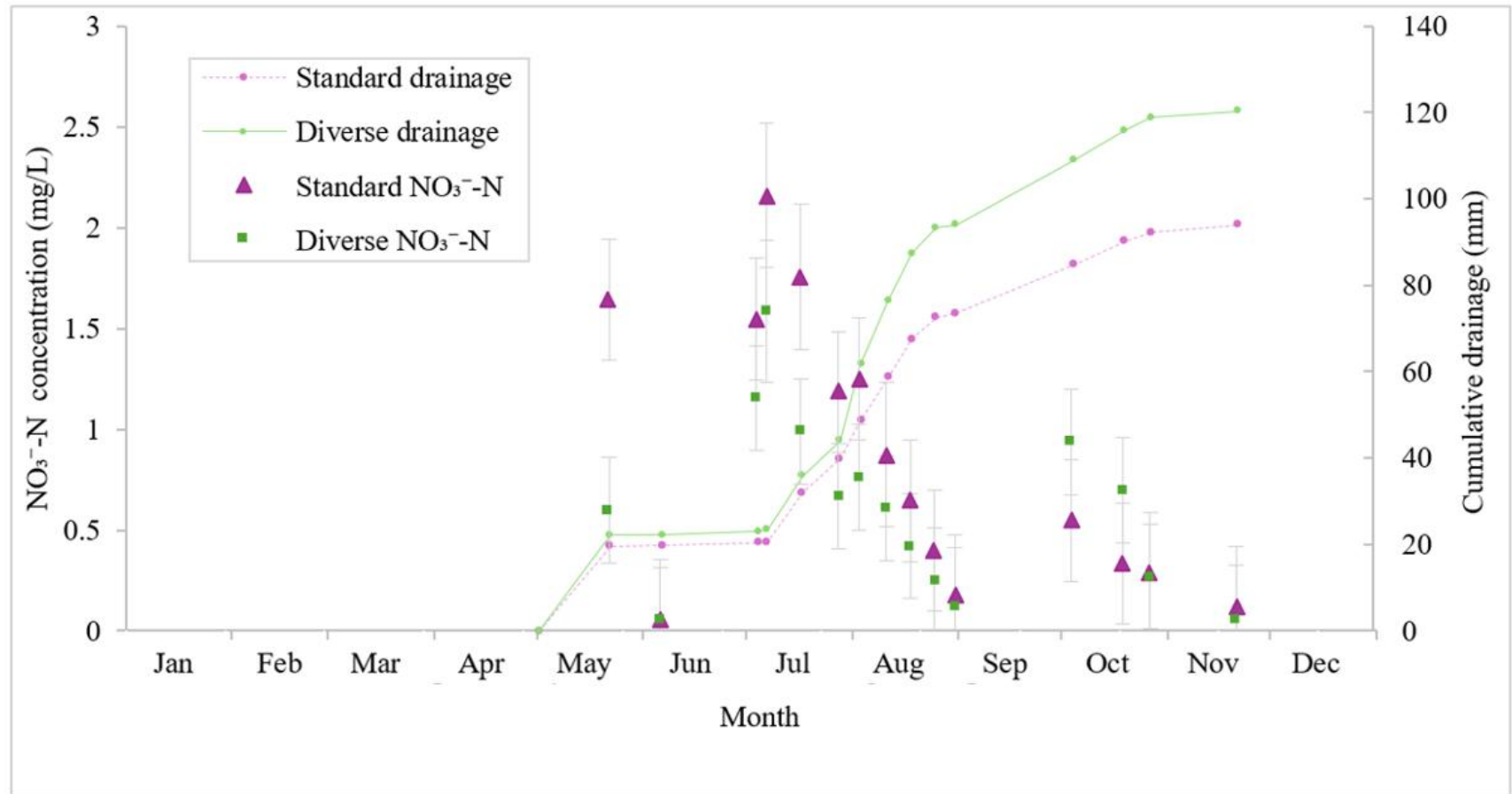


Figure 4.3 Measured cumulative drainage (mm) and concentrations of NO₃⁻-N (mg/L) in mole-pipe drainage from May to November 2023 under the pasture treatments (standard pasture and diverse pasture) grazed by sheep. Values are least-square means. Error bars represent standard error of the mean of each sampling event.

