Dairy farm system solutions that reduce nitrate leaching and their consequences for profitability:

Using plantain, fodder beet and oats

on a Canterbury case study farm

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Abstract

Dairy products provide nutrition, energy and income for much of the world. It is currently necessary to continue their supply albeit in a more environmentally sustainable manner. Excess nitrate (NO_3^-) from dairy cow urine patches can leach from soils with significant consequences for receiving waters. Some potential on-farm management solutions exist, but can be costly to adopt.

The research aim of this thesis was to test prescribed management solutions for reducing NO_3^- leaching by 20%, in comparison to an existing farm management baseline for the 2017/2018 dairy season, whilst maintaining profitability. Nitrate leaching and profitability were estimated for a south Canterbury case study dairy farm using the models FARMAX Dairy and OVERSEER® Nutrient Budgets.

Prescribed management practices from the Forages for Reduced Nitrate Leaching (FRNL) programme were modelled to achieve this target. The principles were: (i) reducing nitrogen (N) in cows' diets through low-N feed (fodder beet), (ii) recapturing N from soils through catch crops (oats) and (iii) diluting urinary N (through ingested plantain). Two crop treatments were applied to the Baseline to address (i) and (ii). Plantain was included in pastures to address (iii). A number of key assumptions were made about plantain's efficacy for reducing NO_3^- leaching. Plantain was not expected to persist in pasture swards without active management and so a persistence curve and maintenance treatments were incorporated. A sensitivity analysis investigated the influence of soil type and poorer persistence of plantain on treatment success.

Most treatments reduced NO_3^- leaching, but significant management inputs were required to achieve a 20% reduction from the Baseline. Plantain was identified as the key forage for reducing NO_3^- leaching. When plantain was included in pasture swards and undersown every second year to increase its presence, NO_3^- leaching could be reduced by 21-24%, however, profitability was reduced by 5-10%. Fodder beet and oats had little impact on NO_3^- leaching because the crop area was small in comparison to the rest of the farm (4%). There were no treatments that achieved a 20% reduction in NO_3^- leaching and maintained profitability.

The implications of this modelling study for real-life application are that if plantain can be maintained in the pasture sward at high enough levels NO_3^- leaching can be substantially reduced, though this would likely result in a loss of profit.

Keywords

nitrate leaching, plantain, fodder beet, catch crop, oats, modelling, dairy farm system, mixed pasture, profitability, Canterbury

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List of definitions and abbreviations

Abbreviation	Definition
APC	Average pasture cover.
BW	Breeding worth.
Case study farm	The south Canterbury dairy farm that the model scenarios were based off.
CH_4^+	Methane.
DIM	Days in milk. Number of days a cow produces milk for in a dairy season.
Dry cows	Cows that have been dried-off *i.e.* they are not currently milking.
Effective ha	Area of productive land used to grow feed such as pastures and crops to support the milking mob.
Farmax	FARMAX Dairy Generation 7 Version 7.1.2.41.
FB	Fodder beet.
FRNL	Forages for Reduced Nitrate Leaching programme (https://www.dairynz.co.nz/about-us/research/forages-for-reduced-nitrate-leaching-programme/).
GMP	Good Management Practices.
Milking mob	Herd of lactating cows.
Milking platform	Area of the farm that hosts the milking shed, milking mob and most of the dairy farm activities.
MS	Milksolids – New Zealand convention. Only includes fat + protein. Does not include minerals/ash or lactose (*i.e.* milk solids).
N	Nitrogen.
N loading rate	Rate of nitrogen applied to soil (kg N/ha/yr).
N surplus	Indicates the difference between N inputs and N outputs. It can be viewed as a measure of the N at risk of leaching or loss to the atmosphere
N_2	Dinitrogen gas.
N_2O	Nitrous oxide – a potent greenhouse gas.
NH_4^+	Ammonium.
NO_3^-	Nitrate.
OA	Oat catch crop.
Overseer	OVERSEER® Nutrient Budgets Version 6.3.2.
OverseerScience	Online research version of Overseer with more functionality than the commercial software.
PL	Plantain.
Plantain maintenance	Direct drilling 4 kg plantain seed/ha into existing pastures to increase plantain population in pasture.
PR	Perennial ryegrass.
PR/WC	Perennial ryegrass and white clover pasture mix.
PR/WC + PL	Perennial ryegrass, white clover and plantain pasture mix.
PSC	Planned start of calving.
PSM	Planned start of mating.
R2s	Rising two-year-olds. Heifers between 1 and 2 years of age and before their first calf.
Renewal	Replacement of pasture after 10 years. Some paddocks are cultivated and resown with new pasture species while others are cropped with fodder beet (and possibly oats) for approximately 13 months before being cultivated and resown in new pasture.
Scenario	An individual treatment modelled.
Support block	Area of the farm (physically separate from the milking platform) providing feed over winter for dry cows.
Treatment	Variation on the Baseline management. Either through changes in crops or plantain presence.
WC	White clover.
Whole farm system	Milking platform + support block.

1 Introduction

Humanity faces major environmental, social and economic challenges in demands for food, water, nutrients, and energy, (Janzen *et al.*, 2011). In part, these challenges are driven by growing populations. Our global population is predicted to grow to 9.8 billion by 2050 and continue increasing for most of the 21st century (United Nations, 2017). Globally, humans are dependent on a fixed area of land suitable for food production. In the short term, at least, we cannot increase the area of our most productive land. The availability of productive land is declining per person due to soil degradation, population growth and urban expansion onto productive soils. Due to more efficient and intensive methods of agriculture, less land is needed to produce the same quantity and quality of food as in previous decades (Bruinsma, 2009). However, a serious consequence of the methods employed to increase food production per unit area (and our demand for animal products) is greater environmental damage. The environmental footprint of producing animal protein is significantly greater than for plant protein (Tilman & Clark, 2014). While the demand for animal products has stabilised in developed countries, increasing affluence within developing countries is positively correlated with demand for animal products such as dairy, exacerbating the global environmental issue (OECD/FAO, 2018).

Agricultural intensification is considered to be an increase in inputs such as water, feed, agrichemicals, and stocking rate per hectare of land to increase the output of food (Eurostat, 2017; Ministry for the Environment & Statistics New Zealand, 2018). In New Zealand, major agricultural intensification has occurred over the last 50 years, characterised by greater inputs per unit area (MacLeod & Moller, 2006; Parliamentary Commissioner for the Environment, 2004). Dairy farming in New Zealand is considered an intensive land use. An obvious example of agricultural intensification in New Zealand has been the conversion of sheep and beef farms to dairy farms. This has been particularly prevalent in Canterbury within the last two decades (Ministry for the Environment & Statistics New Zealand, 2018). This widespread intensification caused serious environmental damage such as the pollution of freshwater bodies via nitrate (NO_3^-) leaching from farms (Ministry for the Environment & Statistics New Zealand, 2018; Parliamentary Commissioner for the Environment, 2004). However, NO_3^- leaching is not the only environmental concern related to agriculture. Farm systems are complex. Altering some part of the system inevitably affects another part (Doole *et al.*, 2013). For example, changing to a cheaper feed type may increase profitability but also change emissions to the environment. Trade-offs are important to consider when discussing the merits of a solution as pollution-swapping may result. It is often difficult to standardise and compare the impact of each component involved in a trade-off (Chobtang *et al.*, 2017). The importance of greenhouse gases and their impact on climate change is recognised here, but will not form a significant part of this thesis.

A very important long-term challenge for dairy farmers is being able to operate within more restrictive environmental regulations (Reserve Bank of New Zealand, 2018). One of the objectives of the amended National Policy Statement for Freshwater Management (NPS-FM; 2017) is “to enable communities to provide for their economic well-being, including productive economic opportunities, in sustainably managing freshwater quality, within limits” (Ministry for the Environment, 2017a). Dairy farms are businesses existing in rural communities (Kay *et al.*, 2004). They play a significant role in producing food and income, particularly in New Zealand (Ministry for Primary Industries, 2019). Therefore, under the NPS-FM they should be allowed to continue producing milk, providing they comply with environmental regulations.

Public perception and consumer demand have a significant impact on the acceptability of agricultural practices, particularly those relating to environmental health (Aerni, 2009). However, changes in farm management are often restricted by a farm’s financial situation. In New Zealand, the dairy industry is highly indebted, but most farms are profitable (Reserve Bank of New Zealand, 2018). Finding relatively low-cost strategies and alternative management systems to manage NO_3^- leaching from dairy farms is essential given the urgent need for environmental protection and the financial status of economically and environmentally significant stakeholders – the dairy farmers. Solutions to reduce NO_3^- leaching exist, but their adoption can be costly and may result in unforeseen impacts on business profitability (Doole *et al.*, 2013; Doole & Romera, 2015).

Reducing NO_3^- leaching has been shown to significantly reduce operating costs, revenue and operating profit (Doole & Romera, 2015; Muller & Neal, 2019). However, strategies involving alternative crop species have demonstrated more favourable financial outcomes while reducing NO_3^- leaching (Beukes *et al.*, 2018; Beukes *et al.*, 2017).

Physical experiments at the farm level are time and resource-intensive. Such experiments are complicated by climate, market and between-farm variation. Variations in management capability, productivity, mitigation costs and profitability result in differences in farm performance, even between farms of a similar nature and management (Doole *et al.*, 2013). The complexity of farm systems made experimental replication somewhat impossible for this study. In addition, measuring NO_3^- leaching at the farm level is impractical (Addiscott, 1996; Oenema *et al.*, 2003; Selbie *et al.*, 2015).

In the last few years, farmlet and paddock trials under the Canterbury-based Forages for Reduced Nitrate Leaching (FRNL) programme have examined a range of potential management practices to reduce NO_3^- leaching from farm systems. The FRNL programme was a cross-sector approach to addressing NO_3^- leaching from agricultural land. The approach was to incorporate forages with particular characteristics into the every-day and long-term management (DairyNZ, n.d.-b). The FRNL mitigations investigated in this thesis target NO_3^- leaching from dairy cow urine patches by (i) reducing nitrogen (N) intake by feeding fodder beet during late lactation, (ii) diluting N loading in urine patches by incorporating plantain into the pasture base and (iii) capturing N from soils at risk of leaching over winter by catch-cropping with oats (Beukes *et al.*, 2018; Beukes *et al.*, 2017). Scenarios using these forages were analysed using FARMAX Dairy (Version 7.1.2.41) and OverseerScience (OVERSEER® Version 6.3.2) to determine NO_3^- mitigation potential and farm physical and financial feasibility.

Thesis objective

The objective of this thesis was to provide management examples where combinations of FRNL solutions could reduce NO_3^- leaching and maintain profitability. This was for done within a modelling framework for a case study dairy farm in south Canterbury. The Baseline for comparison was the 2017/2018 season observed by the farm. The target was to reduce NO_3^- leaching by 20% from the Baseline using practical management strategies that the case study farm could adopt. Based on the results of the FRNL project and preliminary budgeting, it was hypothesised that by integrating fodder beet, oats and plantain into the existing farm system it would be possible to reduce NO_3^- leaching by 20% and increase profitability above that of the Baseline.

2 Literature review

The introduction of this thesis described the short-term- and long-term food production challenges faced by humanity all around the globe. Current challenges to food production will be discussed in greater detail in this literature review chapter and will then focus on dairy farm management to reduce nitrate leaching to freshwater. This chapter's format is to (i) first provide a national overview for the environmental challenges addressed in this thesis, (ii) then narrow the discussion down to the significance of nitrate (NO_3^-) leached from individual farm systems and (iii) finally discuss the management solutions that will be investigated to achieve the thesis objective.

Section i

A national overview of food production and environmental challenges

2.1 Environmental pollution is a global concern

The biggest challenges humans face today relate to food supply, distribution and the state of the environment. Animal production is a major contributor to global food production and environmental pollution. It is well known that the environmental footprint created during the production of animal-based protein is significantly greater than that of plant-based protein (Tilman & Clark, 2014). A noteworthy trend is that while the demand for animal products has stabilised in developed countries, increasing affluence within developing countries is tantamount to their demand for animal products. Basically, the richer people are, the greater their demand for animal protein, therefore the greater their environmental footprint (OECD/FAO, 2018). If this trend holds and if economic circumstances for larger groups of the global population improve, the pressure on the environment to provide for our wants and needs will only increase (United Nations, 2017).

Climate change is an imminent threat to food production and ultimately our survival, but alongside climate change, we must also face the increasing scarcity of quality freshwater (United Nations, 2018). While beyond the scope of this thesis, it is important to recognise that there is more than one way to solve our food-related environmental problems and that we need to adopt multi-faceted solutions. The challenges of sustainably feeding a growing population can be addressed through strategies targeting the supply and/or demand of food. This thesis explores approaches that will assist continuing the supply of high-quality New Zealand dairy products, albeit in a more environmentally and financially sustainable manner than at present.

New Zealand agriculture is predominantly pasture-based animal production systems. The temperate conditions, land available, evidence-based management systems, product quality and reputation make it an ideal place for pasture-based food production (DairyNZ, 2018; OECD/FAO, 2019). Forty percent of the land in New Zealand is under exotic grassland and used for animal-derived food production. In contrast, less than 2% is under cropping and horticulture, used for plant-derived food production (Statistics New Zealand & Ministry for the Environment, 2018). New Zealand plays a significant international role in supplying milk products and is known as the most “export-oriented producer” of dairy. It is the world’s primary exporter of whole milk powder and butter accounting for more than half of the global exports of these products (OECD/FAO, 2019).

2.2 New Zealand dairy farm systems

There are different models for animal production ranging from confinement production to pasture-based grazing systems, the latter being the standard in New Zealand (Dillon *et al.*, 2005). New Zealand dairy farms are businesses reliant on the seasonal production of sufficient pasture dry matter (DM) and metabolisable energy (ME) to support milk production from their herds. To operate in the long-term, New Zealand dairy farmers must either produce or import enough feed of sufficient quality to produce milk, as they are paid based on the quantity of milksolids (MS; fat + protein components of milk) they produce (DairyNZ, 2019; Ledgard *et al.*, 1999).

Until the 1980’s, traditional New Zealand dairy farms were based on low N-fertiliser input, binary pastures. These pastures were perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) mixes (PR/WC) (Ledgard *et al.*, 1999; Parfitt *et al.*, 2012; Statistics New Zealand, 2019). Dairy systems have since intensified which can be seen through an increase in nitrogen (N) fertiliser use, increased stocking rates and imported feed use (Eurostat, 2017; Ministry for the Environment & Statistics New Zealand, 2018).

The dawn of chemical manufacture of urea fertiliser revolutionised agriculture as N could be easily and cost-effectively added to crops and pastures to boost DM production (Parfitt *et al.*, 2012). The addition of N to N-limited systems boosts plant productivity, resulting in greater yields (Kemp *et al.*, 1999a). In addition, providing the marginal costs of applying N fertiliser do not exceed marginal revenue, and the additional pasture produced is utilised, profitability will increase. In a N-limited system, pasture and crop yields and subsequently milk production would decline without N applications. This would impact a farm's financial ability to operate. If N was withheld and the resulting reduction in productivity was not met by reduced production costs, a business could become unprofitable very quickly (Kay *et al.*, 2004; Kemp *et al.*, 1999a). Agricultural systems nowadays tend to be N-rich from regular application of N-based fertilisers and increases in imported feeds (Di & Cameron, 2002; Ministry for the Environment & Statistics New Zealand, 2018).

The current dairy management system is still based on PR/WC pastures which has been the norm since the 1930's (Charlton & Stewart, 1999; Dodd *et al.*, 2019; White, 1999). More recently, dairy farmers have begun including forage crops on their milking platforms and importing supplemental feed (Dodd *et al.*, 2019). Feeding supplements tends to increase the unit cost of MS production, thereby increasing financial risk. The reason for feeding supplements is increase or maintain high MS production to increase profitability (Doole, 2014). Of course, supplemental feeds are only profitable if they are fed at a time when there is a pasture deficit and/or a high MS price. The profitability of supplemental feeds also depends on the farm system, however, supplement use is not always efficient in New Zealand (Doole, 2014; Ho *et al.*, 2013). There appears to be an expectation that growing crops on milking platforms can improve profitability because expensive imported feeds can be substituted with home-grown crops although there are significant costs involved with cropping (Bryant *et al.*, 2010a; Romera *et al.*, 2015).

Increasing the production of home-grown pasture is considered an inexpensive way to improve farm profitability (Glassey *et al.*, 2013), especially on farms where pasture production and/or utilisation could be improved (Dillon *et al.*, 2005; Macdonald, 1999). However, pasture is not the only feed type grown in New Zealand pastoral systems. In the South Island, it is common for crops to be grown on the milking platform. There are a variety of reasons for the decision to do this e.g. to provide feed at times of the year where pasture growth is limiting, to transition cows onto crops before moving off farm during the winter (Edwards *et al.*, 2017), to enable better weed control when renewing pasture (Harker & O'Donovan, 2013), to increase total home-grown feed production (Malcolm *et al.*, 2016, 2017), and/or to have a low-N feed available to compliment high-N pasture (Dalley *et al.*, 2017).

As well as providing a cost-effective source of feed (Dillon *et al.*, 2005), consumption of (home-grown) N-rich pastures carries a risk of N loss from the farm system and can lead to environmental damage, for example via NO_3^- leaching and greenhouse gas emissions (see section 2.4). In general, increasing productivity on a farm requires intensification of the system via increasing inputs. This can result in greater environmental pollution (Chobtang *et al.*, 2017; Dalley *et al.*, 2018; de Klein *et al.*, 2010; PCE, 2004; Pembleton *et al.*, 2015).

2.3 Environmental policy in New Zealand

Regulation of water quality is complicated by the heterogeneity of farms and land uses that contribute to water pollution due to differences in management, the cost of mitigation and the profitability of farms. Policies that focus on reducing NO_3^- load to the environment, as in New Zealand, are preferable to those restricting inputs because there is greater freedom for farmers to operate and stimulate innovation to reduce NO_3^- leaching (Doole *et al.*, 2013). In New Zealand, NO_3^- leaching is estimated using the nutrient budgeting tool, OVERSEER® Nutrient Budgets (Overseer) (Wheeler *et al.*, 2006). Overseer is now a widely-adopted policy tool used by local governments to monitor and enforce policies to reduce NO_3^- leaching (Freeman *et al.*, 2016). This is briefly discussed in section 2.8.

While not the only source of environmental degradation, dairy farming has major impacts on the state of the environment. This is obvious from declining trends in environmental indicators e.g. (Ministry for the Environment & Statistics New Zealand, 2018), and a body of evidence pointing to dairying as a major contributor e.g. (Di & Cameron, 2002; PCE, 2004). A large proportion of N emissions to the environment come from dairying: the largest proportion of New Zealand's greenhouse gas emissions come from agriculture (48%), most of the impact comes from the dairy sector via enteric methane (Ministry for the Environment, 2019b); and the majority of N pollution in freshwater comes from intensive dairy farming (Di & Cameron, 2002; Ministry for the Environment & Statistics New Zealand, 2018; Selbie *et al.*, 2015). If the New Zealand dairy industry is to maintain an environmentally responsible profile, under current policies such as the National Policy Statement for Freshwater Management 2017 (NPS-FM) and Essential Freshwater (Ministry for the Environment, 2018), significant changes need to be made at the farm level to reduce N pollution of freshwater resources (Di & Cameron, 2002; Ministry for the Environment, 2017a; PCE, 2004).

In 1991, the Central Government of New Zealand released the Resource Management Act (RMA), which gave the responsibility of local environmental management to regional councils. The Central Government is still responsible for providing national direction for environmental management, but regional councils are tasked with managing the environment within their territorial boundaries (Ministry for the Environment, 2017b).

The Environment Canterbury Regional Council is responsible for the Canterbury region. Canterbury is a unique region in New Zealand. As well as its internationally and nationally significant braided river ecosystems (Environment Canterbury, 2011), it is a very productive dairy region. As of the 2017-2018 New Zealand Dairy Statistics survey, 19% of the dairy cows in New Zealand are farmed in Canterbury. It has, by far, the most dairy cows in any region of the South Island and in New Zealand is second only to the Waikato region (22.7%). In the 2017/2018 dairy season, Canterbury produced 21.2% of New Zealand's total MS production, again second only to the Waikato region (22.1%) (DairyNZ & Livestock Improvement Corporation, 2019). As described earlier, there is a strong link between agricultural intensity and the state of the environment. Canterbury is an intensive dairying region, supporting 63.8% of the total irrigated land in New Zealand. Significant areas of Canterbury's braided river, wetland and tussock grassland ecosystems are under threat due to human influence and agricultural intensification (Ministry for the Environment & Statistics New Zealand, 2018). The braided river and wetland ecosystems are of particular interest in this thesis as they are highly susceptible to NO_3^- inputs and the environmental pressures caused by irrigation from nearby dairy farms. However, the discussion of this thesis does not extend to the impacts of NO_3^- leaching on these ecosystems. The scope of the discussion is restricted mostly to the farm system.

The case study farm for this thesis is in the Orari Temuka Opihi Pareora Zone (OTOPs Zone), which is primarily administered by the Timaru District Council. A small southern section is administered by the Waimate District Council. The Canterbury Matrix of Good Management was a cross-sector project established to estimate nutrient losses from different farm systems operating at good management practice (GMP) across Canterbury. Good management practices were defined in this project and communicated to relevant land-users (farmers) with the intention that the GMPs would be incorporated in Farm Environment Plans to reduce their environmental impact. The GMPs were developed for the Canterbury region, but were intended to be applicable to other regions in New Zealand (Matrix of Good Management Governance Group, 2015). In the meantime, GMPs have been adopted nationwide and reframed as "Good Farming Practices". At present, providing they are farming within their resource consents, farmers in the OTOPs Zone do not need to make changes to their current management beyond ensuring they comply with GMP (and do not exceed their 2009-2014 GMP NO_3^- leaching baseline), however this may change. This thesis was carried out to provide management examples resulting in significant (>20%) reductions in NO_3^- leaching from a Canterbury case study dairy farm whilst maintaining profitability, specifically using principles identified in the Forages for Reduced Nitrate Leaching (FRNL) programme (see section 2.6).

Section ii

The significance of nitrate leached from individual farms

2.4 Nitrogen cycling in New Zealand agriculture

Nitrogen is an essential element for life, forming the basis of protein. The production of milk therefore requires N (Di & Cameron, 2002). In New Zealand, a dairy cow's diet is predominantly made up of pasture with some home-grown crops and imported supplements, depending on the management of the system (Dodd *et al.*, 2019). New Zealand dairy pastures have high metabolisable energy (ME; ~11.5 MJ ME/kg DM) and N contents (usually >30% crude protein; CP) (Waghorn *et al.*, 2007). However, there is a large difference in the amount of N consumed by cows grazing these high-N pastures and the actual requirements of these cows (Totty *et al.*, 2013). This results in a mismatch between N supply and demand (section 2.4.2).

While inert dinitrogen gas (N_2) makes up 78% of the atmosphere, this form of N is unavailable to most plants and animals (Schimel & Holland, 2005). To overcome N limitations, N fertiliser use has increased globally and in New Zealand (Di & Cameron, 2002; Lu & Tian, 2017; Statistics New Zealand, 2019). Before urea-based fertilisers became common-place in New Zealand, grass and herb species within pastures were dependent on biological N fixation, mainly via white clover, for their primary source of N. White clover is a legume and has a symbiotic relationship with nitrogen-fixing bacteria. These bacteria infect the roots of clover plants causing the formation of root nodules where they live. The bacteria reduce N_2 gas into plant-available ammonium (NH_4^+) and in exchange are provided with a carbohydrate/energy source and niche by the host plant (McLaren & Cameron, 1996).

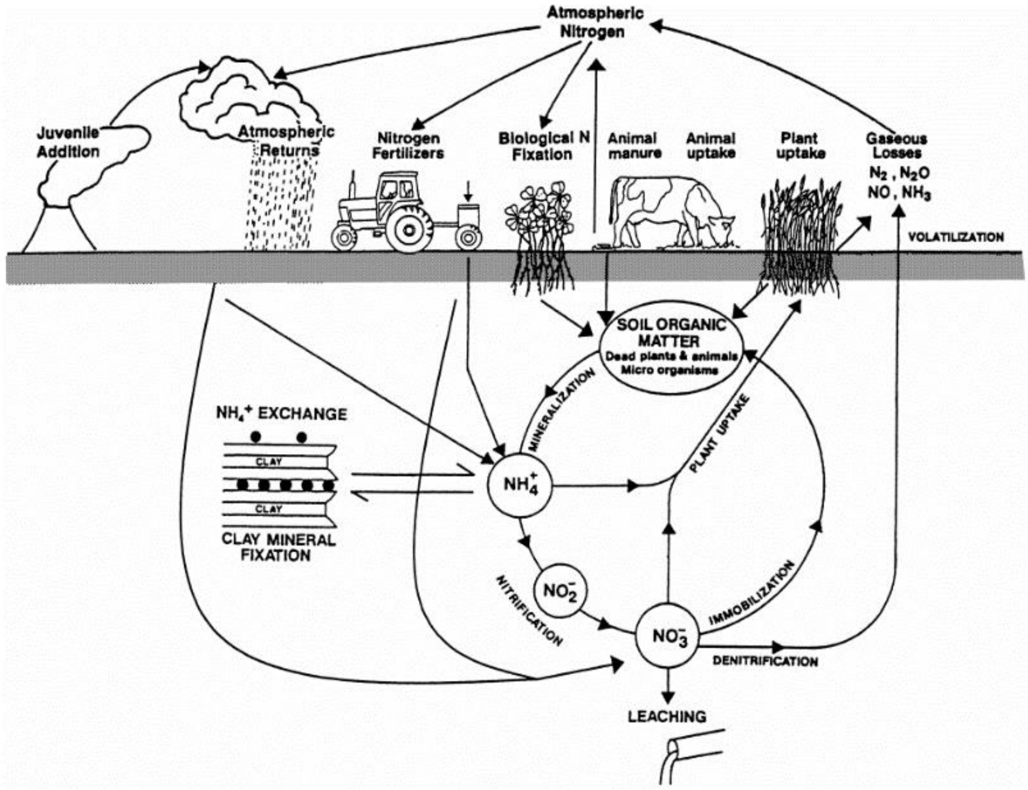

Figure 2.1: The nitrogen cycle on a dairy farm (Di & Cameron, 2002).

2.4.1 Nitrate leaching from soils

Nitrogen has many organic and inorganic forms in nature. A smaller proportion of N taken up by pasture plants is organic, while most is taken up in mineral form as NO_3^- and NH_4^+. Ammonium is rapidly converted to NO_3^- via nitrification when soil is aerated (Haynes, 1986). Because of the speed of this process and the rate of mineralisation (conversion of organic matter to mineral N forms), there is often more NO_3^- than NH_4^+ available for plant uptake (Selbie *et al.*, 2015). However, NO_3^- is a highly soluble and mobile form of N. The negative charge of the NO_3^- ion means that it does not adsorb to soil particles – it is repelled – as soils generally have a net negative charge. Because of this repulsion the high solubility of NO_3^- in water, during periods of drainage, excess NO_3^- is leached from the soil, often to groundwater and aquifers. The fate of NO_3^- in soil depends on environmental factors such as the C:N ratio of the soil, soil moisture content, plant demand and microbial populations present. If NO_3^- is in excess to plant demand, and/or when drainage is high then it can leach from the system and enter freshwater resources, causing environmental degradation. Leaching is considered to have occurred when NO_3^- has left the rooting zone of the soil profile and enters the vadose zone (it is inaccessible to plants) (Di & Cameron, 2002).

The major source of NO_3^- leaching risk from dairy farms is excess NO_3^- (above plant requirements) arising from cow urine patches. Nitrate leaching is driven by drainage and is dependent on local soil characteristics, climate and management practices. Fine-textured 'heavy' soils have poorer drainage and therefore less risk of NO_3^- leaching than coarse-textured 'light' or stony well-drained soils. Most drainage and therefore NO_3^- leaching occur during periods of high drainage. During late autumn and winter, drainage increases due to low evaporation, higher soil moisture contents and higher seasonal rainfall (Di & Cameron, 2002). Drainage events can be caused by high rainfall and over-irrigation, especially from free-draining soils and those with little water storage capacity (Selbie *et al.*, 2015). Poor drainage can also affect N cycling and therefore NO_3^- leaching via denitrification (the conversion of NO_3^- to gaseous forms) (Di & Cameron, 2002). This is because there is more NO_3^- available for conversion to gaseous forms of N. Also, poor drainage means that soils drain slowly so NO_3^- is less likely to leach than from a lighter, stony soil. The case study farm for this thesis has heavy, poorly drained soils. The soils are: Claremont moderately deep silty loam, Waitohi deep silty loam and Studholm moderately deep silty loam over clay (section 9, Appendix 3).

Autumn tends to be the beginning of the main drainage period due to increased rainfall and falling temperatures. At the same time, plant growth and subsequently N uptake slow as temperature decreases (Selbie *et al.*, 2015). In their meta-analysis, Selbie *et al.* (2015) calculated that the proportion of NO_3^- lost from urine patches based on the season of application was: autumn 24%, winter 20%, spring 17% and summer 16%.

Three mechanisms are responsible for the transport of NO_3^- below the rooting zone (Selbie *et al.*, 2015):

1. convection through the profile with drainage water,
2. diffusion and hydrodynamic dispersion (physical mixing and diffusion of solutes during drainage), and

3. Also, significant NO_3^- can be lost from soils through preferential flow and bypassing the soil matrix, reducing the chance of uptake by plants.

Di and Cameron (2002) and McLaren and Cameron (1996) report that NO_3^- leaching is also affected by other soil characteristics such as:

1. profile depth (the deeper the soil profile is, and the easier it is for plant roots to grow, the deeper the rooting zone which could lead to greater plant N uptake),
2. macroporosity (the presence of large pores provides pathways for preferential (non-matrix) flow. Water can bypass the soil profile, carrying NO_3^-),
3. presence of root or earthworm channels and cracks (affecting drainage),
4. compaction (affecting infiltration, drainage and availability of water), and
5. quality and quantity of organic matter (nutrient retention and maintaining soil physical structure).

In addition, they also report that NO_3^- leaching is also affected by external factors such as:

6. rainfall and
7. water table height (a high water tables reduce the depth of the soil profile and limits oxygen supply, resulting in anaerobic conditions that affect growth and populations of plants and microorganisms).

The factors listed above play an important role in NO_3^- leaching, but their role is outside the scope of this thesis so they will not be discussed further.

2.4.2 Contribution of animals to nitrate leaching

The main source of excessive N in New Zealand's freshwater is NO_3^- loss from urine patches on dairy farms (Di & Cameron, 2002; Ministry for the Environment & Statistics New Zealand, 2018; Selbie *et al.*, 2015). As stated earlier, traditional PR/WC pastures supply more N than cows need (Waghorn *et al.*, 2007). While applying N-fertilisers to N-limited pastures will increase yield and subsequently milk production, the N consumed per hectare also increases, increasing the excess N processed by the cows. Between 70 – 95% of N consumed by ruminants, such as dairy cattle, is excreted as a result of excess dietary N (White, 1999). The majority of this is partitioned to urine over dung. Rius *et al.* (2012) reported that approximately twice as much of the excess N ingested was partitioned to urine over dung in a study of New Zealand dairy cows. In addition, there is a greater proportion of N as dissolved inorganic forms than organic forms, in urine than dung (Oenema *et al.*, 2005; Williams & Haynes, 2000). Rapid conversion from urea (the main form of N in urine) to NH_4^+ to NO_3^- results in high concentrations of NO_3^- in the urine patch (Di & Cameron, 2002). As a result, N loading rates in dairy cow urine patches exceed pasture requirements and what is not taken up is vulnerable to leaching. Given the significance of the urine patch to NO_3^- leached, the excretion of excess N *via* urine is a major issue of intensification (Oenema *et al.*, 2005; Williams & Haynes, 2000).

2.4.3 The urine patch: nitrate leaching at the farm level

The rate of N deposition in urine patches is termed the 'urine patch N loading rate' (expressed as kg N/ha/yr/urination). As stated earlier, dairy cows excrete highly concentrated N in their urine. This results in a high N loading rate in the urine patch (Di & Cameron, 2002; Haynes & Williams, 1993; Selbie *et al.*, 2015). Selbie *et al.* (2015) reported the literature average urinary N loading rate for dairy cows to be 613 kg N/ha/yr. For context, the case study farm applies N fertiliser at 279 kg N/ha/yr. This is spread out over ten months with a maximum rate of 49 kg N/ha in November *i.e.* the maximum fertiliser rate for the case study farm is only 8% of the average urine patch, as reported by Selbie *et al.* (2015).

In New Zealand dairy systems, there are two N supply and demand pathways contributing to the high N loading rate of urine patches. The first is the mismatch between pasture N supply and animal N demand. Standard PR/WC pastures contain more N than animals need so the excess is concentrated and excreted. The second is the mismatch between urine patch N supply and the N demand of plants. Low plant demand relative to N supply puts excess NO_3^- in soil at risk of leaching. Higher stocking densities due to intensification on grazed pastures and the higher yields of crops lead to a greater risk of urine patch overlaps. Overlap of urine patches results in a greater risk of NO_3^- leaching (if one urine patch already exceeds plant demand, then two or more overlapping patches will far exceed plant demand) (Pleasants *et al.*, 2007). Under urine scorch marks where both mineral-N and pH are too high, plants are stressed so their ability to take up NO_3^- is reduced (Selbie *et al.*, 2015). Reducing the N loading rate of the urine patch can therefore improve the efficiency between animal N supply (via excretion) and plant demand and the ability of plants to take up N deposited in urine.

Plant uptake is dependent on temperature, sunlight hours, soil moisture and plant-available N and is greatest during warm, wet seasons (Selbie *et al.*, 2015). It is possible for pastures to take up more N than they need, termed "luxury uptake". The adsorbed NO_3^- is protected from leaching as it is held (as NO_3^-) in the plant. However, when ingested by cows, this additional excess is subject to the same fate as most other NO_3^- ingested – urine deposition. As cows already consume more N than they need from ryegrass pastures, instead of this distributing N around the paddock more evenly through subsequent urination events, this just transports the problem (excess N) to future urine patches (Kemp *et al.*, 1999a; Selbie *et al.*, 2015). Worth noting are the implications for animal health: excess NO_3^- in foliage can be deadly to animals. If 'free' NO_3^- ions are consumed, they are converted to nitrite in the rumen, which is adsorbed into the bloodstream and binds (in place of oxygen) to haemoglobin in the blood, usually resulting in death (O'Hara & Fraser, 1975).

Section iii

Farm-scale management solutions investigated

Excess N in organic soils is lost to the environment, particularly to water bodies (Di & Cameron, 2002). To address this issue, solutions should be focused at the **source** of the pollution, within the zone of influence of farmers. Altering farm systems management is a good place to start. Here we can work on improving the efficiency of N cycling on farms *i.e.* reducing the amount of N lost from the system. This section covers ways to reduce NO_3^- leaching from dairy farms. Testing the efficacy of management practices to reduce NO_3^- leaching from the urine patch is a major motivation of this thesis.

2.5 Current solutions

Strategies to reduce NO_3^- leaching from dairy farms have been proposed (de Klein *et al.*, 2010; Di & Cameron, 2002), but can be costly to adopt and in some cases are impractical. To address the food production issues we face, solutions to reduce NO_3^- leaching from dairy farms must be environmentally and financially sustainable. Some of the solutions currently available and explored as mitigation strategies in New Zealand are reported in Table 2.1. However, the discussion in this section focuses on forage solutions that reduce dietary N, dilute urinary N and recapture mineral N from soils. Such solutions are based on the use of alternative pasture and crop species identified in the FRNL programme (section 2.6).

Table 2.1: Examples of currently explored nitrate leaching mitigation strategies for New Zealand dairy farms. N = nitrogen.

