Assessing Soil Physical Properties for Diverse and Standard Pastures Under Regenerative and Contemporary Grazing Management

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ABSTRACT

This thesis investigates the influence of pasture type and management practices on soil physical properties within New Zealand's agricultural systems, focusing on the Whenua Haumanu Programme (WHP) at Massey University's Dairy Farm One and Pasture Crop Research Unit (PCRU). WHP is a seven-year trial aiming to assess the suitability and relevance of regenerative agriculture to New Zealand, taking our climate, soils and management systems into consideration. WHP explores contemporary and regenerative farming practices across both standard (ryegrass and white clover) and diverse pastures (multi species of grasses, herbs and legumes).

This master's thesis presents two key research chapters. Chapter 3 outlines 2023-2024 baseline soil physics data for WHP, to support ongoing and future annual comparisons to test whether there are any differences in soil physical properties between standard and diverse pastures or contemporary and regenerative grazing managements. Results to date demonstrate that no statistically significant differences exist between the treatments. Significant differences are found between soil types, reflecting natural differences in soil texture. Differences are also observed between sampling years and can be attributed to changes in moisture content.

Chapter 4 investigates the short-term impact of dairy cattle grazing on soil physical properties under two contrasting management systems at Massey University's Dairy Farm One. Soil physical properties were measured for a regeneratively managed diverse pasture and a contemporary management standard pasture before and after a grazing event under saturated spring 2024 conditions. Both paddocks displayed compaction with distinct spatial patterns linked to daily rainfall and the location of water troughs and shelter belts. High pre grazing pasture covers also appear to be linked with less treading damage, however, further analyses is required to confirm any potential trends.

Key words: Soil Physical Properties, Regenerative Agriculture, Pasture Management, Bulk Density, Soil Penetration Resistance, Volumetric Water Content (VWC), Diverse Pastures, Contemporary Management, Grazing Practices, Soil Compaction

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Dedicated to my parents, Qingjun Ma and Yongdi Guo…

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COMMON ABBREVIATIONS

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

RA	Regenerative agriculture
Std-Con	Standard pasture and contemporary management
Div-Reg	Diverse pasture and regenerative management
Div-Con	Diverse pasture and contemporary management
Std-Reg	Standard pasture and regenerative management
VWC	Volumetric Water Content
WHP	Whenua Haumanu programme
PCRU	Pasture Crop Research Unit

CHAPTER ONE: INTRODUCTION

Regenerative agriculture, a term with no set definition, was coined in the United States through the 1970's. It generally involves managing farms to improve soil health, plant and animal nutritive quality and reducing animal stress and dependence on agricultural chemicals. It's gaining in popularity and there is abundant anecdotal evidence of environmental, economic and social benefits (Cosgrove et al., 2024; Stronge et al., 2020).

Regenerative grazing management has received widespread attention because it can affect livestock production efficiency and long-term ecosystem health. In particular, the interaction between pasture species diversity, regenerative grazing methods, and soil health has become a global research focus (Bartley et al., 2023; Matt, 2024; Sher et al., 2024). Some studies have shown that diversified pasture systems, especially those with deep-rooted plant species and regenerative grazing strategies, can increase organic matter content and improve soil structure (Dodd et al., 2011; Gao et al., 2016; Khangura et al., 2023; Teague, 2023). However, any positive effects are tightly linked to geographic setting, soil and pasture type, climate, time and history of landuse (Vallentine, 2000; Milazzo et al., 2023; Rehberger et al., 2023). Currently, there is a lack of research to assess the potential advantages and disadvantages of regenerative agriculture, particularly from a New Zealand perspective.

This thesis explores the potential influence of regenerative grazing management and diverse pastures on soil physical properties in Palmerston North, New Zealand. The study involves a sheep and beef and dairy farmlet established as part of Whenua Haumanu, a seven-year project funded through the Ministry for Primary Industries (MPI) to assess the suitability and relevance of regenerative agriculture to New Zealand, taking our climate, soils and management systems into consideration.

Sunflowers on Massey Universities Dairy Farm One in 2024, sown as part of the Whenua Haumanu regenerative agriculture trial.

Thesis Aims and Objectives

1. Establish baseline soil physics data for the Whenua Haumanu programme to allow potential changes to be identified over the 7-year trial.
2. Assess any potential short-term (2 years) influence of regenerative vs. contemporary grazing management and diverse vs. standard pastures on soil physical properties.
3. Evaluate treading damage under regenerative vs. contemporary dairy grazing and diverse vs. standard pastures on the Manawatu sandy loam under saturated conditions.

Thesis Structure

This thesis has been arranged as a single volume with seven chapters as outlined below. Note it forms part of the wider Whenua Haumanu Programme (WHP) which aims to critically evaluate the impact of different pasture types and regenerative practices on soil, plants, livestock products, and the environment, from a New Zealand pastoral perspective.

This thesis has been structured as a thesis by publication, with Chapters 3 and 4 intended for publication in peer reviewed journals. This choice of style introduces a certain amount of repetition, for instance, both Chapter 3 and 4 need to outline the study area including its geographic setting and how it fits into the WHP. Despite this drawback, the author is confident that by taking this approach the quality of the text is of a much higher standard than could otherwise have been achieved.

The thesis is structured as follows:

- **Chapter 1 – Introduction:** The first chapter provides a general overview of the research topic, outlining the proposed objective, research outputs and thesis layout.
- **Chapter 2 - Literature review:** Chapter 2 provides an overview of regenerative agriculture from a New Zealand pastoral farming perspective. It also introduces soil physical properties, how they are measured and why they are important for pastoral production.
- **Chapter 3 - Establishing baseline soil physics data to support the Whenua Haumanu regenerative agriculture trial in New Zealand:** This chapter presents two years of soil physics data collected at Massey University's Dairy Farm One and the Pasture and Crop

Research Unit (PCRU), establishing baseline data and allowing potential difference between treatments to be identified as the WHP progresses.

- **Chapter 4 - Assessing pugging under regenerative versus contemporary dairy grazing and diverse versus standard pastures in New Zealand:** This chapter explores the spatial variability of treading damage and soil physical properties on Massey University's Dairy Farm One, focusing on a single grazing event during saturated conditions in Spring 2024.
- **Chapter 5 – Discussion:** This chapter draws on ideas and results outlined in each of the proceeding chapters, exploring possible implications and recommendations for future work.
- **Chapter 6 – Conclusion:** The final chapter summarises the results of the entire research project.

CHAPTER TWO: LITERATURE REVIEW

2.1 Regenerative agriculture in New Zealand

Regenerative agriculture (RA) is an emergent, farmer-led approach that rethinks farming as the management of dynamic, living systems rather than a means solely for production (Eckberg et al., 2020). Its history began with farmers experimenting and adopting practices aimed at restoring soil health, water quality, biodiversity, and overall farm resilience (Singh et al., 2025).

The popularity of RA in New Zealand is marked by growing farmer uptake across pastoral, arable, and viticulture sectors, where practices such as year-round ground cover and no-till planting are being applied (Burns, 2021). Despite the emergence of RA practices, broader adoption is still in its early stages (Grelet et al., 2021). Formal recognition has begun to take shape through government reports and pilot projects that position regenerative methods as central to meeting environmental and climate goals, yet a full-scale integration into national regulatory or market frameworks remains forthcoming (Curran-Cournane et al., 2024).

While numerous case studies and anecdotal reports have documented benefits including improvements in soil organic carbon, enhanced plant recovery, and better nutrient cycling (Schon et al., 2024), there is a clear shortage of replicated long-term studies that comprehensively compare RA systems with contemporary agriculture, particularly from a New Zealand perspective. Furthermore, there is uncertainty regarding how New Zealand's unique biogeographical attributes, such as young, carbon-rich soils and grass-based farming systems, affect RA outcomes (Grelet et al., 2021). Specifically, there are gaps in understanding the long-term dynamics of soil carbon sequestration, particularly beyond the top 30 cm of soil, and in quantifying the full ecosystem benefits in terms of water quality and biodiversity (Dynarski et al., 2020). Social science aspects, such as farmer perceptions, motivations, and the links

Diverse pasture on Massey Universities Dairy Farm One in 2024, sown as part of the Whenua Haumanu regenerative agriculture trial.

between regenerative practices and market premiums, also remain poorly explored compared to the wealth of data on mainstream farming systems in New Zealand.

2.2 Forage and grazing systems on New Zealand sheep and beef farms

New Zealand sheep and beef farms are predominantly extensive, with more than 95% of feed sourced from natural pastures (Morris, 2013; Foote et al., 2015). Beef cattle are used to help manage pasture vigor and quality, especially on steeper or less fertile areas (Hodgson et al., 2019; Dodd & Mackay, 2011). Forage on New Zealand sheep and beef farms is mainly permanent pastures dominated by perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) (Moot, 2022). Livestock numbers are adjusted to achieve pasture cover and animal weight and condition targets in winter. A high proportion of breeding ewes and cows are carried over winter, aiming to align increased feed supply in spring to increased feed demand with lambing and calving. Brassica crops and herb-based pastures (plantain and chicory) are increasingly being used to provide high feed value to support lactating ewes or ewe hoggets (Morris, 2013; Kemp et al., 2010).