4.2 Nitrate concentration in drainage

At the beginning of the drainage season, both standard and diverse pasture treatments showed numerically higher nitrate concentrations, relative to latter part of the drainage season (Figure 4.3). However, in both treatments, the second drainage event showed very low nitrate concentrations and very low drainage volume captured during that particular event for both treatments. During late May to end of August, the standard treatment generally had numerically higher nitrate concentrations at each sampling date compared to the diverse treatment (Figure 4.3). On May 22 the standard treatment had higher ($p=0.0107$) nitrate concentrations than the diverse pasture treatment and also tended to have higher concentrations on July 17 ($p=0.0885$). Both the pasture types showed their peak nitrate concentration values in the 4th drainage event on July 7. Between mid-July to end of August the nitrate concentrations of both treatments exhibited a declining trend.

There were no drainage events from early September to early October. The two drainage events in October (October 4 and 19) had numerically higher nitrate concentrations than the last events that occurred in August. Also, the nitrate concentrations in the diverse treatment were numerically higher than the standard treatment during these events. The concentration continued to decrease in both treatments from late October to late November until the final drainage event.

4.3 Nutrient loads in drainage

The cumulative load of nitrate leached (kg/ ha) was not different ($p>0.05$) between the treatments, however the standard pasture had a numerically greater amount of leaching than the diverse pasture (Table 4.1). The total loads of nitrite-N leached in the drainage were minute in both treatments and did not differ ($p>0.05$). Also, the total load of ammonium-N leached was not different ($p>0.05$) between the treatments. The overall loads of SIN leached (kg/ ha) were not different ($p>0.05$) between the treatments. Also, the loads of DRP leached (kg/ ha) were not different ($p>0.05$) between the treatments.

Table 4.1 Total loads of nitrate-nitrogen (NO_3^- -N), nitrite-nitrogen (NO_2^- -N), ammonium-nitrogen (NH_4^+ -N), soluble inorganic nitrogen (SIN), dissolved reactive phosphorus (DRP) leached (kg/ha) and mean cumulative drainage (mm) in mole-pipe drainage from May to November 2023* under sheep grazing of the pasture treatments (standard pasture and diverse pasture). Values are present as mean \pm standard error of the mean.

	Standard	Diverse	P-value
Variable			
Cumulative drainage	93 \pm 6.6	120 \pm 7.6	0.0478
NO_3^- -N	1.04 \pm 0.266	0.73 \pm 0.307	0.4732
NO_2^- -N	0.01 \pm 0.001	0.01 \pm 0.001	0.2263
NH_4^+ -N	0.14 \pm 0.032	0.24 \pm 0.037	0.1045
SIN	1.08 \pm 0.256	0.96 \pm 0.296	0.7755
DRP	0.07 \pm 0.011	0.08 \pm 0.012	0.7211

* Drainage events occurred - May, June, July, August and November

4.4 Pasture production

4.4.1 Pasture growth rate

Diverse pasture treatments, including both contemporary and regenerative management types, showed a higher growth rate during the summer and autumn periods compared to standard pasture treatments. However, in the winter, all treatment types exhibited similar growth patterns. In late spring, diverse pastures displayed a numerically higher growth rate than standard pastures. (Figure 4.4).