<table>
<tr><th>Address sources of excess N</th><th>Improve resource use efficiency</th><th>Study</th></tr>
<tr><td colspan="2">Use stand-off facilities and collect effluent. Apply to pasture and crops when plant demand is high, and risk of drainage is low.</td><td>Beukes et al. (2017); DairyNZ (n.d.-a); Di and Cameron (2002); Romera et al. (2017a)</td></tr>
<tr><td colspan="2">Match water, fertiliser and effluent applications to plant demands. Apply small and timely amounts, avoiding applications in late autumn and winter.</td><td>Beukes et al. (2017); DairyNZ (n.d.-a); Di and Cameron (2002)</td></tr>
<tr><td colspan="2">Use nitrification inhibitors such as dicyandiamide (DCD).</td><td>Di and Cameron (2002); Romera et al. (2017a)</td></tr>
<tr><td>Use edge of field mitigation techniques, such as riparian margins or denitrification walls, to immobilise or denitrify NO_3^- in buffer zones between the farm and waterways.</td><td></td><td>Di and Cameron (2002); Schipper and Vojvodic-Vukovic (2000)</td></tr>
<tr><td colspan="2">Match animal feed demand to plant supply and reducing total N imports. Feed demand is affected by stocking rate. Dry cows off earlier in autumn and sell culls earlier in the season.</td><td>DairyNZ (n.d.-a); Di and Cameron (2002)</td></tr>
<tr><td colspan="2">Use low-N feed alternatives such as maize and fodder beet instead of grass silage and kale, especially during autumn/winter.</td><td>Beukes et al. (2017)</td></tr>
<tr><td colspan="2">Sow alternative species such as fodder beet, plantain and Italian ryegrass. Fodder beet and plantain reduce the N concentration in urine and winter-active Italian ryegrass can take N up when ryegrass productivity is reduced.</td><td>Beukes et al. (2018); Beukes et al. (2017)</td></tr>
<tr><td></td><td>Add salt to the diet to increase the frequency of urination events and dilute N in urine by increasing the total volume of urine.</td><td>Ledgard et al. (2007)</td></tr>
<tr><td colspan="2">Follow winter forage crops like fodder beet and kale with catch crops such as oats to take up excess N instead of leaving paddocks fallow over winter.</td><td>Beukes et al. (2018); Beukes et al. (2017); DairyNZ (n.d.-a); Di and Cameron (2002); Malcolm et al. (2016)</td></tr>
</table>

2.5.1 Low-nitrogen diets

One method to reduce NO_3^- leaching losses from urine patches is to reduce the total amount of N ingested by the cow. Using low-N feeds allows a cow to consume her ME and DM requirements while reducing her total N consumption. Using mass-balance, ingesting less N should result in less N diverted to urine as long as there are no confounding metabolic pathways (Selbie *et al.*, 2015). Fodder beet and maize are examples of low-N feeds (Dalley *et al.*, 2017; Matthew *et al.*, 2011). Fodder beet is discussed below and used as a mitigation strategy for the case study farm (section 2.6.2).

Gregorini *et al.* (2016) identified diets that could be used to reduce negative urinary N outputs, methane (CH_4) emissions and increase MS production. They screened 50 different feeds (over 10,000 diet combinations) for their suitability for use in New Zealand dairy farm systems. They concluded that there was no single diet that achieved the greatest production with the least emissions. They found that cereals and sugar/fodder beets were the most common components in binary diet combinations that could achieve higher MS productions and reduced urinary-N outputs however there was often a trade-off between minimising CH_4 and urinary-N. Fodder beet can reduce urinary-N and therefore NO_3^- leaching. However, depending on the type of feeds making up the remainder of the diet Gregorini *et al.* (2016) concluded that low-N diets including fodder beet may also result in an increase in CH_4 emissions.

2.5.2 Increased mineral intake

Minerals (salt) can be added to the diet to increase water intake and therefore the urination volume and frequency (Ledgard *et al.*, 2007). This dilutes the N loading rate of urine patches (Selbie *et al.*, 2015). Mineral additives are not investigated in this master's thesis, however the principle of increasing minerals in the diet to dilute urine may be applicable to plantain, an alternative pasture species (section 2.6.3). Plantain is reported to have a higher mineral concentration than RG/WC pastures (Charlton & Stewart, 1999). This may contribute to a reduction in urine patch N loading rates by diluting urine in a similar way to salt as in (Ledgard *et al.*, 2007).

2.5.3 Alternative pasture species

Traditionally, New Zealand pastures have been a simple binary combination of a grass and a legume species such as perennial ryegrass and white clover (Ledgard *et al.*, 1999). The inclusion of an individual species, with specific beneficial traits, to a grass pasture base can introduce some advantageous characteristics in terms of feed supply, energy content and some environmental benefits (Cranston *et al.*, 2015; Kemp *et al.*, 1999b; Luo *et al.*, 2018; Nobilly *et al.*, 2013; Pembleton *et al.*, 2015; Totty *et al.*, 2013). White clover in ryegrass pastures is probably the most well-known example in New Zealand agriculture. Being a legume, clover biologically fixes N via symbiosis with rhizobium, providing ryegrass plants with an accessible source of N. Including clover in N-limited pastures, can increase annual DM production through N supply to ryegrass plants. Grazing management that protects clover from over-grazing and too much shading allows the plants to spread via stolons and establish in gaps in the pasture sward, providing protection against weed invasion. Being more tolerant of warmer temperatures than ryegrass, white clover also contributes to increased pasture growth in summer (Kemp *et al.*, 1999b).

Two recent reviews on pastures under dairy (Pembleton *et al.*, 2015) and sheep grazing (Vibart *et al.*, 2016), agree that mixed pastures either maintain or improve DM production when compared to PR/WC pastures. The quality (ME) of the DM produced is an essential component to consider as milk is an energy-intensive product to produce, thus lactating cows require more energy than dry cows. Therefore, pasture produced on the milking platform must be of sufficient quality throughout the season to support milk production. When considering the addition of alternative pasture species both production and quality must be considered. Alternative species must offer high DM production, high MS production, environmental benefits and improved persistence to be considered suitable for use in New Zealand dairy farm systems (Nobilly *et al.*, 2013).

The review by Vibart *et al.* (2016) compared the performance of standard ryegrass-white clover pastures to mixed pastures with three or more species. They concluded that mixed-species pastures can both (i) increase total annual herbage production and (ii) increase N use efficiency by influencing farm N dynamics. The review also confirmed that the inclusion of plantain and chicory can reduce N loading in urine patches. This reduction in NO_3^- leaching has been well-documented in a number of other studies (Box *et al.*, 2017; Bryant *et al.*, 2017; Minnée *et al.*, 2017; Totty *et al.*, 2013). In addition to reducing N loading rates in urine patches, mixed pastures can reduce N losses by increasing N uptake as plants have variable rooting depths, nutrient requirements, and seasonal growth patterns. They can coexist if they have symbiotic relationships and different nutritional requirements and/or occupy different ecological niches. They can potentially obtain nutrients from various depths in the soil and at different times of the year, reducing competition and increasing the range of depths that N can be taken up from. For example, Italian ryegrass is a winter-active ryegrass species. Its ability to grow in the winter where traditional perennial ryegrass and other pasture species have reduced growth is advantageous both from a production and environmental perspective. This winter growth advantage , Italian ryegrass can be a reliable source of feed during winter (Charlton & Stewart, 1999) and in doing so, it takes up N from the soil at the time of year when it is most at risk of leaching (Woods *et al.*, 2018). This is environmentally desirable. However, it does not perform as well as PR/WC pastures in the summer (Charlton & Stewart, 1999) and needs to be resown more frequently (Chapman *et al.*, 2008).

There are trade-offs to including other species in pasture and these must be considered when assessing them for use. One trade-off reported for mixed pastures is that weed control can be more difficult and expensive as many common herbicides used for PR/WC pastures may target desirable, alternative species such as plantain (Pembleton *et al.*, 2015). Another is different DM production curves to PR/WC pastures. This can be beneficial if the species provides a source of feed during seasonal deficits (*e.g.* summer-dry and the cool seasons; late autumn/winter/early spring), but can be a draw-back if it does not perform as well as PR/WC at other times of the year.

Adding alternative species to a pasture base may require changes in grazing management. This could complicate the farm system or, as in the case of Dodd *et* *al.* (in press), result in farmers maintaining *status quo* management practices, suited for PR/WC pastures. In summary, alternative species in pastures could reduce NO_3^- leaching from dairy farms, but there are trade-offs that need to be considered.

2.5.4 Farm systems management

There are major benefits of farm systems studies. While resource-intensive, they are useful in determining whether mitigation strategies can be scaled up from plot/paddock-scale trials to maintain their desired effect. There have been a couple of large research programmes testing different strategies. The FRNL programme (fully described in section 2.6) is similar to the earlier DairyNZ Pastoral 21 (P21) project, which also had a goal of reducing NO_3^- leaching while maintaining profitability. These two programmes differ based on the mitigation strategies tested. For the Canterbury region, the P21 project compared general farm management strategies based on input intensity in farmlet trials in Lincoln from 2011-2014. The focus of the project was to examine the outcomes of potential future farm systems designed to reduce NO_3^- leaching (Chapman *et al.*, 2017). For Canterbury, two combinations of mitigation strategies were trialled to investigate the effect on NO_3^- leaching, pasture and animal production and profitability on the milking platform. Two possible systems were compared through farmlet trials: low-input, high efficiency and high-input, high efficiency. The outcomes of this research were that NO_3^- leaching could be reduced under both low-input and high-input systems when compared to the Canterbury benchmark and the performance of the research farm the farmlets were located on. However, the high-intensity farmlet appeared to have limited success. The profitability of the farmlets depended on the milk price with the low-intensity farmlet being profitable at $4.40, $5.25 and $6.30/kg MS and the high-intensity farmlet only being profitable at all three prices $5.25 and $6.30/kg MS. At $6.30/kg MS, the high-intensity farmlet had only a 3% higher operating profit (OP) than the low-intensity farmlet. The conclusion was that there was a profitable solution to reducing NO_3^- leaching from the milking platforms of Canterbury dairy farms. However, these solutions required significant changes to the existing farm management, particularly the stocking rate. In contrast, in this thesis the farm system will be kept as similar as possible to the Baseline farm to determine the effect of FRNL treatments alone on NO_3^- leaching and profitability.

2.6 Forages for Reduced Nitrate Leaching (FRNL) solutions

The DairyNZ-led FRNL programme was a cross-sector approach to reducing NO_3^- leaching from land under agricultural production. The aim of FRNL was to deliver *affordable* management strategies to commercial farmers, that could reduce NO_3^- leaching by 20%, by 2020 (Beukes *et al.*, 2017). This project is related to the Matrix of Good Management programme (see section 2.3) which was established to estimate the N footprint of Canterbury farming systems to use as a base for improving water quality (Matrix of Good Management Governance Group, 2015).

Both trials and modelling from the FRNL programme have shown that fodder beet, plantain and oats can reduce NO_3^- leaching on individual dairy farms (Beukes *et al.*, 2018; Beukes *et al.*, 2017; Malcolm *et al.*, 2018; Minnée *et al.*, 2019). They do so via quite different pathways (sub-section 2.6.1). Given the success of the FRNL programme in identifying solutions to reduce N leaching, the next step was to investigate their impact at farm scale.

2.6.1 Reducing nitrate leaching from urine patches

Reductions in N leaching from the milking platform of the case study farm will be targeted through three pathways (Figure 2.2). These are based on the main findings of the FRNL programme. These findings were the following three principles:

1. Reducing the amount of N consumed by the cow in autumn through low-N feed (fodder beet; Figure 2.3 & Figure 2.4). Fodder beet was fed during late lactation (autumn) to reduce the total amount of N ingested and dilute N excreted in urine.
2. Diluting N excreted in urine by feeding pastures, pasture silage and crops containing plantain (Figure 2.5 & Figure 2.6), especially during mid-summer/autumn.
3. Recycling N by reusing the excess held in soils during winter. Oats (a winter-active plant species; Figure 2.7 & Figure 2.8, are sown immediately following the fodder beet crop to take up N at risk of

leaching. This could be ensiled and fed to dry cows at the end of the season.

Use of these three forages were modelled for the Canterbury case study farm to investigate the impacts on NO_3^- leaching and profitability.

2.6.2 Fodder beet crops

Fodder beet is a common winter-fed crop (Figure 2.3) (Edwards *et al.*, 2017). It has a high ME content (12-12.5 MJ ME/kg DM) (DairyNZ, 2017), and is considered a low-N feed (7.6% CP for the whole plant; bulb + leaves) (Dalley *et al.*, 2017). Grazing dairy cows on fodder beet reduces N intake and subsequently N excreted via urine and dung (Gregorini *et al.*, 2016).

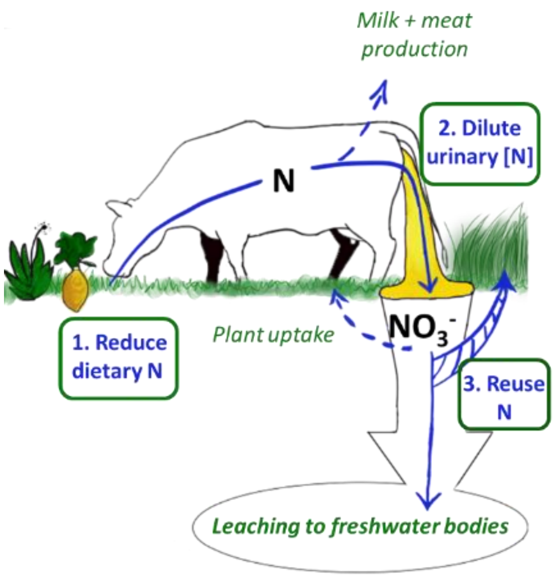

Figure 2.2: Conceptual diagram showing how fodder beet, oats and plantain alter nitrogen (N) cycling between plants and animals to reduce nitrate (NO_3^-) leaching from urine patches (section 2.6.1). Pathway 1 is to reduce the amount of N consumed and therefore excreted by feeding fodder beet. Pathway 2 is to dilute urinary N excreted by feeding plantain. Pathway 3 is to recycle N by catch cropping with oats.

Figure 2.3: Mature fodder beet bulb. Image: DairyNZ.

Figure 2.4: Young stock grazing winter fodder beet crop *in situ*. Image: DairyNZ.

Fodder beet can be grazed *in situ* (Figure 2.4) or lifted and fed on paddocks/a feed pad. When the tops (leaves) are removed, the bulbs store well so do not have to be fed immediately after lifting. Fodder beet is a demanding and therefore expensive crop to establish and grow, but as it is a high-yielding crop (up to 34 t DM/ha (Judson *et al.*, 2016)) and offers high ME, it results in a cheap supplemental feed per unit of DM. It is usually fed to dry cows rather than lactating cows (it is more commonly grown as a winter-feed on the support block than on the milking platform) Fodder beet must be fed with care as consumption increases the risk of animal health issues caused by nutrient deficiencies and acidosis (Waghorn *et al.*, 2019). Lactating cows are more at risk than dry cows (Waghorn *et al.*, 2018; Waghorn *et al.*, 2019). All cows must be carefully monitored as they are transitioned onto and off fodder beet to also ensure they do not succumb to acidosis.

Feeding fodder beet can reduces total dietary N compared to pasture-based diets. However, if it is grazed *in situ* (as is normal practice), the high DM yield forces farmers to feed the crop at very high instantaneous stocking rates *e.g.* a crop yielding 25 t DM/ha fed at 5 kg DM/cow/day is recommended to be allocated at an area of 200 m^2/100 cows (DairyNZ, 2017). This results in an instantaneous stocking rate of 5,000 cows/ha. While there might be less total N excreted by the cows than if they were eating ryegrass for example, the area that the herd urinates upon is smaller and the risk of urine patch overlap is greater (see section 2.4.3). As the risk of NO_3^- leaching increases with urine patch overlaps, this risk increases further with increasing stocking rates (Pleasants *et al.*, 2007).

2.6.3 Plantain as an alternative pasture species

Where urine patch N loading rates are reduced there will be decreases in NO_3^- leaching (Selbie *et al.*, 2015). Including plantain (Figure 2.5) in the diet (such as through grazing mixed pastures; Figure 2.6), reduces N output in urine (Box *et al.*, 2017). Plantain has a similar N content to ryegrass, but the division of this between soluble, degradable and undegradable compounds is different (Martin, 2018; Minnée *et al.*, in press). Partitioning N from urine to faeces reduces the risk of N loss from excreta deposits. Plantain tends to have high concentrations of mineral compounds (Charlton & Stewart, 1999) and three secondary compounds have been identified, two of which (aucubin and catalpol) may affect N partitioning (Box *et al.*, 2019). Partitioning N from urine to dung reduces the risk of loss *via* both NO_3^- leaching and N_2O emissions because of the way N is bound in dung (Jarvis *et al.*, 1995) – the organic fraction reduces the rate of decomposition of dung resulting in a slower release of N as the dung breaks down rather than the immediate deposition of excessive quantities of N as in urine (Jarvis *et al.*, 1995).

Figure 2.5: Plantain crop. Image: DairyNZ.

Figure 2.6: Plantain in mixed pasture. Image: DairyNZ.

Ingested plantain reduces N loading in urine patches, primarily through diuresis (section 2.6.3.1). Eating plantain makes cows urinate a greater daily volume and more frequently, while diverting more N to dung. Nitrogen is therefore diluted in the urine and urinary N is spread over a greater area in the paddock (Minnée *et al.*, 2019). A definitive threshold value or a range of plantain DM intakes to reduce

NO_3^- leaching have not been established. However, the evidence from a series of studies (Box *et al.*, 2017; Judson & Edwards, 2016; Minnée *et al.*, 2019) strongly suggest that more than 30% of the diet DM is required before significant urinary N dilution effects can be observed. An earlier study suggests this proportion could be as low as 20% (Minnée *et al.*, 2017), but needs to be confirmed. Cheng *et al.* (2018) reported inconsistent results relating to urinary N concentrations when including plantain in a grazing trial. However, they concluded that this inconsistency was due to the nature of their trial as they had less control over external factors that may have constrained their quantification of urinary N excretion, and DM, ME and N intake, than in a controlled cut-and-carry study. Dodd *et al.* (in press) summarise these published data and defined a tentative threshold of 30-40% of the diet DM as plantain for significant reductions of NO_3^- leaching to be observed. In addition, they propose that if plantain makes up <20% of the diet the effects on urinary N are not expected to be large.

In the past, plantain has been included in New Zealand pastures (Kemp *et al.*, 1999b), though generally making up <20% of the sward (Charlton & Stewart, 1999). Enough plantain must be ingested at the right time of the year to reduce NO_3^- leaching from urine patches. This is particularly important in late summer-autumn (between the months of February to May) as urine patches deposited in these seasons are at the greatest risk of leaching (Di & Cameron, 2002; Selbie *et al.*, 2015; Shepherd *et al.*, 2011). If plantain is to be a mitigation strategy for NO_3^- leaching, further work needs to be carried out to determine what management is necessary to provide enough plantain in pastures and ultimately dairy cows' diets to achieve the necessary threshold for NO_3^- leaching reductions (Dodd *et al.*, in press).

Plantain has a deeper rooting system than ryegrass and can access water and nutrients from deeper in the soil (Stewart, 1996). While there are no formal publications comparing the roots of these two species, plantain roots differ to ryegrass roots, mainly due to the presence of a short taproot in addition to fibrous roots in plantain (Cranston *et al.*, 2016). In pure swards, this may give it a competitive edge over ryegrass in summer when growth is limited by heat and water availability. This competitive edge has not been established in current literature and is an area for future research. Whether plantain has a competitive edge over ryegrass in PR/WC + PL (plantain) pastures is also unclear and warrants further research. In addition to reductions in NO_3^- leaching, alternative forages can offer the additional benefits of increasing pasture resistance to weed incursion (Woodward *et al.*, 2013), increasing pest resistance by interrupting life cycles or reducing the availability of certain pastures species to pests (Musgrave & Daly, 2004), however plantain can be susceptible to other pests such as plantain moth (DairyNZ, 2014).

2.6.3.1 Plant-animal interactions: reduction in N loading rate

Ingestion of plantain is reported to have a diuretic effect on ruminants which is characterised by an increase in total urine volume and frequency without increasing total water intake (O'Connell *et al.*, 2016). However, even with restricted water intake, sheep fed plantain did not exhibit signs of dehydration, suggesting this increased urine volume may not be detrimental to grazing animals. This study reported that sheep eating ryegrass as opposed to plantain had slightly greater DM intakes although water intakes were the same. Sheep eating plantain also produced greater faecal weights with higher water content, though this was offset by their greater DM intake. In sheep eating plantain diuresis was confirmed, rather than diversion of water from faecal matter to urine – the difference between faecal water volumes for these two groups did not explain all the difference in urine volumes. These results were supported by Judson *et al.* (2018) who reported no significant difference in faecal water content despite the greater volume of urine produced by sheep eating plantain. In a study on the effects of plantain on dairy cows, Minnée *et al.* (2019) concluded that diuresis (which they defined as an increase in urine volume) occurred in cows eating more than 15% plantain diets. The study compared dairy cows eating varying levels of plantain, ranging from 0% plantain (100% PR/WC) to 45% plantain (55% PR/WC). Plantain has a lower DM content than RG/WC. The more plantain cows ate, the greater their water intake, despite a significant decline in trough water intake. The mechanism driving this diuresis, was not confirmed, but the authors proposed it could be due to the low DM content of plantain, resulting in excessive consumption of water in the feed (E. Minnée, personal communication, 25

November, 2019). No detrimental health implications were identified for the cows in this study. While cows ingesting greater quantities of plantain urinated more, they remained well-hydrated (there was no difference in plasma sodium concentration or excretion of sodium in urine), which could be due to plantain's low DM so that cows eating greater quantities of plantain actually had higher total water intakes (E. Minnée, personal communication, 25 November, 2019). While no diuresis-related health risks were identified for the animals in this study, the long-term effects of sustained diuresis, which may be harmful, have not been fully discussed and further research is warranted.

The combination of the division of N in plantain plants and the diuretic effect caused by ingestion reduces the N loading rate in urine patches. While the total N excreted and the volume or urine per event may not change much, both total urine volume and frequency of urination events increase, reducing urinary-N concentrations.

2.6.3.2 Milk solids production

Separate trials by Bryant *et al.* (2017), Totty *et al.* (2013), Box *et al.* (2017), Woodward *et al.* (2013) concluded that there was no change in MS production when cows were fed pastures containing forbs such as plantain and chicory, compared to standard PR/WC pastures. In contrast, the metabolism stall trial by Minnée *et al.* (2019) showed that MS production increased when cows ate more plantain than PR/WC. The different outcomes between these trials may be due to differences in pasture quality as MS production is dependent on the feed quality (ME) offered (Jacobs & Woodward, 2010; Minnée *et al.*, 2017; Nobilly *et al.*, 2013; Waghorn *et al.*, 2007).

2.6.3.3 Production

As utilisation and production of plantain in PR/WC + PL swards is currently underexplored, there are no long-term studies reporting DM production and persistence of such pastures in New Zealand. Consequently, production cannot be fully reviewed so readers are referred (i) back to the reviews of Pembleton *et al.* (2015) and Vibart *et al.* (2016) in section 2.5.3 which concluded that mixed pastures either maintain or improve DM production when compared to PR/WC pastures, and also to (ii) the methods, section 3.4.3 where growth and quality data from (Minnée *et al.*, in press) were analysed. However, it was clear that there was not enough data from past or current studies to conclude how plantain would persist and a mixed PR/WC + PL pasture would perform in terms of ME and DM production.

2.6.3.4 Plant-soil interactions: nitrification inhibition

In addition to a lack of data on DM production, plant-soil interactions affecting N cycling are not well understood for plantain, though there is evidence that nitrification and N mineralisation can be affected.

Two laboratory experiments by Dietz *et al.* (2013), where shredded plantain leaves or aucubin isolated from plantain leaves were incorporated into low-N soils, soil N mineralisation and nitrification were supressed. A field study by Gardiner *et al.* (2019) used the same application rate of aucubin as Dietz *et al.* (2013). The application to PR/WC pastures was made via urine collected from cows grazing PR/WC pasture. Gardiner *et al.* (2019) determined that these laboratory-determined application rates did not have a significant effect on nitrification and did not reduce nitrous oxide (N_2O) emissions. In contrast, results from Luo *et al.* (2018), Carlton *et al.* (2019) and Minnée *et al.* (2019) concluded that where pastures contain plantain, significant differences in nitrification inhibition were observed. Luo *et al.* (2018) found that N_2O emissions from lysimeters treated with fresh dairy cow urine (applied at a loading rate of 622 kg N/ha) were 35% lower under plantain than from perennial ryegrass. The authors concluded this decrease was due to plant-soil interactions, and not an effect of ingested plantain as the urine applied to the lysimeters was from cows grazing ryegrass-white clover pastures. In a similar study, Carlton *et al.* (2019) also reported that nitrification inhibition occurred under PR/WC + PL pastures containing 20-30% plantain. Luo *et al.* (2018) theorised that the plantain plants in their study altered the soil microclimate and/or influenced N cycling by inhibiting biological nitrification (transformation of NH_4^+ to NO_3^-).

In summary of this research, if plantain can directly inhibit nitrification in the soil, without the need for animal ingestion and excretion, further reductions in NO_3^-

leaching may be possible by including plantain in farm systems, beyond its influence on urine patch N loading rates.

2.6.4 Oat catch crops

In Canterbury, it is common for dairy farms to leave cropped paddocks fallow (see bare soil in Figure 2.8) over the winter period as pastures sown at this time will fail due to poor growing conditions (Edwards *et al.*, 2017; Malcolm *et al.*, 2018). Unfortunately this is the time of the year when NO_3^- is at its greatest risk of leaching from soils due to reduced plant growth and increased drainage (Di & Cameron, 2002). An alternative use to fallowing unproductive land over winter, is growing a winter-active catch-crop (Di & Cameron, 2002), such as oats (Figure 2.7). A catch crop's potential for recapturing NO_3^- is dependent on its ability to grow and take up mineral N when temperatures are low (Martinez & Guiraud, 1990). Carrying on from the fodder beet example above, instead of leaving paddocks fallow after *in situ* grazing, sowing oats straight after paddock(s) are finished (*i.e.* there is no more fodder beet to graze) will increase the opportunity for the oat crop to reduce NO_3^- leaching from the soil. The sooner oats establish, the greater the opportunity for NO_3^- uptake (Malcolm *et al.*, 2016).

Figure 2.7: Oat crop. Image: DairyNZ

Figure 2.8: Bare soil after fodder beet crop is grazed in autumn/winter. Image: DairyNZ.

Catch crops can also reduce the amount of water draining from soils via evapotranspiration (McLenaghen *et al.*, 1996). As well as reducing drainage, water uptake results in uptake of mineral N (NO_3^- and NH_4^+), reducing the pool of NO_3^- at risk of leaching from the soil. The result of both processes is a reduction in NO_3^- leaching risk.

The catch crop also provides the farm with a feed source as it can be grazed or ensiled for later use (DairyNZ, n.d.-d).

2.7 The cost to farmers of reducing nitrate leaching

A dairy farm is a business. Dairy farms produce and sell milk (and to a lesser extent meat and breeding stock) with a common aim of earning income and profit to meet loan repayments, build equity and make a living. According to the Financial Stability Report from the Reserve Bank of New Zealand (2018), "most dairy farms are currently profitable". However, farms remain vulnerable to changes in dairy price and borrowing costs. Tighter restrictions on environmental outputs such as the amount of NO_3^- allowed to be leached per hectare of land could reduce farm profit. While this could reduce the environmental footprint of the dairy sector, restrictions could result in significant financial loss for already highly indebted farmers and impact regional economics. Other factors can also affect the overall profitability of dairy farms such as global and therefore national interest rates

(Reserve Bank of New Zealand, 2018), exposing farmers to financial risks they cannot mitigate.

Ideally, options to reduce NO_3^- leaching will not jeopardise a farm's economic sustainability. Dairy farms have a significant role in New Zealand's economy. Dairy is our major primary export sector. The dairy industry is dependent on the value of MS (fat + protein). It generates 3.5% ($7.8 billion) of New Zealand's total Gross Domestic Product (GDP) and in recent years has earned an average of $14.4 billion/annum in export value. This is more than a quarter of total merchandise export value. In addition, the dairy industry contributes to regional economies, primarily by providing jobs and income. The industry is still growing despite the significant drop in global milk prices between 2014 – 2016 (Ballingall & Pambudi, 2017). However, the dairy industry is one of the three key vulnerabilities of New Zealand's financial sector. In particular, since 2014 the proportion of debt held by highly indebted farmers (farms with >$35 debt/kg annual MS produced) has increased. However, the proportion of cash-flow positive farms is expected to remain around 90% (Reserve Bank of New Zealand, 2018). Cash flow is an indication of liquidity *i.e.* how able a business is to meet its financial obligations (Kay *et al.*, 2004).

Dairy farmers face both regulatory/environmental and financial pressures. They are responsible for ensuring their activities do not breach their resource consents. At the same time, they must generate enough revenue to offset the costs of production. In the past, dairy supply/processing companies have insisted on high levels of dairy production. This pressure has been to maintain a year-round supply of dairy products for national consumption and international export (Guan & Philpott, 2011). Since deregulation of the dairy industry began in the 1980's, agricultural subsidies have been discontinued and farmers themselves have been exposed to the volatility of the international MS price. Intensification was seen as a way to achieve economies of scale and maintain or increase profitability (Chobtang *et al.*, 2017; Pembleton *et al.*, 2015; Shadbolt, 2004). However, the profitability of dairy farm systems have been shown to be dependent on the MS price with more intensive farms being more profitable at higher payouts and less intensive farms being more profitable at lower payouts (Shadbolt, 2004). In addition, Doole (2015) showed that by focusing on increasing milk production, operating profit could be significantly reduced. Therefore, intensification and/or increasing production do not always lead to increased profitability.

Banks and loan agencies require repayments on loans and yet intensification (which has been seen as a way to increase farm profitability) is strongly linked with environmental degradation (Chobtang *et al.*, 2017; Dalley *et al.*, 2018; de Klein *et al.*, 2010; PCE, 2004; Pembleton *et al.*, 2015). Policy has changed in recent years, focusing national and regional efforts on reducing impacts on the environment, for example by targeting improvements in freshwater quality in many catchments (Ministry for the Environment, 2017a). While not unexpected, these changes have put a lot of pressure on farmers to continue operating profitably, particularly as the intensity of dairy farming in New Zealand and Canterbury has increased in the last decade (Table 2.2).

Dairy farm intensity can be measured by a range of factors: stocking rate, MS produced/ha, extent of irrigation and system type as defined by DairyNZ (2017). DairyNZ has classified dairy systems into five production systems of increasing intensity based on the quantity and use of imported supplemental feed. Based on this metric, Canterbury farms tend to be intensive and have increased in intensity over the last decade. Table 2.2 table shows that system intensity has tended to increase both in Canterbury and nationally.

Table 2.2: System intensity of dairy farms in Canterbury and New Zealand, with 1 being the lowest intensity and 5 the highest. Data for three of the last twelve dairy seasons are presented. Data are from DairyBase and are published with permission of DairyBase DairyNZ (2019b).

System	System description	Feed imported	2005-06	2010-11	2017-18
Canterbury					
1	All grass self-contained	0%	0%	2%	1%
2	Feed imported for dry cows	1-10%	17%	14%	6%
3	Feed imported to extend lactation	11-20%	60%	40%	33%
4	Feed imported to extend lactation	21-30%	17%	38%	51%
5	Feed imported all year	>31%	6%	6%	9%
New Zealand					
1	All grass self-contained	0%	12%	6%	6%
2	Feed imported for dry cows	1-10%	35%	26%	20%
3	Feed imported to extend lactation	11-20%	36%	38%	38%
4	Feed imported to extend lactation	21-30%	14%	22%	26%
5	Feed imported all year	>31%	3%	8%	10%

Note that the system descriptions in this table were simplified to omit the overlap between the quantity of total feed as imported feed between the five systems as described by DairyNZ (2017).

2.8 Model selection

In New Zealand, it is common to estimate NO_3^- leaching losses from agricultural land through modelling. Overseer is routinely used to estimate N leaching losses and in recent years has been included in policy as an official tool for calculating NO_3^- leaching from different land uses (Ministry for the Environment, 2019a; Selbie *et al.*, 2013). FARMAX Dairy (Farmax) is a commonly-used decision support tool for dairy businesses that can be used to examine farm finances and "can be used to accurately predict the outcome of farm management changes on animal performance, pasture cover and total yields" (Bryant *et al.*, 2010b).

Modelling allows us to explore ways to mitigate NO_3^- leaching without the cost and complexity of experiments and trials. Modelling approaches also allow sensitivity analyses to be performed to determine key parameters that influence success and the sensitivity of mitigation strategies to changes in these factors. A modelling approach using Farmax and Overseer was chosen for this study because these two models combined provided the opportunity for examining the impact of different mitigation strategies at the farm level. The research identifying fodder beet, oats and plantain as forages that can be used to reduce NO_3^- leaching had already been done (see section 2.6). The next step was to determine cost-effective ways to integrate these forages into an existing farm system.

2.9 Summary of current research gaps

The major research gaps identified in this literature review, relevant to this thesis, relate to the integration of FRNL principles via fodder beet, oats and plantain into existing dairy farms and their environmental and financial impacts. In particular, plantain is an under-explored mitigation option that could have significant impacts on NO_3^- leaching.

At present, most of the research linking plantain to reductions in NO_3^- leaching from soils relates to the plant-animal interactions (section 2.6.3.1). However, there is evidence that there are plant-soil interactions capable of measurably influencing N dynamics (section 2.6.3.4.) In addition, research into the production and environmental performance of PR/WC + PL pastures is yet to be fully explored: annual and seasonal production of PR/WC + PL pastures have not been widely researched, and research into the persistence of plantain populations in pastures is lacking (section 2.6.3.3).

Trials have shown that if ingested in great enough quantities, plantain can reduce urinary N concentrations and subsequently reduce the N loading rate of individual patches – the main contributors of NO_3^- inputs to freshwater from dairy farming. Therefore, research into the persistence of plantain is very important as plantain is reported to have little to no effect on urinary N concentrations (and presumably NO_3^- leaching) below 20% of total diet DM. Maintaining production of sufficient plantain will be key to achieving reductions in NO_3^- leaching (section 2.6.3).

Investigations into the links between plantain and NO_3^- leaching are currently gaining popularity and are of high importance in New Zealand. However, it is imperative that change at the farm level is also investigated. The dairy industry currently maintains a major influence on both New Zealand's economy and environment. Changing farm management to incorporate principles identified in the FRNL programme will influence both N dynamics and profitability. Whether or not NO_3^- leaching can be reduced and profitability maintained using the three FRNL principles discussed on a milking platform is yet to be addressed[1].

Small-scale trials are necessary to determine plantain's potential to mitigate NO_3^- leaching. However, investigations must also be made at farm scale to determine how all three forages (fodder beet, oats and plantain) can be integrated and maintained long-term to reduce whole-farm NO_3^- leaching. This thesis aims to address this current research gap, through modelling.

1 The author would like to note that there are a few case studies (Beukes *et al.*, 2018; Beukes *et al.*, 2017) that have investigated the environmental and financial trade-offs FRNL principles when integrated into existing Canterbury dairy farms. However, these studies also investigated changes in effluent area, substituting imported feeds, reducing N fertiliser and changing animal and feed movements between the milking platform and support blocks *i.e.* they did not exclusively investigate the three FRNL principles described. The implications of these research pieces are fully discussed in the discussion chapter, sub-section 5.1.5.

3 Methods

The following methodology was developed to investigate the mitigation of nitrate (NO_3^-) leaching, using fodder beet, oats and plantain on the milking platform of the modelled farm. The methodology below includes the reasoning for the model selections, the case study approach, a description of the Baseline scenario, the treatments applied to the Baseline, the assumptions made, and how the scenarios were analysed and compared. Detailed descriptions of the model inputs are appended in sections 7 and 8 (Appendices 1 and 2). A generalised depiction of the process followed with references to the relevant sections is outlined in Figure 3.1. Note that not all steps are reported as this is intended as a high-level overview of the methods.

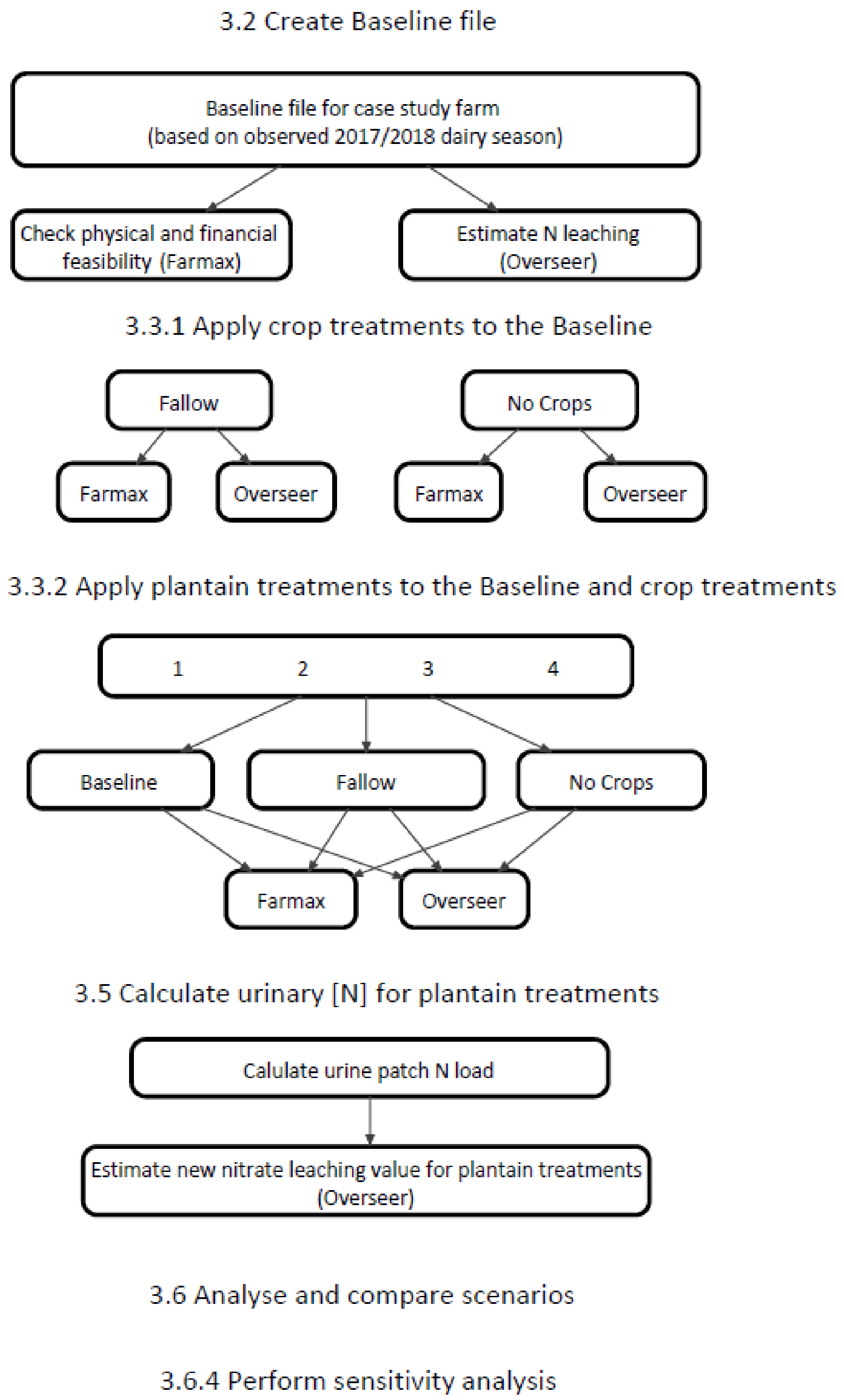

Figure 3.1: Diagram of the general process followed in the methods. Numbers indicate the relevant sections of the methods. Note that not all steps are reported as this is intended as a high-level overview of the methods.