2.3 Pasture-based feeding and seasonal calving on New Zealand dairy farms

Standard New Zealand dairy pastures have evolved to optimise milk production and are dominated by a mixture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), which delivers high yields with minimal dependence on imported feeds (Lee et al., 2012; Clark et al., 2001). Rotational grazing is common on New Zealand dairy farms, where cattle move through a planned sequence of subdivided farmlets. This allows each paddock to rest, improving pasture quality, utilisation and animal health (Mulliniks et al., 2015). Rotation length is adjusted based on seasonal grass growth, weather and feed demand (Kay et al., 2015)

A key feature of the standard pasture system is that the calving cycle is synchronised with the seasonal growth pattern of the pasture. Seasonal calving is usually carried out in late winter-early spring, so that the peak lactation period of the dairy cow is matched with the optimal period of pasture feed supply (Garcia & Holmes, 1999). This strategic timing helps the dairy cow to consume more dry matter in the early lactation period, thereby reducing the dependence on high-priced supplementary feed (Clark et al., 2007). In addition, since the dairy cows are in similar physiological stages, this synchronisation can also improve the efficiency of herd management and simplify the operation process of the entire dairy farm (Garcia & Holmes, 1999).

The nutritional status of pastures plays a key role in maintaining high milk production. Studies have shown that standard New Zealand dairy pasture systems usually contain high levels of crude protein and have good digestibility, which can provide sufficient metabolic energy for dairy cows (Kolver, 2003). Supplementary feed is still needed during periods of insufficient pasture feed supply, such as summer drought or winter growth restriction (Clark et al., 2007). At this time, farmers can use stored feed or combine with additional feed crops to ensure that dairy cows receive adequate nutrition during these critical periods.

2.4 New Zealand diverse pasture systems

New Zealand pastoral systems have traditionally relied on a binary mix of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) (Pembleton et al., 2015). However, as environmental issues become more prominent and the need to improve production efficiency continues to increase, the livestock industry has begun to incorporate more diverse or multi-species pastures. In New Zealand, diverse pasture often include a range of grasses, legumes and herbs selected based on their unique and complementary functional characteristics. The aim of using diverse pastures is to improve livestock performance, extend seasonal feed supply cycles, and improve nutrient use efficiency while reducing environmental impacts such as nitrogen leaching (Albers & Albach, 2024; Sanderson et al., 2007; Guyader et al., 2016).

For example, forages such as chicory and plantain can have a positive effect on animal metabolic processes and soil nitrogen cycling by reducing nitrogen concentrations in livestock urine (Guyader et al., 2016; Cheng et al., 2017). In addition, incorporating legumes and deep rooting pasture species can improve soil fertility and enhance pasture drought tolerance (Ovalle et al., 2015). However, further work is required to understand this potential, particularly from a New Zealand perspective. Diverse pastures also present management challenges for maintaining species balance and adjusting grazing to account for fluctuations in feed supply (Pembleton et al., 2015; Rouque, 2015; Fynn et al., 2017).

One of the challenges for managing pastoral systems in New Zealand is soil quality, particularly issues around soil compaction and the influence this has on pastoral production and the environment (Drewry, 2006d). Adjusting management practices and pasture type have been suggested as possible ways of improving soil health (Grelet et al., 2021). However, further work is required to assess this potential under New Zealand conditions, with the key soil physical properties forming the focus of this thesis outlined below.

2.5 Soil physical properties

Soil physical properties encompass a range of interrelated characteristics such as soil texture, structure, bulk density, porosity, aggregate stability, pore size distribution and water retention (Drewry et al., 2022). These properties determine the capacity of soil to store and conduct water and air, promote root penetration, and support overall soil life. Understanding these parameters is important on New Zealand pastoral farms, where pasture performance and nutrient cycling are directly impacted by soil physical quality (Houlbrooke et al., 2021). A variety of methods are employed to measure soil physical properties. In this thesis, I focus on measuring soil bulk density, soil penetration resistance, and soil volumetric water content (VWC).

2.5.1 Bulk Density

Soil dry bulk density is defined as the mass of oven-dry soil per unit volume, including both solids and pore space (Al-Shammary et al., 2018; Robinson et al., 2022). It affects infiltration, effective rooting depth, porosity, water holding capacity, aeration and the availability of nutrients. Sandy soils have relatively high bulk density because they have less total pore space compared to silty or clayey soils (Al-Shammary et al., 2018; Hao et al., 2018).

Bulk density can be used to assess soil compaction from stock or vehicle traffic (Houlbrooke et al., 2011). Compaction can reduce porosity, affecting air supply to roots and negatively impacting pastoral production. It can also reduce infiltration, leading to higher runoff and potential loss of topsoil and phosphate to freshwater (Chambers et al., 2000; Haghnazari et al., 2018).

2.5.2. Penetration Resistance

Soil penetration resistance quantifies the force required to mechanically penetrate the soil (Herrick & Jones, 2002). This can be used as an indicator of soil strength and compaction. High penetration resistance values from soil compaction can limit the downward growth of plan roots (Bécel et al., 2011; Valentine et al., 2012). Root restriction will limit access to subsoil moisutre and therefore the sward's ability to withstand dry conditions. It can also increase pasture pulling during grazing and therefore pasture persistence. Potential carbon sequestration in subsoil will also be limited by restricted root penetration (Lal, 2021). Compaction can negatively impact infiltration, causing greater runoff and potential loss of topsoil and phosphate. Soil will naturally repair through time as drying cracks, roots, and soil organisms create new pore spaces. However, a severely damaged paddock can take several years to repair, leading to reduced pastural production and increased costs if mechanical intervention is required (Drewry, 2006d).

Penetration resistance is highly sensitive to soil water content; wet soils generally exhibit lower resistance compared to dry soils owing to reduced friction between particles. This dependency necessitates the simultaneous measurement of VWC to allow meaningful comparisons to be made (Dodd & Mackay, 2011; Celik et al., 2010).

2.5.3 Volumetric Water Content (VWC)

Soil VWC is defined as the ratio of the volume of water in the soil to the total soil volume. When soil is saturated or near saturation, it typically displays reduced friction between soil particles, leading to lower penetration resistance (Bengough et al., 2011; Wang et al., 2016). Conversely, dry soil often displays higher penetration resistance due to the loss of moisture (Al-Shammary et al., 2018; Celik et al., 2010).

Measuring VWC is traditionally performed using gravimetric methods and converting gravimetric water content to VWC using dry bulk density or by estimating using Time Domain Reflectometry (TDR). TDR sends an electromagnetic pulse through probes inserted into the soil and measures the time it takes for the pulse to travel and reflect. This can then be correlated to the dielectric constant of the soil-water mixture to estimate the soils VWC (Skierucha, 2000).

2.6 Pugging and soil compaction

Soil compaction can occur at low to moderate levels of soil saturation, resulting in compressed soil aggregates and reduced porosity which can negatively affect plant growth (Drewry et al., 2008). Compaction from vehicle and stock movement can be difficult to see as the surface of the soil can still be flat with no obvious signs of damage. Often compaction can be identified by a reduction in yield or pasture production (Houlbrooke et al., 2021), highlighting the need for closer inspection and soil testing.

In contrast, pugging is the deformation and remoulding of soil and generally occurs when the soil is at or close to saturation and is behaving plastically (Howes, 2019). It is often associated with cattle grazing but can also occur under sheep grazing (Drewry and Paton, 2005). Pugging can damage pasture, resulting in reduced growth, utilisation and issues with weeds (Drewry, 2003). It also damages soil structure and can increase loss of sediment, nutrients and pathogens via surface runoff (MfE, 2023). Pugging results in a very rough, uneven and muddy soil surface, making it much easier to observe. Often pugging and compaction occur together on New Zealand pastoral farms and although they tend to mainly impact the upper topsoil, they can influence soil physical properties down to around 30 cm depth (Drewry, 2024).

A range of factors influence the susceptibility of a soil to pugging and compaction including the soils inherent strength, moisture content, stock class and intensity, grazing duration and vegetative cover (Houlbrooke et al., 2021). One of the most critical factors influencing pugging damage is soil moisture content. The plasticity of the soil under wet conditions makes it more prone to deformation upon the application of pressure from livestock hooves. Furthermore, experimental results show that extended grazing durations on wet soil substantially increase the depth and density of pug marks when compared to shorter grazing periods (Howes, 2019).

While a single grazing event can inflict measurable pugging damage, repeated grazing over consecutive seasons or within the same season can lead to cumulative damage that is more difficult to reverse. Continuous or intense grazing regimes may not allow sufficient recovery time for the soil, resulting in a long term decline of soil structure and pastoral production (Howes, 2019; Houlbrooke et al., 2021). Over time, the repetitive force exerted by grazing animals leads to a persistent increase in bulk density and reduced porosity, ultimately compromising its capacity to support healthy pasture ecosystems (Houlbrooke et al., 2021).

2.7 Practical implications for pastoral agriculture

Soil physical properties play a crucial role in determining the suitability of soil for plant growth. High bulk density and penetration resistance can limit root penetration and reduce the soil volume accessible to roots, thereby restricting water and nutrient uptake and limiting agricultural production (Mackay, 2008). New Zealand pastoral systems rely on high-quality pasture that requires optimal water availability, root growth, and nutrient uptake. When soil has low bulk density and high porosity, it facilitates adequate water storage and drainage, ensuring that the root zone remains aerated and that water is accessible when needed (Drewry et al., 2022; Houlbrooke et al., 2021). In contrast, compaction hinders water infiltration, restricts root expansion and can lead to a reduction in readily available water capacity (Drewry et al., 2022, Foote et al., 2015).