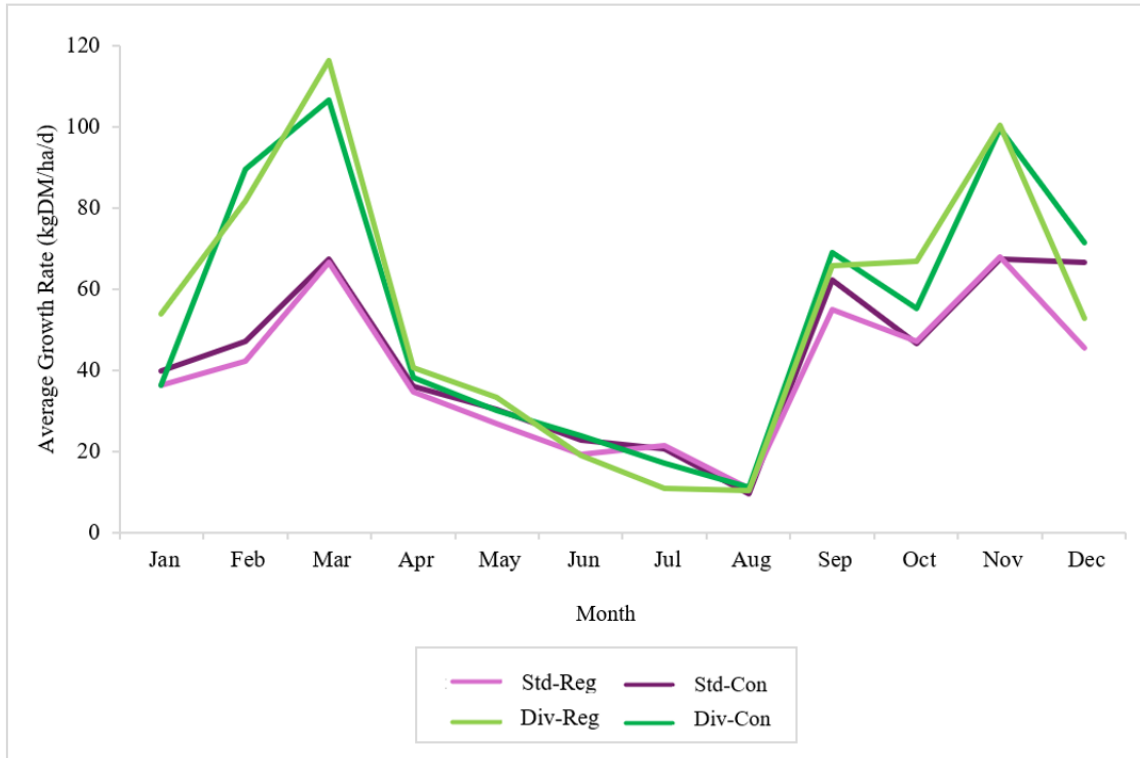


Figure 4.4 Measured average pasture growth rate (t/DM/ha) at PCRU farmlet from January to December 2023 under the pasture and management treatments (Std-Con (standard pasture contemporary management), Std-Reg (standard pasture regenerative management), Div-Con (diverse pasture contemporary management) and Div-Reg (diverse pasture regenerative management)) grazed by sheep.

4.4.2 Pasture dry matter mass

Throughout the year, the accumulated growth was numerically higher in diverse pastures under both regenerative and contemporary pasture management practices than the standard pasture treatments (Figure 4.5).