3.1 Modelling strategy to test hypothesis

A modelling approach was chosen to assess the potential for reducing NO_3^- leaching while maintaining profitability on dairy farms using recommendations developed during a research programme Forages for Reduced Nitrate Leaching (FRNL) (Beukes *et al.*, 2017; Waghorn *et al.*, 2018). There were several reasons for selecting a modelling approach. It was impractical to measure NO_3^- losses from multiple farms and impossible to replicate climatic conditions between seasons on real farms. Additionally, time and budget constraints also prevented farmlet trials, hence the modelling approach. The main advantages of using computer models were (i) the flexibility in the number and type of scenarios that could be run, (ii) the omission of random error caused by variation in experimental units and (iii) the lack of time and physical resource constraints. However, a significant disadvantage of modelling is that NO_3^- leaching outputs are estimates, not supported by physical measurements of a representative system.

3.1.1 Steady state assumption

All scenarios assume that the farm system is in a steady state. This means that the system runs the same year-to-year *i.e.* when treatments are applied, it is assumed the system is not transitioning and always operates in this way.

A modelling environment was suitable for this study as the same conditions (*e.g.* climate and financial) could be replicated for multiple scenarios.

3.1.2 Models used

Due to the complexity of the nitrogen (N) cycle and the capability of available models, two mechanistic farm system models, FARMAX Dairy Generation 7 Version 7.1.2.41 (Farmax) and OVERSEER® Nutrient Budgets Version 6.3.2 (Overseer), were used to explore management strategies that were designed to reduce N leaching and evaluate their costs.

Farmax was used to assess the technical feasibility of each scenario tested before modelling the scenarios in Overseer as Overseer does not have inbuilt 'sense checks' to identify unrealistic activities. Farmax Dairy Pro is a decision support tool for dairy businesses and "can be used to accurately predict the outcome of farm management changes on animal performance, pasture cover and total yields" (Bryant *et al.*, 2010b). Farmax was also used for the financial feasibility analysis. The recently released OverseerScience online model Version 6.3.2 was used to estimate NO_3^- leaching from all scenarios (section 3.5).

3.2 Case study farm

Data from a south Canterbury FRNL monitor dairy farm were used in a modelling context to analyse a variety of scenarios incorporating the three FRNL principles into management of the milking platform (section 2.6 and Figure 2.2). This monitor farm, termed the 'case study farm' henceforth was selected for this study as to-date there had been little in-depth research carried out for this farm, but there was extensive data available for immediate use.

The milking platform is where most of the dairy activities occur and where the mitigation strategies were targeted. The support block is part of the dairy system (see section 3.2.2). In this thesis, a support block was included to fairly represent the system-wide impacts of changes made on the milking platform.

The farm's location is shown in Figure 3.2. Data for the 2017/2018 dairy season was used to set up the Baseline scenario (section 3.2.2) for this farm, as this was the most recent full-season data available. The monitor farm started incorporating alternative species (including plantain) into their pasture renewal programme about 10 years ago and started cropping fodder beet and oats on the milking platform in the last five years. Detailed records and the farm owner/manger's knowledge and experience were combined to model a simplified version of the farm system.

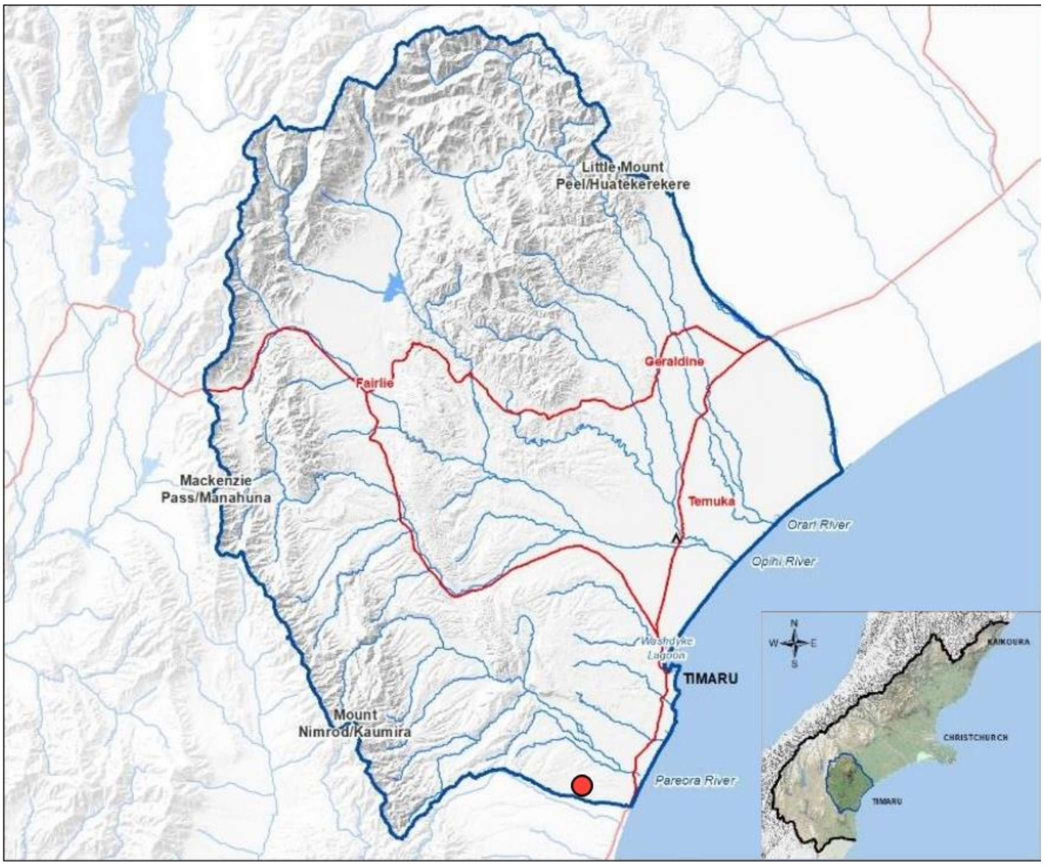

Figure 3.2: Location of the monitor farm (red dot) in the Environment Canterbury Orari-Temuka-Opihi-Pareora Zone (OTOP zone). Red lines are main roads, the blue line outlines the OTOP zone. The black line in the inset map outlines the whole Canterbury region.

3.2.1 Creation of the Baseline file

Detailed descriptions of the inputs used for the Overseer and Farmax files are attached in chapters 7 and 8 (Appendices 1 and 2). Data from FRNL diaries (Excel spreadsheets filled out daily by the farm manger to capture detailed farm activities), DairyBase Physical and Financial Data Summaries and personal communication with the farmer were used to create the baseline file.

The Baseline file was a simplified representation of the 2017/2018 dairy season. While the management of the farm remained the same, some of the inputs were simplified to allow representation in the model and to make the results (especially the financials) more generalised for the Canterbury region. Some of the changes made to create the simplified representation were:

1. Where small quantities of uncommon supplements such as red clover silage were used, they were substituted with similar feeds

on a metabolisable energy (ME) basis. This was done to make the system more generic and to optimise feed production and intake.

2. A staggered dry-off strategy (section 7.10, Appendix 1) was implemented to achieve Body Condition Score (BCS) targets at calving, match end-of-season milk production and generate an average dry-off strategy for the farm. On the monitor farm, the dry off is staggered through the month of May, but most of the herd is milked until the end of May. The modelled strategy resulted in more cows being dried off earlier than usual for the case study farm, but this was necessary to achieve BCS and milk production targets.
3. The transfer of dry cows from the support block to the milking platform was similar to the actual herd movements, but did not include 'holding' pregnant cows on a block of land adjacent to the milking platform for a week or so until they calved, as done in reality. It was assumed that dry cows were transferred directly to the milking platform at least one week prior to their estimated calving date.
4. The farm was assumed to have transitioned to the described system. Day-to-day and long-term management was therefore at steady state *i.e.*it was not necessary to model more than one year to represent the Baseline.

3.2.2 Farm Baseline description

The main features of the model farm system were a milking platform and a support block, described below. For specific input details, see chapter 7 (Appendix 1).

The modelled milking platform was 312.8 effective ha, 96% irrigated and on heavy soils. It was stocked at 3.7 crossbred cows/ha (1,142 peak milking cows and 1235 wintered). Pastures were a standard mix of perennial ryegrass/white clover (PR/WC), fertilised at 284 kg N/ha/year on the non-effluent block and 275 kg N/ha/year on the effluent block. Each year 10% of the farm was renewed with PR/WC; 6% directly from old pasture and 4% following an autumn-grazed fodder beet crop and a winter-grown oat catch crop. On the milking platform, around 1,200 kg dry matter (DM)/cow/year of supplements and crops were eaten, consisting of homegrown fodder beet, pasture silage and oat silage, and imported pasture silage, wheat and protein pellets. Cows were transitioned onto fodder beet in late lactation on the milking platform. Milksolids (fat + protein from milk; MS) production was 445 kg MS/cow/year and 1,624 kg MS/ha/year. All dry-cow wintering and grazing of weaned young stock were done on the support block.

The real support block for the monitor farm system was not used because of its complexity: multiple enterprises were fed on this block and supplemental feed was imported from other blocks. Instead, a self-sufficient support block was designed to winter dry stock and rear weaned young stock. The support block was 180 effective ha, unirrigated and on heavy soils, like the milking platform. Pastures were a standard mix of perennial ryegrass/white clover (PR/WC), fertilised at 30 kg N/ha/year (19 kg/ha/application to pasture in August and March). Each year 10% of the support block was renewed with PR/WC, following two years of back-to-back crops. Each year 18 ha of kale and 18 ha of fodder beet were grown, primarily for wintering dry cows. The cropping regime was:

1. Year 1 kale, oats/fallow;
2. Year 2 fodder beet, oats/fallow;
3. Year 3 new pasture.

On the support block, the dry cows consumed around 3,900 kg DM/cow/year consisting of homegrown fodder beet, kale, pasture silage and oat silage. No feed was imported. The rising 2 year olds (R2s) consumed around 930 kg DM/heifer/year consisting of homegrown pasture silage, oat silage and fodder beet.

3.2.3 FARMAX Dairy (Farmax) model inputs

As stated above, the Farmax files were set up first to ensure that the farm system was financially and physically feasible. This was a straightforward exercise that did not require much detail, therefore the methodology for this section is not very complex.

The Baseline milking platform and support block were modelled in Farmax. The milking platform and support block were created as separate files to ensure pasture and crops were eaten or grazed on the appropriate block unless harvested and to allow the milking platform to be analysed separately. However, the files were linked so that mobs could be to be 'transported' from the milking platform to the support block and back for wintering and rearing. Changes to the feed regime on one block affected the long-term performance of animals regardless of which block they were on because of the links between the two files. For specific input details, see chapter 7 (Appendix 1).

3.2.4 Overseer® Nutrient Budgets (Overseer) model inputs

Block, climate data and soil type are based on actual 2017-2018 data and regional averages where applicable. Here a "block" refers to a parcel of land that undergoes a particular type of management. The land does not have to be contiguous. In Overseer, the blocks were set up based on their soil type, irrigation type and whether they were part of the effluent block or not. The Overseer Baseline file had nine blocks of varying size based on these parameters.

The pasture type, stock classes and numbers, feed type and destinations were made to represent the system described in Farmax as closely as possible.

For specific input details, see chapter 8 (Appendix 2).

3.3 Treatments

The three treatments investigated were based on the following FRNL principles: (section 2.6.1):

1. reducing the amount of N consumed by the cow in autumn through low-N feed (**fodder beet**),
2. diluting N excreted in urine by feeding pastures and pasture silage containing **plantain**, especially during mid-summer/autumn, and
3. reusing excess N in soils during winter by growing **oats**, immediately following the fodder beet crop to take up N at risk of leaching.

No changes were made to the support block. A factorial combination of two levels of treatment (two crop and five plantain) were modelled and applied to the Baseline milking platform, as described in Table 3.1.

The first level of treatment was the crop treatment creating treatments "Fallow" and "No Crops". Plantain treatments were then applied to the Baseline and Fallow and No Crops. The plantain treatments were labelled by adding the treatment number to the crop treatment name (see Table 3.1).

Due to the limited information available for plantain, a list of assumptions regarding its properties, management and effect on NO_3^- leaching – including the rationale for these assumptions – are detailed in section 3.4. It is important to note that in a rapidly evolving field some of these assumptions were challenged by new data coming in. Given the time constraints of this thesis, it was not feasible to adjust the model inputs to accommodate all new data. The importance of these new data and their implications for the assumptions are included in the discussion (chapter 5).

Table 3.1: Names of the model scenarios and descriptions of the crop and plantain treatments applied to the Baseline. "Maintenance" means that pastures are direct drilled with 4 kg plantain seed/ha. This was necessary to maintain/increase the proportion of plantain in the pasture sward (see Figure 3.5). See Table 3.2 below for the maintenance schedule for plantain treatment 2: 'Maintenance of new pastures in 4th year'..

		Plantain treatment			
Description	*No plantain*	*No maintenance*	*Maintenance of new pastures in 4th year*	*Maintenance of new pastures in 4th and 7th year*	*Maintenance of new pastures every 2nd year*
Crop treatment	Baseline (fodder beet and oats)	B1	B2	B3	B4
	Fallow (F) (oats removed)	F1	F2	F3	F4
	No Crops (NC) (fodder beet and oats removed)	NC1	NC2	NC3	NC4

3.3.1 Crop treatments

The two crop treatments were applied to the Baseline milking platform and labelled as Fallow and No Crops (Figure 3.3). No changes were made to stock numbers, farm management or the support block. The purpose of these treatments was to determine the size of the impact the crop regime had on NO_3^- leaching.

As the monitor farm had already implemented fodder beet and oat crops on the milking platform, the crop treatments applied to the model were subtractive. The effect of these crops could still be investigated at the farm level. Fallow involved removing the oat catch crop (leaving paddocks fallow) and substituting harvested oat silage with imported pasture silage. No Crops involved removing the fodder beet and oat crop and substituting fodder beet with barley grain. As more pasture was grown in No Crops, some imported pasture silage was substituted with harvested pasture silage. In addition, the cows were transitioned onto fodder beet on the support block, rather than as milkers on the milking platform. In this case, fodder beet fed to the Rising 2-Year-Olds (R2s) was substituted with pasture silage fed to the (non-lactating cows) dries.

3.3.2 Plantain treatments

Five treatments (including no plantain) were applied to introduce plantain to the milking platform in the Baseline and the two crop treatments. As plantain does not persist well in RG/WC + PL pastures (Dodd *et al.*, in press), and it was impractical to sow pure plantain across the entire farm (Mangwe *et al.*, 2019), the treatments were based on increasing the frequency of plantain maintenance (Plantain Treatments: Treatment .1 to Treatment .4). Maintenance involved direct drilling existing PR/WC + PL pastures with 4 kg plantain seed/ha to increase to proportion of plantain in the pasture (Figure 3.4 and Figure 3.5). An example of a maintenance schedule for treatment B2 is given in Table 3.2.

Grazed PR/WC + PL pastures and harvested PR/WC + PL pasture silage (Judson & Edwards, 2016) were the two possible sources of plantain in the diet. In general, to increase the proportion of plantain in the diet (%PL diet) the percentage of plantain in the pasture (%PL pasture) was increased.

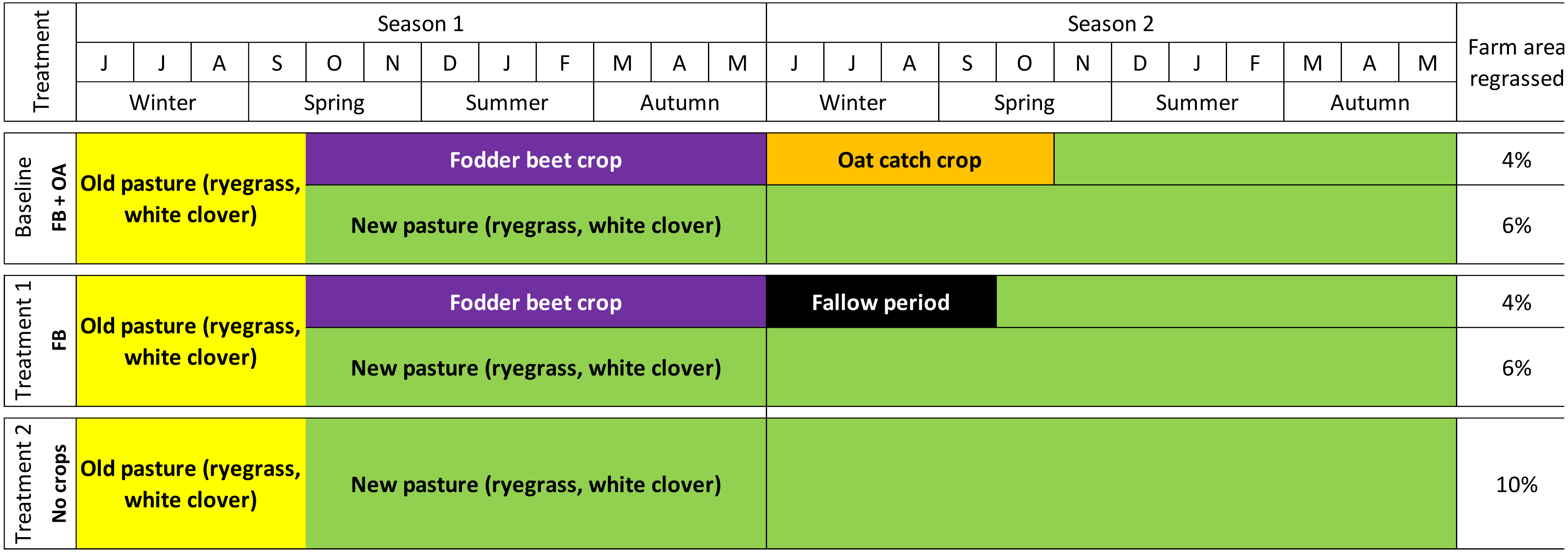

Figure 3.3: Timelines for the Baseline and two crop treatments over two seasons. For any paddock in No Crops, renewal is completed within one dairy season. For the Baseline and Fallow, two seasons are required to complete the renewal process.

10% of farm regrassed	Year 1	2	3	4	5	6	7	8	9	10
1	50%	40%	20%	50%	40%	20%	10%	10%	10%	10%
2	10%	50%	40%	20%	50%	40%	20%	10%	10%	10%
3	10%	10%	50%	40%	20%	50%	40%	20%	10%	10%
4	10%	10%	10%	50%	40%	20%	50%	40%	20%	10%
5	10%	10%	10%	10%	50%	40%	20%	50%	40%	20%
6	20%	10%	10%	10%	10%	50%	40%	20%	50%	40%
7	40%	20%	10%	10%	10%	10%	50%	40%	20%	50%
8	50%	40%	20%	10%	10%	10%	10%	50%	40%	20%
9	20%	50%	40%	20%	10%	10%	10%	10%	50%	40%
10	40%	20%	50%	40%	20%	10%	10%	10%	10%	50%
Average DM as plantain	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**

Table 3.2: Maintenance schedule for plantain treatment B2: 'Maintenance of new pastures in 4th year'. The schedule is based on the persistence assumed for plantain (Figure 3.5). Each year, 10% of the farm is regrassed (see divisions 1-10 on left representing one-tenth of the farm area and years 1-10 across the top). Green cells indicate regrassing in the first year (new RG/WC + PL). Yellow cells represent maintenance in the fourth year (direct drilling of 4 kg plantain seed/ha into existing RG/WC + PL pasture). For the first tenth of the farm, new RG/WC + PL pasture is established in the first year. The "Average DM as plantain" is the average proportion of the farm pasture DM that is plantain (%PL pasture).

3.4 Data sources and assumptions

All models have assumptions. Some assumptions are well supported by literature. Others are based on current understanding, or have little impact on the model's outputs.

An extensive sensitivity analysis, to identify the key assumptions that influence the model's outputs is important, but was out of scope for this thesis. Only a short sensitivity analysis was carried out (section 3.6.4).

3.4.1 Overseer assumptions

The Overseer model was used to estimate N leaching losses for each scenario. A key assumption of this case study was that plantain would decrease nitrate leaching. This assumption was based on recent evidence that suggested that a reduction in the urine patch N load *via* more dilute and frequent urinations is the primary mechanism through which plantain can decrease N leaching (Box *et al.*, 2017; Mangwe *et al.*, 2019; Minnée, in submission).

Overseer does not model individual urine patches. Instead it calculates two conceptual areas: a total urine patch area and a non-urine patch (background) area based on the stock present on the block (Selbie *et al.*, 2013). There are two sources of NO_3^- leaching from soil in Overseer: the urine patch and the non-urine patch area. These are driven by two sub-models. The first is the background sub-model which deals with the non-urine patch area (between urine patches) and the additions of dung, fertiliser, effluent and other organic inputs to these areas. The second is the urine patch sub-model which deals with N applied via urine (Shepherd & Wheeler, August 2012).

At the time of this study, plantain was not modelled as a forage in Overseer, therefore the model could not account for:

1. the impacts of plantain on urinary N concentration in dairy cattle, as described in (Box *et al.*, 2017; Judson & Edwards, 2016; Mangwe *et al.*, 2019; Minnée, in submission),
2. any plant-soil interactions that may affect N cycling (Dietz *et al.*, 2013; Luo *et al.*, 2018)

3. or subsequent reductions in NO_3^- leaching.

For this study, manual adjustments of urine patch N loads were used to estimate the impact of plantain on NO_3^- leaching (described in section 3.5). This was the best solution based on data availability and model ability.

There are no published articles to reference most of the following section. Where no references are given, the information is based on personal communication (M. Shepherd & D. Selbie, 1 August, 2019).

A work-around for this limitation was made available through OverseerScience. This made it possible to manually adjust of the N loading rate of the urine patch. The standard N loading rate of the conceptual urine patch in Overseer is 750 kg N/ha/yr for dairy cattle, regardless of feed type (Selbie *et al.*, 2013). This is a value that is used to calibrate the model as it gave a good fit to the farmlet trials that the mode was calibrated to.

Total monthly urinary N excreted which is affected by dietary N intake. Dietary N intake is based on the estimated feed intake x N content of the feed less N removed in milk and meat. The excess N the cow ingested is then partitioned between dung and urine depending on the N concentration of the diet. At present, it is assumed that there is no difference in total N content between PR/WC and PR/WC + PL pastures (section 3.4.3). In addition, Overseer currently assumes that plantain does not change N partitioning to urine and dung.

When the urine patch N loading rate is reduced any N not leached is diverted to other pathways such as N uptake in pasture, denitrification *etc*. Some may be assumed to go to milk, but this is a user input. There are two other ways that N loading in the urine patch can be reduced. I assume that this is through dilution of N in urine, but that the total monthly N output remains the same (preliminary results using Overseer confirmed this assumption). The other way is for ingested N to be partitioned differently (*e.g.* to dung). This partitioning effect was assumed not to occur given there was no change in total monthly urinary N excretion and there was no additional source of N when the urine patch N load was altered.

3.4.2 Assumptions for plantain's influence on nitrate leaching

As discussed above, plantain affects urinary N concentrations which directly impacts NO_3^- leached from urine patches. The following assumptions relate to factors that could affect plantain's influence on NO_3^- leaching:

1. The effect of plantain on urinary N load is not affected by plant age.
2. At or above 15% of the diet DM, plantain will affect urinary N load (Box *et al.*, 2017; Minnée, in submission) (Figure 3.4), regardless of where the remainder of the dietary DM comes from.
3. Consumption of PR/WC + PL pasture and pasture silage have the same impact on urinary N load *i.e.* plantain does not have to be 'fresh' to affect urinary N (Judson & Edwards, 2016).
4. The volume per urination event remains the same, but the frequency of urination increases proportionally, to maintain monthly total N excreted in urine regardless of urine patch N loading rate. Preliminary results using Overseer confirmed this assumption.
5. Diuresis continues long-term *i.e.* cows do not revert to original urination patterns (fewer events and less total daily volume) when continuously eating plantain.

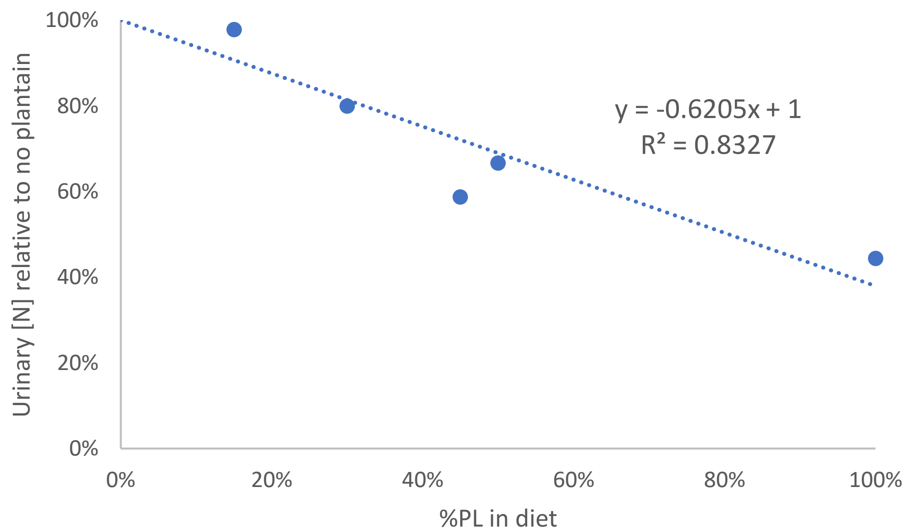

Figure 3.4: Response of urinary nitrogen (N) concentration to plantain (PL) in the diet. Data are from Minnée (in submission) and Box *et al.* (2017). Values are given in Table 3.3

Table 3.3: Raw data used to predict the size of the effect plantain has on urinary nitrogen (N) loads at varying proportions of diet dry matter (DM). These data were used in Figure 3.4.

	Minnée (in submission)		**(Box et al., 2017)**		**Combined data**
Proportion of diet DM as plantain	**Urinary [N] (g N/L)**	**[N] relative to 0% PL**	**Urinary [N] (g N/L)**	**[N] relative to 0% PL**	**[N] relative to 0% PL**
0%	7.49	1.0	5.4	1.0	
15%	7.33	1.0			1.0
30%	5.99	0.8			0.8
45%	4.4	0.6			0.6
50%			3.6	0.7	0.7
100%			2.4	0.4	0.4

3.4.3 Mixed pasture production assumptions

Data used for a meta-analysis by Minnée *et al.* (in press) were examined to determine if significant growth and quality differences exist between standard perennial PR/WC pastures and perennial ryegrass/white clover + plantain (PR/WC + PL) pastures. At the time of review, there were no available publications reporting full-season quality and growth data for PR/WC pastures compared to PR/WC + PL pastures. The data available at the time were limited to monocultures and multi-species pastures, usually containing additional legumes. Most data were from plot trials. Few studies were part of livestock grazing systems such as farmlet studies (Minnée *et al.*, in press). Trends indicate that plantain increases pasture production in summer, but reduces it in winter when compared to a RG/WC base. This difference was not significant however, even at different rates of N fertiliser application. Pembleton *et al.* (2015) reviewed studies comparing binary and mixed pastures. They concluded that mixed pastures have either no effect or increase annual DM production when compared to simple pastures. These gains were attributed to individual species rather than overall pasture diversity. It could not be determined that plantain caused significant changes in herbage production. The following assumptions were made regarding the impact of plantain in PR/WC pastures on pasture production and quality:

1. Changing the proportion of plantain in pasture swards on a commercial, irrigated dairy farm in Canterbury would not affect monthly pasture growth rates or annual pasture yield regardless of the proportion of plantain in the sward and regardless of N fertiliser

rates (Minnée *et al.*, in press; Pembleton *et al.*, 2015). This assumption is also based on communication with experts (D. Chapman, personal communication, 24 June, 2019; M. Dodd, personal communication, 1 July, 2019) and a review of data from Martin (2018).

2. There is no difference in ME or growth between PR/WC and PL + PR/WC pastures.
3. The type and content of N in plantain is not affected by plant age.
4. All treatments experience the same standard of pasture management (which is assumed to be best practice) which means that there will be no difference in maturity of the swards and therefore no change in herbage N content between treatments.
5. Cows do not prefer to graze one species over others (Pembleton *et al.*, 2015).
6. The proportion of plantain (%PL) in pasture silage harvested from paddocks containing plantain will be the same as the farm average %PL of pasture DM.

3.4.4 Pasture renewal assumptions

Assumptions of the pasture renewal programme are:

1. Ten percent of the farm is renewed every year in spring and all paddocks require renewing in their tenth year.
2. Where crops are present, 4% of the farm is regrassed following the crop rotation and 6% following old pasture (10% total).
3. The lowest producing paddocks are selected for renewal.
4. Low pasture production is a pasture persistence/plant density rather than a soil/fertility limitation and renewing pastures will increase plant density and improve pasture production.

3.4.5 Cropping assumptions

1. The crop cycle takes 12 months and rotates through the effluent block of the milking platform. Paddocks are not cropped for more than one 12-month cycle in ten years.

2. Fodder beet is sown in October and grazed in autumn.
3. Oats are sown immediately after the final fodder beet grazing (approx. 1 June), as weather permits.
4. The oat crop is harvested at the flag leaf stage where feed quality and quantity are optimised.
5. A pasture mixture of plantain, ryegrass and white clover is sown immediately after harvesting the catch crop.

3.4.6 Plantain persistence assumptions

Plantain was introduced in mixed-species pastures PR/WC + PL (plantain) in all plantain treatments (Table 3.1). Currently, plantain populations do not appear to persist above 10% of herbage DM in mixed pastures. The following are the assumptions made for plantain persistence in mixed pastures based on personal communication with experts (D. Chapman, personal communication, 24 June, 2019; M. Dodd, personal communication, 1 July, 2019):

1. The proportion of pasture herbage as plantain is increased via pasture renewal or maintenance (direct drilling plantain seed into existing pasture).
2. When renewing pasture, 4 kg/ha of plantain seed sown with 14 kg/ha of ryegrass and 4 kg/ha of white clover in spring results in a PR/WC + PL mix where 50% of the herbage DM is plantain.
3. The proportion of new pasture herbage DM as plantain beginning in spring is 50% in the first year, 40% in the second year, 20% in the third year and 10% in the following years (Figure 3.5) (M. Dodd, personal communication, 1 July, 2019).
4. The proportion of plantain in the pasture remains constant throughout the season, until spring where the population drops to the level appropriate for the following year or increases to 50% due to maintenance.
5. Maintenance increases the proportion of herbage as plantain to 50% (as in first year: Year 1, Figure 3.5), regardless of the proportion of plantain already existing in the pasture.

6. After maintenance, the persistence curve (level of plantain cover) described in assumption 3 would apply.

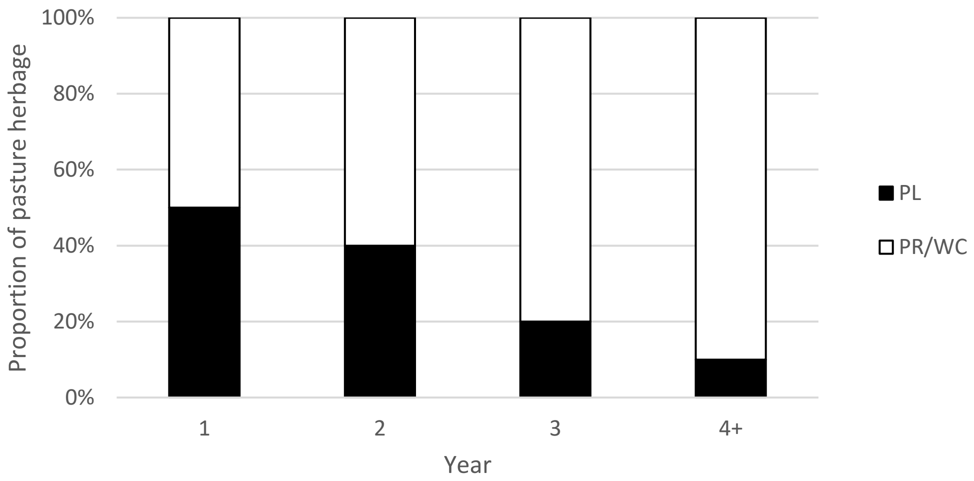

Figure 3.5: Plantain persistence (level of plantain cover) in pasture. Pasture herbage is expressed as plantain (PL) or perennial ryegrass/white clover (PR/WC) (M. Dodd, personal communication, 1 July, 2019).

3.4.7 Supplemental feed assumptions

1. Consumption of supplemental feeds does not affect the N load of the urine patch.
2. Fodder beet could not make up >40% of the diet DM in lactating cows to avoid acidosis (Dalley *et al.*, 2017; Waghorn *et al.*, 2018) and excessive Fat Evaluation Index gradings (DairyNZ, n.d.-e) (which neither model would identify).
3. The max quantity of in-shed feed consumed during milking is 2.5 kg DM per cow per milking (5 kg shed supplements per cow per day).

3.4.8 Financial assumptions

Financial inputs (costs, milk price, *etc.*) are based on Canterbury averages for the 2017-2018 season (or as close as possible) (Askin & Askin, 2016; DairyNZ, 2019).

1. Plantain has no effect on milk composition so milk revenue will not be affected directly by ingested plantain.

3.5 Nitrogen leaching calculations

The process used to calculate the final NO_3^- leaching values for each scenario is described below. An example of this process is given below for the Baseline.

For the Baseline, Fallow and No Crops, the NO_3^- leaching values were taken directly from Overseer. The following sections (3.5.1 to 3.5.5) are relevant only to scenarios where plantain treatments were applied because plantain is not adequately described in Overseer, at present.

3.5.1 Linear relationship between ingested plantain and urinary nitrogen concentration

Data from Box *et al.* (2017) and Minnée (in submission)were used to determine a linear relationship between the quantity of ingested plantain and the resulting urinary N concentration for lactating dairy cows (Figure 3.4). The equation for the relationship had an R^2 value of 0.83 (Figure 3.4). As limited data were available for this relationship, no extrapolation was applied. For diets containing <15%PL, it was assumed that there was no effect (0%) on urinary N load and therefore no impact on NO_3^- leaching.

The relationship between the reduction in the urinary nitrogen (N) load of a urine patch and the proportion of plantain (PL) in the diet of lactating dairy cows was calculated using equation (1), where plantain made up >15% of the diet.

$$Reduction\ in\ urinary\ N\ load = -0.6205(\%PL\ in\ diet) + 1 \qquad (1)$$

3.5.2 Calculating the proportion of the diet affected by plantain

The proportion of the diet affected by plantain was estimated by calculating the ratio of the diet that came from feeds containing plantain to feeds without plantain. Feeds containing plantain were: PR/WC + PL pasture and PR/WC + PL pasture silage harvested from the milking platform.

For Baseline treatments B.1 to B.4, it was calculated from the Farmax files that 82% of the diet of mature (dry and lactating) cows on the milking platform came from feeds containing plantain. The diets of the dry and lactating cows were combined because:

1. Only one urinary N load adjustment could be made for each file – Overseer did not allow N loads to be specified for different stock classes or months.
2. Feed consumed by bulls and calves did not contribute substantially to the total feed consumed on the milking platform.
3. Most NO_3^- leaching comes from urine patches deposited in late-summer/autumn (Selbie *et al.*, 2015). There were no dry cows on the milking platform in summer/autumn until May so almost all urine patches deposited in this critical period were assumed to be from lactating cows.
4. The proportion of the diet derived from plantain-containing sources for the dries 79% was very similar to that from the milkers 82%.

The same procedure was followed for the crop treatments.