In a dairy context, maintaining soil physical quality can be challenging due to higher stocking rates and generally heavier grazing animals. Avoiding grazing when soil moisture is high, reduces the likelihood of soil damage and promotes a more stable and resilient soil structure (Aarons et al., 2015; Houlbrooke et al., 2021). In many New Zealand dairy systems, macroporosity levels below the critical threshold of 10% are associated with decreased pasture production and higher runoff, directly compromising the sustainability of dairy production (Drewry et al., 2022, Foote et al., 2015). This 10% macroporosity threshold generally refers to the top 0–10 cm of the soil profile, where hoof impacts and surface macropores most influence infiltration and pasture rooting (Drewry et al., 2022; Shepherd et al., 2000). Management strategies to minimise pugging and compaction include reducing stocking density, increasing post grazing residuals or restricting grazing during wet conditions by using feed pads, wintering barns or runoff blocks (Clark et al., 2007; Houlbrooke et al, 2011). Mechanical intervention can also be used to alleviate soil damage and increase pastoral production, including cultivation or soil aeration (Laurenson et al., 2015).

Regular soil quality monitoring can be used to assess compaction and inform management practices and remedial actions. The Visual Soil Assessment (Shepherd et al., 2000) is a practical tool that can be used by farmers and landowners to check for issues associated with pugging and compaction. A range of laboratory measurements such as bulk density, macroporosity and hydraulic conductivity can also be used to evaluate soil (Clark et al., 2007), however, these can sometimes be cost prohibitive. Monitoring soil quality allows farmers and landowners to look after soil structure and address issues with soil compaction, erosion or loss of organic matter (Shepherd et al., 2000).

CHAPTER THREE: BASELINE DATA

The following chapter contains an article intended for publication in the New Zealand Journal of Agricultural Research. This work assesses 2023-2024 penetrometer and bulk density data collected as part of the Whenua Haumanu regenerative agriculture trial on Massey University's Dairy Farm One and Pasture and Crop Research Unit in Palmerston North, New Zealand. The goal is to establish baseline data for ongoing annual comparisons to test whether there are any differences in soil physical properties between standard and diverse pastures and contemporary and regenerative grazing management.

Key discussion points include:

- Baseline data on soil physical properties (bulk density, penetration resistance) across the Whenua Haumanu farmlets over the first two years of the trial.
- No significant differences in soil physical properties were detected between pasture types (standard vs diverse) or management approaches (contemporary vs regenerative) at this stage.
- Differences in soil physical properties largely reflect changes in soil texture associated with different soil types.
- Seasonal fluctuations in soil moisture content influence soil physical measurements.

View north up the Manawatū River valley from Turitea Pā in 2023. Dairy Farm One farmlets visible on the far-right hand side of the photograph.

Establishing baseline soil physics data to support the Whenua Haumanu regenerative agriculture trial in New Zealand

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3.1 Abstract

Regenerative agriculture generally involves managing farms to improve soil health, plant and animal nutritive quality, and reduce animal stress and dependence on agricultural chemicals. Despite rapidly gaining popularity, there has been little research conducted to assess the potential advantages and disadvantages of regenerative agriculture, particularly from a New Zealand perspective. To help address this knowledge gap, Massey University in partnership with New Zealand's Ministry for Primary Industries and a range of other key stakeholders have established Whenua Haumanu, a seven-year trial aimed at evaluating the suitability of regenerative agriculture within the unique context of New Zealand's climate, soils, and farming practices. This paper presents 2023 and 2024 penetrometer and bulk density data gathered across 34 transects on Massey University's Dairy Farm One and Pasture and Crop Research Unit in Palmerston North, New Zealand. The objective is to establish baseline data for ongoing annual comparisons to test whether there are any differences in soil physical properties between standard vs diverse pastures and contemporary vs regenerative grazing treatments. The results demonstrate that no statistically significant differences exist between the treatments at this stage of the study. Significant differences were found between soil types, largely reflecting differences in soil texture. Differences were also observed between sampling years and can be attributed to seasonal changes in moisture content. This paper provides a valuable baseline that will allow potential differences to be measured as the trial progresses.

3.2 Introduction

In New Zealand, regenerative agriculture (RA) is a relatively new and developing concept, which is receiving attention from farmers, researchers and policy makers (Grelet et al., 2021). It generally involves managing farms to improve soil health, plant and animal nutritive quality and reduce animal stress and dependence on agricultural chemicals (Sharma et al., 2024). Although there is a lot of anecdotal evidence about the environmental, economic and social benefits of RA, there is limited scientific research to support these claims, particularly from a New Zealand perspective (Grelet et al., 2021; Burns, 2021; Curran-Cournane et al., 2024).

To address this knowledge gap, Massey University, in partnership with the Ministry for Primary Industries (MPI) and a consortium of industry stakeholders, established the Whenua Haumanu Programme (WHP). WHP is a seven-year trial designed to evaluate the suitability and relevance of RA practices for New Zealand, taking local climate, soils and management systems into account. The programme investigates contemporary and regenerative farming practices across both standard pastures (perennial ryegrass and white clover) and diverse pastures (multi-species swards composed of grasses, herbs and legumes) at multiple research sites, including those at Massey and Lincoln Universities. It's a comprehensive trial measuring and monitoring from below the ground, to above the ground and into the animals and animal products, including nutrient leaching, greenhouse gas emissions, carbon storage, animal welfare, product quality and taste, and economics.

This paper focuses on the physical quality of soils under RA, examining resistance to penetration and bulk density as tools for assessing compaction from stock and vehicle traffic. Soil compaction reduces the downward growth of grassroots, limiting access to subsoil moisture and therefore the swards' ability to withstand dry conditions. It can also negatively affect pasture persistence (Crush and Thom, 2011) and the potential for carbon sequestration (Brevik et al., 2022). Compaction negatively affects soil infiltration, leading to higher runoff and potential topsoil and phosphate loss (Hu et al., 2021). Soil will naturally recover through time as drying cracks, roots, and soil organisms create new pore spaces. However, a severely damaged paddock can take several years to repair, leading to reduced pasture production and increased costs if subsoiling or mechanical aeration is required (Drewry, 2006d).

Pasture type and grazing management may influence the amount of and severity of soil compaction. Previous work in the United States (Machmuller et al., 2015; Williams et al., 2017; Blanco-Canquil et al., 2024), Poland (Gajda et al., 2016), Switzerland (Oliveira et al., 2024), India (Ramasamy et al., 2024) and New Zealand (Reganold et al., 1993) suggests RA practices can lead to the development of more favourable soil physical properties such as reduced bulk density and resistance to penetration, often associated with increased organic matter and earthworm numbers. However, many of these studies focus on sites that have been subject to long-term continuous cultivation and depletion of organic matter. More research is required to quantify the potential benefits of RA on different New Zealand soils and farming systems and how long it takes for these changes to occur, particularly for soils that have been under long-term permanent pasture.

This paper presents the 2023-2024 baseline penetrometer and bulk density results from the WHP to allow potential differences to be measured as the trial progresses. Bulk density and penetrometer analysis are two of the tools used to assess whether any compaction has taken place and can be used to assess whether there are any significant differences between the treatments over time. This research supports ongoing work to better understand the potential benefits and trade-offs associated with the adoption of RA practices in New Zealand, which can inform decision-making by farmers, researchers, and policymakers.

3.3 Study area

This research was conducted on two of the WHP farmlets, Dairy Farm One (40°22'34"S 175°36'36"E NZTM) located between the Massey University campus and Palmerston North City and the sheep and beef farmlet located at the Massey University Pasture Crop Research Unit (PCRU) (40°23'26"S 175°36'31"E), Palmerston North, New Zealand (Figure 3.1). The mean annual rainfall (2002-2023) is 977 mm as measured off Poultry Farm Road adjacent to

Dairy Farm One (Palmerston North EWS, NIWA Station Number 053613). Average monthly soil temperatures at 10 cm depth are 7.1℃ in July and 18.2℃ in January (Chappell, 2015).

Dairy Farm One occurs on the active flood plain of the Manawatū River at approximately 30 m above sea level. The farm is underlain by free-draining, sandy quartzo-feldspathic river alluvium over gravel that hosts a shallow aquifer connected with the Manawatū River. The area is subject to floods and sediment deposition, with the last major flood in 2004 resulting in up to 30 cm of sediment being deposited.

In contrast, PCRU is situated on the Tokomaru marine terrace above the Massey University campus at approximately 50 m above sea level. This high terrace is underlain by several metres of poorly drained, fine loess material that accumulated between 15-30 thousand years ago and acts to hydraulically isolate the coarse sand and gravel deposits of the 125,000-year-old marine terrace at depth. The Tokomaru marine terrace is characterised by an extensive network of mole and tile drains in an attempt to remove excess water during the wet season.