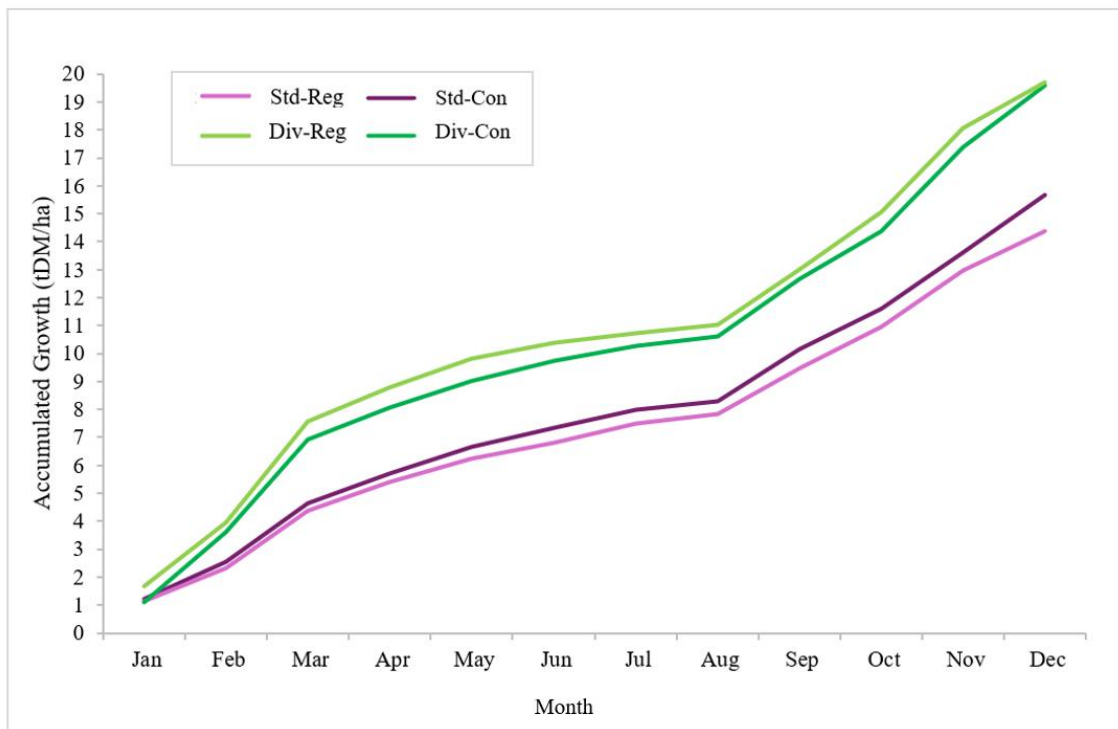


Figure 4.5 Measured accumulated growth yield (tDM/ha) at PCRU farmlet from January to December 2023 under the pasture and management treatments (Std-Con (standard pasture contemporary management), Std-Reg (standard pasture regenerative management), Div-Con (diverse pasture contemporary management and Div-Reg (diverse pasture regenerative management)) grazed by sheep.

4.4.3 Botanical composition

Some trends were observed for pasture composition. In summer and autumn, Std-Con and Std-Reg treatments had higher grass percentage than Div-Con and Div-Reg treatments (Figure 4.6). In contrast, in those two seasons, Div-Con and Div-Reg treatments had higher herb percentage than Std-Con and Std-Reg treatments.

In summer, legume percentage was higher in Std-Con treatment than Std-Reg, Div-Con and Div-Reg treatments which were similar (Figure 4.6). In contrast, in autumn, Std-Con and Std-Reg treatments had more legume percentage than Div-Con and Div-Reg treatments. Dead percentage was similar across all the treatments in both summer and autumn. Weed percentage

was similar in summer across treatments but in autumn was higher in Div-Con treatment than in all other treatments (Figure 4.6).