3.5.3 Estimating the proportion of plantain in the diet dry matter

To estimate the %PL of the total diet DM, the proportion of the diet from feeds containing plantain was multiplied by the proportion of plantain in each feed category (Table 3.4). Feed was classed into one of four categories:

1. 1st year pasture,
2. 2nd year pasture,
3. 3rd year pasture,
4. Supplements/4th year+ pasture or

Supplements and 4th year+ pasture were combined as category because the 4th year + pastures had <15% plantain cover (section 3.4.2) and other than harvested pasture silage, none of the supplements contained plantain. There was no effect on urinary N for this category.

Table 3.4: Calculations for the proportion of plantain in the diet (%PL diet) The Baseline is used as an example. Eighty-two percent of the diet comes from feeds containing plantain. Note that the %PL in the Supplements/4th year+ pasture category is 0%, even though the 4th year + pastures contain 10%PL. This is explained in section 3.4.2.

Plantain treatment	Feed category/age of plantain cover	Assumed %PL pasture cover (plantain DM)	%PL in diet (%PL pasture*0.82)
.1 No maintenance			
	1st year pasture	50%	41%
	2nd year pasture	40%	33%
	3rd year pasture	20%	16%
	Supplements/4th year+ pasture	0%	0%
.2 Maintenance in 4th year			
	1st year pasture	50%	41%
	2nd year pasture	40%	33%
	3rd year pasture	20%	16%
	Supplements/4th year+ pasture	0%	0%
.3 Maintenance in 4th and 7th year			
	1st year pasture	50%	41%
	2nd year pasture	40%	33%
	3rd year pasture	20%	16%
	Supplements/4th year+ pasture	0%	0%
.4 Maintenance every 2nd year			
	1st year pasture	50%	41%
	2nd year pasture	40%	33%
	3rd year pasture	20%	16%
	Supplements/4th year+ pasture	0%	0%

3.5.4 Calculating urinary N load to use in Overseer

The next step was to estimate the urinary N load for each scenario where plantain treatments were applied. Equation (1) was used to estimate the relative urinary N load for each scenario as compared to the Baseline (no plantain). In the cases of crop treatments F1 to F4 and NC1 to NC4, the plantain treatments were compared to Fallow and No Crops (no plantain). The average annual NO_3^- leaching output from Overseer for each feed category was then used to estimate NO_3^- leaching under the different plantain treatments (Table 3.5).

Table 3.5: Process for estimating annual nitrogen (N) leaching from the milking platform by estimating the urinary N load, using this as an input in Overseer with some post-model processing to overcome Overseers current limitations related to plantain.

Pasture class, based on age	**Proportion of plantain in the diet (see Table 3.4)**	**Urinary N load relative to Baseline (no plantain)**	**Estimated urine patch N loading rate**	**Estimated annual N leached for affected area (Overseer output)**	**Proportion of milking platform affected**	**Contribution to NO_3^- leached at the farm level**
			kg N/ha/yr	**kg N/affected ha/yr**	**%**	**kg N leached/ effective ha/yr**
Baseline		*1*	*750*	*38*		
		A = -0.6205*(%PL in diet)+1	B = 750*A	C	D	E= C*D
1st year pasture	41%	0.75	559	29	10%	2.9
2nd year pasture	33%	0.8	597	31	10%	3.1
3rd year pasture	16%	0.9	674	34	10%	3.4
Supplements/4th year+ pasture	0%	1	750	38	70%	26.6
Total					100%	36

The values shown are for treatment B.1 (Baseline, plantain sown at renewal without further maintenance). First the relative impact on urinary N of each class of pasture (A) was estimated using Equation (1). Then the urine patch N loading rate (B) was estimated and entered into Overseer to estimate the average N leaching/affected ha (C) for each category. This was multiplied by the proportion of the milking platform covered under each class (D), to calculate the contribution of each class to the whole farm nitrate (NO_3^-) leaching (E).

3.5.5 Assessing treatment effectiveness on nitrate leaching

The effectiveness of each plantain treatment was then calculated by dividing the scenario's overall leaching value by the original leaching value for the Baseline. For example, treatment B.1 reduced NO_3^- leaching by 5% from the Baseline ($\frac{36\ kg\ N/ha/yr}{38\ kg\ N/ha/yr} = 5\%$).

3.6 Analyses

3.6.1 Environmental indicators

Nitrate leaching results were obtained directly from Overseer for the Baseline, Fallow and No Crops there was no plantain present. In all other scenarios (see Table 3.1) where different strategies for integrating plantain into the milking platform were modelled, post-model processing was done (as described in section 3.5) before a final leaching value was calculated for the farm.

3.6.2 Financial indicators

Obtaining financial results was a straightforward process. Operating profit and farm working expenses (FWE) were exported directly from Farmax for all scenarios. The cost of mitigation was then calculated for all treatments and was defined as the reduction in operating profit compared to the Baseline. In the cases of Fallow and No Crops, the plantain treatments were compared to Fallow and No Crops, rather than the Baseline to determine the impact of plantain in these alternative systems.

3.6.3 Test of hypothesis

To determine the size of the trade-off between NO_3^- leaching mitigation and profitability, all scenarios were ranked based on their effectiveness in reducing NO_3^- leaching and the cost of each strategy.

All scenarios were tested to see if they achieved a 20% reduction in NO_3^- leaching at farm scale and maintained/improved profitability (chapter 1,Thesis objective).

3.6.4 Sensitivity analysis

A sensitivity analysis was performed to determine whether variation in key parameters was likely to significantly affect outcomes, potentially making profitable solutions unprofitable. The factors investigated were soil type and plantain persistence.

3.6.4.1 Soil type

Two short analysis was performed to determine whether successful solutions could reduce NO_3^- leaching on stony, well-drained soil types in Canterbury. A moderate (Lismore shallow silty loam) and a very light (Rangitata shallow sandy loam) soil type were selected for the milking platform (Carrick *et al.*, 2013). As soil type was the only input changed in this analysis, no changes were made to the Farmax files. In each analysis, 100% of the soil on the milking platform was changed to either (i) Lismore shallow silty loam (S-MAP reference Lism_1a.1) or Rangitata shallow sandy loam (S-MAP reference Rang_5a.2 (see chapter 9, Appendix 3). The same process outlined in section 3.5 was used to determine NO_3^- leaching.

3.6.4.2 Plantain persistence

Nitrate leaching results for a less optimistic persistence curve were obtained using the same process outlined in section 3.5. The new persistence curve was based on unpublished data from a survey of plantain in paddocks on dairy farms across New Zealand over the last 4 years (M. Dodd, personal communication, 1 July, 2019). The same assumptions as in section 3.4.6 apply to this curve however, the proportion of new pasture herbage DM as plantain beginning in spring is 40% in the first year, 20% in the second year and 10% in the following years (M. Dodd, personal communication, 1 July, 2019).

3.7 Summary of methods

Given the length of the methods chapter, the main steps are summarised below.

Farmax was used to assess the physical and financial feasibility of scenarios. Overseer was used to estimate nitrate (NO_3^-) leaching from each scenario.

The Baseline scenario (the reference system) was based on the 2017/2018 observed dairy season for a farm in Canterbury. The farm system was simplified to allow representation in the model and to make the results (especially the financials) more generalised for the Canterbury region. The system modelled was:

1. a 96% irrigated (312.8 ha) milking platform producing and 1,600 kg MS/ha 445 kg milksolids (MS)/cow;
2. stocked at 3.7 crossbred cows/ha (1,142 peak milking cows, 1,235 wintered);
3. with standard perennial ryegrass/white clover (PR/WC) pastures fertilised at 282 kg N/ha/yr on the non-effluent block and 275 kg N/ha/yr on the effluent block;
4. with 10% of the farm undergoing pasture renewal each year – 6% from old pasture straight to new pasture and 4% of the farm is cropped in fodder beet, followed by oats and then renewed;
5. dominated by Claremont moderately deep silty-loam soils (poorly drained);
6. supported with approximately 330 kg DM eaten/cow/yr of imported wheat grain, protein supplement and pasture silage. Supplemental feed included homegrown feed: 19 t DM pasture silage harvested, 315 t DM fodder beet crop, and 126 t DM oat silage grown on the milking platform.

All wintering of dry cows and rearing of young stock was done on the support block. The 180 ha support block was idealised as the actual system had other enterprises on it. The support block was made self-sufficient (no imported feed). The support block was unirrigated and fertilised with 37 kg N/ha/yr. Thirty-six hectares of land are cropped each year. The cropping regime consisted of 18 ha kale, followed by fodder beet in the second year and finally oats where grazing of fodder beet finished before 1 July. The stock consisted of 1,235 dry cows, 373 heifer calves and 270 replacement heifers.

The treatments applied were based on forages and principles identified in the Forages for Reduced Nitrate Leaching (FRNL) programme:

1. Reducing the amount of N consumed by the cow in autumn through low-N feed (fodder beet). Fodder beet was fed during late lactation (autumn) to reduce the total amount of N ingested and dilute N excreted in urine.
2. Diluting N excreted in urine by feeding pastures, pasture silage and crops containing plantain, especially during mid-summer/autumn.
3. Recycling N via catch cropping with oats sown immediately following fodder beet. The oats were ensiled and fed to dry cows in the following season.

These three principles were used to develop the following crop and plantain treatments (Table 3.1) explored through modelling that predicted NO_3^- leaching and financial performance. Nitrate leaching was estimated using Overseer for the crop treatments and a combination of Overseer and post-model processing for the plantain treatments. Finally, a sensitivity analysis of soil type and plantain persistence were performed to determine how variations in these could affect NO_3^- leaching.

4 Results

The results are presented based on the following outline. First, a brief overview of the nitrate (NO_3^-) leaching results at the farm level (milking platform + support block) is presented in section 4.1. The support block is then excluded from further analysis as no treatments were applied to it and thus had the same general effect on the milking platform nitrate leaching and performance. Only the milking platform NO_3^- leaching results are analysed further. Then the cost of reducing NO_3^- leaching is reported for each imposed treatment (section 1.1), followed by the results of the sensitivity analysis in 4.3.

An important note to make is that the farm average NO_3^- leaching reported by Overseer is *unweighted*. It is calculated by directly averaging NO_3^- leaching from the different blocks (compare Table 9.5 and Table 9.6). This means that relatively small blocks can have a disproportionate effect on NO_3^- leaching. However, because there are eight blocks, the difference between the two calculated values for the Baseline, Fallow and No Crops are not dissimilar (38-39 kg N/ha/yr unweighted *vs.* 40 kg N/ha/yr weighted). Because these unweighted results are the main output for NO_3^- leaching and it is assumed that Overseer is used as is for policy, these have been used in this thesis for consistency, even though the weighted values are more correct.

4.1 Effectiveness of crop and plantain treatments for reducing nitrate leaching

This section compares all crop and plantain treatments to the Baseline.

4.1.1 Whole-farm nitrate leaching for the Baseline

Nitrate leaching from the milking platform (312.8 ha) for the Baseline (fodder beet + oats) scenario was 38 kg N/ha/yr. When whole farm was analysed by including the support block (180 ha), NO_3^- leaching was reduced to 28kg N/ha/yr (over 492.8 ha; Table 4.1). This reduction was because the support block was less intensively managed than the milking platform, resulting in a reduction of the rate of NO_3^- leaching, as the management intensity of the milking platform was partially offset by the lower intensity of the support block.

Beyond this point, the support block is not factored into the results because all treatments were applied to the milking platform and not the support block, which remained the same for all treatments.

4.1.2 Crop treatments

As the crop treatments applied to the milking platform affected only a small area (4%), the whole farm NO_3^- leaching results for Fallow and No Crops were also 28kg N/ha/yr.

At the crop-paddock level, the Baseline (fodder beet + oats) leached 36 kg N/ha/yr while Fallow (fodder beet only) leached 44 kg N/ha/yr from the crop area (Table 4.1). Therefore, leaving crop paddocks fallow after autumn grazing of fodder beet increased NO_3^- leaching by 8kg N/ha/yr (22%) from the crop paddocks and 1 kg N/ha/yr (3%) when considering the whole milking platform area. Removing both the fodder beet crop and the oat catch crop (No Crops) had no impact on NO_3^- leaching as No Crops and the Baseline both leached 38 kg N/ha/yr (Table 4.1).

Table 4.1: Average nitrate (NO_3^-) leaching losses for the Baseline and crop treatments from paddock to whole farm system levels.

	Milking platform (including crops)	Crop paddocks on the milking platform	Whole farm system (milking platform + support block)
		NO_3^- leached (kg N/ha/yr)	
Baseline	38	36	28
Fallow	39	44	28
No Crops	38	-	28

4.1.3 Plantain treatments

When plantain was introduced as PR/WC + PL pastures (with no maintenance), NO_3^- leaching was reduced from the Baseline leaching of 38 kg N/ha/yr to 36 kg N/ha/yr for B1, 37 kg N/ha/yr for F1 and to 36 kg N/ha/yr for NC1. More frequent plantain maintenance resulted in greater reductions in NO_3^- leaching (Figure 4.1; Table 4.2).

As the frequency of plantain maintenance increased, the size of the difference between the Baseline and Fallow treatments declined (Table 4.2; Figure 4.1). This meant the relative effect of the catch crop became less important when more plantain was included in the system. With more frequent plantain maintenance, NO_3^- leaching from No Crops plantain treatments decreased more than for plantain treatments applied to the Baseline and Fallow.

To achieve the initial objective of a 20% reduction in NO_3^- leaching, it was necessary to maintain PR/WC + PL pastures every second year, regardless of crop treatment (treatments B4, F4 and NC4) (Figure 4.1; Table 4.2). This frequency of maintenance required 40% of the milking platform pasture area to be maintained and 10% to be renewed each year. The plantain treatments with less frequent maintenance (B1-B3, F1-F3 and NC1-NC3) reduced NO_3^- leaching but did not achieve the 20% reduction target.

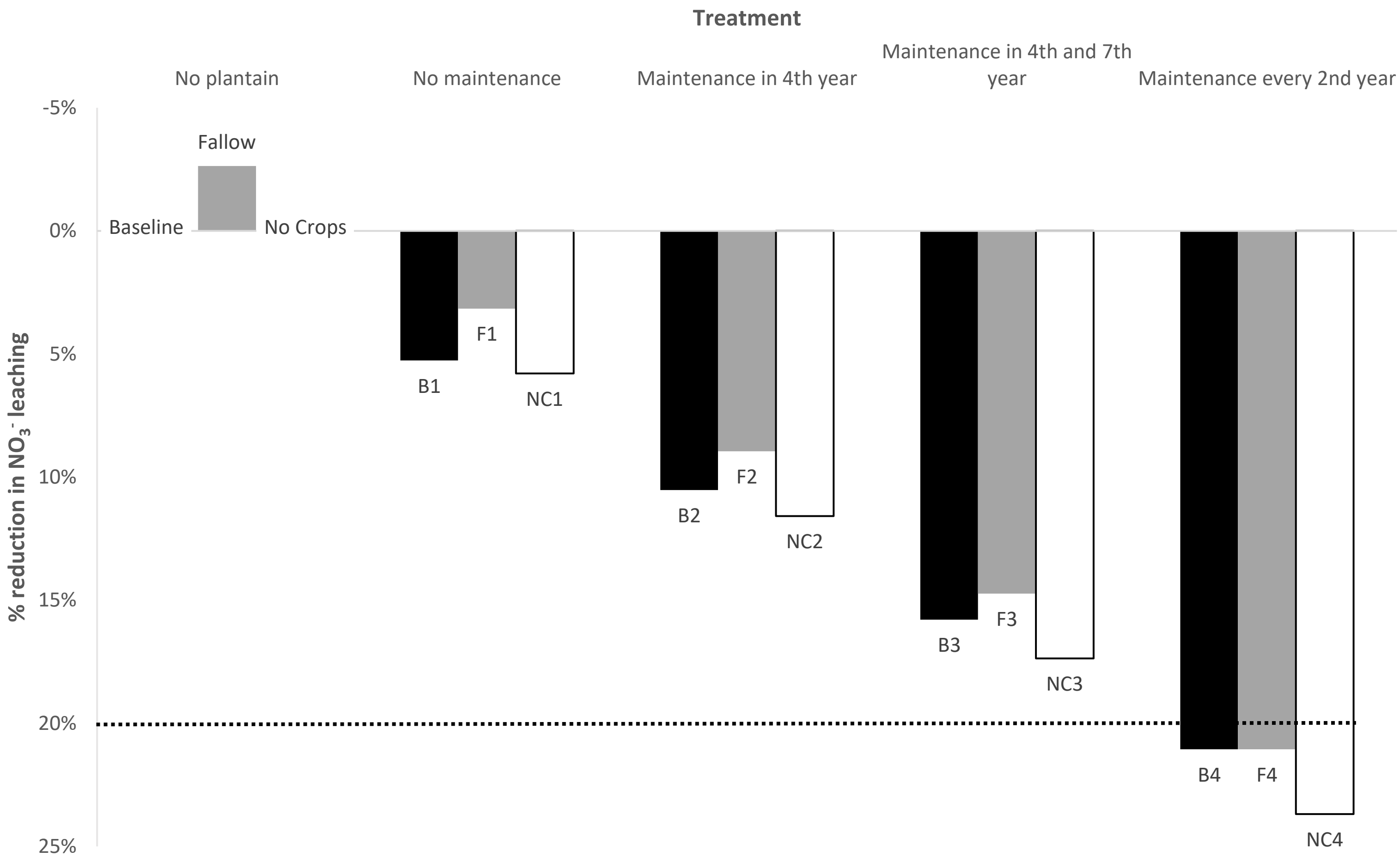

Figure 4.1: Milking platform nitrate (NO_3^-) leaching relative to the Baseline for all treatments. The dotted line indicates the initial objective of reaching a 20% reduction in NO_3^- leaching. N = nitrogen. See Table 3.1Table 3.1 for description of treatments.

Table 4.2: Milking platform nitrate (NO_3^-) leaching and operating profit for all treatments. The reductions are reported relative to the Baseline. **Bolded** lines indicate treatments that achieved the targeted 20% reduction in NO_3^-. N = nitrogen.

Treatment	Description of plantain treatment	NO_3^- leached kg N/ha/yr	Reduction	Operating profit $/ha	Reduction
Baseline	No plantain	38		2501	
B1	No maintenance	36	5%	2487	1%
B2	Maintenance in 4th year	34	11%	2467	1%
B3	Maintenance in 4th and 7th year	32	16%	2443	2%
B4	**Maintenance every 2nd year**	**30**	**21%**	**2385**	**5%**
Fallow	No plantain	39	-3%	2432	3%
F1	No maintenance	37	3%	2418	3%
F2	Maintenance in 4th year	35	9%	2396	4%
F3	Maintenance in 4th and 7th year	32	15%	2374	5%
F4	**Maintenance every 2nd year**	**30**	**21%**	**2328**	**7%**
No Crops	No plantain	38	0%	2342	6%
NC1	No maintenance	36	6%	2328	7%
NC2	Maintenance in 4th year	34	12%	2306	8%
NC3	Maintenance in 4th and 7th year	31	17%	2283	9%
NC4	**Maintenance every 2nd year**	**29**	**24%**	**2239**	**10%**

4.2 Cost of mitigation: nitrate leaching *vs.* operating profit

The dairy business operates year-round regardless of where the animals are located so splitting costs, such as animal health, between the milking platform and support block is difficult. The financial results are therefore reported for the whole farm system. Note that the NO_3^- leaching results reported still refer to those estimated for the milking platform only and not the support block, as the treatments did not affect NO_3^- leaching from the support block. There were not changes on the support block that would alter financials.

The financial results showed that all crop and plantain treatments decreased profitability, relative to the Baseline (Figure 4.2 and Figure 4.3). This meant that using the modelled strategies to reduce NO_3^- leaching below the Baseline resulted in costs that exceeded milksolids (MS and meat) income. Sequentially removing the oat (Fallow) and fodder beet crops (No Crops) from the Baseline decreased profitability by \$69/ha for Fallow and \$159/ha for No Crops respectively (Table 4.2). As well as reducing profitability, removing these crops had minimal effect on NO_3^- leaching (see data points Baseline, Fallow and No Crops in Figure 4.2 and Figure 4.3).

Including plantain in pastures reduced NO_3^- leaching. Increasing the frequency of plantain maintenance reduced NO_3^- leaching even further, but also reduced operating profit. The reduction in operating profit was due to an increase in the total cost of plantain maintenance.

For the three treatments that achieved the initial objective of reducing NO_3^- leaching by 20%, the following reductions in operating profit are reported relative to the Baseline. The relative cost for B4 was \$116/ha, \$173/ha for F4 and \$262/ha for NC4. In these treatments, plantain was maintained every second year (the most frequent maintenance schedule). Out of all treatments explored, NC4 was the most effective, but also the most expensive, treatment for reducing NO_3^- leaching.

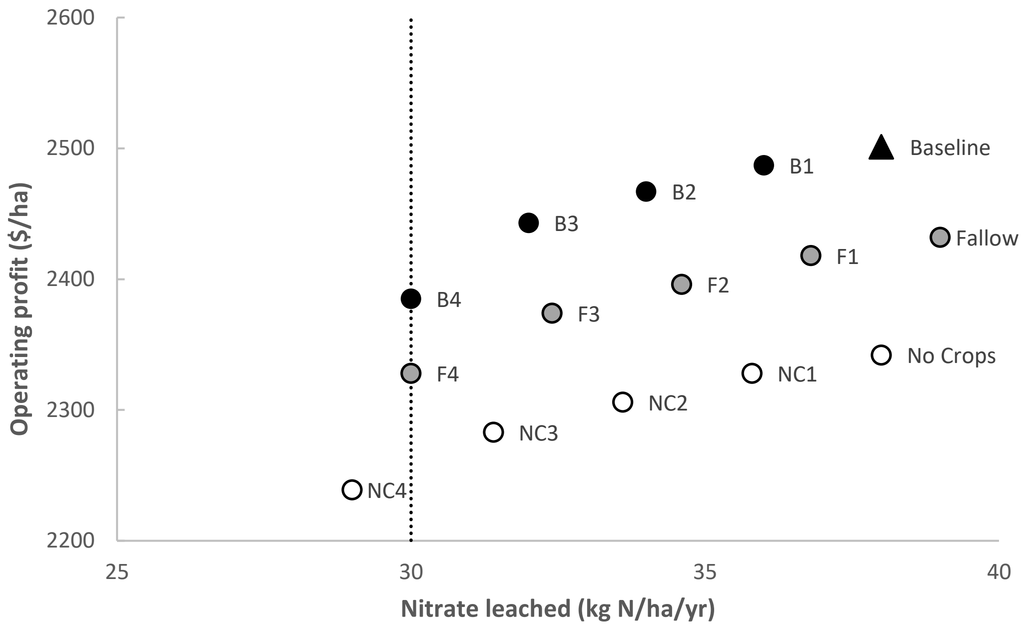

Figure 4.2: Farm operating profit of all treatments, compared to absolute nitrate (NO_3^-) leaching from the milking platform. See Table 3.1 for description of treatments. The dotted line marks the targeted 20% reduction in NO_3^- leaching compared to the Baseline. The black triangle is the Baseline (fodder beet + oat catch crop, no plantain).

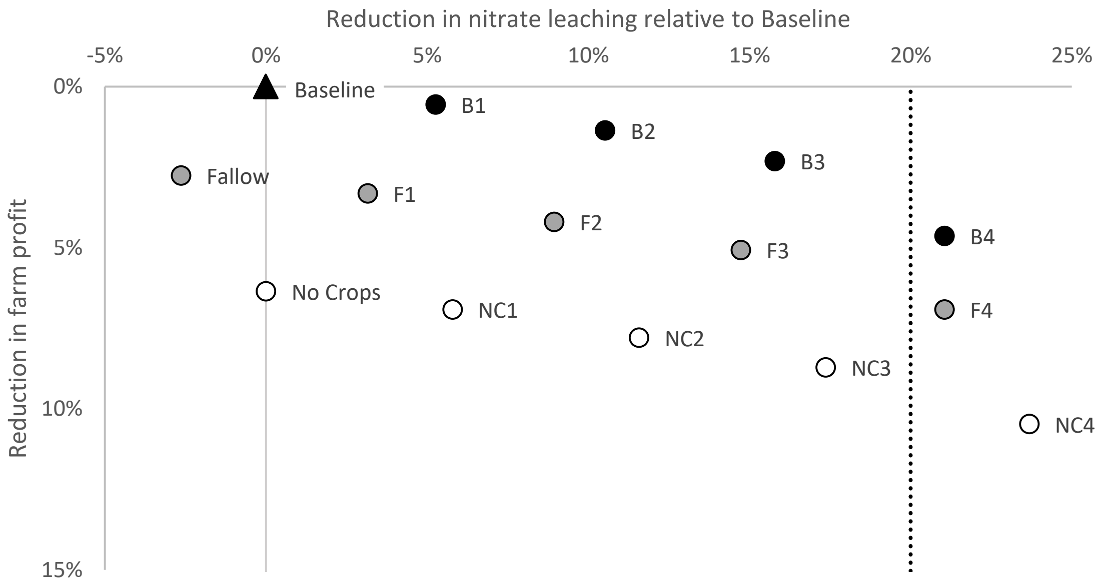

Figure 4.3: Reduction in farm operating profit relative to the Baseline (black triangle), compared to the nitrate (NO_3^-) leaching reductions achieved. See Table 3.1 for description of treatments. The dotted line marks the target NO_3^- leaching reduction of 20%. The black triangle is the Baseline. For Fallow, a -3% reduction in NO_3^- leaching loss represents an *increase* of 3%, relative to the Baseline.

4.3 Sensitivity analysis

Two parameters were analysed in this sensitivity analysis: soil type and the persistence curve of plantain.

4.3.1 Soil type

Two stony soil types were substituted for the 'heavy' (poorly drained) silt-loams found on the case study farm (see chapter 9, section 9.8 for the relevant soil reports). The first soil (Lismore) was well-to-imperfectly drained and was referred to as the 'moderate' soil. The second soil (Rangitata) was well-drained and was referred to as the 'light' soil type.

Table 4.3: Comparison of milking platform nitrate (NO_3^-) leaching from the moderate (Lismore) and light (Rangitata) soil type as compared to the Baseline. **Bolded** lines indicate treatments that achieved the targeted 20% reduction in NO_3^-. Bracketed values are the %reduction in NO_3^- leaching for the treatments that achieved the 20% reduction target when compared to their Baseline.

Treatment	**Description of plantain treatment**	**NO_3^- leached kg N/ha/yr**		
		Baseline soil	**Moderate soil**	**Light soil**
Baseline	No plantain	38	44.0	92.0
B1	No maintenance	36	41.8	87.4
B2	Maintenance in 4th year	34	39.6	82.8
B3	Maintenance in 4th and 7th year	32	37.4	78.2
B4	**Maintenance every 2nd year**	**30 (21%)**	**35.0 (20%)**	**73.0 (21%)**
Fallow	No plantain	39	45.0	93.0
F1	No maintenance	37	42.5	88.4
F2	Maintenance in 4th year	35	40.0	83.8
F3	Maintenance in 4th and 7th year	32	37.5	79.2
F4	**Maintenance every 2nd year**	**30 (21%)**	**35.0 (20%)**	**74.0 (20%)**
No Crops	No plantain	38	43.0	89.0
NC1	No maintenance	36	40.5	84.5
NC2	Maintenance in 4th year	34	38.0	80.0
NC3	Maintenance in 4th and 7th year	31	35.5	75.5
NC4	**Maintenance every 2nd year**	**29 (24%)**	**33.0 (25%)**	**70.5 (23%)**

With increased drainage, NO_3^- leaching from the milking platform increased (Table 4.3). Nitrate leaching for the Baseline, Fallow and No Crops increased to 44 kg N/ha/yr, 45 kg N/ha/yr and 43 kg N/ha/yr respectively, under the moderate soil type. Nitrate leaching for the Baseline, Fallow and No Crops increased to 92 kg N/ha/yr, 93 kg N/ha/yr and 89 kg N/ha/yr respectively, under the light (well-drained) soil type.

Overall, there was little difference in the relative reduction in NO_3^- leached for any treatment relative to the Baseline for each soil type (Table 4.3). For both soil types, NO_3^- leaching could be reduced by at least 20% where plantain maintenance was scheduled for every second year. Soil type had little effect on relative reductions in NO_3^- leaching in this initial analysis.

4.3.2 Plantain persistence

The original persistence curve, representing the proportion of pasture DM as plantain in PR/WC + PL pastures was assumed to be 50% of pasture DM in the first year, 40% in the second year, 20% in the third year and 10% in the following years. Plantain maintenance was assumed to return plantain populations to those of first-year pastures *i.e.* 50% pasture DM as plantain. A second persistence curve was modelled where plantain establishment was not as successful and plantain content in the pasture decreased more rapidly than the original persistence curve (see methods section 3.6.4.2). This curve was 40% of pasture DM in the first year, 20% in the second year and 10% in the following years. Plantain maintenance was assumed to return plantain populations to those of first-year pastures *i.e.* 40% pasture DM as plantain.

This second persistence curve was based on recent data from different regions in New Zealand, mainly from the Tararua area (M. Dodd, personal communication, 18 September, 2019). Review of these data suggested that the establishment and persistence of plantain in PR/WC + PL pastures was less than the initial curve assumed for the original scenarios. The analysis, using a more rapid decline in plantain persistence, resulted in a 14% reduction in NO_3^- leaching, at most (Table 4.4). This was for NC4 (No Crops) where plantain was maintained every second year (Table 4.4).

Table 4.4: Milking platform nitrate (NO_3^-) leaching and operating profit for all treatments under the second plantain persistence curve. The reductions are reported relative to the Baseline.

Treatment	Description of plantain treatment	NO_3^- leached kg N/ha/yr	Reduction compared to Baseline
Baseline	No plantain	38.0	0%
B1	No maintenance	37.0	3%
B2	Maintenance in 4th year	36.0	5%
B3	Maintenance in 4th and 7th year	35.0	8%
B4	Maintenance every 2nd year	33.0	13%
Fallow	No plantain	39.0	-3%
F1	No maintenance	37.8	1%
F2	Maintenance in 4th year	36.6	4%
F3	Maintenance in 4th and 7th year	35.4	7%
F4	Maintenance every 2nd year	33.0	13%
No Crops	No plantain	38.0	0%
NC1	No maintenance	36.9	3%
NC2	Maintenance in 4th year	35.8	6%
NC3	Maintenance in 4th and 7th year	34.7	9%
NC4	Maintenance every 2nd year	32.5	14%

5 Discussion

The discussion has been structured in the following sections. First, nitrate (NO_3^-) leaching results of the crop treatments are discussed, followed by the NO_3^- leaching results of the plantain treatments. Then the financial feasibility of these treatments is explored, followed by comparisons of the NO_3^- and financial leaching results to the current literature and sensitivity analysis of the NO_3^- leaching results. Alternative solutions for reducing NO_3^- leaching (section 2.5) are briefly compared to the solutions identified in this study. The discussion then shifts from the results of this case study to the implications of limited data and model ability for research in this area. Finally, recommendations are made for future work and the conclusions arising from this case study are summarised to synthesise this thesis.

5.1 Feasibility of Forages for Reduced Nitrate Leaching (FRNL) solutions

In this modelling study, the crop (sequential removal of oats, then fodder beet) and plantain treatments were incorporated into the management of the Baseline to reduce NO_3^- leaching and maintain profitability. These treatments were identified as having the potential to reduce NO_3^- leaching while maintaining profitability by experiments conducted as part of the FRNL programme. Here, the primary focus was to reduce NO_3^- leaching. Maintaining profitability was an important secondary focus.

Previous studies (Beukes *et al.*, 2018; Beukes *et al.*, 2017; Pinxterhuis & Edwards, 2018) explored the use of fodder and catch crops, but the role of plantain on nitrate leaching has not been fully examined. In particular, the persistence of plantain in the sward has not been included in any published modelling studies to date, which is not surprising considering interest in plantain as a tool for NO_3^- mitigation is relatively new. Methods for establishing and maintaining plantain (Bryant *et al.*, 2019) and associated costs (Edwards & Pinxterhuis, 2018) in mixed pastures have explored, but the implications of plantain persistence in mixed pastures for NO_3^- leaching have not.

The results of this study showed that in a modelling framework under the assumptions described in the methods chapter (section 3), it was possible to reduce NO_3^- leaching by >20%, though this resulted in a reduction of operating profit of between $116/ha (B4) and $262/ha (NC4). To achieve these reductions, renewal of mixed perennial ryegrass/white clover + plantain (PR/WC + PL) pastures followed by plantain maintenance every second year was required, regardless of the crop treatment applied (treatments B4, F4 and NC4).

5.1.1 Ensuring comparability between scenarios

This section describes the key parameters that were considered when creating the model scenarios for each treatment. These key parameters were vital for ensuring the scenarios for all treatments could be directly compared to the Baseline.

Maintaining milksolids (MS) production was a key strategy that ensured all scenarios were directly comparable and that the effects of the three forages and their management could be distinguished. Maintaining parameters such as dry-off dates, culling decisions, dietary ME and pasture management were essential. Changes in these parameters would likely have affected MS production (Waghorn *et al.*, 2007) and potentially NO_3^- leaching (Clark *et al.*, 2019; Di & Cameron, 2002). Crop and pasture production affected the quantity and quality of feed available and influenced whether supplemental feed was necessary to maintain MS production. Milksolids production was maintained through isoenergetic calculations *i.e.* ensuring that dietary ME was maintained between all treatments, regardless of the diet composition. Future modelling work in this area may explore the consequences of varying these critical management practices.

5.1.1.1 Substituted feeds

It was necessary to import feed onto the milking platform in place of homegrown oat silage and fodder beet for Fallow and No Crops. This substitution had the potential to confound NO_3^- leaching results, based on the choice of imported feeds due to differences in N content. For Fallow, oat silage (grown on the milking platform of the Baseline) was substituted with imported pasture silage. A survey on Canterbury dairy farm wintering practices by Edwards *et al.* (2017) reported that straw then pasture silage were the most common supplemental feed types used for wintering dry stock. While pasture silage has been more expensive per kg dry matter (DM) than straw and less commonly used for wintering, pasture silage was the preferred substitute for oat silage. Pasture silage was more similar than straw to oat silage in terms of DM, ME and N (DairyNZ, 2017; Dalley *et al.*, 2017). In addition, straw (a low-ME feed) is commonly fed with high ME crops such as fodder beet (Edwards *et al.*, 2017), not pasture. In the modelled case study farm, the diet for dry cows on the milking platform pre-calving was pasture-based. As pasture has lower ME than fodder beet, it made more sense to import and feed pasture silage than straw.

Barley grain was considered an appropriate feed substitute for fodder beet in No Crops, based on its low N and high ME contents (Dalley *et al.*, 2017). The low-N, high-ME options recommended by Dalley *et al.* (2017) to reduce urinary N were fodder beet, swedes, turnips, barley and wheat grain. Importing barley grain made sense as the grain could be fed *via* the existing in-shed feeding system and barley grain had more similar characteristics to fodder beet than wheat grain.

Maintaining MS production between all treatments made it possible to observe the impacts of each forage type and each treatment on NO_3^- leaching. Fair comparisons were able to be made between the treatments because confounding management factors were mitigated and in the case of imported feeds, they were carefully chosen based on feed characteristic similarities and their current popularity in Canterbury.

5.1.2 Nitrate leaching from crop treatments

In this sub-section, given the crop and plantain treatments were only applied to the milking platform, nitrate leaching from the whole farm system was analysed before shifting the focus exclusively to the milking platform.

Only crop treatments are discussed here. When the whole dairy farm system (support block + milking platform) was analysed for the Baseline, Fallow, and No Crops, the rate of NO_3^- leaching from all land was 28 kg N/ha/yr compared with 38-39 kg N/ha/yr for the milking platform alone. This 26-28% decrease in average NO_3^- leached per hectare is unsurprising, considering the support block was less intensively managed than the milking platform (no irrigation, fewer cow days and no lactating stock) and so diluted the higher NO_3^- leaching rate from the milking platform. The contribution of the support block was not a focus of the current work so the remainder of this discussion focusses on NO_3^- leaching from the milking platform.

Nitrate leaching from the milking platform was similar between the Baseline and the two crop treatments without plantain (Fallow and No Crops). This lack of difference in NO_3^- leaching between the crop treatments was not surprising given that the crop area on the milking platform was small (only 4% of the effective area). Consequently, the removal of cropped land (with higher NO_3^- leaching) had only a very small contribution to NO_3^- leaching when expressed at the milking platform level.

For the case study farm, there was a fixed area of land available (312.8 ha milking platform) which restricted the area available for fodder beet and oat crops. The fodder beet yield was 25 t DM/ha over the 8-month period it was in the ground. In comparison, pastures on the farm yielded less than half of this (11.5 t DM/ha) over the same period. Pasture can be grazed year-round in Canterbury, though it is common for stock to be transported to a support block where there is a reliable source of feed (Edwards *et al.*, 2017) to minimise damage to pastures and ensure enough feed is available for spring as winter growing conditions tend to be unfavourable. Unlike pasture, fodder beet is a single-graze crop and therefore does not provide a reliable source of feed throughout the year (Malcolm *et al.*, 2016).