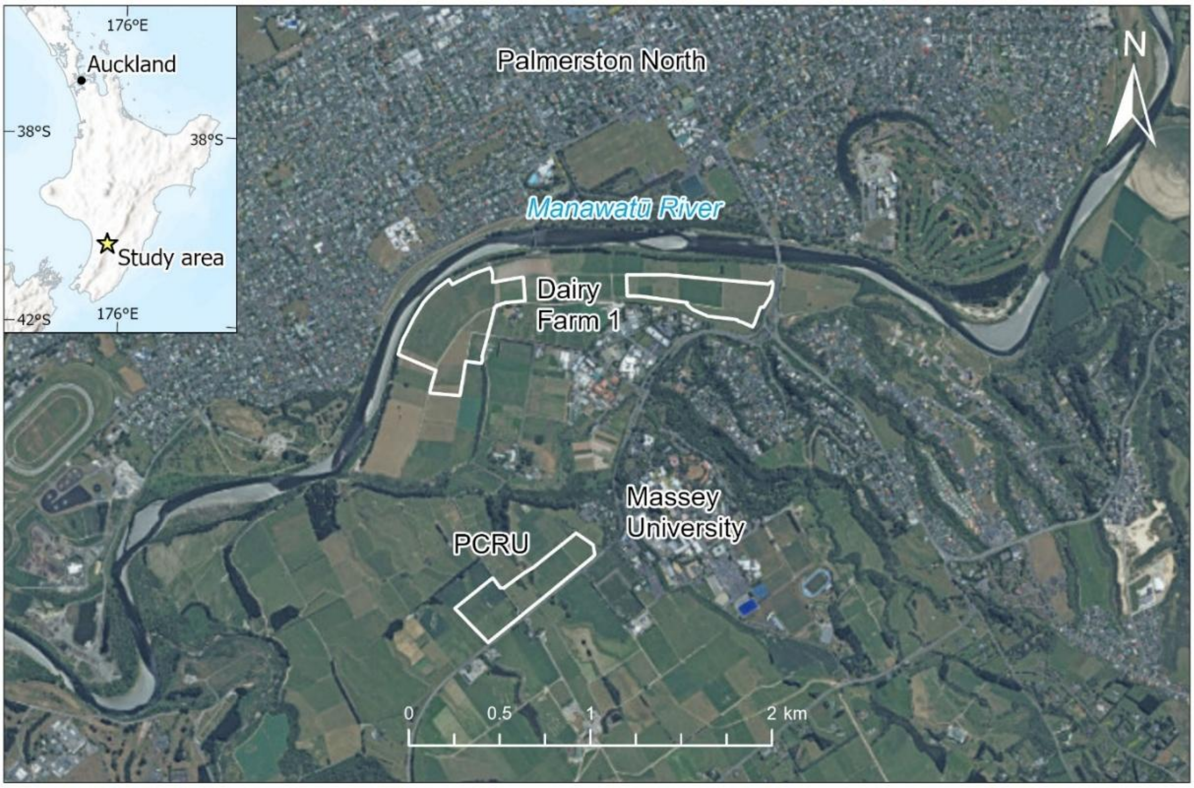


Figure 3.1: Location of the Whenua Haumanu farmlets (white polygons) on Massey University's Dairy Farm One and Pasture Crop Research Unit (PCRU) in Palmerston North.

Soil types

The soils of the Massey University campus and farms in Palmerston North were mapped by the late James (Jim) Armstead Pollok (former Reader in Soil Science at Massey University) between ~1950-2008 at an approximate scale of ~1:5,000. Final map compilation was assisted by Michael Richardson, Frances Lewis and Alton McDonald and digitisation was undertaken by Paul Nelson and Mike Tuohy (Tuohy and Irwin, 2008; Neall and Tonkin, 2015).

Associate Professor Alan Palmer and Dr Mike Bretheron (Massey University) undertook a ground truthing survey of the Massey soil map data across the Whenua Haumanu farmlets in 2022 to ensure sampling transects were positioned on a single soil type and fair comparisons could be made over time.

Dairy Farm One

The soils on Dairy Farm One are dominantly well-drained sandy recent soils that reflect floodplain deposition over the last ~2000 years. They are characterised by high natural variation, with texture classes commonly grading into one another. Due to difficulties encountered in taking intact soil core samples on the coarser-textured soils and in an effort to increase replication across treatments, the WHP science advisory team decided to consolidate soil physics sampling across two of the most widespread soils on the farm, the Manawatu sandy loam and Rangitikei loamy sand.

The Manawatu sandy loam is a well-drained Weathered Fluvial Recent Soil (RFW) developed in sandy alluvium over gravel at 60-120 cm depth. It occurs on the higher free-draining parts of the Manawatū River levees. It is more free-draining than Manawatu silt loam or fine sandy loam, meaning it can dry out in summer, but has less tendency for pugging and compaction in winter (Cowie, 1978). Leaching risk is high due to the free draining nature of the soil and the presence of a shallow gravel aquifer connected to the Manawatū River.

The Rangitikei loamy sand is a well to excessively well drained Typic Sandy Recent Soil (RST) that occurs on the lowest river flats. Soil profiles often display variable textures and flood layering over gravel at between 60-120cm from the surface (Cowie, 1978). Rangitikei soils are mapped as rapidly accumulating due to frequent flooding and deposition, however, on Dairy Farm One the last major flood was in February 2004 and resulted in up to 30 cm of sediment deposited across some paddocks. No major flood deposition event has occurred since, although surface water ponding is common in winter when the water table and Manawatū River are high, causing the Turitea Stream to backup.

PCRU

In contrast to the Manawatū floodplain, PCRU has a simple soil pattern dominated by Tokomaru silt loam, a poorly drained Fragic Perch-gley Pallic Soils (PPX). Tokomaru silt loam occurs on high terraces east of the Manawatū River that have thick deposits of wind-blown, quartzofeldspathic silt or loess. The profile contains dense, blocky and mottled subsoil with low permeability transitioning into a compact silt horizon called a fragipan at ~0.8 m depth (Pollock, 1975; Palmer et al., 2006). The fragipan is very dense, limiting the effective rooting depth and causing a perched water table to form in winter. The soil becomes very wet and sticky in winter and is prone to pugging. All of PCRU has been mole and tile drained in an effort to remove excess water through the wet season. The tile drains consist of slotted plastic pipe installed above the fragipan at ~0.6-0.8m depth and spaced 20-40m apart. Above and perpendicular to these drains at ~0.4-0.5 m depth are mole drains installed at 2 m spacings (Palmer et al., 2006).

3.4 Experimental setup

Dairy Farm One

Massey Universities Dairy Farm One is a low-input system that uses minimal supplementary feed, with cows milked once a day throughout the season. The WHP on Dairy Farm One consists of 36 hectares divided into three ~12-hectare farmlets. Each farmlet has its own herd of cows, which are balanced by breed (jersey, friesian and crossbred) and breeding worth (Table 3.1). Each farmlet has distinct pasture mixes and management strategies: **Std-Con**:

standard pasture under contemporary management; **Div-Con**: diverse pasture under contemporary management, and **Div-Reg:** diverse pasture under regenerative management. Contemporary farmlets are managed in alignment with DairyNZ recommendations (DairyNZ, 2021), while the regenerative farmlet adopts a range of alternative practices, including longer rest periods between grazing, higher post-grazing pasture mass, reduced synthetic fertiliser inputs, and the use of amendments that aim to support soil microbial function.

All pastures were direct drilled in April 2022 when the farmlets were being setup. Standard pasture includes a traditional mix of Italian ryegrass (*Lolium multiflorum*), perennial ryegrass (*Lolium perenne*), white clover (*Trifolium repens*), and red clover (*Trifolium pratense*). Diverse pasture includes the traditional pasture species together with phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*), tall fescue (*Lolium arundinaceum*), and prairie grass (*Bromus willdenowii*); herbs including plantain (*Plantago lanceolata*) and chicory (*Chicorium intybus*); a range of clovers including white, red, crimson (*Trifolium incarnatum*), persian (*Trifolium resupinatum*), subterranean (*Trifolium subterraneum*), balansa (*Trifolium michelianum*); and other legumes such as lucerne (*Medicago sativa*).

PCRU

Whenua Haumanu established four ~3 ha sheep farmlets on PCRU in 2022, each consisting of twelve paddocks ranging from 0.19 to 0.33 ha. Each farmlet has its own stock, distinct pasture mixes and management strategies: **Std-Con:** standard pasture under contemporary management; **Std-Reg**: standard pasture under regenerative management; **Div-Con**: diverse pasture under contemporary management, and **Div-Reg**: diverse pasture under regenerative management. All flocks of sheep are rotationally grazed within their farmlet year-round except during the lambing period, when they are set-stocked within their farmlet until at least docking. Contemporary grazing management includes 3-6 days per paddock without back fencing with a maximum 72-day rotation. Regenerative grazing includes 1-3 days per break with back fencing and a longer rotation to increase grazing intensity and maximise rest periods between grazing events. In addition to longer grazing intervals, the regenerative farmlets adopt a range of alternative practices, including higher post-grazing pasture mass, reduced synthetic fertiliser inputs, and the use of amendments that aim to support soil microbial function. Ewes are used as a tool across all farmlets to achieve the different grazing outcomes and stocking rates (Table 3.1). All lambs are removed from the farmlets at weaning.

All pastures were sown in 2022 with standard pastures comprising a mix of Italian ryegrass (*Lolium multiflorum*), perennial rygrass (*Lolium perenne*), white clover (*Trifolium repens*), and red clover (*Trifolium pratense*). Diverse pastures included the traditional pasture species together with meadow fescue (*Lolium pratense*), cocksfoot (*Dactylis glomerata*), timothy (*Phleum pratense*); herbs including plantain (*Plantago lanceolata*), chicory (*Chicorium intybus*), *Lotus corniculatus*, sainfoin (*Onobrychis sp.*), sheep's burnet (*Sanguisorba sp.*); a range of clovers including balansa (*Trifolium michelianum*), persian (*Trifolium resupinatum*), arrowleaf (*Trifolium vesiculosum*), subterranean clover (*Trifolium subterraneum*), strawberry clover (*Trifolium fragiferum*), and other legumes such as vetch (*Vicia sativa*).