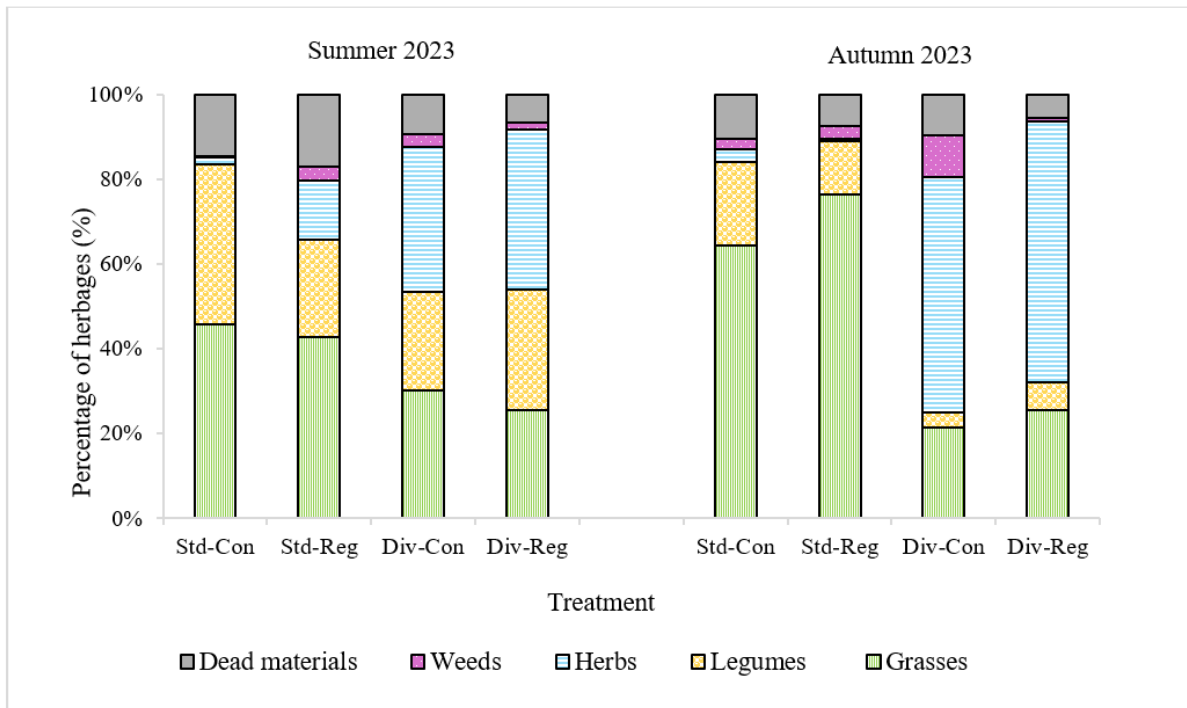


Figure 4.6 Percentage (%) of grasses, legumes, herbs, weeds and dead materials during summer and autumn 2023 under pasture management treatments; Std-Con (standard pasture contemporary management), Std-Reg (standard pasture regenerative management), Div-Con (diverse pasture contemporary management), Div-Reg (diverse pasture regenerative management).

CHAPTER 5: DISCUSSION

The effects of nitrate leaching on water quality under different pasture-soil systems and mitigation practices have been widely documented in the context of dairy farming in New Zealand (Cameron et al., 2013; Christensen et al., 2019; Dalley et al., 2017; Malcolm et al., 2014; Nguyen et al., 2023). However, most of the mitigation practices applied in dairy systems do not fit easily into sheep and beef farming systems due to the differences in management and economic viability (Anastasiadis et al., 2012). For instance, a dairy cow stand-off system applied to reduce urine-N load to soil, in a dairy system in winter cannot be applied to sheep because of the high stock numbers and associated housing costs (Anastasiadis et al., 2012). However, a few recent studies have focused on reducing nitrate leaching under intensive sheep farming systems, using alternative forages (Algharibeh, 2024; Maheswaran et al., 2023). Although these studies have focussed on investigating the benefits of short-term forage mixtures, such as Italian ryegrass and plantain, relative to RGWC (Algharibeh, 2024; Maheswaran et al., 2023). In New Zealand, there is renewed interest by farmers in the use of perennial diverse pasture mixtures, as opposed to resowing more traditional pasture mixtures of RGWC (Vibart et al., 2016). Evidence from dairy cattle studies suggests long-term diverse pasture mixtures may be used to reduce nitrate leaching (Graham et al., 2024; Talbot, 2020) which would be advantageous if the same result held in sheep systems. Therefore, it is vital to investigate the potential benefits of long-term, diverse pasture species in sheep production systems particularly in comparison to conventional RGWC pastures. This study compared perennial diverse pasture mixtures over RGWC pastures under two different management practices (regenerative and contemporary) over a one-year period and investigated their influence on nitrate leaching and drainage water quality via nitrite-N, ammonium-N, SIN and DRP under modern intensive sheep farming.