Cropping increases NO_3^- leaching compared to grazing pasture (Di & Cameron, 2002), but when this makes up a small proportion of total land, in this case 4% of the milking platform, the observed increases in NO_3^- leaching can be masked.

Fodder beet crops are sown in spring in south Canterbury (Edwards *et al.*, 2014). On the case study farm and in all modelled scenarios, fodder beet was sown in October. In the modelled scenarios, pasture renewal (regrassing) and plantain maintenance were also started around the same time. The timing of these activities was important as these activities removed pasture from the grazing rotation, which resulted in a reduction in potential pasture production. This reduction had to be managed in a way that did not compromise the average pasture cover, total/seasonal feed availability or animal feed supply. The aim was to simplify the management of the system and minimise the costs associated with these activities by minimising the need to purchase and feed out imported supplements. Restricting the crop area to 12.6 ha (4% of the milking platform), based on the case study farmer's experience, ensured sufficient DM and ME were produced to the support the milking and dry stock present on the milking platform with some imported supplemental feed.

5.1.2.1 Oat catch crop

The rate of NO_3^- leaching from the crop block of the Baseline was less than the Fallow treatment. When an oat catch crop was grown immediately following the grazed fodder beet crop (Baseline), NO_3^- leaching was 36 kg N/ha/yr from the crop block as opposed to 44 kg N/ha/yr when paddocks were left fallow over winter (Fallow; Table 4.1). This amounted to an 18% decrease in NO_3^- leaching at the crop-paddock level (when the oat catch crop was used in the Baseline). When analysed at the farm level, there was a very small difference in NO_3^- leaching between the Baseline and Fallow; only a 1 kg N/ha/yr increase from 38 to 39 kg N/ha/yr. Initially, this was attributed to the effect of the cropped paddocks as only a small area (4%) was affected. However, upon further investigation, there were changes in NO_3^- leaching from pasture blocks that had a greater impact on this farm-level NO_3^- loss. While the removal of the oat crop was the only treatment applied to the Fallow scenario, this increase was still considered an effect of removing the catch crop. It was therefore determined that while the presence of a catch crop reduced NO_3^- leaching from the cropped area, this alone had little impact at the farm level and the overall difference in NO_3^- leaching between the Baseline and Fallow was due to the system-wide impact of removing the catch crop. In short, more feed and therefore N was imported and fed out on pastures, increasing the N input to the farm system in Fallow. In addition, more NO_3^- was leached from the cropped paddocks so overall NO_3^- leaching from Fallow was greater than from the Baseline.

The catch crop area was limited to the area used for the fodder beet crop. In the system modelled, the sowing date of the oat catch crop was dependent on the final grazing date of the fodder beet crop. The paddocks had to be finished (no more fodder beet available for grazing) before the oat crop could be sown.

The effectiveness of a catch crop in reducing NO_3^- leaching was dependent on the length of time it is in the ground and the date of sowing – later sowing dates reduce the opportunity for NO_3^- uptake before the final harvest (Malcolm *et al.*, 2016). In addition, when drainage occurs NO_3^- is leached (Di & Cameron, 2002; Selbie *et al.*, 2015) so where wet soils have to drain following grazed fodder beet crops before a catch crop can be established, less NO_3^- will be available for recovery. The impacts of delayed catch crop establishment were not investigated in this thesis, though this would make an important future sensitivity analysis.

5.1.3 Nitrate leaching from plantain treatments

No Crops leached less than the Baseline (fodder beet + oats) when plantain treatments were applied, due to the greater area (100% instead of 96% of the milking platform) that was sown in PR/WC + PL pastures. The implications of a greater area of the farm under plantain are that more plantain can be incorporated into the system. Plantain was the most important forage for reducing NO_3^- leaching, achieving up to a 24% reduction (9 kg N/ha/yr) in NO_3^- leaching (NC4) from the Baseline (38 kg N/ha/yr). This will be compared to other mitigation strategies later.

The impact of plantain on reducing NO_3^- leaching was not surprising considering: (i) the area of the milking platform affected by plantain (96%) was far greater than the area cropped (4%), (ii) the greater length of time plantain contributed to dietary DM on the milking platform (10/12 months) compared to fodder beet (3/12 months), and (iii) the impact plantain has on the N load of urine patches (refer to literature review sub-section 2.6.3.1). The more plantain there was at the milking platform scale, the greater the reduction in NO_3^- leaching predicted by the combination of Overseer and post-model processing.

Plantain in PR/WC + PL pasture silage was assumed to have the same effect on the concentration of urinary N as grazed PR/WC + PL pasture (Judson & Edwards, 2016). This is an advantage as PR/WC + PL silage can be deferred for feeding in February-May – the time of the year where plantain could be most advantageous for reducing NO_3^- leaching (Selbie *et al.*, 2015; Shepherd *et al.*, 2011). In the Farmax scenarios, the quantity of plantain in the diet was increased between March and May by feeding PR/WC + PL pasture silage harvested earlier in the season. However, any benefit from this strategy was not captured by Overseer, due to its current feed regime limitations (section 5.4.2).

In a Waikato-based analysis by Romera *et al.* (2017b), it was predicted that 40% reductions in N leaching could be achieved and milk production maintained by farming with diverse pastures (including plantain in the sward) as opposed to PR/WC pastures. However, the authors reported that the economic incentives of diverse pastures alone would not be enough for large-scale adoption. However, the environmental benefits and maintenance of milk production through diverse pastures together would be worth further consideration (Box *et al.*, 2017).

5.1.3.1 Plantain crops

A preliminary model run was carried out to determine whether plantain could be modelled as a pure crop. However, it became apparent that even with the post-model process used for PR/WC + PL pasture in this study (refer to methods, section 3.5), nonsensible results were modelled *e.g.* a farm average of 33 kg N/ha/yr of N fixation where there was no clover on the milking platform. Consequently, modelling pure plantain crops was abandoned as an option and would require further data availability and future model developments.

5.1.3.2 Plantain as a mitigation tool for NO_3^- leaching is a new research area

Due to the recent interest in using plantain to reduce NO_3^- leaching, there is a lack of data in key areas. More data is needed on plantain for implementation at scale and for modelling. Key data needs include:

1. the seasonal production/feed availability of PR/WC + PL pastures,
2. confirmation of the dietary threshold for a reduction in urinary N concentration from dairy cows ingesting plantain,
3. the relationship between ingested plantain/urinary N concentration and NO_3^- leaching,
4. the impacts of plantain on long-term animal health,
5. milk taste and consumer perception,

6. whether plantain crops could be a suitable mitigation tool,
7. confirmation of the extent of plant-soil interactions on N losses as NO_3^- leaching (and N_2O emitted), and
8. what the persistence curve of plantain in PR/WC + PL pastures is and how plantain can be maintained in these pastures.

Other gaps are likely to be identified in due course. For now, this list is only an outline of key research gaps identified in this study.

5.1.4 Financial feasibility

5.1.4.1 Cost of cropping

Growing an oat catch crop on the milking platform was more profitable than importing pasture silage as a substitute (Table 4.2). Growing fodder beet on the milking platform was also more profitable than importing barley as a substitute. Growing and harvesting these crops required a financial (and time) investment, but their production reduced the need to purchase imported supplemental feeds (Appendix 3, Table 9.9). For No Crops the cost was $1,285/ha for imported feed and harvested pasture silage. For Fallow (fodder beet) the feed cost was $1,122/ha and for the Baseline (fodder beet and oats) a total of $1,000/ha was spent on imported feed, homegrown crops and harvested pasture silage. In the modelled systems where income did not change, it was more profitable to grow fodder beet and oats on the milking platform than import supplemental feeds.

5.1.4.2 Comparison to other studies

While not directly comparable to the results of this case study, Beukes *et al.* (2018), reported that the operating profit of their Baseline was approximately $2,462/ha, similar to the $2,501/ha calculated for this case study, indicating that the calculated operating profit was realistic.

5.1.4.3 The cost of plantain maintenance

The cost of plantain maintenance, was estimated assuming that direct drilling was the most effective method for establishing new plantain plants into existing pastures (Bryant *et al.*, 2019). For this case study, the cost of maintenance *via* direct drilling was estimated to be $200/ha maintained where 10% of the farm was maintained each year. The cost of direct drilling alone was $100/ha (Askin & Askin, 2016), half the total cost. For treatments B2, F2 and NC2, where 10% of the farm was maintained each year, the cost was $20/effective ha (Appendix 3, section 9.3).

Bryant *et al.* (2019), reported that direct drilling had better establishment rates than broadcasting plantain seed, but that this difference was not large. The advantage of broadcasting over direct drilling is its simplicity. Plantain seed can be broadcast with fertiliser as part of the farm fertiliser plan, removing the $100/ha maintained cost of direct drilling. The cost of broadcasting was assumed to be $20/ha (Askin & Askin, 2016), though if plantain seed is sown with fertiliser, there is no additional cost of broadcasting *i.e.* the plantain seed is the only relevant cost. The cost of plantain maintenance (including broadcasting) was estimated to be $120/ha maintained ($10/effective ha for 10% of the farm). Broadcasting is therefore a cheaper option than direct drilling and it would be up to individual farmers to decide which method of maintaining plantain suits their system best.

5.1.5 Comparisons to other modelling studies

There have been a few studies modelling combinations of fodder beet, oats and plantain on milking platforms with the aims of reducing NO_3^- leaching and maintaining/improving profitability. The modelling studies by Beukes *et al.* (2017), Beukes *et al.* (2018) and Pinxterhuis and Edwards (2018) report NO_3^- leaching from actual and hypothetical scenarios for five commercial dairy farms in Canterbury. These dairy farms (including the case study farm modelling in this current study) were part of the Forages for Reduced Nitrate Leaching (FRNL) monitor farm network. The greatest point of difference between this case study and these previous studies was that in this case study the impacts of plantain persistence on NO_3^- leaching and profitability were investigated. No studies were found that investigated the role of plantain persistence on NO_3^- leaching from pasture-based dairy farms.

Beukes *et al.* (2017) modelled the 2014/2015 dairy season for the milking platform and support block as the Baseline of Canlac Holdings in north Canterbury. Canlac Holdings is a 335 ha milking platform and 155 ha support block on a Lismore soil (of the same soil family as the moderate soil used in the sensitivity analysis). Some farm management parameters are compared to the case study farm in Table 5.1.

Table 5.1: Management differences between the similar-sized south Canterbury case study dairy farm and the north Canterbury Canlac Holdings dairy farm. Note that the “case study farm” in the table refers to the farm that has been investigated throughout this thesis. “Canlac Holdings” is the case study farm for Beukes *et al.* (2017), but to avoid confusion, it is referred to by its commercial name in this thesis.

Parameter	Case study farm	Canlac Holdings
Milking platform area (ha)	312.8	335
Support block area (ha)	180	155
Dominant soil	Claremont moderately deep silty loam	Lismore
Dominant cow breed	Cross-bred	
Stocking rate (cows/ha)	3.7	4.1
Peak cows milked	1,142	1,380
Average liveweight on 1 December (kg/cow)	509	480
N fertiliser use (kg N/ha/yr)	279	290

The average NO_3^- leaching at the whole farm level (support block + milking platform) for Canlac Holdings Baseline was 65 kg N/ha/yr. This is more than twice that for the case study Baseline which was 28 kg N/ha/yr for the whole farm.

On the Canlac Holdings farm, a hypothetical scenario was modelled to assess its impact on NO_3^- leaching. A feed pad was implemented, and the effluent block area increased. In addition to these changes, FRNL options were also implemented. A 12.5 ha area was sown in fodder beet, which was lifted and fed on the feed pad rather than grazed *in situ* as for the case study farm, the fodder beet crop was followed by an oat catch crop and one-third of the milking platform was sown in mixed pastures (though the species present were not specified beyond “grasses, herbs and legumes”). This hypothetical scenario averaged a 19% decrease in NO_3^- leaching to 53 kg N/ha/yr for the whole farm.

These mitigations modelled for Canlac Holdings were not as effective as the plantain treatments applied to the case study Baseline. However, it is not completely possible to fairly compare the NO_3^- leaching results from these two farms. There are many other factors that affect NO_3^- leaching (refer to literature review, section 2.4). While some of the difference in NO_3^- leaching could be due to the higher stocking rate and well-drained soils on Canlac Holdings, this does not take farm management (an important factor affecting NO_3^- leaching (Monaghan &

de Klein, 2014; Selbie *et al.*, 2015)) into account. In addition, the treatments/hypothetical scenarios applied to the model farms were not comparable although a similar fodder beet and oat catch crop area was used. The hypothetical scenario modelled by Beukes *et al.* (2017) also included changes to the farm effluent system, which is not an FRNL strategy. The assumptions made by Beukes *et al.* (2017) regarding the efficacy of the mixed pastures were also different to those used in this case study. For example, the persistence of specific pasture species had not been taken into account as the aim of this previous work was to look at what was necessary to achieve a substantial reduction in NO_3^- leaching, based on currently available research on the feed composition of mixed pastures (P. Beukes, personal communication, November 24, 2019).

A later study by Beukes *et al.* (2018) investigated the effects of mixed pastures, catch crops and the replacement of kale crops with fodder beet crops on NO_3^- leaching and profitability. The 2016/2017 dairy season Baseline leaching value for their case study farm (Ballindalloch) was 44 kg N/ha/yr from the milking platform (310 ha) + support block (210 ha). In addition to a milking platform and support block, there was an additional beef block (255 ha) for their beef enterprise. When the beef block was included in the analysis, the Baseline leaching for the entire farm dropped by 4 kg N/ha/yr to 40 kg N/ha/yr. The beef block was relatively intensely managed: 90% irrigated, with 200 kg N fertiliser/ha/yr applied so did not dilute NO_3^- leaching for the entire farm system very much.

Beukes *et al.* (2018) employed similar strategies to the previous study (Beukes *et al.*, 2017) and also modelled NO_3^- leaching for the entire farm. However, the conclusion of this study was that if FRNL solutions were applied to the entire farm system, NO_3^- leaching could only be reduced by 8% (to 37 kg N/ha/yr).

These studies show that the potential for NO_3^- leaching reductions from farm systems depends on the farm system, its management and the mitigation strategies applied. Farms differ in numerous ways and are subject to significant environmental and financial variation (Doole *et al.*, 2013). This study investigated one dairy farm in Canterbury. This variability indicated that dairy farm management solutions to reduce NO_3^- leaching need to be tailored to suit individual farms. In addition, the plantain treatments explored in this thesis resulted in far greater reductions in NO_3^- leaching than the crop treatments. While strategies need to be tailored for different farms, it is likely that of the three forages investigated, plantain will be the most popular and efficient.

5.2 Sensitivity of modelled results to soil type and plantain persistence

While assumptions are always necessary when using modelling approaches to test mitigation strategies, subsequent sensitivity analyses are an important consideration. Sensitivity analyses are used to test the sensitivity of results to changes in key parameters. Soil type and plantain persistence were analysed to determine how changes in these parameters could influence NO_3^- leaching results. However, milk price is discussed first as this was initially considered for analysis, but for reasons explained below, was omitted.

Milk price was an important candidate parameter to vary in sensitivity analysis. It is a key driver of profit across time and is a key source of business risk, together with climate (Ballingall & Pambudi, 2017). However, the modelling approach used in this study focused on equilibrium cases where milk production was maintained across all treatments (1,600 kg MS/ha). The most meaningful analysis of how each strategy behaves with response to milk price would require a change in management in each scenario for a broad range of prices. This makes comparison complicated. There is a wide set of potential responses based on strategic decisions to a change in milk price within each scenario. In addition, a farm system is often optimised to a steady-state or average milk price, rather than high or low extremes. For these reasons, milk price was held constant at its 2017/2018 price of $6.50/kg MS. This assumption had minimal impact on model output given that milk production, and therefore revenue, was held constant across the scenarios.

5.2.1 Soil type

This was a simple analysis because soil type was changed, without considering the implications of the difference in profile available water and therefore seasonal irrigation requirements. Therefore, Overseer could not be expected to predict changes in pasture production. Changes in pasture production would be expected because the well-drained, lighter soils, such as the Lismore and Rangitata soils used in this sensitivity do not store as much water as the heavy, poorly-drained Claremont soils of the case study farm (see Appendix 3, section 9.8) for comparison of soil types). As pasture production and therefore feed availability should have been affected, the system management would also have to change. Regardless of their limitations, the following results have some indicative use: these scenarios are likely to work on different soil types. Obviously, additional work is needed to confirm these assumptions.

When the milking platform soil type was changed from heavy, poorly-drained soils to moderate and light, well-drained soils, absolute leaching values increased. Relative leaching values (% reductions) were similar to those for the original scenarios (Table 4.2, Table 9.11 and Table 9.12). However, this result could be due to the internal calculations of the model as the urine N load is related to the proportion of N excretion that is leached. This is independent of soil type, therefore the percentage reduction in NO_3^- leaching will remain the same (M. Shepherd, personal communication, 8 August, 2019). That aside, this analysis suggests that the management solutions explored for the case study farm could be applied to different soil types with similar efficacy in reducing NO_3^- leaching.

In comparison, Beukes *et al.* (2017) reported that NO_3^- leaching from the Lismore soils Canlac Holdings operated on was 65 kg N/ha/yr on average over three-years, which is higher than those reported for this case study farm on its original soil type. However, Beukes *et al.* (2017) used a combination of three sophisticated software packages instead of Overseer to estimate NO_3^- leaching. In addition, in the later study, Beukes *et al.* (2018) used the same three software packages to estimate NO_3^- leaching and compared these to results obtained from Overseer. The software packages were DairyNZ's Whole Farm Model (WFM) and Urine Patch Framework (UPF), and the Agricultural Production System Simulator. Their results indicated that on average, Overseer's estimates of NO_3^- leaching were 23% higher than the combined software packages. Had Canlac Holdings been analysed in Overseer, it is likely that the NO_3^- leaching results reported by Beukes *et al.* (2017) would have been higher than 65 kg N/ha/yr. This indicated that the results of the soil sensitivity analysis for this case study were probably similar to NO_3^- leaching from Lismore soils.

5.2.2 Plantain persistence

The persistence of plantain populations in PR/WC + PL pastures affects the quantity of plantain in pastures and therefore affects NO_3^- leaching, as seen in the results of this study. For example, including plantain in pastures reduced NO_3^- leaching from the Baseline by 1-3 kg N/ha/yr (3-6% for plantain treatment 'No maintenance'). Maintaining plantain increased the size of this reduction; when plantain was maintained every second year, the reductions in NO_3^- leaching ranged from 8-9 kg N/ha/yr (21-24%).

Long-term data of plantain persistence were not available for PR/WC + PL pastures. Though Bryant *et al.* (2019) reported that in their experiment, it was rare for plantain seed sown into existing PR/WC + PL to result in an increase of plantain to more than 30% of pasture dry matter (DM). This is not in line with the assumptions of this case study, where it was assumed that plantain maintenance would result in pastures returning to 50% plantain as the pasture DM. It is important to note that the persistence of plantain is not well understood so the assumptions made based on personal communication with experts (methods section 3.4.6) were not unrealistic at the initiation of this case study.

5.3 Other mitigation options

In the literature review, section 2.5, other NO_3^- leaching mitigation strategies addressing sources of excess N and improving resource use efficiency were briefly discussed (Beukes *et al.*, 2018; Beukes *et al.*, 2017; DairyNZ, n.d.-a; Di & Cameron, 2002; Ledgard *et al.*, 2007; Malcolm *et al.*, 2016; Romera *et al.*, 2017a; Schipper & Vojvodic-Vukovic, 2000).

In this case study, plantain achieved a 20% reduction in NO_3^- leaching if it was maintained at a high enough proportion in pastures. Here, other mitigation strategies are explored for comparison.

5.3.1 Low N feeds

Low N feeds have been explored in this thesis as fodder beet and barley grain. Barley grain was a low-N, high-ME feed (Dalley *et al.*, 2017) substituted for fodder beet to reduce NO_3^- leaching but this reduced profitability (No Crops). This was likely because fodder beet (low-N, high-ME feed) was already part of the Baseline. However, pasture silage was a staple supplement for the case study farm. While maize is not commonly grown in Canterbury, it is a low-N feed that could be substituted for high-N pasture silage. This would make an interesting sensitivity analysis, but given the infeasibility of growing maize crops in South Canterbury and the lack of popularity of maize silage as a feed in the South Island, it was not considered a realistic mitigation strategy for this case study farm at present.

There were no scenarios where high-N feeds were used as the major component of the diet in late lactation (autumn). The Baseline already included fodder beet, as did Fallow, and barley grain was substituted for fodder beet in No Crops. This meant that the benefit of using fodder beet as opposed to a high-N feed such as pasture silage was already accounted for. Hypothetically, the observed reductions in NO_3^- leaching may have been greater if the Baseline had not included fodder beet at this time of the year. However, the purpose of this thesis was to investigate ways to reduce NO_3^- leaching from the case study farm as it operated in the 2017/2018 dairy season.

5.3.2 Feed crops on the feed pad

Fodder beet can be lifted (mechanically harvested) instead of grazed *in situ* to reduce NO_3^- leaching. When fodder beet is lifted, it is harvested using a specialised tractor bucket. The harvested fodder beet can then be fed out in paddocks or on a structure designed to capture effluent, such as a feed pad. The case study farm had a feed pad. Their standard practice was to lift and feed out a 0.125 ha headland (approximately 3,500 t DM of fodder beet) width-wise across the paddock to increase the length of the crop feeding face. This was done to maximise the length of the grazing face to ensure fodder beet was allocated to all cows as evenly as possible. In all scenarios, the feed pad was omitted from the analysis due to limitations in Overseer's feed regime and the small quantity of fodder beet that the case study farm fed on the feed pad. For modelling purposes, all fodder beet was assumed to be grazed *in situ* for this case study.

As an option to further reduce NO_3^- leaching, a preliminary investigation was made though Overseer to test whether feeding fodder beet on the feed pad could have a large influence on NO_3^- leaching for the case study farm. The treatment is referred to as "Baseline + Feed Pad". For the Baseline + Feed Pad scenario, NO_3^- leaching from the milking platform was 37 kg N/ha/yr, 1 kg less than the original Baseline, though NO_3^- leaching from the forage crop rotation block (fodder beet followed by oats) was reduced by 31% from 36 kg N/ha/yr to 25 kg N/ha/yr. Nitrate leaching from the pasture blocks on Baseline + Feed Pad was up to 5% less than the Baseline. This is because when the feed pad was used, Overseer assumed the utilisation of fodder beet was greater than when grazed *in situ* – more is eaten and less is wasted. The better fodder beet utilisation meant that less pasture was eaten to produce the same quantity of MS. This resulted in slightly less N excretion on paddocks compared to the Baseline due to the high-N content of pasture (Waghorn *et al.*, 2007). The substitution of pasture with fodder beet was assumed to be responsible for the reduction in NO_3^- leaching from the pasture blocks.

Nitrate leaching from the forage crop rotation in the Baseline + Feed Pad was less than from most of the pasture blocks (see Table 9.10, Appendix 3). Putting aside the effect of the catch crop, this was surprising given that NO_3^- leaching from crops is generally greater than from pasture (Di & Cameron, 2002). Perhaps the effect of grazing *in situ* was underrepresented in Overseer, or perhaps this could be explained by the poor drainage of the soils. The small reduction achieved at the milking platform scale suggested that the strategy of lifting fodder beet would not substantially reduce NO_3^- leaching from the case study farm.

5.3.3 Reduce stocking rate

Reducing the intensity of dairy farming by reducing stocking rate is a strategy that is known to reduce NO_3^- leaching (Ledgard *et al.*, 1999). Farmers may have to reduce the intensity of their activities by reducing their stocking rates if cheap and effective solutions to reducing NO_3^- leaching are not available. Reducing stocking rate reduces the demand for N inputs into a dairy farm system (Di & Cameron, 2002), and can directly reduce NO_3^- leaching and N_2O emissions (Glassey *et al.*, 2013; Ledgard *et al.*, 1999; van der Weerden *et al.*, 2018), though this affects profitability (Glassey *et al.*, 2013). Less N fertiliser and less imported supplements (which contain N) are necessary to support a dairy system with a lower stocking rate, which reduces the risk of NO_3^- leaching (Ledgard *et al.*, 1999; van der Weerden *et al.*, 2018).

As a side note, it would be important to include the support block in the analysis and look at the whole farm system if any decisions made on the milking platform impact on management of the support block. For example, reductions in stocking rate will also affect the support block as fewer cows need to be wintered. This reduction in wintering cow numbers would affect the operation of both the milking platform and the support block, making it more difficult to determine what changes cause a reduction in NO_3^- leaching and what changes correlate with a reduction in NO_3^- leaching.

5.4 Limitations of Overseer not yet discussed

There are more limitations to using Overseer than have been discussed so far in this thesis. Some other limitations for this case study are discussed below, including a summary of the current lack of plantain in the model – a very important component of this case study (section 5.4.4).

5.4.1 Crop inputs

For the crop treatments, the cropping regime was limited by the number of activities (one) that could be entered per month. This prevented the harvest of one crop and sowing of another crop in the same month. In addition, forage crop rotations are limited to 12 months, where the forage crop rotation must be resown in permanent pasture on or by the final month. This effectively reduces the forage crop rotation to 11 months. The forage crop rotation for the case study farm was modelled in Farmax as at least a 13 month crop rotation; fodder beet was sown in October, harvested by 31 May, followed by oats which were harvested by mid-October, after which the ex-crop paddocks were sown in permanent pasture. In Overseer, the forage crop rotation was condensed as follows: fodder beet was sown in November with the final harvest in May. The oat crop was then sown in June and harvested in September with the permanent pasture being sown in October. The inability to accurately model the crop regime could have affected the absolute leaching values, though again all scenarios were affected in a similar way so they were still able to be compared to target a 20% reduction in NO_3^- leaching from the Baseline.

5.4.2 Feed regime

Designing the feed regime for the case study farm in Farmax was important for ensuring the system was physically and financially feasible. The Baseline and treatment scenarios were tailored to maintain a balance between management simplicity and NO_3^- mitigation effectiveness.

Overseer is not designed to be a pasture or feed management tool for dairy farmers. It is used to understand nutrient processes and identify imbalances through budgeting (Wheeler *et al.*, 2006). It is not possible to model a feed regime to the level of detail achievable in Farmax as the two models are designed for different purposes. A few limitations were particularly restrictive. These were the inability to specify the correct quantity of feed consumed for multiple months for (i) fodder beet crops, (ii) feed fed on the feed pad and in the milking shed, and (iii) the inability to feed a crop + supplement-only diet (Overseer required animals to have access to pasture).

Not all strategic decisions could be implemented in Overseer. This lack of flexibility was limiting as feed affects NO_3^- leaching. This was an important limitation for this case study. However, the focus was on reducing NO_3^- leaching by a proportionate amount (target of 20% compared to the Baseline). In addition, the protocol for allocating feed in Overseer was the same between treatments. The results of this case study are therefore still valuable as the reductions they have shown in NO_3^- leaching are appropriate for these strategies when compared to the literature (see section 5.1.5).

The limitations described above meant that the milking shed and feed pad could not be represented well in Overseer so the use of the feed pad and in-shed feeding were not included in the subsequent analysis. This did not have a substantial impact on NO_3^- leaching (only 1 kg N/ha/yr difference; see section 5.3.2) so this was not considered a limitation for this study, however it is surprising that the feed pad had so little effect on NO_3^- leaching when the fodder beet crop was lifted and fed out rather than grazed *in situ*, as would be expected (Beukes *et al.*, 2017; Di & Cameron, 2002; Romera *et al.*, 2017a).

5.4.3 Pasture production

Unlike Farmax, Overseer is not a mechanistic model. Pasture production and intake are back-calculated based on animal ME requirements, and crop and supplements fed (Selbie *et al.*, 2013). Overseer far overestimated pasture production at more than 20 t DM/ha while modelling in Farmax based on a realistic growth curve for the case study farm resulted in pasture production of 14.1 t DM/ha. This would be affected by the feed regime specified, given that Overseer relies on the inputs of supplemental feed to calculate pasture production. As explained in section 5.4.2, it was not possible to match the feed regime between the two models (Appendix 2, section 8.4.1For feeding supplements). It is therefore unsurprising that pasture production between the two models differs. As explained above (section 5.4.2) for this case study the focus was on reducing NO_3^- leaching by a proportionate amount.

5.4.4 Plantain

As has been discussed extensively throughout this thesis, research on plantain and its role in controlling N cycling is a relatively new field. Most of the data available were based on recent studies made available within the last few years. Within Overseer, the role of plantain was not specifically modelled as a crop or mixed pasture at the initiation of this case study. Plant-animal and plant-soil interactions were not fully represented. However, it was possible to represent the effect of plantain on the N loading rate of urine patches (a plant-animal interaction) by adjusting the N loading rate manually in Overseer Science (the same model used for Overseer® Nutrient Budgets, but with extra functionality). This, combined with data from Minnée (in submission) and Box *et al.* (2017) made it possible to estimate the impact of plantain on NO_3^- leaching (methods, section 3.5). In Overseer it was not clear what the ultimate fate was for the N that would otherwise have been leached as NO_3^-, had the urine patch N loading rate not been changed. The alternative fate for this NO_3^- is briefly addressed in the following sub-section.

5.4.4.1 N surplus

Only NO_3^- leaching from plantain treatments B1-B4 directly applied to the Baseline are discussed here.

N surplus indicates the difference between N inputs and N outputs. It can be viewed as a measure of the N at risk of leaching or loss to the atmosphere. An N surplus of 0 would mean that 100% of N inputs are converted to N product output. Nitrogen surpluses between 40-700 kg N/ha/yr have been reported for a wide variety of dairy farm systems (de Klein *et al.*, 2017). Nitrogen surplus is calculated by aggregating N flows over time and space, regardless of the N form. The N cycle on a farm is so complex that this simplification of potential environmental impact will not necessarily indicate the risk of NO_3^- leaching (Einarsson *et al.*, 2018). Modelling NO_3^- leaching is a far more direct estimate of the impact of NO_3^- losses from land under dairy farming. However, NO_3^- leaching is very hard to model, let alone measure, so N surplus is sometimes used as a proxy. Nitrogen surplus is discussed here as it is used to highlight the value of NO_3^- leaching estimates and the importance of identifying where mitigated N ends up in a system as there is still potential for surplus N to be lost to the environment.

In this thesis, the N surpluses calculated by Overseer are reported in Table 5.2 for the Baseline. Nitrogen surplus is attractive as an index of environmental footprint because of the simplicity of its calculation, unlike NO_3^- leaching estimates which require more inputs and a model such as Overseer. However, N surplus does not consider or report on the potential fate of the surplus N and does not cover drainage, as determined by soil type, weather and irrigation in Overseer.

Table 5.2: Inputs and outputs for nitrogen (N) estimated by Overseer for the Baseline.

		kg N/ha/yr
Inputs	Fertiliser	259
	Irrigation	9
	Supplements	51
	Rain/clover fixation	108
Outputs	As product	113
	Supplements and crop residue	5
N surplus	Inputs - Outputs	309

Note that the 'supplements and crop residue' output should be 0 kg N/ha/yr and the 'supplement' input should be 46 kg N/ha/yr. In the Baseline, the oat catch crop was exported and replaced with imported triticale silage to gain flexibility in supplemental feeding in Overseer (section 8.5, Appendix 2). Assuming these two feeds have the same N content in Overseer, the 5 kg N/ha recorded as the 'supplement and crop residue' output should be automatically offset by 5 of the 51 kg N/ha in the 'supplement' input.

The N surplus calculated by Overseer included supplements, irrigation, fertiliser, rain and biological N fixation as inputs and plant and animal product exports as outputs (Table 5.2). Nitrogen surplus was reported to correlate with NO_3^- leaching on this case study farm (identified as Farm E) in a study by Pinxterhuis and Edwards (2018). However, this relationship did not hold in the current study, even when NO_3^- leaching was decreased by 21% (B4), because calculations for N surplus do not consider the fate of the surplus, therefore N surplus is not necessarily an appropriate indicator of leaching risk (de Klein *et al.*, 2017). In this case study, Overseer estimations indicated that including plantain in the diet may reduce NO_3^- leaching (but N surplus would have remained constant as this treatment did not affect N inputs or outputs as plant and animal exports). These results highlight some limitations of N surplus as a measure of environmental impact and even for use as a regulatory tool.

In this case study, plantain reduced N loading rates of dairy cow urine patches. Some of the major assumptions surrounding the inclusion of plantain in PR/WC + PL pastures were that pasture total N content, ME content and grazing management would not affect MS production and therefore N outputs in milk (methods, section 3.4.3). These assumptions paired with the brief discussion on N surplus above raised a question in another area: what happened to the N that would have leached had the plantain treatments not been applied? Between these treatments, no inputs or product outputs were changed. The surplus N was likely to have been taken up by pasture or denitrified (M. Shepherd, personal communication, 31 July, 2019), but this was not clear from the results. This is an important question to answer. While NO_3^- leaching may be reduced by including plantain in the system, in the scenarios modelled, this was not reflected in N surplus estimates. In addition, plantain and ryegrass have similar total N contents so cows grazing PR/WC + PL pastures consume the same quantity of N as cows grazing PR/WC pastures (Martin, 2018; Minnée *et al.*, in press). The N not leached due to the presence of plantain must then either be (i) retained within the system (most likely in the soil, though this capacity is limited (Schipper *et al.*, 2004)) or (ii) it is lost through other mechanisms, for example as ammonia, N_2 or greenhouse gases.

6 Conclusions and future work

The hypothesis of this study was that the use of fodder beet and oats in the existing dairy farm system with the addition of plantain in perennial ryegrass/white clover + plantain (PR/WC + PL) pastures could achieve a 20% reduction in nitrate (NO_3^-) leaching whilst profitability was maintained. The modelling approach used here showed that it was possible to reduce NO_3^- leaching from a Canterbury dairy farm using these three forages in a modelling context. However, profitability was not maintained but reduced by 5-10% due to increased costs.

Based on the results of this case study, it was concluded that:

1. Plantain was the most important forage for reducing NO_3^- leaching when applied across the milking platform.
2. An oat catch crop was necessary to reduce NO_3^- leaching after autumn-grazed fodder beet.
3. Fodder beet crops increased profit, but increased NO_3^- leaching when followed by a fallow period.
4. Fodder beet followed by an oat catch crop increased profit but had minimal effect on NO_3^- leaching with current Overseer defaults for fodder beet N content and catch crop N uptake pattern. The lack of impact on NO_3^- leaching was because the crop area was very small – only 4% of the milking platform area.
5. Maintenance of plantain populations in the pasture sward every second year (40% of farm area maintained and 10% renewed each year) in mixed perennial ryegrass/white clover + plantain (PR/WC + PL) pastures was essential to achieve a 20% reduction in NO_3^- leaching.
6. Greater frequency of plantain maintenance reduced NO_3^- leaching, but this reduced profitability when compared to the Baseline.

Overall, most of the reduction in NO_3^- leaching was attributed to the presence of plantain in PR/WC + PL pastures. The use of plantain as a mitigation tool is a relatively new and the persistence of plantain in PR/WC + PL remains a major research gap. Analysis of the plantain treatments showed that intensive management was necessary to maintain populations high enough to promote a substantial reduction in NO_3^- leaching.

6.1 Future work and further considerations

This thesis focused on one dairy farm business in Canterbury, using a case study approach. While modelling results produced useful research for this farm and might be generalised for farms with very different soil types (though this analysis was very simplistic) and climate in the wider South Canterbury region, its value in terms of providing directly adoptable solutions to reduce NO_3^- loss from other dairy farms needs to be carefully considered. This thesis provides additional information on how the FRNL solutions investigated can be integrated into an existing farm system to reduce NO_3^- leaching and their potential impact on profitability. Catchment scale work where different farm types/activities are integrated beyond the farm level could be one of the next steps (Martin *et al.*, 2016) to achieve reductions in NO_3^- leaching at scales larger than a single dairy farm. In section 2.7 of the literature review, it was reported that in the 2017/2018 dairy season, 51% of dairy farms in Canterbury were classed as System 4 – the same system as this case study farm (21-30% of total feed is imported with the primary purpose of extending lactation). A further step for this current research could be to determine the suitability of the management strategies used in this case study for other farm systems of similar intensity.

Based on the results of this case study, a new critical research question is proposed: how can we maintain a large enough population of plantain in PR/WC + PL pastures to achieve substantial reductions in NO_3^- leaching? If advances in breeding to enhance persistence cannot address this issue, then further development of management practices including under or oversowing new seed is the next logical step for this line of research to achieve cost-effective NO_3^- leaching mitigation.

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7 Appendix 1: Baseline set up and verification (FARMAX Dairy)

The following details are for the Baseline which is based off the 2017/2018 season observed by the case study farm. Crop treatment Fallow was created by duplicating and editing the Baseline (section 7.14.1). No Crops was created by the same process, but using Fallow (section 7.14.2).

Inputs used for setting up the Baseline and treatment files in FARMAX Dairy Generation 7 Version 7.1.2.41 (Farmax) are described in the steps below. There is some duplication in the descriptions below as two individual farm files had to be created to represent the physically separate support block and milking platform. The two files are later linked by the transfer of young and dry stock.

Milking platform properties

1. 312.8 ha
2. Start June 2017
3. Convert to Long Term

7.1 Expenses database

Marlborough-Canterbury 2017-2018 DairyBase financial data was used to input average expected expenses for the farm system described. Expenses for the milking platform are detailed in Table 7.1 below.