Table 3.1: Whenua Haumanu treatments on Dairy Farm One and the Pasture and Crop Research Unit (PCRU).

Treatment	Pasture management system	Dairy Farm One	PCRU	Dairy Farm One (cows/ha)		PCRU (ewes/ha)	
				2022/23	2023/24	2023	2024
Std-Con	Standard pasture under contemporary management	✓	✓	2.0	2.5	14.0	14.0
Std-Reg	Standard pasture under regenerative management	x	✓	-	-	12.0	12.0
Div-Con	Diverse pasture under contemporary management	✓	✓	2.0	2.5	13.0	13.0
Div-Reg	Diverse pasture under regenerative management	✓	✓	2.0	2.5	12.0	12.0

Note Dairy Farm One years are based on a production year from 1st June to 31st May, while PCRU is run on a calendar year.

Rainfall and soil moisture deficit

Mean daily rainfall and modelled soil moisture deficit data for the Manawatu sandy loam on Dairy Farm One was sourced from Wittahachchi (2025) and the Palmerston North Ews climate station (NIWA Station Number: 053613) located off Poultry Farm Road, adjacent to Dairy Farm One (40°22'55.0"S 175°36'32.9"E). Note the rainfall pattern is considered representative of both the PCRU and Dairy Farm One farmlets (Figure 3.2). The soil moisture deficit for Manawatu sandy loam was calculated by Wittahachchi (2025) using the method of Scotter et al. (1979). In 2023, rainfall occurred frequently throughout the year leading to a wet winter and negligible soil moisture deficit during 26-28th July 2023 soil sampling. In contrast, rainfall in 2024 was concentrated over late winter and spring, meaning the soil profile had not fully wet up by the time 9-11th July 2024 soil sampling took place. The dry start to winter 2024 was followed by floods in August 2024.

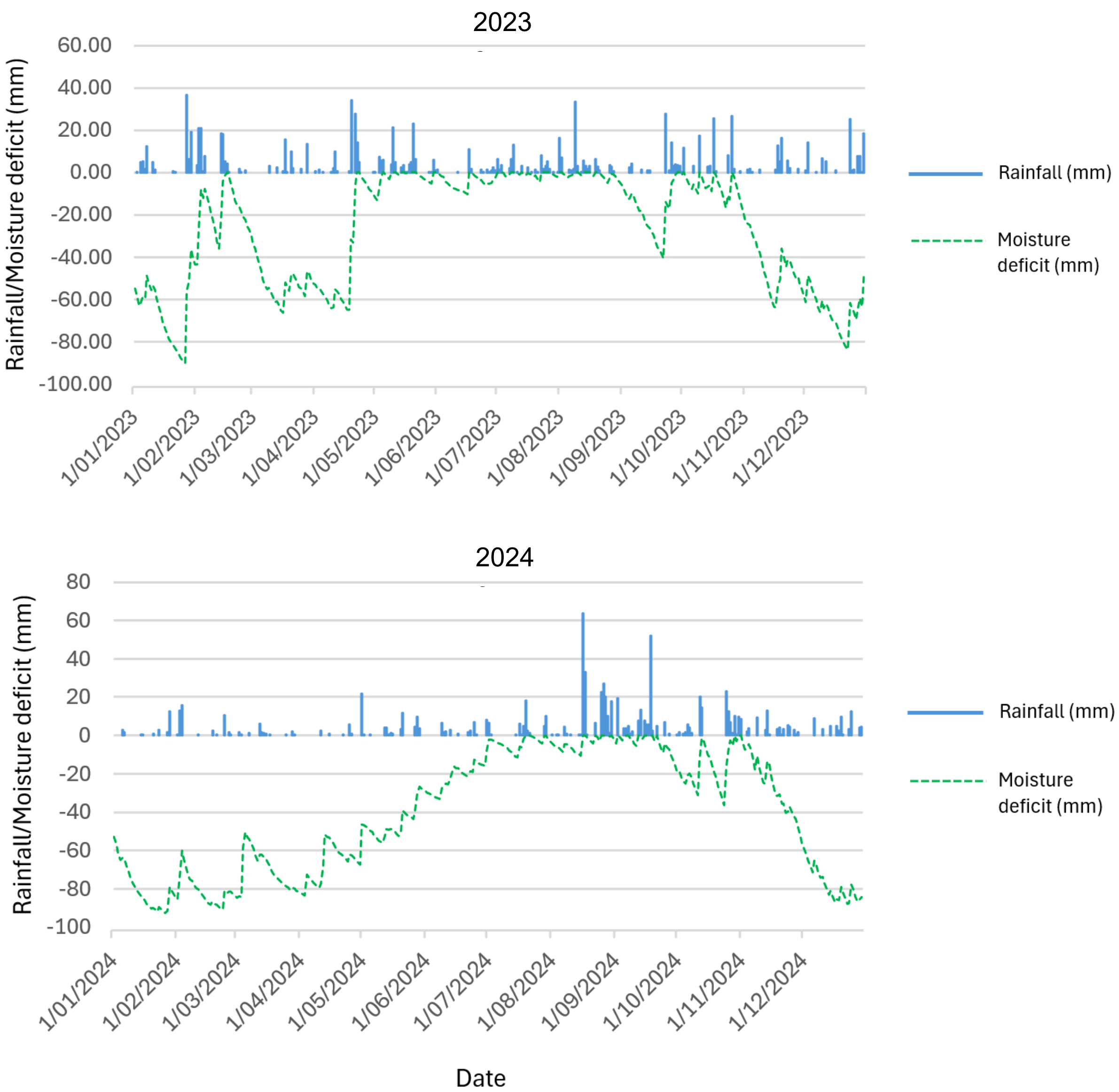


Figure 3.2: Mean daily rainfall and modelled soil moisture deficit for the Manawatu sandy loam on Dairy Farm One in 2023 and 2024 (Wittahachchi, 2025). Soil moisture deficit has been displayed as negative values for visualisation.

3.5 Sampling

All soil sampling was undertaken along intensively monitored transects in winter, targeting moist but not saturated soil conditions. Sampling was targeted for June to July and completed in the shortest timeframe possible, aiming for similar soil moisture content between sampling years. We aimed to maximise the time since the last grazing event to reduce the impact of an individual grazing event on resulting soil properties. The aim was to capture representative data of the soil at an instant in time reflecting the physical condition of the soil over that season. Sampling was completed at the same time of year in winter, following the recommendations from Schon and Mackay (2023).

Dairy Farm One

Eighteen intensively monitored transects were established on Dairy Farm One for annual soil physics sampling and analysis (Figure 3.3). Note that twelve of these eighteen transects were only sampled for the first time in 2024. This was due, in part, to issues encountered in 2023 in retrieving intact soil cores from shallow, coarse soils. In an effort to avoid these issues and increase replication, the Whenua Haumanu science advisory team decided to consolidate the intensively monitored transects in 2024 to focus on two of the most widespread soils on the farm, Manawatu sandy loam and Rangitikei loamy sand (Figure 3.3). This allowed for three replicates per treatment on each soil type. The transects were established based on a farm-scale soil map to ensure each transect is contained within a single soil type. These eighteen transects represent the final monitoring network and have been measured annually since 2024.

PCRU

Sixteen intensively monitored transects are established on PCRU for annual soil physics sampling and analysis (Figure 3.3). Due to the simple soil pattern on this landscape unit, all transects were able to be positioned on Tokomaru silt loam. There are four replicates per treatment on PCRU.

Bulk Density

Intact soil cores were taken at three equally spaced positions along each transect at depths of

0-5 cm and 5-10 cm in June/July 2023 and June 2024. Although treading damage can affect soil physical properties down to 30 cm depth, it more commonly impacts the upper topsoil (Drewry, 2024). Therefore, two sampling depths were selected, focusing on the upper topsoil while allowing potential differences in treading damage between the treatments to be assessed over time.

In 2023, six cores were taken per transect, but this was reduced to three cores per transect in 2024 to streamline the sampling process, with the proviso that additional cores would be collected if high variability was observed. All bulk density samples were analysed in the soil physics laboratory at Massey University. The undisturbed soil cores were oven-dried at 105°C until no further weight loss, and the dry weight was used to calculate bulk density. Operational details are provided in Appendix A.