5.1 Study design

The study was designed with two replicates per treatment (due to high capital cost of the infrastructure). However, one of the replicates did not function correctly. Consequently, that replicate had to be removed from the data. As a result, the study focused solely on comparing pasture types including three replicates under diverse pasture and four replicates under standard

pasture. This potential for failure indicates why it is crucial to maintain a minimum of three replicates in future study designs to avoid similar issues.

It is challenging to draw definitive conclusions about the effectiveness of diverse pasture treatment compared to standard pasture systems based on this study due to its short monitoring period, number of replicates and being site specific. Also nitrate loads were not significantly different and the values were numerically very small. For this reason, it is important to extend the study over a period of at least three years at different locations.

5.2 Cumulative drainage

The drainage pattern observed is consistent with previous studies carried out on nearby sites under the same soil type (Christensen et al., 2019; Maheswaran et al., 2023). The drainage season began by recording the highest drainage in both the treatments observed throughout the season. However, the size of drainage events from May to August was relatively consistent in both treatments, potentially due to the observed rainfall being relatively low in the June- July period compared to long-term average rainfall pattern. At the end of the drainage season (August to November period), a considerable difference between the treatments was observed.

One unexpected finding was the extent to which the total cumulative drainage of diverse pastures was higher compared to standard pastures throughout the drainage season. Potential explanations include soil physical properties. For example, porosity differences with pasture root penetration in the soil profile or differences in ground cover in diverse mixes may result in lower evaporation conditions. It is known that chicory has a deep tap root, and plantain has dense lateral fibrous roots and both have been identified as perennial rosette-forming herbs with larger leaves relative to grass species (Cranston, 2017; Crush et al., 2005). A trench lysimeter leaching study on a well-drained sedimentary soil under the dairy farmlet system of the same Whenua Haumanu research program however, measured lower drainage under diverse pastures (Udara Wittahachchi pers.comm). This highlights the need for longer term monitoring to confirm these results.

5.3 Nitrate concentration in drainage water

Nitrate concentrations for both treatments started at a higher value and then gradually increased to a peak during the first few drainage events of the season (late May to early July), and then slowly decreased with subsequent drainage events (early July to late August). A similar pattern was observed in a previous study conducted under mole and pipe drainage systems in the same soil and climate (Christensen, 2013). Nitrate concentrations in drainage typically follow a trend of peaking during the first few drainage events and then declining as the season progresses in sheep (Algharibeh, 2024; Maheswaran et al., 2023) and dairy (Christensen et al., 2019; Hanly et al., 2017) grazed pasture studies, both in the vicinity of the study site and at other locations (Monaghan et al., 2016). This trend can be explained by the accumulation of excess nitrates in the soil profile under urine patches over the typically drier summer and autumn periods (Di & Cameron, 2002). Research indicates that most nitrate leaching occurs from urine patches due to the high proportion of excreted N present in urine (Christensen, 2013; Ledgard et al., 2008). However, Figure 4.3 illustrated nitrate concentration in a bi-modal pattern, with a smaller peak occurring towards the end of the drainage season in October. Notably, no drainage took place in September, which resulted in a higher nitrate concentration for this second peak compared to the last events in August. At the same time, the paddocks were set stocked with ewes during the lambing period, leading to the likely accumulation of urine nitrate concentrations, contributing to the observed second peak in nitrate concentration during the subsequent drainage.