Assumptions:

1. Milk price: Simple, year 2017, \$6.50/kg MS. No premiums or added value.
2. Cost of Urea (nitrogen) fertiliser is \$500/t Urea. This is based off the 10 June 2017 and 13 February 2018 Ravensdown price lists (Ravensdown, 2017, 2018).
3. The support block is owned by the case study farm. A support block adjustment was included to allow financial comparison with other

Canterbury farms that lease or rent land for a support block (Edwards *et al.*, 2017). An $800/ha support block adjustment was used to reflect the cost of leasing land, based on the 2017/2018 DairyBase calculation (DairyBase DairyNZ, 2019a) (M. Newman, personal communication, 13 August, 2019).

4. The milking platform and support block together represent one farm system. For simplicity, most expenses were entered in the milking platform database. Only relevant support block expenses, such as crops and the support block adjustment were included for the support block.

Table 7.1: Expenses database for the Baseline milking platform. 2017/2018 average Marlborough-Canterbury region data was used. **Bolded** numbers indicate the cost that was used for each expense category. MS = milksolids; N = nitrogen; R&M = repairs and maintenance. Some expenses are not reported e.g. management wage and cash crop because they do not apply and/or they were incorporated into another category.

Category	**Expense**	**$ Total**	**$/ha**	**$/cow**	**$/kg MS to factory**
			312.8 ha	*1,124 cows*	*507,687 kg*
Wages	Wages	393,400	1,258	**350**	0.775
		393,400	*1,258*	*350*	*0.775*
Stock	Animal health	94,416	302	**84**	0.186
	Breeding	65,192	208	**58**	0.128
	Farm dairy	26,976	86	**24**	0.053
	Electricity	44,960	144	**40**	0.089
		231,544	*740*	*206*	*0.456*
Feed	Pasture conserved	**26,600**	85	24	0.052
	Feed crop	**39,186**	125	35	0.077
	Bought feed	**247,188**	790	220	0.487
	Calf feed	**7,960**	25	7	0.016
		320,934	*1,026*	*286*	*0.632*
Other farm working expenses	Fertiliser (excl. N)	115,110	**368**	102	0.227
	Nitrogen fertiliser	**95,178**	304	85	0.187
	Irrigation	96,342	**308**	86	0.190
	Regrassing	31,593	**101**	28	0.062
	Weed & pest	10,322	**33**	9	0.020
	Vehicles	50,769	162	45	**0.100**
	Fuel	30,461	97	27	**0.060**
	R&M land & buildings	140,760	**450**	125	0.277
	Freight	20,307	65	18	**0.040**
		590,843	*1,889*	*526*	*1.164*
Overheads	Administration	50,674	**162**	45	0.100
	Insurance	29,090	**93**	26	0.057
	ACC	8,992	29	**8**	0.018
	Rates	25,024	**80**	22	0.049
		113,780	*364*	*101*	*0.224*
	Depreciation	248,767	795	221	**0.490**
Total Operating Expenses		**1,899,267**	**6,072**	**1,690**	**3.741**

7.2 Physical input databases

This includes crops and feeds, calving spreads and pasture utilisation.

7.2.1 Crops and feeds

Table 7.2: Details for crops and feeds used on milking platform. MP = milking platform *i.e.* pasture silage harvested from the milking platform. Note that there is no cost for regrassing as a 'crop' because this is captured in the expenses database as $/effective ha

	Energy MJ ME/kg DM	**Utilisation %**	**Digestibility %**	**NDF %**	**Yield t DM/ha**	**Available _days from_**	**Cost $t/ DM**	**Cost $/ha**
Pasture silage (MP)	10	75	69	45	2	0 finish	140	
Pasture silage bought								
Fodder beet	13	90	73	16	25	160 start		2,600
Kale	11.5	80	76	28	14	0 start		1,200
Oat silage	11	75	76	55	10	150 start		510
Plantain maintenance	0	0	0	0	0	0 start		350
Regrassing	0	0	0	0	0	0	0	0
Barley grain	13	95	83	19			410	
Pasture silage (SB)	10	75	69	45			180	
Protein pellets	12	95	64	60			500	
Wheat	12.6	95	90	13			500	

Assumptions:

1. Residual cover after pasture silage is harvested is 1500 kg DM/ha.
2. All other crops return to rotation at farm average pasture cover (APC).

7.2.2 Calving spread

The mating/calving spreads for the R2s and mixed-age cows were bulked as this is how the case study farm 'DairyBase Physical Summary' reported the calving spread.

1. Created "Calving spread 1". Farmax assumes 0% empty rates in the current season because it is assumed that no empty cows/heifers were carried over. Submission rates are manipulated to adjust the empty rates. See section 7.9.6.

Table 7.3: Calving spread.

	Calving spread 1 (2017)	
Weeks from start	**% calved**	**Cumulative %**
1	20	20
2	25	45
3	22	67
4	8	75
5	7	82
6	6	88
7	5	93
8	2	95
9	2	97
10	3	100

7.2.3 Pasture utilisation pattern

Table 7.4: Pasture utilisation pattern.

Month	Utilisation %
Jan	90
Feb	90
Mar	90
Apr	90
May	85
Jun	80
Jul	80
Aug	85
Sept	90
Oct	90
Nov	90
Dec	90

7.3 Land use on the milking platform

Two blocks were created to represent the non-effluent (185 ha) and effluent (127.8 ha) blocks. “Irrigated” pasture type was selected.

7.3.1 Pasture growth rates

The growth rates in Table 7.5 below are exclusive of N fertiliser response rate. They do not equal the net growth rates are as Farmax takes N responses into account in a later step (section 7.4).

Note that when pasture has been calibrated, pasture silage yield/ha is adjusted automatically to accommodate the user-defined area harvested.

Table 7.5: Calibrated block pasture growth rates (kg DM/ha/day) excluding nitrogen fertiliser response. See section 7.4 for further detail.

Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual kg DM/ha
10.2	8.0	29.1	36.8	59.5	53.1	50.1	66.4	56.1	51.4	32.2	10.9	14,073

Assumptions:

1. Growth rates (excluding N fertiliser response rate) are the same for the non-effluent and effluent blocks.

7.3.2 Non-effluent block crops

Table 7.6: Crops grown on non-effluent block.

Name	Area ha	Out of rotation From	To	Days	Followed by	Yield t DM/ha	Total t DM
Pasture Silage (MP)	55	12-Sept-17	12-Oct-17	31		2	110
Regrassing	8.8	1-Oct-17	11-Nov-17	42	New pasture	0	0
Regrassing 2	9.9	1-Dec-17	11-Jan-18	42	New pasture	0	0
Pasture Silage 2	40	10-Dec-17	9-Jan-18	35		2	80

The following formula was used to calculate the number of days out of rotation for pasture silage:

$$Number\ of\ days = \frac{Pasture\ harvested\ (2000\ t\ DM/ha)}{Monthly\ pasture\ growth\ rate\ (kg\ DM/ha/day)}$$

This formula assumes that paddocks are shut for pasture conservation and harvested when the cover reaches 3500 kg DM/ha, returning to the farm rotation at 1500 kg DM/ha post-harvest. The 'shut' period only accounts for silage DM production, not regrowth to pre-grazing levels after harvest.

7.3.3 Effluent block crops

Table 7.7: Crops grown on effluent block.

Name	Area ha	Out of rotation From	To	Days	Followed by	Yield t DM/ha	Total t DM
Oats (silage MP)	12.6	2-Jun-17	20-Oct-17	141	Regrassing	10	126
Fodder Beet	12.6	1-Oct-17	31-May-18	243	Oats	25	315
Regrassing OA	12.6	21-Oct-17	1-Dec-17	42	New pasture	0	0

7.3.4 Nitrogen fertiliser applications

The non-effluent block fertiliser rates differ from to those in the OVERSEER® files because Farmax only accounts for the area under pasture. Crop area is excluded. To overcome this and maintain the same annual N fertiliser rate (279 kg N/ha/year), the N fertiliser rate was increased on the pasture area in Farmax. The effluent block had no crops so there was no need to adjust the fertiliser rates.

Table 7.8: Non-effluent block nitrogen fertiliser application to pasture.

Name	**Date**	**Rate** **kg N/ha**	**Response** **kg DM/kg N**	**Length of response** **days**	**Area** **ha**
Nitrogen	01 Aug 17	8	5	30	185
Nitrogen 2	01 Sep 17	19	10	30	185
Nitrogen 3	01 Oct 17	37	10	30	176
Nitrogen 4	31 Oct 17	52	15	30	176
Nitrogen 5	01 Dec 17	33	15	30	175
Nitrogen 6	31 Dec 17	31	15	30	175
Nitrogen 7	30 Jan 18	30	12	30	185
Nitrogen 8	01 Mar 18	33	12	30	185
Nitrogen 9	01 Apr 18	38	12	30	185
Nitrogen 10	01 May 18	9	10	30	185
Total (whole block)		282			185

Table 7.9: Effluent block nitrogen fertiliser application to pasture.

Name	**Date**	**Rate** **kg N/ha**	**Response** **kg DM/kg N**	**Length of response** **days**	**Area** **ha**
Nitrogen	01 Aug 17	8	5	30	115
Nitrogen 2	01 Sep 17	20	10	30	115
Nitrogen 3	01 Oct 17	46	15	30	103
Nitrogen 4	01 Nov 17	51	15	30	103
Nitrogen 5	01 Dec 17	30	15	30	115
Nitrogen 6	31 Dec 17	35	12	30	115
Nitrogen 7	30 Jan 18	36	12	30	115
Nitrogen 8	01 Mar 18	26	12	30	115
Nitrogen 9	01 Apr 18	46	12	30	115
Nitrogen 10	01 May 18	14	10	30	115
Nitrogen 11	01 Oct 17	29	10	30	13
Total (whole block)		275			128

7.4 Calibrating pasture

While pasture calibration is the final step in setting up file, this section was purposely inserted here for reading continuity. Pasture growth rates were calibrated after stock numbers, liveweight gains, supplementary feeding, block growth rates, milk production and body condition score profiles were finalised. This step was done by adjusting the APC which subsequently adjusted the pasture growth rates at the farm level (Table 7.10).

Table 7.10: Target average pasture covers (APC). Targets are based off actual APC observed in 2017/2018.

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
APC	2,200	2,300	2,400	2,200	2,200	2,200	2,000	2,200	2,200	2,100	2,400	2,000

Table 7.11 reports the farm pasture growth rates (for the whole milking platform, not blocks). These growth rates include the DM response from N fertiliser therefore are greater than the growth rates specified at the block level.

Table 7.11: Net farm pasture growth rates (kg DM/ha/day) after calibration. Includes nitrogen fertiliser response.

Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual kg DM/ha
6.6	5.3	25.9	38.6	72.2	64.0	62.7	76.2	62.9	58.3	43.7	8.9	15,949

Support block properties

The following does not represent the case study farm's actual support block. Instead, a self-sufficient support block was created to eliminate the influence of other enterprises, the additional land required and the contract grazing of young stock. Therefore, this does not fully represent the case study farm system. However, the advantage of the customised support block is simplification. All financial, physical and environmental results relate only to the dairy farm.

1. 180 ha
2. Start June 2017
3. Convert to Long Term

7.5 Expenses database

Marlborough-Canterbury 2017-2018 DairyBase financial data was used to input average expected expenses. Expenses for the support block are detailed in Table 7.12 below. Most expenses for this farm system were entered in the milking platform database. These can be found in section 7.1.

Assumptions:

1. Cost of Urea (nitrogen) fertiliser is $500/t Urea. This is based off the 10 June 2017 and 13 February 2018 Ravensdown price lists (Ravensdown, 2017, 2018).
2. The support block is assumed to be owned in all scenarios, which is not uncommon in Canterbury (Edwards *et al.*, 2017). In 2017-2018, DairyBase was using an $800/ha rental rate for the support block adjustment (DairyBase DairyNZ, 2019a) (M. Newman, personal communication, 13 August, 2019). This is an 'additional' expense included in cases where the support block is owned, not leased. The adjustment is used to allow farms with different support block ownership to be compared.
3. The milking platform and support block together represent one farm system. For simplicity, most expenses were entered in the milking platform database. Only relevant support block expenses were included for the support block.

Table 7.12: Expenses database for the Baseline support block. 2017/2018 average Marlborough-Canterbury region data was used. **Bolded** numbers indicate the cost that was used for each expense category. N = nitrogen; R&M = repairs and maintenance.

Category	**Expense**	**$ Total**	**$ / ha (180)**
Feed	Pasture conserved	**47,600**	264
	Feed crop	**82,170**	457
		129,770	*721*
Grazing	Owned run-off adjustment	144,000	800
		144,000	*800*
Other farm working expenses	Fertiliser (excl. N)	16,560	**92**
	Nitrogen	**7,338**	41
	Regrassing	18,180	**101**
	Weed & pest	5,940	**33**
	R&M land & buildings	29,160	162
		77,178	*429*
Overheads	Administration	2,880	**16**
	Insurance	4,140	**23**
	Rates	7,200	**40**
		14,220	*79*
Total operating expenses		**365,168**	**2,029**

7.6 Physical input databases

7.6.1 Crops and feeds

Table 7.13: Details for crops and feeds used on support block (SB).

	Energy MJ ME/kg DM	Utilisation %	Digestibility %	NDF %	Yield t DM/ha	Available _days from_	Cost $
Pasture silage (SB)	10	75	69	45	2	0 finish	140/t DM
Fodder beet	12.5	90	73	16	22	160 start	2,600/ha
Kale	11.5	80	76	28	14	0 start	1,200/ha
Oats (silage SB)	11	75	76	55	10	150 start	510/ha
Regrassing	0	0	0	0	0	0	0

Assumptions:

1. Residual cover after pasture silage is harvested is 1500 kg DM/ha.
2. All other crops return to rotation at farm average pasture cover (APC).

7.6.2 Pasture utilisation pattern

Same as milking platform. See section7.2.3.

7.7 Land use on the support block

One block was created as pasture management was assumed to be the same across the 180 ha support block. “Irrigated” pasture type was selected.

7.7.1 Pasture growth rates

The growth rates in Table 7.14 are exclusive of N fertiliser response rate. Lower entries for growth rates are expected as Farmax takes N responses into account in a later step (pasture potential see section 7.8).

Note that when pasture has been calibrated, pasture silage yield/ha is adjusted automatically to accommodate the user-defined area harvested.

Table 7.14: Calibrated pasture growth rates (kg DM/ha/day) excluding nitrogen fertiliser response. See section 7.8 for further detail.

Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual kg DM/ha
8.9	5.7	13.4	44.0	72.6	45.2	30.1	20.8	17.6	21.4	29.1	20.0	10,011

7.7.2 Crops

Table 7.15: Crops grown on support block (SB). The Farmax dairy season begins on 1 June. As fodder beet and kale crops are sown on 1 October and grown until they are grazed in the following winter there are more than two entries for these crops. The 'early' and 'late' entries for fodder beet and kale crops indicate areas that were grazed first and therefore could be sown in oats sooner. FB = fodder beet.

Name	Area	Out of rotation			Followed by	Yield	Total
	ha	From	To	Days		t DM/ha	t DM
Kale	18	1-Oct-17	31-May-18	243			
Kale (early)	9	1-Jun-17	14-Jul-17	44	Oats	14	126
Kale (late)	9	1-Jun-17	28-Aug-17	89	Fallow	14	126
Fodder Beet	18	1-Oct-17	31-May-18	243			
Fodder Beet (early)	9	1-Jun-17	14-Jul-17	44	New pasture	22	198
Fodder Beet (late)	9	1-Jun-17	28-Aug-17	89	New pasture	22	198
Oats (silage KA early)	9	15-Jul-17	30-Sep-17	78	Fodder beet	7	63
Oats (silage FB early)	9	15-Jul-17	20-Nov-17	129	New pasture	10	90
Pasture Silage (SB) 2	90	22-Aug-17	30-Sep-17	40			180
Fallow (KA late)	9	29-Aug-17	30-Sep-17	33	Fodder beet		
Oats (silage FB late)	9	29-Aug-17	6-Dec-17	100	New pasture		90
Pasture Silage (SB)	80	1-Oct-17	31-Oct-17	31			160
Regrassing (FB early)	9	21-Nov-17	1-Jan-18	42	New pasture		
Regrassing (FB late)	9	7-Dec-17	17-Jan-18	42	New pasture		

7.7.3 Nitrogen fertiliser applications

Table 7.16: Support block nitrogen fertiliser application to pasture.

Name	Date	Rate	Response	Length of response	Area
		kg N/ha	kg DM/kg N	days	ha
Nitrogen	1-Aug-17	19	10	30	144
Nitrogen 2	1-Nov-17	10	10	30	126
Nitrogen 3	1-Mar-18	19	10	30	144
Total (whole block)		37			

7.8 Calibrating pasture

As for the milking platform in section 7.4, while pasture calibration is the final step in setting up file, this section was purposely inserted here. Pasture growth rates were calibrated after stock numbers, liveweight gains, supplementary feeding, block growth rates, milk production and body condition score profiles were finalised. This step was done by adjusting the APC which subsequently adjusted the pasture growth rates at the farm level (Table 7.19).

Table 7.17: Target average pasture covers (APC) for support block. Targets are based off actual APC observed in 2017/2018.

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
APC	2,300	2,200	2,200	2,400	2,500	2,500	2,400	2,300	2,000	2,000	2,200	2,300

Table 7.18 reports the farm pasture growth rates (for the whole milking platform, not blocks). These growth rates include the DM response from N fertiliser therefore are greater than the growth rates specified at the block level.

Table 7.18: Net farm pasture growth rates (kg DM/ha/day) after calibration. Includes nitrogen fertiliser response.

Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual kg DM/ha
4.2	3.2	21.0	40.3	66.6	39.5	25.4	18.5	14.1	25.5	25.8	15.3	9,139

7.9 Animal numbers, mating and calving

The milking platform and support block were set up as two separate farm files. They are linked in this step by the transfer of dry cows and young stock as part of the wintering and grazing programme. The dairy season begins 1 June and ends 31 May in the following year. On 1 June, the cows are dry so begin on the support block. Note that bobby and heifer calf mobs were automatically generated by Farmax when the calving/mating pattern was specified. Bobby calves do not feature below as they were automatically managed by Farmax.

7.9.1 Fat cow mob

Opened with 620 mixed age, Friesian X(F12J4), 570 kg, 5.0 BCS (body condition score), 100% pregnant, 0% lactating, 84 BW (breeding worth) mixed-age cows.

7.9.2 Thin cow mob

Opened with 615 mixed age, Friesian X(F12J4), 520 kg, 4.5 BCS, 100% pregnant, 0% lactating, 84 BW mixed-age cows.

7.9.3 18-month bull mob

On 1 October, purchased 16 Friesian X(F12J4), 142 BW bulls born April 2017. Sold all to works 16 January. As these bulls are run with the R2s (rising 2-year-olds), they had the same diet. The recommended ratio of 15-20 bulls to 100 heifers was achieved (DairyNZ, n.d.-f).

7.9.4 Bull mob

On 1 December, purchased eight Friesian X(F12J4) 142 BW bulls born September 2016. Sold all to works 16 January. These bulls run with the milking mob after six weeks of artificial breeding (AB) to mate with the remaining cows. They had the same diet as the milkers excluding in-shed feed.

7.9.5 Heifer replacements

The first 340 Friesian X(F12J4), 113 BW heifer calves born in 2017 were kept for replacements as the farm had a 31% replacement rate. They were transferred to the support block on 1 December. These then aged into the R2 mob. At 1 June there were 319 Friesian X(F12J4), 228 kg, 113 BW heifers in the 1-year Heifer mob.

7.9.6 Mating and calving

Dry cows from the fat and thin mobs were transferred to the milking platform prior to calving. There was no separation of cows based on condition score. All formed one milking mob.

The planned start of mating (PSM) for all cows and R2s was 28 October. Cows were mated by AB for six weeks before being run with the bull mob (natural mating) for three weeks. The R2s were mated naturally. The planned start of calving (PSC) was 3 August. It was assumed that the PSM, PSC and calving spreads would remain the same year-to-year.

Farmax assumes there are no carry-overs of empty (non-pregnant) cows from the previous season which explains the 0% empty rate for the original calving spread (Table 7.3). An empty rate of 10% was assumed for the modelled farm.

Table 7.19: Mating submission rates for 2016 and calving spread for 2017. Assumes 100% of cows are pregnant (0% empty/non-pregnant rate).

Weeks from start	Submission %	% calved	Cumulative % calved
1	33	20	20
2	42	25	45
3	37	22	67
4	13	8	75
5	12	7	82
6	10	6	88
7	8	5	93
8	3	2	95
9	3	2	97
10	5	3	100

Table 7.20: Mating submission rates for 2017 and calving spread for 2018. Assumes 90% of cows are pregnant (10% empty).

Weeks from start	Submission %	% calved	Cumulative % calved
1	33	20	20
2	42	25	45
3	37	22	67
4	10	6	73
5	8	5	78
6	8	5	83
7	5	3	86
8	5	3	89
9	2	1	90
10			90

7.10 Animal movements

The following tables (Table 7.21-Table 7.25) describe sales, deaths, transfers and drying-off dates in chronological order for each mob. In Farmax, these are "Events".

Table 7.21: Chronological events for fat cows on support block.

Date	Event	From	Group	Quantity	Number	Destination
4 Jun	Died	All	Random	#	1	
30 Jun	Sold	"	"	"	2	Works
6 Jul	Sold	All	"	"	35	Works
24 Jul	Transfer out	In calf	Early Calving	"	230	Cows milking platform
5 Aug	Transfer out	"	"	"	120	Cows milking platform
19 Aug	Transfer out	"	"	"	100	Cows milking platform
31 Aug	Transfer out	All	Random	All	All (132)	Cows milking platform

Table 7.22: Chronological events for thin cows on support block.

Date	Event	From	Group	Quantity	Number	Destination
19 Jul	Died	“	“	“	3	
6 Jul	Sold	“	“	“	35	Works
24 Jul	Transfer out	In calf	Early Calving	“	230	Cows milking platform
5 Aug	Transfer out	“	“	“	120	Cows milking platform
19 Aug	Transfer out	“	“	“	100	Cows milking platform
31 Aug	Transfer out	All	Random	All	All (127)	Cows milking platform

Table 7.23: Chronological events for milking cows on milking platform.

Date	Event	From	Group	Quantity	Number	Destination
16 Aug	Died	All	Random	#	6	
16 Sept	Died	“	“	“	3	
30 Sept	Sold	Empties	“	“	8	Works
16 Oct	Died	All	“	“	1	
18 Oct	Sold	Empties	“	“	15	Works
15 Nov	Died	All	“	“	2	
16 Dec	Died	”	“	“	2	
16 Dec	Sold	Empties	“	“	5	Works
19 Dec	Sold	All	Worst CS	“	1	Store
16 Jan	Died	“	Random	“	1	
16 Jan	Sold	“	“	“	1	Store
15 Feb	Died	“	“	“	3	
16 Mar	Sold	Empties	“	“	12	Works
11 Apr	Sold	“	“	“	All (96)	Works
10 May	Dry off	In calf	Early Calvers	“	200	
15 May	Sell	Milkers	Worst CS	“	60	Works
20 May	Dry off	“	“	“	200	
25 May	Dry off	“	“	“	200	
26 May	Dry off	“	“	All	All (243)	
27 May	Transfer out	Dries	Worst CS	#	323	Thin cows support block
31 May	Transfer out	All	Random	All	All (620)	Fat cows support block

Table 7.24: Chronological events for heifer calves born on the milking platform and transferred to the support block.

Date	Event	From	Group	Quantity	Number	Destination
Milking platform						
1 Sept	Sold	All	Heaviest	#	1	Store
4 Oct	Sold	“	“	“	1	Store
1 Dec	Transfer out	“	“	All	All (338)	Heifers support block
Support Block						
10 Jan	Died	All	Random	#	5	
16 Jan	Sold	“	Heaviest	“	1	Store
23 Feb	Died	“	Random	“	1	
16 Mar	Sold	“	Heaviest	“	1	Store

Table 7.25: Chronological events for R2s, aged from heifer calves on support block.

Date	Event	From	Group	Quantity	Number	Destination
2 Jun	Died	All	Random	#	1	
5 Sept	Died	"	"	"	1	
21Feb	Died	"	"	"	1	
16 Mar	Sold	Empties	"	All	All (33)	Works
31 May	Transfer out	All	Heaviest	All	All (291)	Thin cows support block

7.11 Performance targets

The following performance targets were used in setting up the Baseline. These targets were also used when setting up Crop Treatments 1 and 2.

7.11.1 Milk production

In Farmax, milksolids (MS) production is driven by metabolisable energy (ME). Differences in actual and estimated MS production are to be expected as there are variations in day-to-day management and environmental conditions that cannot be captured in the model. Variations between actual and modelled MS production were ±3%.

It is important to note that the actual data concerning milk production do not include harvested milk that was diverted from the factory supply to calves or withheld from sale because of penicillin.

Table 7.26: Milksolids (fat + protein; MS) production of the case study farm for the 2017/2018 season and the targets for the model estimates. Actual MS fed to calves on the case study farm is unknown, but were estimated by Farmax.

Month	Actual kg MS to factory	Model kg MS to factory	Model estimated kg MS to calves	Model total kg MS produced
August	21,742	22,100		22,100
September	55,149	56,100	1,300	57,400
October	70,244	70,300	4,400	74,700
November	64,768	64,900	4,800	69,700
December	60,077	60,900		60,900
January	56,023	56,400		56,300
February	48,104	48,400		48,400
March	54,663	54,100		54,100
April	47,845	47,600		47,600
May	27,945	27,000		27,000
Total	506,558	507,800	10,500	518,200

7.11.2 DairyBase Physical Detail summaries

Actual farm data were used to calibrate the Baseline to what happened in the 2017/2018 season.

Table 7.27: Actual physical outputs for the case study farm milking platform in the 2017/2018 season and outputs estimated by Farmax for the Baseline.

Variable	Units	Actual	Model
Peak cows milked		1,142	1,142
Stocking rate		3.7	3.7
Cow liveweight 1 December	kg/cow	509	503
Liveweight (kg/ha)	kg/ha	1,858	1,810
Nitrogen applied for the year	kg N/ha	280	279
Milksolids (MS) production	Total kg MS	506,558	507,687
	kg MS/ha	1,619	1,623
	kg MS/cow	444	445
	% of liveweight	87	90
Peak MS	kg/day/cow	2.04	2.13
Days in milk[2]	Days/cow	267	259
Planned start of calving[3]		6-Aug	3-Aug
Proportion calved by week 3	%	71	67
Proportion calved by week 6	%	88	88
Proportion calved by week 9	%	97	97
Empty rate	%	11	10
Replacement rate[4]	%	31	24

[2] This difference is assumed to be the due to the difference in calving spreads, particularly the % calved by week 3, between the DairyBase report for the case study farm and calving spread modelled in Farmax. Recall that the modelled farm system was simplified (section 3.2.1, methods chapter).

[3] The farm planned start of mating was 28 October in 2017/2018 (and in previous seasons too). Farmax automatically calculates the planned start of calving based on this date.

[4] Different because a long-term average has been assumed.

7.12 Feed on farm

Table 7.28: Feed produced and imported on the milking platform and support block (SB) for the case study farm 2017/2018, the Baseline and Crop Treatments 1 and 2. Fodder beet and oats were grown on the milking platform of the Baseline. Fodder beet only was grown on the milking platform of Fallow and no crops were grown on the milking platform of No Crops.

Feed available	Location fed	t DM Actual 2017-2018	Baseline	Fallow	No Crops
Milking platform					
Pasture	*In situ*	~4710	4,448	4,452	4,538
Pasture silage harvested	Feed pad	166	190	190	230
Pasture silage bought	Feed pad	138	101	240	160
Feed exported		0.3	-	-	-
Oat silage	Feed pad on MP, paddock on SB	126	126	-	-
Fodder beet	Feed pad on MP	315	315	315	-
PKE bought	Feed pad on MP, paddock on SB	120	-	-	-
Hay bought	Feed pad	19	-	-	-
RC silage bought	Feed pad	57	-	-	-
Wheat bought	Milking shed	383	373	373	373
Protein pellets bought	Milking shed	57	57	57	57
Colostrum/milk	To calves	Not recorded	188	188	188
Calf meal	To calves	Not recorded	11.4	11.4	11.4
Barley grain bought	Milking shed	-	-	-	253
Support block					
Pasture	*In situ*	N/A	858	858	858
Pasture silage	Crop paddock		255	255	255
Kale	*In situ*		202	202	202
Fodder beet	*In situ*		356	356	356
Oat silage			182	182	182

Assumptions:

1. Silage produced in the previous season is used in the current season (to allow for fermentation and to ensure enough silage is available for use when needed. Silage produced in the current season is carried over to the next season. The same amount of silage is produced in each season.
2. As daily feed offered is averaged over each month, time-steps were not small enough to detail transition periods. Good transition management requires animals to be gradually introduced to crops to avoid health issues such as acidosis (Dalley *et al.*, 2017). This was represented in the Baseline and Crop Treatments 1 and 2 by increasing crop intakes by month. Transitioning off crops is also necessary although it can occur

faster than transitioning on. Transitioning off was not represented in the files for simplicity and because it did not affect any model outputs.

3. On the milking platform, supplements excluding protein pellets are fed on the feed pad. Fodder beet crops are grazed *in situ*.
4. On the support block, supplements are fed out onto crop and pasture.
5. It was assumed that minerals such as magnesium and calcium were fed in the milking shed to milkers and dusted, incorporated in supplemental feed and/or added to trough water for dry cows as needed. It is expected that cows are supplemented with calcium and magnesium from late gestation through early lactation. However, as Farmax does not model mineral intake/animal health, mineral and trace element supplementation were included under animal health costs.

7.13 Notes

7.13.1 Support block crop policy

Cropping area on the support block was limited to 20%. The cropping policy involved two years of back-to-back cropping. While this is practice is detrimental to soil health (Houlbrooke *et al.*, 2009) it was necessary to achieve sufficient total DM production to keep the block self-sufficient and reflects current Canterbury wintering practices (D. Dalley, personal communication, 11 June, 2019). The rotation policy involved one season of kale with an oat catch crop followed by fodder beet in the second season with an oat catch crop before being regrassed in late spring/early summer. The timing was staggered so that in each season, 10% of the block was cropped with kale and 10% was cropped with fodder beet. This order was chosen because cropping and grazing fodder beet are more intensive than for kale due to yield and crop requirements. A total of 20% of the block was cropped each season. As new pasture only followed fodder beet, the pasture renewal rate was 10% of the block.

7.14 Creating crop treatments 1 and 2

The following comments are for both the support block and the milking platform. Note that feed quantities are not detailed below as they are previously listed in Table 7.28.

Crop Treatments 1 and 2 (Fallow and No Crops) were duplicates of the previous system *i.e.* the Baseline for Fallow and Fallow for No Crops. For each system, average daily ME and DM intake were matched where possible to maintain milksolids production between the systems. Feed substitution between the Baseline and crop treatments was based on isoenergetic principles to ensure that all systems would be similar enough for direct comparison.

Pasture was rationed to maintain a similar monthly APC between the Baseline and Fallow and No Crops.

A standard time of 42 days was used for regrassing periods (DairyNZ, n.d.-c). New pastures entered the farm rotation at farm APC.

7.14.1 Crop treatment 1: Fallow (fodder beet, no oats)

No changes were made to the support block.

On the milking platform, the oat crop was replaced with a fallow period. Oat silage was substituted with purchased pasture silage fed on the feed pad. Regrassing began 1 October. Because of the change in pasture area, the November N fertiliser application was adjusted to maintain the same farm annual N fertiliser rate of 279 kg N/ha (see Table 7.29). The total area regrassed remained the same as that of the Baseline, but the 12.6 ha of regrassing following the oat crop was brought forward to 1 October.

Table 7.29: Milking platform nitrogen fertiliser applications on the non-effluent block to reflect the different pasture area between the Baseline and Fallow.

Name	Date	Rate kg N/ha	Response kg DM/kg N	Length of response days	Area ha
Nitrogen	01 Aug 17	8	5	30	185
Nitrogen 2	01 Sep 17	19	10	30	185
Nitrogen 3	01 Oct 17	37	10	30	176
Nitrogen 4	01 Nov 17	52	15	30	176
Nitrogen 5	01 Dec 17	33	15	30	175
Nitrogen 6	31 Dec 17	31	15	30	175

Nitrogen 7	30 Jan 18	30	12	30	185
Nitrogen 8	01 Mar 18	33	12	30	185
Nitrogen 9	01 Apr 18	38	12	30	185
Nitrogen 10	01 May 18	9	10	30	185
Total (whole block)		282			185

Table 7.30: Milking platform nitrogen fertiliser applications on the effluent block to reflect the different pasture area between the Baseline and Fallow.

Name	**Date**	**Rate** **kg N/ha**	**Response** **kg DM/kg N**	**Length of response** **days**	**Area** **ha**
Nitrogen	01 Aug 17	8	5	30	115
Nitrogen 2	01 Sep 17	20	10	30	115
Nitrogen 3	01 Oct 17	46	15	30	103
Nitrogen 4	01 Nov 17	51	15	30	103
Nitrogen 5	01 Dec 17	30	15	30	115
Nitrogen 6	31 Dec 17	35	12	30	115
Nitrogen 7	30 Jan 18	36	12	30	115
Nitrogen 8	01 Mar 18	26	12	30	115
Nitrogen 9	01 Apr 18	46	12	30	115
Nitrogen 10	01 May 18	14	10	30	115
Nitrogen 11	01 Oct 17	29	10	30	13
Total (whole block)		275			128

7.14.2 Crop treatment 2: No Crops

The dries were transitioned onto fodder beet on the support block in May by swapping fodder beet and pasture allocations for pasture silage between the R2s in April. The support block remained self-sufficient

On the milking platform, the fodder beet crop and fallow period were removed. Because of the increase in pasture availability due to the removal of the fodder beet crop, the pasture silage harvests were changed to 55 ha for 28 days from 1 October and 60 ha for 31 days from 10 December. Fodder beet was replaced with pasture silage fed on the feed pad and barley grain fed in the shed.

The N fertiliser applications on the milking platform non-effluent block were adjusted to maintain the same farm annual N fertiliser rate of 279 kg N/ha (see Table 7.31 and Table 7.31).

Table 7.31: Milking platform nitrogen fertiliser application changed on the non-effluent block to reflect the different pasture area between Fallow and No Crops.

Name	Date	Rate	Response	Length of response	Area
		kg N/ha	kg DM/kg N	days	ha
Nitrogen	01 Aug 17	8	5	30	185
Nitrogen 2	01 Sep 17	19	10	30	185
Nitrogen 3	01 Oct 17	40	10	30	164
Nitrogen 4	01 Nov 17	55	15	30	164
Nitrogen 5	01 Dec 17	33	15	30	175
Nitrogen 6	31 Dec 17	31	15	30	175
Nitrogen 7	30 Jan 18	30	12	30	185
Nitrogen 8	01 Mar 18	33	12	30	185
Nitrogen 9	01 Apr 18	38	12	30	185
Nitrogen 10	01 May 18	9	10	30	185
Total (whole block)		282			185

Table 7.32: Milking platform nitrogen fertiliser application changed on the effluent block to reflect the different pasture area between Fallow and No Crops.

Name	Date	Rate	Response	Length of response	Area
		kgN/ha	kgDM/kgN	days	ha
Nitrogen	01 Aug 17	7	5	30	128
Nitrogen 2	01 Sep 17	18	10	30	128
Nitrogen 3	01 Oct 17	39	15	30	128
Nitrogen 4	01 Nov 17	43	15	30	128
Nitrogen 5	01 Dec 17	25	15	30	128
Nitrogen 6	31 Dec 17	31	12	30	128
Nitrogen 7	30 Jan 18	33	12	30	128
Nitrogen 8	01 Mar 18	24	12	30	128
Nitrogen 9	01 Apr 18	42	12	30	128
Nitrogen 10	01 May 18	13	10	30	128
Total (whole block)		275			128

7.15 Creating plantain treatments 1 to 4

There were five plantain treatments in total (including the Baseline, Fallow and No Crops that are outlined above). Table 7.33 lists all treatments. The following sub-sections describe the changes that were made to the Farmax files to represent these treatments.

Table 7.33: Names of model scenarios and descriptions of crop and plantain treatments applied to the Baseline. “Maintenance” means that pastures are direct drilled with 4 kg plantain seed/ha. This is a duplicate of Table 3.1 in the Methods chapter.

Description		Plantain treatment			
	No plantain	*No maintenance*	*Maintenance of new pastures in 4th year*	*Maintenance of new pastures in 4th and 7th year*	*Maintenance of new pastures every 2nd year*
Crop treatment	Baseline (fodder beet and oats)	B1	B2	B3	B4
	Fallow (F) (oats removed)	F1	F2	F3	F4
	No Crops (NC) (fodder beet and oats removed)	NC1	NC2	NC3	NC4

Two methods were used to increase the quantity of plantain in the farm system (i) including plantain in the pasture base (PR/WC + PL) and (ii) maintaining/increasing the proportion of plantain in pastures long-term via maintenance (direct drilling plantain seed into existing pastures). Table 7.34 lists the estimated costs associated with the activities necessary to achieve the treatments listed in Table 7.33. The estimates were based on the costs obtained through personal communication with PGG Wrightson stores and the 2016 Lincoln Budget Manual 2016 (Askin & Askin, 2016). Table 7.35 lists the costs for inputs and activities.