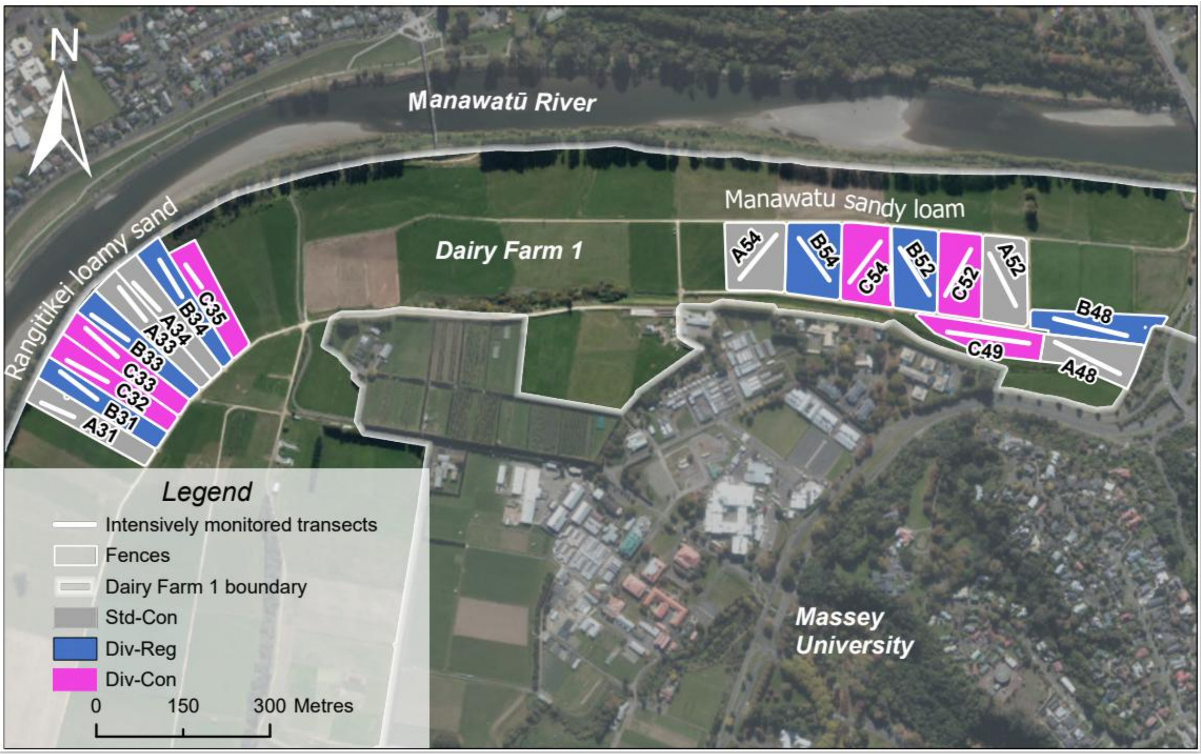


Figure 3.3: Location of the intensively monitored transects used for 2023-2024 soil physics sampling on Dairy Farm One. Note the location of farmlets on Manawatu sandy loam and Rangitikei loamy sand.

Figure 3.4: Location of the intensively monitored transects used for 2023-2024 soil physics sampling and analysis on PCRU. Note all these farmlets are located on Tokomaru silt loam.

Penetrometer

Resistance to penetration was measured at six equally spaced points along each transect to a maximum depth of 40 cm in July 2023 and June 2024. Measurements were taken using a CP40-II penetrometer, which records the force required to insert the cone into the soil at 0-40cm depth intervals. The penetrometer data are summarised by calculating means and standard deviations for each soil type, treatment, depth increment, and year of measurement. Operational details are provided in Appendix B. Soil moisture content was measured at the same time as resistance to penetration. In 2023, soil moisture content was measured by taking two cores to 15cm depth per transect to determine gravimetric and volumetric water content (VWC). In 2024, VWC was estimated using a Field scout Time-Domain Reflectometry (TDR) moisture sensor that provides an average estimated VWC for 0-15cm depth.

Statistical analysis

All statistical analyses were conducted using SAS 9.4®. Treatment effects were evaluated within each sampling year using analysis of variance (ANOVA) in PROC GLM. Treatment, soil type, and depth were specified as fixed effects, including their interactions where appropriate. Where significant main or interaction effects were detected, post-hoc pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test to adjust for multiple comparisons. Model assumptions of normality and homogeneity of variance were tested by examining residual plots and using the Shapiro–Wilk and Levene's tests, respectively.

Significance was determined based on F-tests, with $p < 0.05$ considered statistically significant and values between 0.05 and 0.10 interpreted as indicating marginal trends. Where significant treatment effects were detected, post-hoc pairwise comparisons were carried out using Tukey's honestly significant difference (HSD) test to adjust for multiple comparisons. Inter-annual comparisons were not performed statistically, as variation in seasonal soil moisture conditions was expected to influence measurements more strongly than treatment effects. Instead, treatment-related patterns were only assessed within each sampling year.

3.6 Results

3.6.1 Bulk density

In 2023 and 2024, higher bulk densities were generally measured on Dairy Farm One compared to the PCRU (Figures 3.5, 3.6, and 3.7).

Dairy Farm One

Within Dairy Farm One, no statistically significant differences were seen between the treatments in 2023 or 2024. Standard pasture (Std-Con) on the Manawatu sandy loam at 0-5cm depth displayed slightly higher mean bulk density in 2024 at 1.27 g/cm^3, compared to diverse pastures with a mean of 1.20 g/cm^3 and 1.21 g/cm^3 under the Div-Reg and Div-Con treatments, respectively. However, this potential difference is statistically insignificant ($p>0.05$).

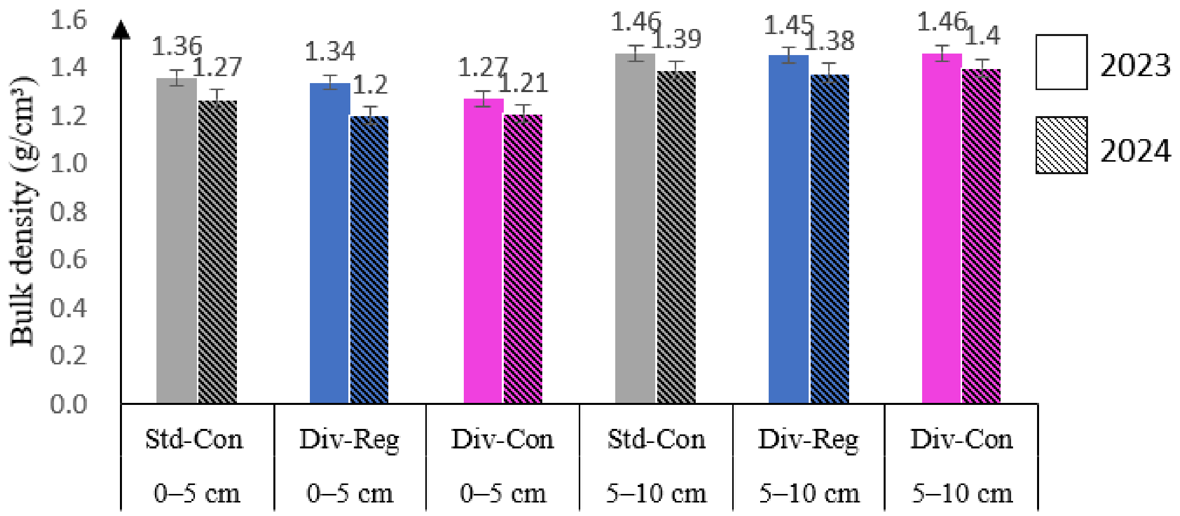


Figure 3.5: Mean bulk density (g/cm³) measured under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg) and Diverse pasture and contemporary management (Div-Con) on Manawatu sandy loam at Dairy Farm One in 2023 and 2024.

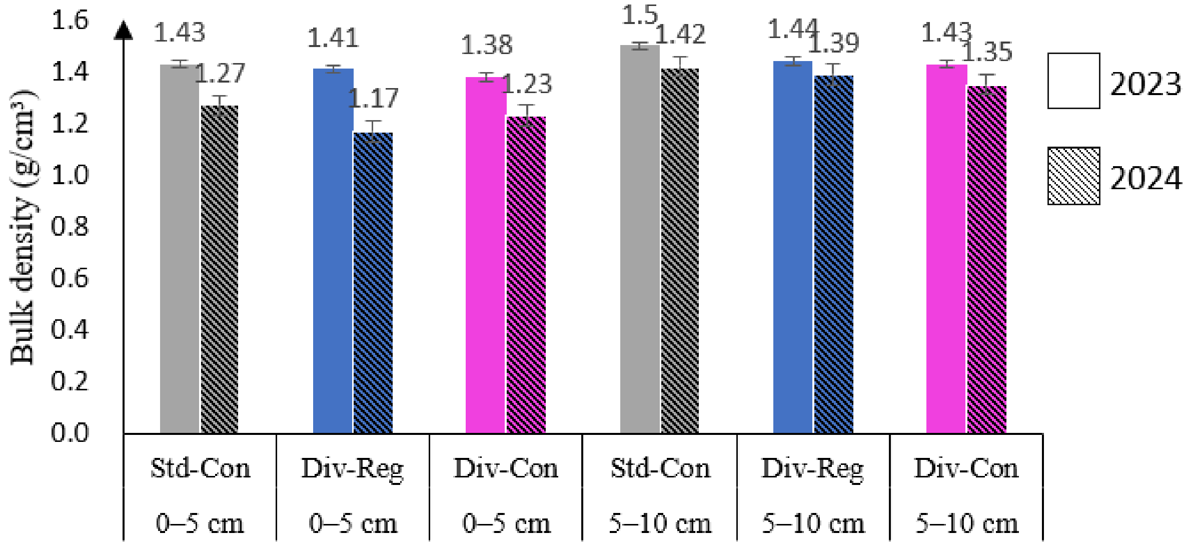


Figure 3.6: Mean bulk density (g/cm³) measured under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg) and Diverse pasture and contemporary management (Div-Con) on Rangitikei loamy sand at Dairy Farm One in 2023 and 2024.