Nitrate concentrations were generally higher in standard pastures than in diverse pastures treatments, particularly early in the drainage season. This is matched by the higher DM production and the herbage growth rates reported in 2023 for diverse pastures compared to standard pastures, particularly during the late summer/early autumn period (Figure 4.4 and Figure 4.5). The greater growth in diverse pastures likely utilised more available nitrates in the soil during their growth, which may have resulted in lower nitrate surpluses in soil and subsequently lower nitrate concentrations in drainage water (Vibart et al., 2016; Woodward et al., 2012). For example, previous research in dairy studies has shown that diverse pasture mixes, including chicory, plantain, red clover, lucerne, fescue, and prairie grass, exhibit higher DM production and greater yields during summer, also resulting in lower urine N excretions than standard RGWC swards (Nobilly et al., 2013; Woodward et al., 2013). Furthermore, pasture mixes that include herbs like chicory and plantain have the potential to reduce dietary N intake and lower urinary N concentration (Bryant et al., 2017; Totty et al., 2013; Woodward

et al., 2012). In the current study, the dominant pastures in standard pastures included ryegrass, white clover, and red clover, while the diverse pastures featured ryegrass, cocksfoot, white clover, red clover, plantain, and chicory. The present study primarily focused on a diverse pasture mixture that contain a higher proportion of herbs (chicory and plantain), with more than 35% in summer and over 60% in autumn. In contrast, the amounts of legumes and grasses were comparatively lower, approximately 25% in summer and between 4-23% in autumn. Previous research has indicated that herbs such as chicory, plantain, and lucerne actively grow during the summer and autumn months (Cranston et al., 2015; Lee et al., 2015; Woodward et al., 2013). It has been reported that these summer/autumn active herbs (like chicory and plantain) included diverse pastures have resulted in low nitrate concentrations in drainage relative to RGWC (Graham et al., 2024; Nobilly et al., 2013). Therefore, the combination of high herbage growth during summer and autumn, coupled with the high herb content in these diverse pastures have likely contributed to the low nitrate concentrations observed in drainage in the diverse pasture treatment.

Several studies have also shown that diverse pastures containing chicory or plantain (deep rooting), timothy, tall fescue and cocksfoot (high surface root mass) are efficient in capturing nitrate-N compared to standard RGWC pastures (Crush et al., 2005; McNally et al., 2015; Popay & Crush, 2010; Snow et al., 2013). This might be an additional reason for the observed lower soil nitrate concentrations under diverse pastures compared to standard pasture swards.

However, during the later part of the drainage season (during October), nitrate concentrations in diverse pastures were found to be higher than in standard pastures. Numerous studies have indicated that diverse pastures, particularly those containing grasses like timothy (Charlton & Stewart, 2000) and herbs like plantain and chicory, show increased activity in the summer but experience poor growth in winter (Cranston et al., 2015; Kemp et al., 2015; Nguyen et al., 2023). This difference may potentially be attributed to the low growth rates of diverse pastures during the winter months (Figure 4.5), which would have resulted in minimal N absorption at that time.

The two potential explanations for the variations in nitrate concentration that are unlikely to account for the differences observed in standard pasture and diverse pasture treatment were stocking rates and N fertiliser applications. There were minimal differences in the apparent stocking rate numbers between the standard (average 13 ewes per hectare) and diverse pasture (average 12.5 ewes per hectare) treatments. These small differences are unlikely to affect nitrate

concentrations, as quantities and frequencies of urination and faeces are likely to be relatively similar. Additionally, the effect of N fertiliser applications on nitrate concentrations in drainage water is likely to be negligible as the annual applications were made at the end of the drainage season, specifically in late October. The effect of previous years application also cannot be considered as the last application of N fertiliser was applied in early October 2022 (with similar application rates for standard and diverse pasture treatments), so given pasture growth rates are usually high during the subsequent spring- early summer periods, it is less likely that the 2022 applications influenced N loss during in the initial drainage events of 2023. A study on dairy pastures has indicated that direct leaching from N fertiliser is often comparatively low in intensive grazing systems (Vogeler et al., 2016).