Pasture maintenance involved a 21 day interval between undersowing and the following grazing. This is based on the method described in Bryant *et al.* (2019) that resulted in successful establishment of new plantain plants in existing pastures in northern Canterbury. Pastures due for maintenance were assumed to be grazed to 1500 kg DM/ha residual. Then 4 kg plantain seed/ha was direct drilled into the grazed pastures and left to grow for 21 days before grazing again at 2900 kg DM/ha, which is achievable at the ~70 kg DM/ha/day growth rate modelled in November, to open the pasture and allow the plants to continue growing. At this stage, cows end up grazing the existing pasture and not the establishing plants as they are small enough to avoid being grazed.

The following two sections describe the changes that were made to the expense and crop databases in Farmax to represent the cost of treatments applied and to allow the treatments to be represented as part of the physical system.

7.15.1 Updating the expense database

All plantain treatments involved sowing plantain in new perennial ryegrass/white clover + plantain (PR/WC + PL) pastures. The cost of regrassing where plantain was included was calculated to be $114/ha (effective) on the milking platform (Table 7.35). The Marlborough-Canterbury 2017/2018 estimate for PR/WC regrassing, used for treatments without plantain was $101/ha for a Canterbury farm. The cost difference between these two estimates was assumed to be due to variations in regrassing methods and potentially some fertiliser inputs being included in the DairyBase estimate. As shown in the calculations in Table 7.35, there was a 13% increase in the cost of pasture renewal when plantain was added to the pasture base. The cost of regrassing PR/WC + PL pastures was estimated to be $101/ effective ha + 13% ($114/effective ha). The increase in the cost of regrassing when including plantain is caused by the additional cost of the plantain seed and the increase in the cost of the herbicide.

The cost of plantain maintenance was estimated to be $350/ha maintained (Table 7.34).

The cost of weed and pest control per effective hectare was estimated to be $47/ha for PR/WC + PL pastures as opposed to the estimated cost of $33/ha for PR/WC pastures in Canterbury (DairyBase). This was to account for the greater cost of the plantain/clover-safe herbicide which (as applied at contractor rates) is approximately twice that of a general broadleaf clover-safe herbicide as applied at contractor rates. This was estimated by:

1. assuming that the cost of broadleaf herbicides used on PR/WC pastures costs approximately $80/ha for herbicide and $25/ha for contractor application, the total cost for broadleaf herbicide application is $105/ha.
2. Assuming that 30% of the farm is sprayed with broadleaf herbicide each year, the total cost of broadleaf herbicide and application is

0.3 * $105/ha = $31.5/ha. This leaves $33/ha - $31.5/ha = $1.5/ha for miscellaneous weed and pest control e.g. rat baiting and knapsack spraying around buildings and structures, to match the DairyBase estimate for Canterbury (M. Neal, personal communication, 18 October, 2019).

3. Assuming the cost of plantain/clover-safe herbicide used on PR/WC + PL pastures is $125/ha and $25 for contractor application, the total cost for broadleaf herbicide application is $150/ha.
4. Assuming that the area requiring broadleaf weed control (30%) does not change when plantain is included in the system, the estimated cost of weed and pest control for a dairy farm under PR/WC + PL pastures in Canterbury is 0.3 * $150/ha = $45/ha.
5. Assuming the cost of miscellaneous weed and pest control is the same as above at $1.5/ha, the total estimated cost of weed and pest control is $47/ha (0 dp).

Table 7.34: Costs for perennial ryegrass/white clover + plantain pastures (PR/WC + PL).

Activity	**Estimated cost (including plantain-specific inputs)** **$/ha**	**Cost for effective or cropped/maintained area?**
Regrassing	114	Effective
Weed and pest control	47	Effective
Plantain maintenance in pasture	350	Maintained

Table 7.35: Costs of regrassing broken down for 31.3 ha (10% of the milking platform area). The cost of regrassing perennial ryegrass/white clover (PR/WC) pastures and perennial ryegrass/white clover + plantain (PR/WC + PL) pastures are compared, based on the costs obtained through personal communication with PGG Wrightson (July, 2019) and the 2016 Lincoln Budget Manual (Askin & Askin, 2016).

PR/WC	**Input/activity**	**Cost/unit $/ha**	**Units ha**	**Total cost**
Preparation	Glyphosate	30	31.3	$1,677
	Spraying	25	31.3	$782
	Shallow cultivation	150	31.3	$4,692
Sowing	Ryegrass	270	31.3	$8,446
	Clover	60	31.3	$1,877
	Direct drill	100	31.3	$3,128
	Rolling	50	31.3	$1,564
Weed control	Broadleaf herbicide	94	31.3	$2,940
	Spraying	25	31.3	$782
Total cost for area regrassed in PR/WC				$25,149
Cost $/ha regrassed (rounded to nearest $10)				$800/ha
Cost $/ha effective (rounded to nearest $10)				**$80/ha**
PR/WC + PL	**Input/activity**	**Cost/unit $/ha**	**Units ha**	**Total cost**
Preparation	Glyphosate	30	31.3	$938
	Spraying	25	31.3	$782
	Shallow cultivation	150	31.3	$4,692
Sowing	Ryegrass	210	31.3	$6,569
	Clover	60	31.3	$1,877
	Plantain	92	31.3	$2,870
	Direct drill	100	31.3	$3,128
	Rolling	50	31.3	$1,564
Weed control	Dynamo	100	31.3	$3,912
	Spraying	25	31.3	$782
Total cost for area regrassed in PR/WC				$27,372
Cost $/ha regrassed (rounded to nearest $10)				$880
Cost $/ha effective (rounded to nearest $10)				**$90**

7.15.2 Updating the crop database

The crop database was updated manually to create appropriate 'crops' to physically represent the maintenance and crop regimes employed. Maintenance was entered as a crop as this was the only way to reflect its impact on the farm system in Farmax.

When implementing the plantain treatments, their timing (and that of existing crops, if necessary) was manipulated to maintain the farm's end-of-month APC to reflect that the same quality of pasture management was maintained between all treatments. Based on discussion with a farm systems specialist (C. Glassey, personal communication, 27 September, 2019), a strategic decision was made, determining that the change in APC due to implementing a plantain treatment could not exceed ±100 kg DM/ha in more than one month when compared to the appropriate 'no plantain' treatment (Baseline/Fallow/No Crops). It was also decided that it was not worth feeding out pasture silage at 1 kg DM/cow/day (44 t DM) in November to maintain APC and milksolids production. Feeding supplements results in an additional cost and may result in an effect of supplement, rather than an effect of plantain maintenance.

The following sub-sections list the changes made to the Farmax files' expense databases, crop databases and the timing of particular 'crops', to accommodate the plantain treatments.

7.15.3 Plantain treatment 1: no maintenance

Same as Baseline/Fallow/No Crops, but assuming pastures are PR/WC + PL.

The permanent pasture on the milking platform is PR/WC + PL pasture. There is no maintenance of plantain in the pastures. As in the Baseline/Fallow/No Crops, 10% of the milking platform is renewed each year (pastures are renewed every 10 years). The cost of regrassing PR/WC + PL pastures is $109/ha. The cost of weed and pest control is $47/ha.

7.15.4 Plantain treatment 2: maintenance in 4th year

Same as Plantain treatment 1 above, but with 31.3 ha of the non-effluent block removed from the farm rotation for 21 days to allow the plantain seedlings to establish (Table 7.36). It is assumed that plantain returns to the farm grazing rotation at 2,900 kg DM/ha.

Table 7.36: Plantain maintenance schedule for plantain treatment 2: maintenance in 4th year. Plantain maintenance occurs on the non-effluent block.

Name	Area	Out of rotation		
	ha	From	To	Days
Plantain maintenance	31.3	12-Nov 17	2-Dec 17	21

7.15.5 Plantain treatment 3: maintenance in 4th and 7th years

Same as Plantain treatment 2 above, but with an additional 31.3 ha of the non-effluent block removed from the farm rotation for 21 days to allow the plantain seedlings to establish (Table 7.37). It is assumed that plantain returns to the farm grazing rotation at 2,900 kg DM/ha.

Table 7.37: Plantain maintenance schedule for plantain treatment 3: maintenance in 4th and 7th years. Plantain maintenance occurs on the non-effluent block.

Name	Area	Out of rotation		
	ha	From	To	Days
Plantain maintenance	31.3	12-Nov 17	2-Dec 17	21
Plantain maintenance2	31.3	1-Dec 17	21-Dec 17	21

7.15.6 Plantain treatment 4: maintenance every 2nd year

Same as Plantain treatment 3 above, but with an additional 62.6 ha of the non-effluent block removed from the farm rotation for 21 days to allow the plantain seedlings to establish (Table 7.38). It is assumed that plantain returns to the farm grazing rotation at 2,900 kg DM/ha.

Table 7.38: Plantain maintenance schedule for plantain treatment 4: maintenance every 2nd year. Plantain maintenance occurs on the non-effluent block.

Name	Area	Out of rotation		
	ha	From	To	Days
Plantain maintenance	31.3	29-Oct 17	18-Dec 17	21
Plantain maintenance2	62.6	9-Nov 17	29-Dec	21
Plantain maintenance3	31.3	1-Dec 17	21-Dec 17	21

8 Appendix 2: Baseline set up and verification (OVERSEER® Nutrient Budgets)

The following details are for the Baseline which is based off the 2017/2018 season observed by the case study farm. Crop treatment Fallow was created by duplicating and editing the Baseline. No Crops was created by the same process, but editing Fallow.

Inputs used for setting up the files in OVERSEER® Nutrient Budgets Version 6.3.2 (Overseer) are described in the steps below. For each scenario, two files were set up. The first file included inputs relevant to the milking platform only. The second file included inputs for both the milking platform and support block. This partial duplication permitted the analysis of either the milking platform alone, or the whole system (milking platform + support block).

There is an existing drain on the monitor farm running parallel to the main race. For simplicity it was omitted from the Overseer analyses.

Milking platform only properties

8.1 Blocks

8.1.1 Pasture blocks

Eight pasture blocks were created, totalling 312.8 ha. The dominant pasture type was ryegrass/white clover. The blocks were named by their dominant soil type, irrigation type and whether they were part of the effluent block (Table 8.1). All paddocks were described as flat and occasionally susceptible to pugging. Default hydrophobic conditions were applied. The same average climate data was applied to all blocks, based on the actual farm location. Average annual climate data were: 11.1 °C ambient air temperature, 509 mm of rainfall and 772 mm of potential evapotranspiration. Overseer estimated pasture utilisation to be 84% on each block. Irrigation water was applied to pasture from September to May based on the soil water budget. The default nitrogen (N) concentration in irrigation water was 2.5 mg N/L.

8.1.2 Fodder crop rotation block

The 12 month fodder crop rotation rotated through the effluent block (Table 8.1). It was assumed to take 10 years for the 12.6 ha crop to rotate through the 128.3 ha effluent block. The crop was irrigated from November to March based on soil moisture sensor readings, estimated by Overseer.

8.1.3 Blocks by soil type

A farm-scale soil map was used to determine the area size of each soil type. Block soils were described by data imported from S-MAP online. The relevant soil reports are provided in chapter 9 (Appendix 3).

Table 8.1: Milking platform blocks by soil and irrigation combinations. The block names were based on the S-MAP reference and the irrigation type used on the block. The fodder crop rotation rotated through the effluent block on a 10 year return.

Block name	ha	Soil 1		Soil 2		Soil 3		Irrigation type	Effluent
Clar_1a.1, Dry	12	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%		Solids
Clar_1a.1, Hardhose	6.2	Clar_1a.1	70%	Ytoh_3a.1	30%			Travelling	Solids
Clar_1a.1, Kline	13.6	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%	Spray lines	Solids
Clar_1a.1, Pivot	106.6	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%	Pivot	Solids
Clar_1a.1, Pivot, Effluent	110.7	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%	Pivot	Liquid
Ytoh_3a.1, Dry	2.5	Ytoh_3a.1	100%						Solids
Ytoh_3a.1, Hardhose	31.9	Ytoh_3a.1	70%	Paha_5a.1	30%			Travelling	Solids
Ytoh_3a.1, Pivot	11.7	Ytoh_3a.1	70%	Paha_5a.1	30%			Pivot	Solids
Ytoh_3a.1 Pivot, Effluent	17.6	Ytoh_3a.1	70%	Paha_5a.1	30%			Pivot	Liquid
Fodder crop rotation	12.6	Clar_1a.1, Pivot, Effluent and Ytoh_3a.1 Pivot, Effluent						Pivot	Liquid

8.1.4 Fodder crop rotation

A total of 12.6 ha of fodder beet, yielding 25 t DM/ha was assumed to be sown by conventional cultivation in November. In FARMAX Dairy Generation 7 Version 7.1.2.41 (Farmax) and on the actual farm this occurs in October, but Overseer limits cropping activity to one item per month and restricts rotation lengths to 12 months. Some adjustments had to be made to crop timing to fit the rotation into 12 months. Fodder beet was grazed for 2 hours a day in April by the milking mob. The final grazing was in May. Ninety-nine percent of the remaining crop was fed to by the milking mob and the remaining 1% to the dries. An oat catch crop was sown in June via minimum till, yielding 10 t DM/ha. It was harvested and exported off-farm in September. Exporting the crop made it easier when analysing N flows as the effect of the catch crop on N uptake was easier to isolate. Exporting also gave the user control over the feed distribution, which would otherwise be restricted to the Overseer defaults. Overseer does not have an oat silage crop so an equivalent amount of triticale silage (the closest available substitute to oat silage) was imported and distributed to the appropriate mobs (see section 8.5). The rotation ended in October with the establishment of new permanent pasture.

8.2 Fertiliser

Only fertilisers containing N were applied to blocks in the Overseer files (Table 8.2 and Table 8.3). No fertiliser was applied to the forage crops on the milking platform because it was assumed that mineral N (ammonium; NH_4^+ and nitrate; NO_3^-) would be available to the fodder beet crop due to mineralisation following the cultivation of old pasture. No N fertiliser was applied to the oat crop following urine and dung N deposition from *in situ* grazing of the fodder beet crop. Also, the purpose of the oat catch crop was to take up excess mineral N from the soil during the high-drainage period so it was counter-intuitive to add mineral N fertiliser.

Table 8.2: Nitrogen (N) content of fertilisers applied to milking platform.

Name	%N	Form of N
SustaiN	45.9%	Urea
Capital Eff	29%	Urea
Capital Non-eff	20%	Urea

Table 8.3: Quantities and timing of nitrogen (N) fertilisers applied to pasture blocks.

Block	Fertiliser	Rate	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Clar_1a.1, Dry	SustaiN	kg N/ha			30	26	15	24	30	26	34	14
	Effluent	kg N/ha	5	11	2	11	8					
	Non-effluent	kg N/ha	4	4	3	7	3					
	Total N rate	kg N/ha	9	15	35	45	26	24	30	26	34	14
Clar_1a.1, Hardhose	SustaiN	kg N/ha			40	42	18	24	38	35	43	8
	Effluent	kg N/ha	3	10		8	6					
	Non-effluent	kg N/ha		10	6		16					
	Total N rate applied	kg N/ha	3	20	46	50	39	24	38	35	43	8
Clar_1a.1, Kline	SustaiN	kg N/ha			27	25	16	32	28	29	44	12
	Effluent	kg N/ha	8	7			8					
	Non-effluent	kg N/ha	2	12		11	10					
	Total N rate applied	kg N/ha	10	19	27	36	34	32	28	29	44	12
Clar_1a.1, Pivot	SustaiN	kg N/ha			33	36	14	32	29	34	38	8
	Effluent	kg N/ha	1	5	0	2						
	Non-effluent	kg N/ha	7	16	1	10	19					
	Total N rate applied	kg N/ha	7	21	35	48	33	32	29	34	38	8
Clar_1a.1, Pivot, Eff	SustaiN	kg N/ha			38	30	14	33	34	24	43	13
	Effluent	kg N/ha	8	18	1	13	10					
	Non-effluent	kg N/ha			0	1						
	Total N rate applied	kg N/ha	8	18	40	44	25	33	34	24	43	13
Ytoh_3a.1, Dry	SustaiN	kg N/ha			39	29	20	29	30	32	41	5
	Effluent	kg N/ha	6	13		1	8					
	Non-effluent	kg N/ha	8	1	7	2						
	Total N rate applied	kg N/ha	14	14	46	32	28	29	30	32	41	5
Ytoh_3a.1, Hardhose	SustaiN	kg N/ha			34	38	17	25	34	30	36	12
	Effluent	kg N/ha	2	11		7	5					

	Non-effluent	kg N/ha	6	3	3	12	3					
	Total N rate applied	kg N/ha	9	13	38	57	25	25	34	30	36	12
Ytoh_3a.1, Pivot	SustaiN	kg N/ha			36	43	13	24	27	39	41	2
	Effluent	kg N/ha										
	Non-effluent	kg N/ha	4	26		19	16					
	Total N rate applied	kg N/ha	4	26	36	61	29	24	27	39	41	2
Ytoh_3a.1 Pivot, Eff	SustaiN	kg N/ha			31	29	16	25	26	20	33	11
	Effluent	kg N/ha	5	18		3	9					
	Non-effluent	kg N/ha										
	Total N rate applied	kg N/ha	5	18	31	32	25	25	26	20	33	11

8.3 Stock reconciliation

A milking mob and replacement heifer mob were created. A Friesian x Jersey cross (F x J) milking mob (average weight, 509 kg on 1 December) was created by stock reconciliation assuming a 24% annual replacement rate. The mean calving date (when half the cows had calved) was 21 August. The dry-off date was 30 May as it was not possible to stagger dry-off dates in Overseer (see section 7.10 of Appendix 1). Lactation length was 259 days and with twice-a-day milking throughout the entire milking season.

Milk production inputs were: 518,252 kg milk solids (MS)/year, 6,142,581 L/year and 292,898 kg fat/year.

Bobby calf and pre-weaning heifer replacement mobs were not created for the following reasons:

1. bobbies were not on farm very long (approximately 4 days),
2. calves were small and they did not graze pasture so their impact on N leaching was insignificant,
3. when heifer calves (from birth to weaning) were included, Overseer assumed these calves were on a 100% pasture diet which was incorrect, and
4. the heifer calves were transported to the support block on 1 December after weaning, as per the method in chapter 7 (Appendix 1).

Eight F x J breeding bulls were purchased 1 December and sold 16 January.

A dry mob was created to accommodate dry cows on the milking platform pre-calving and post-dry off before transferring to the support block (not present in this file). Average herd age was calculated to be 42 months based on 2017/2018 MINDA data.

Table 8.4: Milking mob numbers and events.

Event type	Reason	Date	Number of animals	Closing number
Opening		1 July		0
Bring on	Calved	6 August	247	247
Bring on	Calved	13 August	285	532
Take off	Died	16 August	6	526
Bring on	Calved	20 August	241	767
Bring on	Calved	27 August	96	863
Bring on	Calved	3 September	77	940
Bring on	Calved	10 September	75	1,015
Take off	3 died, 8 sold	16 September	11	1,004
Bring on	Calved	17 September	58	1,062
Bring on	Calved	24 September	24	1,086
Bring on	Calved	30 September	25	1,111
Bring on	Calved	8 October	31	1,142
Take off	1 died, 15 sold	16 October	16	1,126
Take off	Died	15 November	2	1,124
Take off	2 died, 6 sold	16 December	8	1,116
Take off	1 died, 1 sold	16 January	2	1,114
Take off	Died	15 February	3	1,111
Take off	Sold	16 March	12	1,099
Take off	Sold	16 April	96	1,003
Take off	Dried-off	10 May	200	803
Take off	Sold	15 May	60	743
Take off	Dried-off	20 May	200	543
Take off	Dried-off	25 May	200	343
Take off	Dried-off	26 May	343	0
Closing		31 May		0

Table 8.5: Dry mob numbers and events. “Transferred” indicates animals transported between the milking platform and the support block.

Event type	Reason	Date	Number of animals	Closing number
Opening		1 July		0
Bring on	Transferred	24 July	460	460
Bring on	Transferred	5 August	240	700
Take off	Calved	6 August	247	453
Take off	Calved	13 August	285	168
Bring on	Transferred	19 August	200	368
Take off	Calved	20 August	241	127
Take off	Calved	27 August	96	31
Bring on	Transferred	31 August	259	290
Take off	Calved	3 September	77	213
Take off	Calved	10 September	75	138
Take off	Calved	17 September	58	80
Take off	Calved	24 September	24	56
Take off	Calved	30 September	25	31
Take off	Calved	8 October	31	0
Bring on	Dried off	10 May	200	200
Bring on	Dried off	20 May	200	400
Bring on	Dried off	25 May	200	600
Bring on	Dried off	26 May	343	943
Take off	Transferred	30 May	943	0
Closing		31 May	0	0

8.4 Structures

8.4.1 For feeding supplements

After exploring the feeding out options available, it was decided that the system would be modelled without the feed pad or in-shed feeding, despite this being normal practice for the case study farm. The reason for omitting these structures was that Overseer did not allow the user to specify monthly feed distribution patterns for feed on the pad or in the shed. The default feeding regime did not allocate the correct quantity of feed for the appropriate months. A work-around involving adjusting cow numbers on the pad and in the milking shed was trialled, but it was not flexible enough to match the feed regime to Farmax based on ME ingested per mob per month for each feed type – there was more than 10% difference in monthly ME between the two models.

Trial and error showed that overall farm N leaching varied at most by 1 kg N/ha when the feed pad was removed and the feed distributed to the mobs. As the removal of the feed pad and milking shed did not substantially alter NO_3^- leaching at the farm level, they were not included in the analysis. However, it was still assumed that supplements were fed in the milking shed and on the feed pad even though these structures were not included in the Overseer files. This was reflected by specifying excellent utilisation of feed and ignoring the minor variation in NO_3^- leaching.

Note that removing the milking shed structure only removes in-shed feeding capability, not the actual milking shed.

8.4.2 For effluent management

The effluent management system was a holding pond with liquid effluent sprayed regularly. It is assumed that effluent is applied to the two effluent blocks each month throughout lactation at <12 mm to the Clar_1a.1, Pivot, Eff block and low application method to the Ytoh_3a.1 Pivot, Eff block based on actual farm management. Low applications were made to the fodder crop rotation in September, November and January. Pond solids were assumed to be applied to all non-effluent blocks in June each year.

8.5 Supplements

Soya bean meal (extracted), a high-protein supplement, was used in place of protein pellets. Triticale silage was used in place of oat silage because it was the most similar cereal silage available in Overseer (Table 8.6).

Table 8.6: Nutrient composition (%) means for cereal silage supplements available in Overseer. Data from Dalley *et al.* (2017). Triticale is the most appropriate (similar) cereal silage to substitute in place of oat silage as it most closely matched the four feed quality factors below.

Cereal silage	Crude protein	Soluble sugar + starch	Acid detergent fibre	Neutral detergent fibre
Wheat	10.6	22.9	26.5	44.2
Barley	9.5	23.2	28	49.5
Triticale	10.8	19.5	29.5	49.2
Oats	13.3	15.7	29.5	49.8

Table 8.7: Feed types, sources, quantities and destinations for feed fed on the milking platform. Where the feed pad and milking shed are specified as the supplements' destination, the supplements were actually fed to specific mobs on milking platform paddocks to overcome Overseer feed distribution limitations. If "imported" is not specified as the source, the feed was produced and harvested from on the milking platform.

Feed	Source	Quantity (t DM)	Destination
Good quality pasture silage	Imported	101	Milkers on pad
Wheat grain	Imported	373	Milkers in shed
Soya bean meal (extracted)	Imported	57	Milkers in shed
Triticale silage	Imported	126	Dries on pad
Good quality pasture silage	Clar_1a.1, Pivot	110 (October)	Milkers on pad
Good quality pasture silage	Ytoh_3a.1, Pivot	80 (January)	Milkers on pad
Fodder beet	Forage rotation	315	Milkers, grazed *in situ*
Oat silage crop	Forage rotation	126	Exported

Table 8.8: Proportion of each feed type, from Table 8.7, fed per month to milkers and dries on the milking platform. Only the differences between the Baseline milking platform only and the Baseline milking platform and support block files were reported.

Feed	J	J	A	S	O	N	D	J	F	M	A	M
Imported pasture silage, milkers											100%	
Wheat grain, milkers			6%	16%	20%	14%	8%	4%	12%	9%	8%	3%
Soya bean meal, milkers			25%	25%	20%	20%	10%					
Triticale silage, dries		15%	49%	7%	1%							28%
Harvested pasture silage, milkers			26%	34%								40%

Milking platform + support block properties

The description below builds on the milking platform only description (above).

8.6 Blocks

The 180 ha support block was added to the total farm area as a 144 ha pasture block and four 9 ha, two-year crop blocks. It was assumed that the crop blocks were in permanent pasture in eight of the last ten years. The addition of the support block reduced the pasture utilisation per milking platform block from 84% to 83%. Pasture utilisation for the support block was 73%. Utilisation for new permanent pasture is 75% (specified by Overseer). Soil types were based off the predominant soil type on the milking platform. There are no irrigation or effluent applications.

8.6.1 Additional blocks by soil type

Table 8.9 details the area and soil types under each block.

Table 8.9: Area and soil types of support block pasture and crop blocks.

Name	ha	Soil 1		Soil 2		Soil 3	
Support block, Dry	144	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%
Year 1 early	9	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%
Year 1 late	9	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%
Year 2 early	9	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%
Year 2 late	9	Clar_1a.1	70%	Ytoh_3a.1	20%	Stud_1a.1	10%

The dominant pasture type was ryegrass/white clover. The relative production of the support block was 0.6. This meant that on an annual basis, the support block produced 60% of the total pasture DM that the milking platform produced.

The crop blocks were set up separately, so there are no 12-month fodder crop rotations.

Overseer did not allow cows to be fed on crops and supplements alone over winter as supplements could not be fed out on crop blocks. Overseer also assumes the maximum time spent on crops is 20 hours/day so the cows had to have access to pasture for the remaining 4 hours/day. It was therefore assumed that dry cows had access to the support block pasture to eat the supplements fed out from May to August. This was the closest representation of the model farm.

8.6.2 Support block crop blocks

The crop rotation policy on the support block was two years under cropping followed by eight years in permanent pasture. On the support block, in any one year, 18 ha of land was cropped in fodder beet followed by oats. In the same year, 18 ha was also cropped in kale followed by oats. In total, 36 ha of the support block was cropped each year. However as back-to-back cropping is employed with kale in year one and fodder beet in year two, only 18 ha (10%) of the support block is regrassed each year. In total, 144 ha was under permanent pasture each year.

High stocking rates under the wintering policy for dry stock on the kale and fodder beet crops resulted in half the area (9 ha) of each crop being fully grazed in July. An oat catch crop was sown in August while the remaining 9 ha of each crop was being grazed by winter stock. These four 9 ha crop blocks were named according to the stage (year) of the crop rotation and whether the block was grazed early (followed by oat catch crop) or late (short fallow period before fodder beet crop or new pasture was sown in spring). Details for each crop rotation are listed from Table 8.10 to Table 8.13.

Overseer does not allow more than one cropping activity per month. This affected the cropping regime for example by reducing the growing window for the oat catch crop by up to two months and delayed fodder beet sowing by one month in Year 1 early (Table 8.10).

Table 8.10: Timeline of cultivation and harvests for Year 1 of 2, early grazed kale crop (Year 1 early).

Month	Event	Method	Details
October	Kale crop sown	Conventional cultivation	Yield 14 t DM/ha
June	Grazed	100% dries *in situ*	
July	Final grazing	100% dries *in situ*	
August	Oat crop sown	Minimum till	Yield 7 t DM/ha
October	Final harvest	Cut and carry	Exported
November	Fodder beet crop sown	Conventional cultivation	Yield 22 t DM/ha
April	Grazed	100% replacements *in situ*	
May	Grazed	100% replacements *in situ*	
June	Grazed	100% dries *in situ*	
July	Final grazing	100% dries *in situ*	
August	Oat crop sown	Minimum till	Yield 10 t DM/ha

Table 8.11: Year 1 of 2, late grazed kale crop.

Month	Event	Method	Details
October	Kale crop sown	Conventional cultivation	Yield 14 t DM/ha
July	Grazed	100% dries *in situ*	
August	Final grazing	100% dries *in situ*	
October	Fodder beet crop sown	Conventional cultivation	Yield 22 t DM/ha
July	Grazed	100% dries *in situ*	
August	Final grazing	100% dries *in situ*	

Table 8.12: Year 2 of 2, early grazed fodder beet crop.

Month	Event	Method	Details
October	Fodder beet crop sown	Conventional cultivation	Yield 22 t DM/ha
June	Grazed	100% dries *in situ*	
July	Final grazing	100% dries *in situ*	
August	Oat crop sown	Minimum till	Yield 10 t DM/ha
October	Final harvest	Cut and carry	Exported
November	Permanent pasture sown	Conventional cultivation	

Table 8.13: Year 2 of 2, late grazed fodder beet crop

Month	Event	Method	Details
October	Fodder beet crop sown	Conventional cultivation	Yield 22 t DM/ha
July	Grazed	100% dries *in situ*	
August	Final grazing	100% dries *in situ*	
October	Permanent pasture sown	Conventional cultivation	

8.7 Fertiliser

Only fertiliser containing N was applied to blocks in the Overseer files (Table 8.2 and Table 8.3). Overseer had a different template for fertiliser applications to the crop and pasture blocks. For simplicity, the pasture block applications are reported here, while the crop block applications are reported in Table 8.15. The pasture block 'Support block, Dry' received two applications of SustaiN at 19 kg N/ha in August and March, and a 10 kg N/ha application in November.

Table 8.14: Nitrogen (N) content of fertilisers applied to support block.

Name	%N	Form of N
SustaiN	45.9%	Urea
Cropzeal boron boost	16.5%	Di-ammonium phosphate (DAP)
Sulphate of ammonia	20.5%	Other ammonium

Table 8.15: Quantities and timing of nitrogen (N) fertilisers applied to crop blocks.

Block	Fertiliser	Rate	First year			Second year		
Year 1 early			**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**
	SustaiN	kg N/ha		45.9				55.1
	Cropzeal boron boost	kg N/ha	33				33	
	Sulphate of ammonia	kg N/ha					20.5	
	Total N rate	kg N/ha	33	45.9			53.5	55.1
Year 1 late			**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**
	SustaiN	kg N/ha		45.9			55.1	
	Cropzeal boron boost	kg N/ha	33			33		
	Sulphate of ammonia	kg N/ha				20.5		
	Total N rate	kg N/ha	33	45.9		53.5	55.1	
Year 2 early			**Oct**	**Nov**	**Dec**	**Nov**	**Mar**	**Sep**
	SustaiN	kg N/ha		55.1			8.7	8.7
	Cropzeal boron boost	kg N/ha	33			41.3		
	Sulphate of ammonia	kg N/ha	20.5					
	Total N rate	kg N/ha	53.5	55.1		41.3	8.7	8.7
Year 2 late			**Oct**	**Nov**	**Dec**	**Oct**	**Mar**	**Sep**
	SustaiN	kg N/ha		55.1			8.7	8.7
	Cropzeal boron boost	kg N/ha	33			41.3		
	Sulphate of ammonia	kg N/ha	20.5					
	Total N rate	kg N/ha	53.5	55.1		41.3	8.7	8.7

8.8 Stock reconciliation

The milking mob and the eight breeding bulls' events and numbers remained the same.

The dry mob numbers and distribution were adjusted to reflect grazing on the support block. The animal distribution was edited to reflect animal presence on the milking platform and support block at appropriate times of the year. This was not easy as mobs within the same livestock class could not be distributed or fed as individual mobs.

Table 8.16: Changes to dry mob numbers and events. "Transferred" indicates animals transported between the milking platform and the support block.

Event type	Reason	Date	Number of animals	Closing number
Opening		1 July		1,232
Take off	Sold	6 July	70	1,162
Take off	Died	19 July	3	1,159
Bring on	Calved	6 August	247	912
Bring on	Calved	13 August	285	627
Bring on	Calved	20 August	241	386
Bring on	Calved	27 August	96	290
Bring on	Calved	3 September	77	213
Bring on	Calved	10 September	75	138
Bring on	Calved	17 September	58	80
Bring on	Calved	24 September	24	56
Bring on	Calved	30 September	25	31
Bring on	Calved	8 October	31	0
Take off	Dried-off	10 May	200	200
Take off	Dried-off	20 May	200	400
Take off	Dried-off	25 May	200	600
Take off	Dried-off	26 May	343	943
Closing		31 May		94

Sixteen F x J breeding bulls were purchased 1 October and sold 16 January. These bulls were intended for the R2s on the support block, but were actually grouped under the dairy class with the other bull mob and the milkers due to an Overseer limitation that prevents the user from creating a bull mob without a dry or milking mob. The 16 bulls were grazed on the milking platform instead of the support block. However, their location was assumed to have negligible impact on N leaching at the farm level given the relatively small number of bulls.

Replacements were kept on the support block. Replacements consisted of a weaned heifer calf mob (from 4 months of age) and a rising two-year old (R2) mob. Both of these are F x J.

Table 8.17: Weaned heifer calf numbers and events. "Transferred" indicates weaned calves are transported from the milking platform to the support block. This doesn't happen in Overseer as this is the first occurrence of this animal group.

Event type	Reason	Date	Number of animals	Closing number
Opening		1 July		0
Bring on	Transferred	1 December	335	335
Take off	Died + sold	16 January	6	329
Take off	Died	23 February	1	328
Take off	Sold	16 March	1	327
Take off	Died	2 June	1	326
Ending		31 May		326

Table 8.18: Rising two-year olds (R2s) numbers and events. "Transferred" indicates R2s are transferred to the dry cow mob on the support block.

Event type	Reason	Date	Number of animals	Closing number
Opening		1 July		326
Take off	Died	5 September	1	325
Take off	Died	21 February	1	324
Take off	Sold	16 March	32	292
Take off	Transferred	16 May	292	0
Ending		31 May		0

8.9 Crop consumption

Where a supplemental feed or crop was allocated to more than one mob, it was not possible to match the metabolisable energy (ME) requirements to the Farmax outputs. This assumed to be due to limitations in the animal model of Overseer. In particular, the winter feed regimes were problematic. As this limitation could not be overcome, the focus was on getting the feed regime and ME balance for the milkers as close to that of Farmax. This is because they have the greatest impact on N leaching out of all the animal classes present and they make up the majority of animals present on the farm.

A consequence of the animal model limits, the R2s did not graze fodder beet crops on the support block. In Farmax, they transition onto fodder beet in April and May. However, in order to ensure that the milkers' and then the dries' diets were as close as possible to the diets in Farmax, the R2s were not fed any fodder beet. Also due to the limit of one crop-related activity possible per month, the earliest month they could graze fodder beet was June (which ends up in the next season). Finally, the R2s only ate 10% of the total fodder beet grown on the support block.

Overseer reported an error if mobs were on farm but not on pasture blocks. In Farmax, and on the actual farm, the dry mobs were wintered on crops paddocks 24 hours per day, 7 days per week in June and for most of the time they are on the support block. However, Overseer assumes that if no crop grazing hours are specified, then the animals graze the crop for a maximum of 20 hours. To avoid the error message, the dry mob was given access to the pasture block on the support block. This meant that pasture made up a proportion of their diet over winter.

8.10 Supplements

Table 8.19: Feed types, sources, quantities and destinations for feed fed on the milking platform and support block. Where feed pad and milking shed are specified as the supplements' destination, the supplements were actually fed to specific mobs on milking platform paddocks to overcome Overseer feed distribution limitations. Fodder beet and kale were grazed *in situ*. If "imported" is not specified as the source, the feed was produced and harvested from on the milking platform.

Feed	Source	Quantity (t DM)	Destination
Milking platform			
Good quality pasture silage	Imported	101	Milkers on pad
Wheat grain	Imported	373	Milkers in shed
Soya bean meal (extracted)	Imported	57	Milkers in shed
Triticale silage	Imported	126	Milkers on pad
Good quality pasture silage	Clar_1a.1, Pivot	110 (October)	Milkers on pad
Good quality pasture silage	Ytoh_3a.1, Pivot	80 (January)	Milkers on pad
Fodder beet	Forage rotation	315	Milkers, grazed *in situ*
Oat silage crop	Forage rotation	126	Exported
Support block			
Baleage (pasture)	Support block, Dry	340	156 t Dries, 184 t R2s
Fodder beet	Support block, Dry	396	Dries
Kale	Support block, Dry	252	Dries
Oat silage	Support block, Dry	243	Exported
Triticale silage	Imported	243	303 t dries, 66 t R2s

Support block baleage was harvested in September (180 t DM) and October (160 t DM). Average storage conditions and average utilisation were assumed. Triticale silage was substituted for oat silage (see section 8.1.4). Average storage conditions and average utilisation were assumed. The distribution of supplements on the support block are reported in Table 8.20. No changes were made to supplements fed on the milking platform.