PCRU

Within PCRU, bulk density remained relatively consistent across all management treatments at both 0–5 cm and 5–10 cm depths (Figure 3.6). Differences among treatments were minor and statistically non-significant ($p > 0.05$).

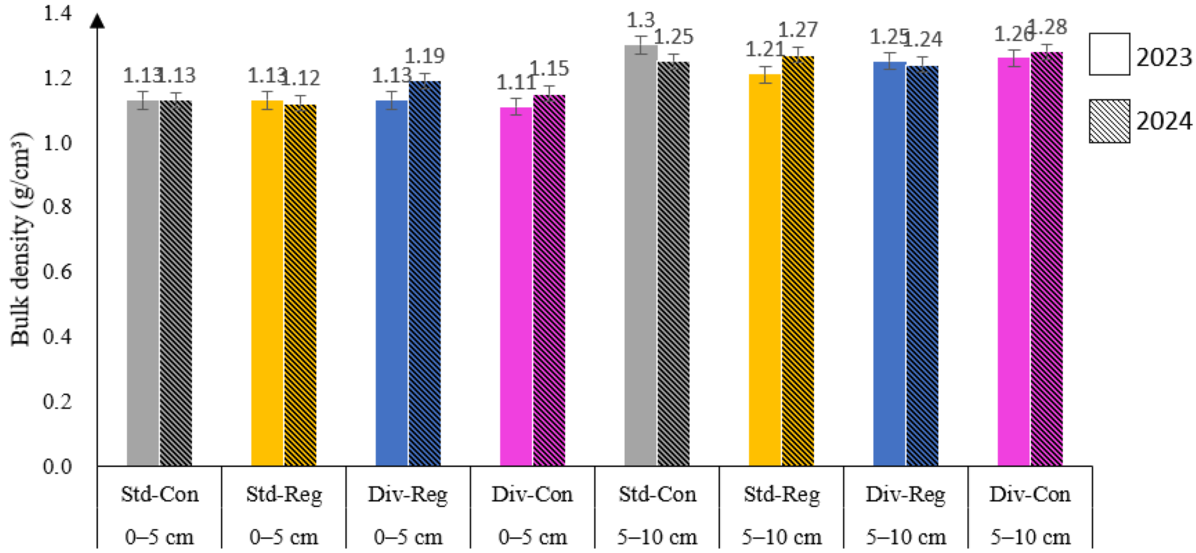


Figure 3.7: Mean bulk Density (g/cm³) measured under standard pasture and contemporary management (Std-Con), standard pasture and regenerative management (Std-Reg), diverse pasture and regenerative management (Div-Reg), and diverse pasture and contemporary management (Div-Con) on Tokomaru silt loam at Pasture Crop Research Unit (PCRU) in 2023 and 2024.

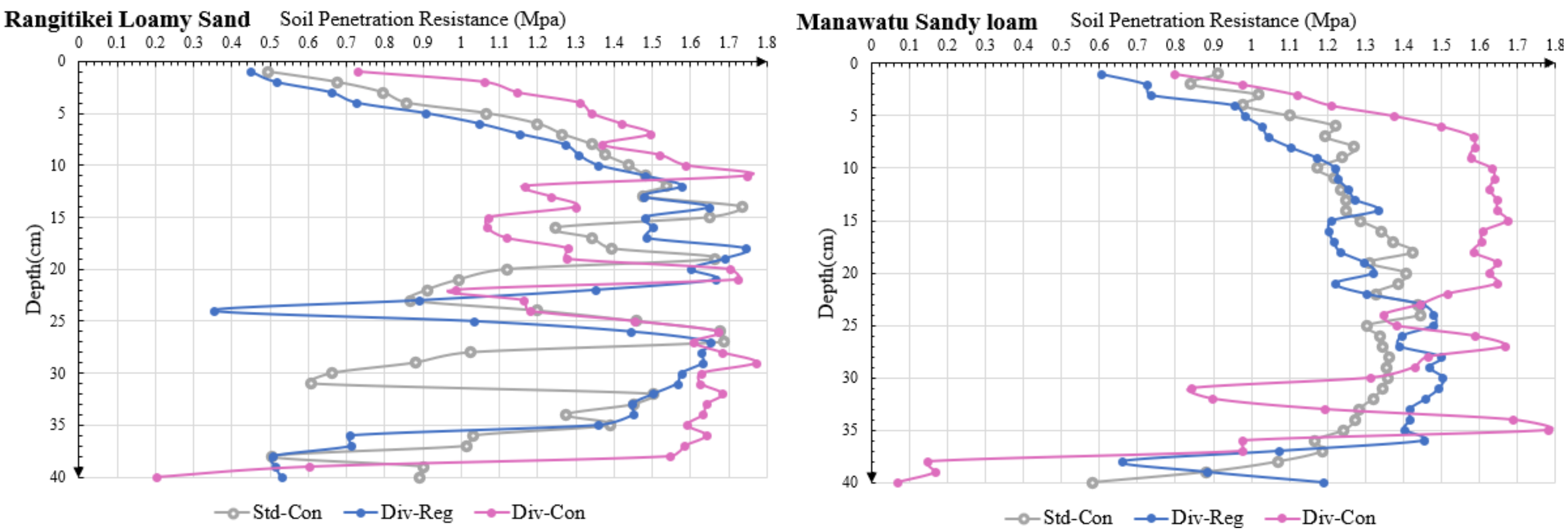
3.6.2 Penetrometer

The penetrometer data showed clear differences between the two farmlets, with the Dairy Farm One soils generally exhibiting higher penetration resistance compared to the finer-textured Tokomaru silt loam at PCRU (Figures 3.8-3.13).

Dairy Farm One

In general, both the Rangitikei loamy sand and Manawatu sandy loam display higher variation between treatments and down the soil profile in 2023 compared to 2024. Both the Rangitikei loamy sand and Manawatu sandy loam displayed markedly higher resistance to penetration in winter 2024 compared to winter 2023, particularly below 10 cm depth. No statistically significant differences can be seen between the treatments on either soil type at this time.

Volumetric water content ranged from 20.6% to 24.4% in 2023 and 22.7% to 30.2% in 2024. Across both sampling years, Manawatu sandy loam treatments consistently exhibited higher moisture content than the Rangitikei loamy sand. The contrast between soil types was more pronounced in 2024 (Figure 3.2). Although winter 2024 was characterised by lower total seasonal rainfall than 2023, soil moisture (0-15 cm depth) at the time of sampling was higher, likely reflecting short-term weather conditions prior to measurement. Although the topsoil (0-15 cm) was moist in winter 2024, the profile had not wetted up fully (Figure 3.2). The difference in topsoil moisture content between the soil types likely relates to the difference in total water holding capacity between the Manawatu sandy loam (22.45 ± 3.63 %v/v) and Rangitikei loamy sand (18.58 ± 7.65 % v/v) at 0-15 cm depth.



Figures 3.8: Mean soil penetration resistance (Mpa) measured under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg), and diverse pasture and contemporary management (Div-Con) on both Manawatu sandy loam and Rangitikei loamy sand at Dairy Farm One in 2023.

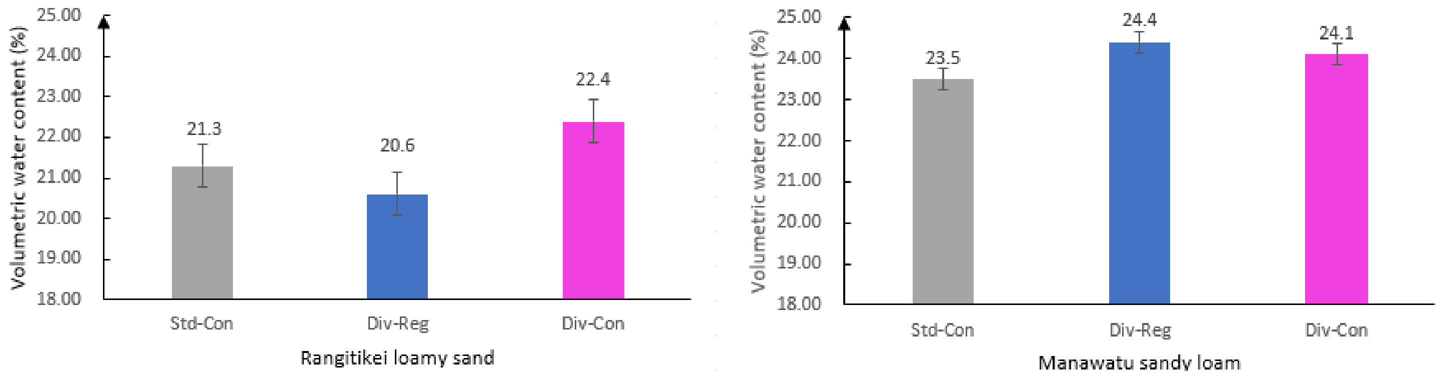


Figure 3.9: Mean volumetric water content (%) measured from 0-15cm depth under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg) and diverse pasture and contemporary management (Div-Con) management for the Rangitikei loamy sand, Manawatu sandy loam at Dairy Farm One measured in 2023.