5.4 Nutrient loads in drainage

The measured nitrate loads in 2023 were very small (≤ 1 kg N/ha) at this study site. The nitrate leaching loads measured in neighbouring sheep farming studies recently under the same soil type with RGWC, Italian ryegrass and brassica swards measured slightly higher nitrate loads (1.5 -3.0 kg N/ha) than the reported results (Algharibeh, 2024; Maheswaran et al., 2023). However, studies conducted earlier, under sheep grazing on the same soil type and under RGWC pastures recorded even higher loads (8-50 kg N/ha) (Heng et al., 1991; Magesan et al., 1996; White et al., 1998).

The reason for the different values reported under different sheep studies under the same soil and climate can be explained by the stocking rates and grazing duration associated with the main source of sheep urine patches. For instance, under the present study rotational grazing was utilised with a stocking rate of 12-14 ewes/ha, similar to Algharibeh (2024) and Maheswaran et al. (2023) who rotationally grazed with a stocking rate equivalent to 14 ewes/ha and they reported loads of 0.4-1.1 kg N/ha. While, White et al. (1998) stocked 320 ewes/ ha in May 1991 and reported a load of 35-43 kg N/ha. The low total nitrate loads reported in the current study are also somewhat explained by the grazing management plan carried out in 2023. Due to the hay production, no grazing occurred in the treatment paddocks until late April/early May. Consequently, little urine loading occurred during the critical summer/early autumn period. Therefore, it is not surprising that the overall nitrate loads were low.

Additionally, small numerical nitrate loads measured under sheep pasture swards can be explained by the transportation of soil N inputs and outputs, which are influenced by soil and

climatic factors. When most of the N added to the soil through urine is taken up by plants, it results in low nitrate loss in drainage, leading to very low leaching loads. Moreover, the concentration of N in urine primarily varies based on the diet, specifically the DM intake and crude protein content (Whitehead, 1970). Hence, pasture characteristics play a major role in reducing nitrate leaching from a grazing system. Furthermore, in the Tokomaru silt loam, there is a potential for nitrates to convert into gaseous forms of N due to denitrification, which can occur under poor drainage conditions (Saggar et al., 2004). However, further research is needed to confirm all these possibilities. Furthermore, under dairy cattle grazing on a nearby site with the same soil type and climate, it has been recorded that nitrate leaching loads of 12-23 kg N/ha (Nguyen et al., 2023), 2-10 kg N/ha (Christensen et al., 2019) and 5-35 kg N/ha (Hanly et al., 2017). This suggests that sheep grazing systems, such as those in present study have a lower environmental impact than dairy grazing.

This study not only quantified nitrate loads but also assessed other contaminants in drainage, including nitrite-N, ammonium-N, SIN and DRP. The measured loads of nitrite-N (<0.01 kg N/ha), ammonium-N (< 0.03 kg N/ha), and DRP (<0.07 kg P/ha) were found to be very low, and the data patterns have not been presented. Furthermore, the low DRP loads observed in drainage indicate that most P losses in New Zealand soils occur through surface runoff (Monaghan et al., 2002). Therefore, in future it may be useful to measure the P loads in surface runoff in parallel with these treatments. Moreover, the study showed that nitrite-N and ammonium-N contribute only a minor fraction to the SIN loads in drainage.

CHAPTER 6 : CONCLUSION

The study shows that overall, very minimal leaching loads occurred under intensive sheep grazing of either standard pastures or diverse pastures on a fine-textured Pallic soil with mole and pipe drainage. The study suggests that sheep have a lower footprint than dairy cattle and that there is potential to increase livestock intensity on sheep farms without observing high negative effects on nitrate leaching loads.

The diverse pasture treatment measured higher cumulative drainage than standard pasture treatment. In contrast, the diverse pasture treatment reported lower nitrate concentrations than standard pasture treatment in most drainage events. Similarly, the diverse pasture treatment measured numerically lower nitrate loads than the standard pasture treatment. These lower loads were likely due to higher summer/autumn DM yields resulting in higher plant uptake of nitrate during that period.

The numerically lower nitrate loads observed under diverse pastures will be of interest to farmers and industry, but longer-term monitoring is needed to understand the key drivers of this and to verify these findings.

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