Table 8.20: Proportion of each feed type fed, from Table 8.19, per month to dries and R2s on the support block.

Feed	J	J	A	S	O	N	D	J	F	M	A	M
Baleage, dries	28%	41%	16%									15%
Baleage, R2s		8%	14%					17%	15%	18%	15%	13%
Triticale silage, dries	24%	33%	27%	13%								3%
Triticale silage, R2s	61%	39%										

8.11 Notes for Fallow

Both files for the Baseline were duplicated and edited as below to create the files for Fallow. Only the changes made to the duplicated files are recorded below.

Milking platform only properties

The oat catch crop was removed from the fodder crop rotation on the milking platform. Triticale silage was removed from the supplements fed on the milking platform. Imported pasture silage was increased to 240 t DM. The extra 139 t DM was fed on the feed pad to dries in place of the triticale silage (Table 8.21).

Production inputs were changed to 518,173 kg milk solids (MS)/year, 6,141,648 L/year and 292,857 kg fat/year.

Table 8.21: Proportion of extra 139 t DM imported pasture silage fed per month to dries on the milking platform. Only difference between the Baseline and Fallow are reported (see Table 8.7).

Feed	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Imported pasture silage		13%	49%	7%	1%							30%

Milking platform + support block properties

As no changes were made to the management on the support block between the Baseline and Fallow, only the changes above were applied. However, as Overseer bulked the triticale silage for the milking platform and support block, the total imported and fed was reduced from 369 to 243 t DM with the R2s receiving 66 t DM and the dries 177 t DM.

8.12 Notes for No Crops

Both files for Fallow were duplicated and edited as below to create the files for No Crops. Only the changes made to the duplicated files are recorded below.

Milking platform only properties

The fodder crop rotation was removed from the milking platform (no crops). Imported pasture silage was reduced to 160 t DM (112 t DM to dries and 48 t DM to milkers) and fed on the feed pad. Harvested pasture silage was increased to 230 t DM (110 t DM in September and 120 t DM in October) and fed on the feed pad. Fodder beet was replaced with pasture silage fed on the feed pad and 253 t DM of barley grain fed in the shed. No silage was fed in August or September to the milkers.

Production inputs were changed to 519,843 kg milksolids (MS)/year, 6,162,713 L/year and 293,661 kg fat/year.

Milking platform + support block properties

As no changes were made to the support block (except for transition to fodder beet which was modelled in Farmax by shifting feed between mobs and not possible in Overseer due to allocation limitations), only the changes above were applied.

Table 8.22: Proportion of supplements fed per month to milkers and dries on the milking platform. Only differences between files for Fallow and No Crops are reported (see Table 8.21).

Feed	J	J	A	S	O	N	D	J	F	M	A	M
Imported pasture silage, 48 t DM to milkers											100%	
Imported pasture silage, 112 t DM to dries		17%	42%	7%	1%						33%	
Wheat grain			6%	16%	20%	14%	8%	4%	12%	9%	8%	3%
Soya bean meal			25%	25%	20%	20%	10%					
Imported pasture silage, 84 t to milkers, 26 t to dries										100%		
Imported pasture silage, 120 t DM to milkers											55%	45%
Barley grain to milkers										14%	51%	35%

9 Appendix 3:

Additional data and information

This appendix contains all other additional data not covered in the first two appendices.

9.1 Plantain maintenance schedules

The maintenance schedules for all four plantain treatments are presented in the tables below. To avoid repetition, the following details apply to all tables in this section. The schedules are based on the persistence assumed for plantain (Figure 3.5). In all schedules, the first tenth of the farm is established in new RG/WC + PL pasture the first year. Each year, 10% of the farm is regrassed (see divisions 1-10 on left representing one-tenth of the farm area and years 1-10 across the top). The "Average DM as plantain" is the average proportion of the farm pasture DM that is plantain (%PL pasture). Green cells indicate regrassing in the first year (new RG/WC + PL). Yellow cells represent maintenance in the fourth year (direct drilling of 4 kg plantain seed/ha into existing RG/WC + PL pasture).

Table 9.1: Schedule for no plantain maintenance of new pastures.

10% of farm regrassed	Year 1	2	3	4	5	6	7	8	9	10
1	50%	40%	20%	10%	10%	10%	10%	10%	10%	10%
2	10%	50%	40%	20%	10%	10%	10%	10%	10%	10%
3	10%	10%	50%	40%	20%	10%	10%	10%	10%	10%
4	10%	10%	10%	50%	40%	20%	10%	10%	10%	10%
5	10%	10%	10%	10%	50%	40%	20%	10%	10%	10%
6	10%	10%	10%	10%	10%	50%	40%	20%	10%	10%
7	10%	10%	10%	10%	10%	10%	50%	40%	20%	10%
8	10%	10%	10%	10%	10%	10%	10%	50%	40%	20%
9	20%	10%	10%	10%	10%	10%	10%	10%	50%	40%
10	40%	20%	10%	10%	10%	10%	10%	10%	10%	50%
Average DM as plantain	**18%**	**18%**	**18%**	**18%**	**18%**	**18%**	**18%**	**18%**	**18%**	**18%**

Table 9.2: Schedule for plantain maintenance of new pastures in 4th year.

10% of farm regrassed	Year									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	50%	40%	20%	50%	40%	20%	10%	10%	10%	10%
2	10%	50%	40%	20%	50%	40%	20%	10%	10%	10%
3	10%	10%	50%	40%	20%	50%	40%	20%	10%	10%
4	10%	10%	10%	50%	40%	20%	50%	40%	20%	10%
5	10%	10%	10%	10%	50%	40%	20%	50%	40%	20%
6	20%	10%	10%	10%	10%	50%	40%	20%	50%	40%
7	40%	20%	10%	10%	10%	10%	50%	40%	20%	50%
8	50%	40%	20%	10%	10%	10%	10%	50%	40%	20%
9	20%	50%	40%	20%	10%	10%	10%	10%	50%	40%
10	40%	20%	50%	40%	20%	10%	10%	10%	10%	50%
Average DM as plantain	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**	**26%**

Table 9.3: Schedule for plantain maintenance of new pastures in 4th and 7th years

10% of farm regrassed	Year									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	50%	40%	20%	50%	40%	20%	50%	40%	20%	10%
2	10%	50%	40%	20%	50%	40%	20%	50%	40%	20%
3	20%	10%	50%	40%	20%	50%	40%	20%	50%	40%
4	40%	20%	10%	50%	40%	20%	50%	40%	20%	50%
5	50%	40%	20%	10%	50%	40%	20%	50%	40%	20%
6	20%	50%	40%	20%	10%	50%	40%	20%	50%	40%
7	40%	20%	50%	40%	20%	10%	50%	40%	20%	50%
8	50%	40%	20%	50%	40%	20%	10%	50%	40%	20%
9	20%	50%	40%	20%	50%	40%	20%	10%	50%	40%
10	40%	20%	50%	40%	20%	50%	40%	20%	10%	50%
Average DM as plantain	**34%**	**34%**	**34%**	**34%**	**34%**	**34%**	**34%**	**34%**	**34%**	**34%**

Table 9.4:Schedule for plantain maintenance of new pastures every second year.

10% of farm regrassed	Year									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	50%	40%	50%	40%	50%	40%	50%	40%	50%	40%
2	40%	50%	40%	50%	40%	50%	40%	50%	40%	50%
3	50%	40%	50%	40%	50%	40%	50%	40%	50%	40%
4	40%	50%	40%	50%	40%	50%	40%	50%	40%	50%
5	50%	40%	50%	40%	50%	40%	50%	40%	50%	40%
6	40%	50%	40%	50%	40%	50%	40%	50%	40%	50%
7	50%	40%	50%	40%	50%	40%	50%	40%	50%	40%
8	40%	50%	40%	50%	40%	50%	40%	50%	40%	50%
9	50%	40%	50%	40%	50%	40%	50%	40%	50%	40%
10	40%	50%	40%	50%	40%	50%	40%	50%	40%	50%
Average DM as plantain	**45%**	**45%**	**45%**	**45%**	**45%**	**45%**	**45%**	**45%**	**45%**	**45%**

9.2 Nitrate leaching from crop treatments

Table 9.5: Nitrate (NO_3^-) leaching by block level. All are pasture blocks except for the forage crop rotation, which is the 12.6 ha fodder beet (and oat) sequence that rotates through the effluent block. Pasture blocks are named as follows: 'S-MAP reference, irrigation type, effluent block'. Only two blocks are part of the effluent block. See section 8.1 for further explanations of the block labels. Changes are calculated relative to the Baseline. Note the 19% reduction in NO_3^- leaching from Ytoh_3a.1, pivot for No Crops. This is due to the greater quantity of pasture silage harvested from this block compared to the Baseline (see methods, section Crop treatments). N = nitrogen.

Block level NO_3^- leaching	**NO_3^- leached (kg N/ha/yr)**			**Relative change**	
Block	**Baseline**	**Fallow**	**No Crop**	**Fallow**	**No Crops**
Clar_1a.1, dry	20.8	20.8	20.8	0%	0%
Clar_1a.1, hardhose	62.9	63.6	62.9	1%	0%
Clar_1a.1, kline	36.3	36.3	36.3	0%	0%
Clar_1a.1, pivot	34.5	34.5	34.5	0%	0%
Clar_1a.1, pivot, effluent	41.6	41.6	41.5	0%	0%
Ytoh_3a.1, dry	21.0	22.0	21.0	5%	0%
Ytoh_3a.1, hardhose	64.2	64.2	63.2	0%	-2%
Ytoh_3a.1, pivot	27.0	27.0	22.0	0%	-19%
Ytoh_3a.1, pivot, effluent	39.3	39.3	38.3	0%	-3%
Forage crop rotation	36.0	44.0		22%	
Average farm NO_3^- leached	38	39	38		

Table 9.6: Weighted nitrate (NO_3^-) leaching by block level, calculated using the block NO_3^- leaching levels from Table 9.6. All are pasture blocks. Note that the 12.6 ha forage crop rotation is not included as it rotates through the effluent block and is not a separate block of land. Pasture blocks are named as follows: 'S-MAP reference, irrigation type, effluent block'. Only two blocks are part of the effluent block. See section 8.1 for further explanations of the block labels. N = nitrogen.

		Total NO_3^- leached (kg N/ha/yr)		
Pasture block	**Area (ha)**	**Baseline**	**Fallow**	**No Crop**
Clar_1a.1, dry	12	249.6	249.6	249.6
Clar_1a.1, hardhose	6.2	390.0	394.3	390.0
Clar_1a.1, kline	13.6	493.7	493.7	493.7
Clar_1a.1, pivot	106.6	3677.7	3677.7	3677.7
Clar_1a.1, pivot, effluent	110.7	4605.1	4605.1	4594.1
Ytoh_3a.1, dry	2.5	52.5	55.0	52.5
Ytoh_3a.1, hardhose	31.9	2048.0	2048.0	2016.1
Ytoh_3a.1, pivot	11.7	315.9	315.9	257.4
Ytoh_3a.1, pivot, effluent	17.6	691.7	691.7	674.1
Total	*312.8*	*12524.1*	*12531.0*	*12405.1*
Weighted average farm NO_3^- leached		40	40	40

9.3 Cost of plantain maintenance

Table 9.7: Cost of plantain maintenance *via* direct drilling plantain seed. Costs are rounded to the nearest $10.

Category	Expense	Units	Cost/unit	Quantity	Total
Seed	Plantain	$/ha	100	31.3	3,128
	Direct drill	$/ha	100	31.3	3,128
	Total				*6,256*
	Rounded $/ha maintained				200
	Rounded $/ha effective				20

Table 9.8: Cost of plantain maintenance via broadcasting plantain seed. Costs are rounded to the nearest $10.

Category	Expense	Units	Cost/unit	Quantity	Total $
Seed	Plantain	$/ha	100	31.3	3,128
	Broadcast	$/ha	20	31.3	626
	Total				*3,754*
	Rounded $/ha maintained				120
	Rounded $/ha effective				10

9.4 Imported feed costs for the Baseline and crop treatments

Table 9.9: Farmax cost of imported feed and pasture conserved (harvested pasture silage) for the Baseline and crop treatments. Calf feed was omitted (and would have made no difference as there were no changes in calf numbers or demands between the treatments). The support block was self-sufficient, so all feed reported here was used on the milking platform.

Treatment	Feed	$ total	$/ha
Baseline	Pasture conserved	26,600	85
	Feed crop	39,186	125
	Bought feed	247,188	790
	Total	*312,974*	*1,000*
Fallow	Pasture conserved	26,600	85
	Feed crop	32,760	105
	Bought feed	291,668	932
	Total	*351,028*	*1,122*
No Crops	Pasture conserved	32,200	103
	Bought feed	369,755	1,182
	Total	*401,955*	*1,285*

9.5 Feeding using a feed pad and in-shed feeding

The results for the Baseline + Feed Pad are reported in this section. A feed pad and in-shed feeding were specified as structures used for feeding the milking mob on the milking platform.

Table 9.10: Nitrate (NO_3^-) leaching by block level for the Baseline and Baseline + Feed Pad. Note that the average NO_3^- leached value calculated by Overseer is 37 kg N/ha/yr, not 36 due to differences in rounding. Also, these values are not weighted. Pasture blocks are named as follows: 'S-MAP reference, irrigation type, effluent block'. Only two blocks are part of the effluent block. See section 8.1 for further explanations of the block labels. N = nitrogen.

Block level NO_3^- leaching	**kg N/ha/yr leached**		**Change**
	Baseline	**+ Feed Pad**	
Clar_1a.1, dry	20.8	20.7	0%
Clar_1a.1, hardhose	62.9	61.9	-2%
Clar_1a.1, kline	36.3	35.3	-3%
Clar_1a.1, pivot	34.5	33.4	-3%
Clar_1a.1, pivot, effluent	41.6	40.6	-2%
Ytoh_3a.1, dry	21.0	21.0	0%
Ytoh_3a.1, hardhose	64.2	62.5	-3%
Ytoh_3a.1, pivot	27.0	26.0	-4%
Ytoh_3a.1, pivot,effluent	39.3	37.3	-5%
Fodder beet	36.0	25.0	-31%
Average farm NO_3^- leached	38	36	

9.6 Soil sensitivity analysis results

Table 9.11: Milking platform nitrate (NO_3^-) leaching results for all treatments under the Lismore (moderate) soil type. The reductions are reported relative to the Baseline. **Bolded** lines indicate treatments that achieved the targeted 20% reduction in NO_3^-. N = nitrogen.

Treatment	**Description of plantain treatment**	**NO_3^- leached kg N/ha/yr**	**Reduction compared to Baseline**
Baseline	No plantain	44.0	0%
B1	No maintenance	41.8	5%
B2	Maintenance in 4th year	39.6	10%
B3	Maintenance in 4th and 7th year	37.4	15%
B4	**Maintenance every 2nd year**	**35.0**	**20%**
Fallow	No plantain	45.0	-2%
F1	No maintenance	42.5	3%
F2	Maintenance in 4th year	40.0	9%
F3	Maintenance in 4th and 7th year	37.5	15%
F4	**Maintenance every 2nd year**	**35.0**	**20%**
No Crops	No plantain	43.0	2%
NC1	No maintenance	40.5	8%
NC2	Maintenance in 4th year	38.0	14%
NC3	Maintenance in 4th and 7th year	35.5	19%
NC**4**	**Maintenance every 2nd year**	**33.0**	**25%**

Table 9.12: Milking platform nitrate (NO_3^-) leaching results for all treatments under the Rangitata (light) soil type. The reductions are reported relative to the Baseline. **Bolded** lines indicate treatments that achieved the targeted 20% reduction in NO_3^-. N = nitrogen.

Treatment	**Description of plantain treatment**	**NO_3^- leached kg N/ha/yr**	**Reduction compared to Baseline**
Baseline	No plantain	92.0	0%
B1	No maintenance	87.4	5%
B2	Maintenance in 4th year	82.8	10%
B3	Maintenance in 4th and 7th year	78.2	15%
B4	**Maintenance every 2nd year**	**73.0**	**21%**
Fallow	No plantain	93.0	-1%
F1	No maintenance	88.4	4%
F2	Maintenance in 4th year	83.8	9%
F3	Maintenance in 4th and 7th year	79.2	14%
F4	**Maintenance every 2nd year**	**74.0**	**20%**
No Crops	No plantain	89.0	3%
NC1	No maintenance	84.5	8%
NC2	Maintenance in 4th year	80.0	13%
NC3	Maintenance in 4th and 7th year	75.5	18%
NC**4**	**Maintenance every 2nd year**	**70.5**	**23%**

9.7 Plantain persistence sensitivity analysis results

Table 9.13: Milking platform nitrate (NO_3^-) leaching results for all treatments under the new plantain persistence curve. In the first year, plantain makes up 40% of pasture dry matter, in the second year, 20%. From the third year onwards, it makes up 10% until maintenance or renewal where it will return to 40%. The reductions are reported relative to the Baseline. **Bolded** lines indicate treatments that achieved the targeted 20% reduction in NO_3^-. N = nitrogen.

Treatment	Description of plantain treatment	NO_3^- leached kg N/ha/yr	Reduction compared to Baseline
Baseline	No plantain	38.0	0%
B1	No maintenance	37.0	3%
B2	Maintenance in 4th year	36.0	5%
B3	Maintenance in 4th and 7th year	35.0	8%
B4	Maintenance every 2nd year	33.0	13%
Fallow	No plantain	39.0	-3%
F1	No maintenance	37.8	1%
F2	Maintenance in 4th year	36.6	4%
F3	Maintenance in 4th and 7th year	35.4	7%
F4	Maintenance every 2nd year	33.0	13%
No Crops	No plantain	38.0	0%
NC1	No maintenance	36.9	3%
NC2	Maintenance in 4th year	35.8	6%
NC3	Maintenance in 4th and 7th year	34.7	9%
NC4	Maintenance every 2nd year	32.5	14%

9.8 Soil reports

The following pages contain soil reports for the case study farm and the sensitivity analyses. These were obtained from https://smap.landcareresearch.co.nz/.

The soils are ordered as in Table 9.14:

Table 9.14: Order of soil reports for the four soil types on the case study farm and the two soils used for the sensitivity analysis.

S-MAP reference	Soil
Case study farm	
Clar_1a.1	Claremont moderately deep silty loam
Ytoh_3a.1	Waitohi deep silty loam
Stud_1a.1	Studholme moderately deep silty loam over clay
Paha_5a.1	Pahau deep silty loam
Sensitivity analysis	
Lism_1a.1	Lismore shallow silty loam
Rang_5a.2	Rangitata shallow sandy loam

S O I L   R E P O R T

Report generated: 29-Jan-2019 from https://smap.landcareresearch.co.nz

This information sheet describes the typical average properties of the specified soil to a depth of 1 metre, and should not be the primary source of data when making land use decisions on individual farms and paddocks.

S-map correlates soils across New Zealand. Both the old soil name and the new correlated (soil family) name are listed below.

Family: Claremont*f*

Smap ref: Clar_1a.1

Claremont*f* moderately deep silty loam

Key physical properties

Depth class (diggability)		Moderately deep (40 - 80 cm)
Texture profile		Silty loam
Potential rooting depth		40 - 85 (cm)
Rooting barrier		Pan
Topsoil stoniness		Stoneless
Topsoil clay range		18 - 25 %
Drainage class		Poorly drained
Aeration in root zone		Very limited
Permeability profile		Moderate over slow
Depth to slowly permeable horizon		40 - 70 (cm)
Permeability of slowest horizon		Slow (< 4 mm/h)
Profile available water	(0 - 100cm or root barrier)	Moderate (91 mm)
	(0 - 60cm or root barrier)	High (90 mm)
	(0 - 30cm or root barrier)	Moderate (47 mm)
Depth to hard rock		No hard rock within 1 m
Depth to soft rock		No soft rock within 1 m
Depth to stony layer class		No significant stony layer within 1 m

Key chemical properties

Topsoil P retention	Low (22%)

About this publication

- This information sheet describes the *typical average properties* of the specified soil.
- For further information on individual soils, contact Landcare Research New Zealand Ltd: www.landcareresearch.co.nz
- Advice should be sought from soil and land use experts before making decisions on individual farms and paddocks.
- The information has been derived from numerous sources. It may not be complete, correct or up to date.
- This information sheet is licensed by Landcare Research on an "as is" and "as available" basis and without any warranty of any kind, either express or implied.
- Landcare Research shall not be liable on any legal basis (including without limitation negligence) and expressly excludes all liability for loss or damage howsoever and whenever caused to a user of this factsheet.

Manaaki Whenua
Landcare Research

Family: Claremont*f*

Smap ref: Clar_1a.1

Claremont*f* moderately deep silty loam

Additional factors to consider in choice of management practices

Vulnerability classes relate to soil properties only and do not take into account climate or management

Contaminant management

MGM N Loss Category	Category cannot be provided as slope is unknown
MGM P Loss Category	Category cannot be provided as slope is unknown
N leaching vulnerability	Medium
P leaching vulnerability	Medium
Bypass flow	Medium or high
Dairy effluent (FDE) risk category	C if slope > 7 deg otherwise B
Septic tank installation category	A1 if slope > 15 deg otherwise A2

Relative Runoff Potential

Slope	0-3°	4-7°	8-15°	16-25°	>25°
Risk	M	H	VH	VH	VH

Soil classification	Fragic Perch-gley Pallic Soils (PPX)
Family	Claremont*f*
Sibling number	1
Profile texture group	Silty
Soil profile material	Stoneless soil
Rock class of stones/rocks	Not applicable
Rock origin of fine earth	From hard sandstone rock
Parent material origin	Loess

Characteristics of functional horizons in order from top to base of profile:

Functional Horizon	Thickness	Stones	Clay*	Sand*
Loamy Fine Slightly Firm	17 - 35 cm	0 %	18 - 25 %	5 - 10 %
Loamy Fine Slightly Firm	10 - 35 cm	0 %	18 - 28 %	5 - 10 %
Loamy Coarse Slightly Firm	0 - 30 cm	0 %	18 - 38 %	5 - 10 %
Loamy Coarse Firm	20 - 60 cm	0 %	18 - 28 %	5 - 10 %

* clay and sand percent values are for the mineral fines (excludes stones). Silt = 100 - (clay + sand)

SOIL REPORT

Report generated: 29-Jan-2019 from https://smap.landcareresearch.co.nz

This information sheet describes the typical average properties of the specified soil to a depth of 1 metre, and should not be the primary source of data when making land use decisions on individual farms and paddocks.

S-map correlates soils across New Zealand. Both the old soil name and the new correlated (soil family) name are listed below.

Family: Waitohi*f*

Smap ref: Ytoh_3a.1

Waitohi*f* deep silty loam

Key physical properties

Depth class (diggability)		Deep (> 1 m)
Texture profile		Silty loam
Potential rooting depth		60 - 90 (cm)
Rooting barrier		Pan
Topsoil stoniness		Stoneless
Topsoil clay range		18 - 25 %
Drainage class		Poorly drained
Aeration in root zone		Limited
Permeability profile		Moderate over slow
Depth to slowly permeable horizon		60 - 90 (cm)
Permeability of slowest horizon		Slow (< 4 mm/h)
Profile available water	(0 - 100cm or root barrier)	Moderate (104 mm)
	(0 - 60cm or root barrier)	Moderate (88 mm)
	(0 - 30cm or root barrier)	Moderate (48 mm)
Depth to hard rock		No hard rock within 1 m
Depth to soft rock		No soft rock within 1 m
Depth to stony layer class		No significant stony layer within 1 m

Key chemical properties

Topsoil P retention	Low (22%)

About this publication

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- Advice should be sought from soil and land use experts before making decisions on individual farms and paddocks.
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Manaaki Whenua
Landcare Research

Family: Waitohi*f*

Smap ref: Ytoh_3a.1

Waitohi*f* deep silty loam

Additional factors to consider in choice of management practices

Vulnerability classes relate to soil properties only and do not take into account climate or management

Contaminant management

MGM N Loss Category	Category cannot be provided as slope is unknown
MGM P Loss Category	Category cannot be provided as slope is unknown
N leaching vulnerability	Very low
P leaching vulnerability	Medium
Bypass flow	Medium
Dairy effluent (FDE) risk category	C if slope > 7 deg otherwise B
Septic tank installation category	A1 if slope > 15 deg otherwise B2

Relative Runoff Potential

Slope	0-3°	4-7°	8-15°	16-25°	>25°
Risk	M	M	H	VH	VH

Soil classification	Argillic Perch-gley Pallic Soils (PPJ)
Family	Waitohi*f*
Sibling number	3
Profile texture group	Silty
Soil profile material	Stoneless soil
Rock class of stones/rocks	Not applicable
Rock origin of fine earth	From hard sandstone rock
Parent material origin	Loess

Characteristics of functional horizons in order from top to base of profile:

Functional Horizon	Thickness	Stones	Clay*	Sand*
Loamy Fine Slightly Firm	18 - 40 cm	0 %	18 - 25 %	5 - 10 %
Loamy Fine Slightly Firm	15 - 25 cm	0 %	18 - 28 %	5 - 10 %
Loamy Fine Firm	15 - 35 cm	0 %	25 - 35 %	5 - 15 %
Loamy Coarse Firm	10 - 40 cm	0 %	18 - 35 %	5 - 20 %

* clay and sand percent values are for the mineral fines (excludes stones). Silt = 100 - (clay + sand)

SOIL REPORT

Report generated: 29-Jan-2019 from https://smap.landcareresearch.co.nz

This information sheet describes the typical average properties of the specified soil to a depth of 1 metre, and should not be the primary source of data when making land use decisions on individual farms and paddocks.

S-map correlates soils across New Zealand. Both the old soil name and the new correlated (soil family) name are listed below.

Family: Studholm*f*

Smap ref: Stud_1a.1

Studholm*f* moderately deep silty loam over clay

Key physical properties

Depth class (diggability)		Moderately deep (50 - 70 cm)
Texture profile		Silty loam over clay
Potential rooting depth		50 - 70 (cm)
Rooting barrier		Pan
Topsoil stoniness		Stoneless
Topsoil clay range		18 - 25 %
Drainage class		Poorly drained
Aeration in root zone		Very limited
Permeability profile		Moderate over slow
Depth to slowly permeable horizon		50 - 70 (cm)
Permeability of slowest horizon		Slow (< 4 mm/h)
Profile available water	(0 - 100cm or root barrier)	Moderate to low (82 mm)
	(0 - 60cm or root barrier)	Moderate (79 mm)
	(0 - 30cm or root barrier)	Moderate (47 mm)
Depth to hard rock		No hard rock within 1 m
Depth to soft rock		No soft rock within 1 m
Depth to stony layer class		No significant stony layer within 1 m

Key chemical properties

Topsoil P retention	Low (22%)

About this publication

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Manaaki Whenua
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Family: Studholm*f*

Smap ref: Stud_1a.1

Studholm*f* moderately deep silty loam over clay

Additional factors to consider in choice of management practices

Vulnerability classes relate to soil properties only and do not take into account climate or management

Contaminant management

MGM N Loss Category	Category cannot be provided as slope is unknown
MGM P Loss Category	Category cannot be provided as slope is unknown
N leaching vulnerability	Medium
P leaching vulnerability	Medium
Bypass flow	Medium
Dairy effluent (FDE) risk category	C if slope > 7 deg otherwise B
Septic tank installation category	A1 if slope > 15 deg otherwise B2

Relative Runoff Potential

Slope	0-3°	4-7°	8-15°	16-25°	>25°
Risk	M	H	VH	VH	VH

Soil classification	Cemented Perch-gley Pallic Soils (PPC)
Family	Studholm*f*
Sibling number	1
Profile texture group	Silty
Soil profile material	Stoneless soil
Rock class of stones/rocks	Not applicable
Rock origin of fine earth	From hard sandstone rock
Parent material origin	Loess

Characteristics of functional horizons in order from top to base of profile:

Functional Horizon	Thickness	Stones	Clay*	Sand*
Loamy Fine Slightly Firm	18 - 28 cm	0 %	18 - 25 %	5 - 10 %
Loamy Fine Slightly Firm	0 - 30 cm	0 %	18 - 30 %	5 - 10 %
Clayey Fine Firm	15 - 35 cm	0 %	30 - 40 %	5 - 10 %
Indurated pan	5 - 20 cm	0 %	30 - 40 %	5 - 20 %
Loamy Coarse Firm	10 - 40 cm	0 %	18 - 25 %	5 - 15 %

* clay and sand percent values are for the mineral fines (excludes stones). Silt = 100 - (clay + sand)

SOIL REPORT

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S-map correlates soils across New Zealand. Both the old soil name and the new correlated (soil family) name are listed below.

Family: Pahau*f*

Smap ref: Paha_5a.1

Pahau*f* deep silty loam

Key physical properties

Depth class (diggability)		Deep (> 1 m)
Texture profile		Silty loam
Potential rooting depth		Unlimited
Rooting barrier		No significant barrier within 1 m
Topsoil stoniness		Stoneless
Topsoil clay range		18 - 35 %
Drainage class		Imperfectly drained
Aeration in root zone		Limited
Permeability profile		Moderate over slow
Depth to slowly permeable horizon		30 - 70 (cm)
Permeability of slowest horizon		Slow (< 4 mm/h)
Profile available water	(0 - 100cm or root barrier)	Moderate to high (135 mm)
	(0 - 60cm or root barrier)	Moderate (87 mm)
	(0 - 30cm or root barrier)	Moderate (49 mm)
Depth to hard rock		No hard rock within 1 m
Depth to soft rock		No soft rock within 1 m
Depth to stony layer class		No significant stony layer within 1 m

Key chemical properties

Topsoil P retention	Low (19%)

About this publication

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Family: Pahau*f*

Smap ref: Paha_5a.1

Pahau*f* deep silty loam

Additional factors to consider in choice of management practices

Vulnerability classes relate to soil properties only and do not take into account climate or management

Contaminant management

MGM N Loss Category	Category cannot be provided as slope is unknown
MGM P Loss Category	Category cannot be provided as slope is unknown
N leaching vulnerability	Medium
P leaching vulnerability	Medium
Bypass flow	High
Dairy effluent (FDE) risk category	C if slope > 7 deg otherwise B
Septic tank installation category	A1 if slope > 15 deg otherwise B3

Relative Runoff Potential

Slope	0-3°	4-7°	8-15°	16-25°	>25°
Risk	L	M	H	H	H

Soil classification	Mottled Argillic Pallic Soils (PJM)
Family	Pahau*f*
Sibling number	5
Profile texture group	Silty
Soil profile material	Stoneless soil
Rock class of stones/rocks	Not applicable
Rock origin of fine earth	From hard sandstone rock
Parent material origin	Alluvium

Characteristics of functional horizons in order from top to base of profile:

Functional Horizon	Thickness	Stones	Clay*	Sand*
Loamy Weak	18 - 30 cm	0 %	18 - 35 %	5 - 15 %
Loamy Fine Slightly Firm	20 - 30 cm	0 %	20 - 35 %	5 - 20 %
Loamy Fine Firm	0 - 30 cm	0 %	25 - 40 %	5 - 30 %
Loamy Coarse Firm	20 - 70 cm	0 %	20 - 40 %	10 - 40 %

* clay and sand percent values are for the mineral fines (excludes stones). Silt = 100 - (clay + sand)

SOIL REPORT

Report generated: 11-Oct-2019 from https://smap.landcareresearch.co.nz

This information sheet describes the typical average properties of the specified soil to a depth of 1 metre, and should not be the primary source of data when making land use decisions on individual farms and paddocks.

S-map correlates soils across New Zealand. Both the old soil name and the new correlated (soil family) name are listed below.

Family: Lismore*f*

Smap ref: Lism_1a.1

Lismore*f* shallow silty loam

Key physical properties

Depth class (diggability)		Shallow (20 - 45 cm)
Texture profile		Silty loam
Potential rooting depth		Unlimited
Rooting barrier		No significant barrier within 1 m
Topsoil stoniness		Stoneless
Topsoil clay range		18 - 25 %
Drainage class		Well drained
Aeration in root zone		Unlimited
Permeability profile		Moderate over rapid
Depth to slowly permeable horizon		No slowly permeable horizon
Permeability of slowest horizon		Moderate (4 - 72 mm/h)
Profile available water	(0 - 100cm or root barrier)	Moderate (99 mm)
	(0 - 60cm or root barrier)	Moderate (86 mm)
	(0 - 30cm or root barrier)	High (61 mm)
Depth to hard rock		No hard rock within 1 m
Depth to soft rock		No soft rock within 1 m
Depth to stony layer class		Shallow

Key chemical properties

Topsoil P retention	Medium (43%)

About this publication

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Manaaki Whenua Landcare Research

Family: Lismore*f*

Smap ref: Lism_1a.1

Lismore*f* shallow silty loam

Additional factors to consider in choice of management practices

Vulnerability classes relate to soil properties only and do not take into account climate or management

Contaminant management

MGM N Loss Category	Category cannot be provided as slope is unknown
MGM P Loss Category	Category cannot be provided as slope is unknown
N leaching vulnerability	High
P leaching vulnerability	Low
Bypass flow	Medium
Dairy effluent (FDE) risk category	C if slope > 7 deg otherwise D
Septic tank installation category	A1 if slope > 15 deg otherwise B4

Relative Runoff Potential

Slope	0-3°	4-7°	8-15°	16-25°	>25°
Risk	VL	VL	VL	VL	L

Soil classification	Pallic Firm Brown Soils (BFP)
Family	Lismore*f*
Sibling number	1
Profile texture group	Silty
Soil profile material	Rounded stony soil
Rock class of stones/rocks	From hard sandstone rock
Rock origin of fine earth	From hard sandstone rock
Parent material origin	Alluvium

Characteristics of functional horizons in order from top to base of profile:

Functional Horizon	Thickness	Stones	Clay*	Sand*
Loamy Weak	18 - 25 cm	0 %	18 - 25 %	5 - 30 %
Loamy Weak	5 - 20 cm	0 - 10 %	18 - 25 %	5 - 30 %
Very Stony Loamy Compact	8 - 20 cm	35 - 60 %	10 - 25 %	10 - 50 %
Very Stony Loamy Loose	0 - 20 cm	50 - 70 %	5 - 12 %	30 - 70 %
Very Stony Sandy Loose	40 - 55 cm	60 - 75 %	1 - 4 %	85 - 95 %

* clay and sand percent values are for the mineral fines (excludes stones). Silt = 100 - (clay + sand)

SOIL REPORT

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S-map correlates soils across New Zealand. Both the old soil name and the new correlated (soil family) name are listed below.

Family: Rangitata*f*

Smap ref: Rang_5a.2

Rangitata*f* shallow sandy loam

Key physical properties

Depth class (diggability)		Shallow (15 - 35 cm)
Texture profile		Sandy loam
Potential rooting depth		40 - 70 (cm)
Rooting barrier		Extremely gravelly
Topsoil stoniness		Slightly stony
Topsoil clay range		3 - 10 %
Drainage class		Well drained
Aeration in root zone		Unlimited
Permeability profile		Rapid
Depth to slowly permeable horizon		No slowly permeable horizon
Permeability of slowest horizon		Rapid (> 72 mm/h)
Profile available water	(0 - 100cm or root barrier)	Low (43 mm)
	(0 - 60cm or root barrier)	Low (43 mm)
	(0 - 30cm or root barrier)	Moderate (36 mm)
Depth to hard rock		No hard rock within 1 m
Depth to soft rock		No soft rock within 1 m
Depth to stony layer class		Shallow

Key chemical properties

Topsoil P retention	Low (19%)

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Manaaki Whenua
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Family: Rangitata*f*

Smap ref: Rang_5a.2

Rangitata *f* shallow sandy loam

Additional factors to consider in choice of management practices

Vulnerability classes relate to soil properties only and do not take into account climate or management

Contaminant management

MGM N Loss Category	Category cannot be provided as slope is unknown
MGM P Loss Category	Category cannot be provided as slope is unknown
N leaching vulnerability	Very high
P leaching vulnerability	Very high
Bypass flow	Medium
Dairy effluent (FDE) risk category	C if slope > 7 deg otherwise E
Septic tank installation category	A1 if slope > 15 deg otherwise B4

Relative Runoff Potential

Slope	0-3°	4-7°	8-15°	16-25°	>25°
Risk	VL	VL	VL	VL	L

Soil classification	Typic Fluvial Recent Soils (RFT)
Family	Rangitata*f*
Sibling number	5
Profile texture group	Sandy
Soil profile material	Rounded stony soil
Rock class of stones/rocks	From hard sandstone rock
Rock origin of fine earth	From hard sandstone rock
Parent material origin	Alluvium

Characteristics of functional horizons in order from top to base of profile:

Functional Horizon	Thickness	Stones	Clay*	Sand*
Sandy Loose	5 - 15 cm	0 - 8 %	3 - 10 %	75 - 95 %
Sandy Loose	10 - 25 cm	0 - 8 %	1 - 6 %	85 - 95 %
Very Stony Sandy Loose	20 - 30 cm	60 - 74 %	0 - 4 %	95 - 98 %
Extremely Stony Sandy	40 - 60 cm	70 - 85 %	0 - 3 %	95 - 98 %

* clay and sand percent values are for the mineral fines (excludes stones). Silt = 100 - (clay + sand)