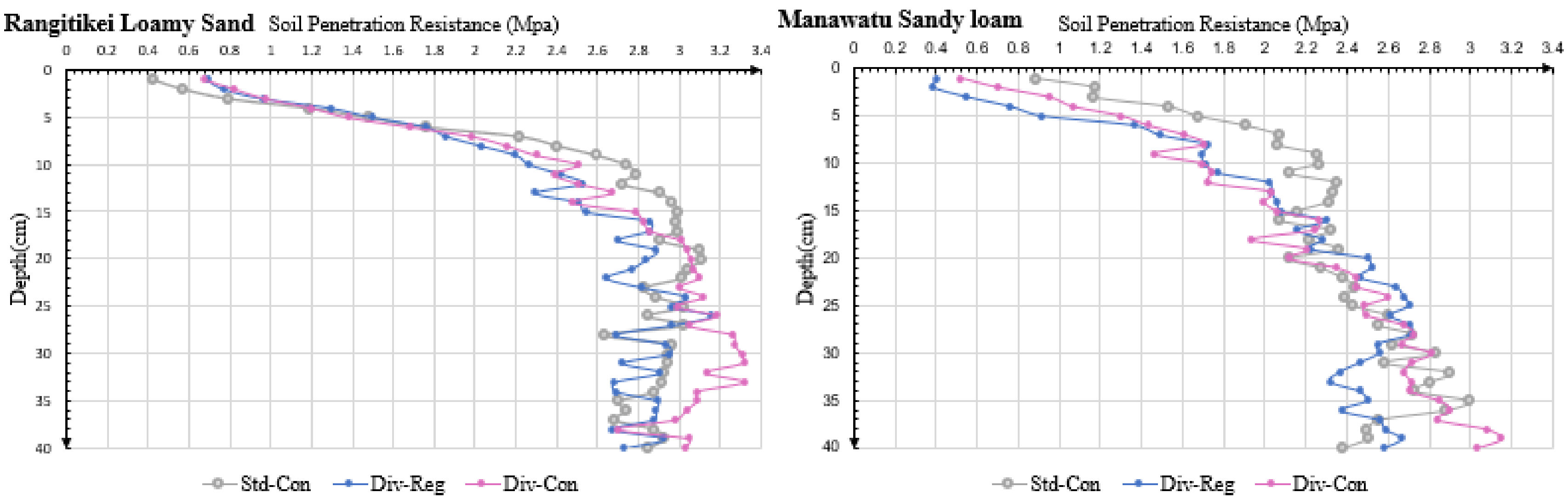


Figure 3.10: Mean soil penetration resistance (Mpa) measured under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg), and diverse pasture and contemporary management (Div-Con) on Manawatu sandy loam and Rangitikei loamy sand at Dairy Farm One in 2024.

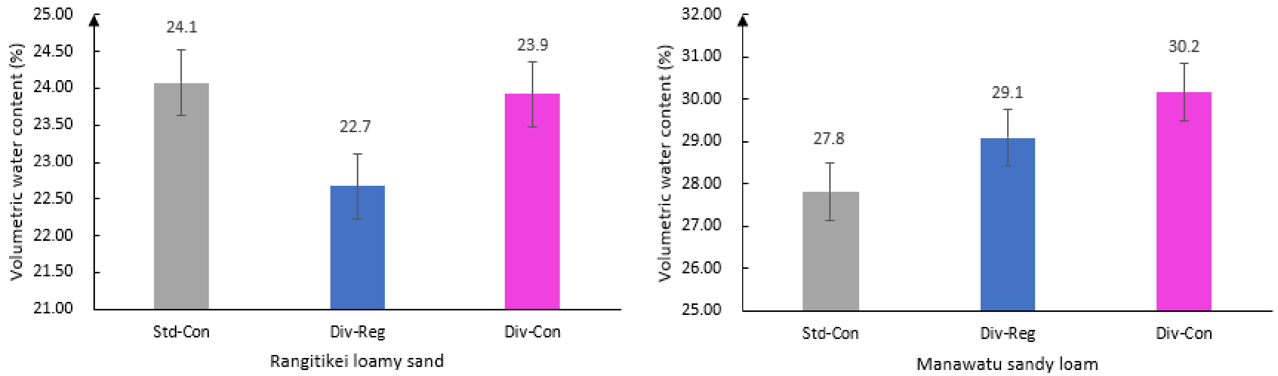
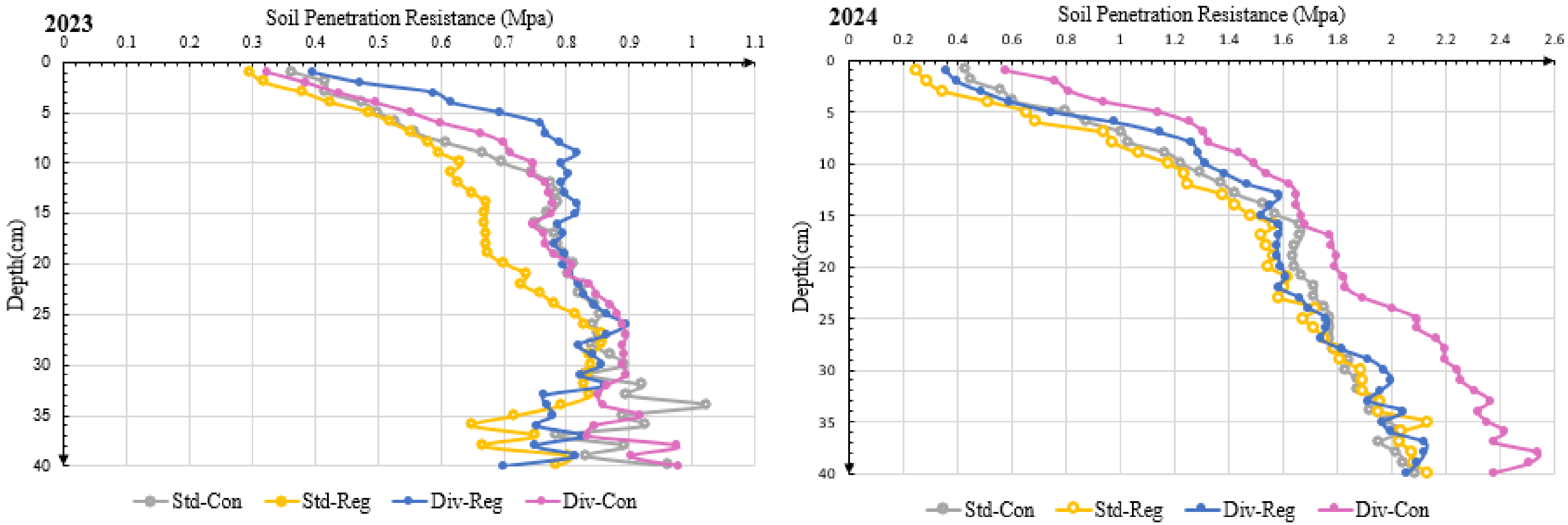


Figure 3.11: Mean volumetric water content (%) measured from 0-15cm depth under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg), and diverse pasture and contemporary management (Div-Con) management for the Rangitikei loamy sand, Manawatu sandy loam at Dairy Farm One measured in 2024.

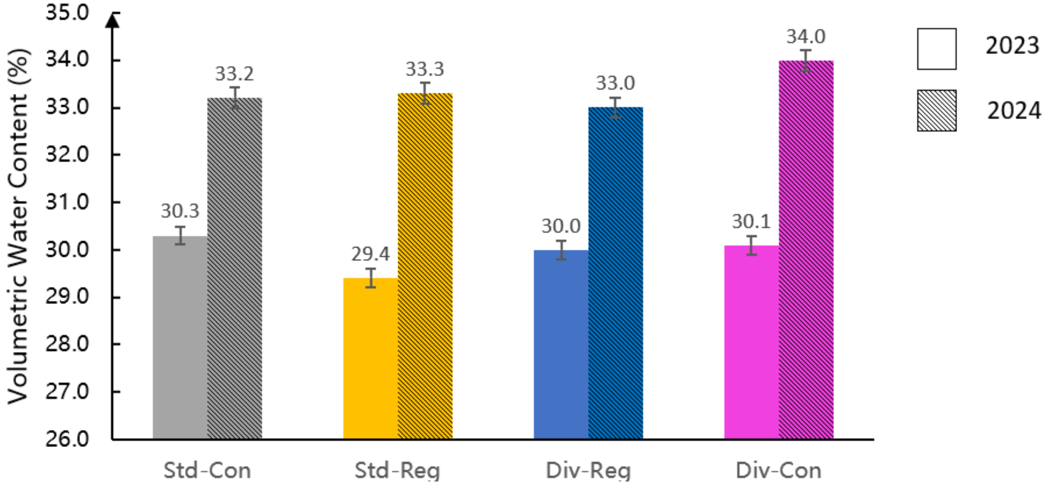
PCRU

In 2023, PCRU displayed lower resistance to penetration compared to the coarse recent soils on Dairy Farm One. However, this difference is less pronounced in 2024, where PCRU displayed higher resistance to penetration.

In 2023 and 2024, VWC values ranged from 29.4% to 34.0%. Mean VWC at 0–15 cm depth was higher in winter 2024 compared to winter 2023. While seasonal rainfall was lower in winter 2024 (Figure 3.2), the higher surface moisture at the time of sampling likely reflects short-term wetting prior to measurement. Although the Tokomaru topsoil (0-15 cm) was moist in winter 2024, a soil water balance calculated by Wittahachchi (2025) for Manawatu sandy loam on Dairy Farm One, demonstrates that winter 2024 was unseasonably dry and that soil profiles had not wet up at depth. The climate data for the soil water balance is considered representative of both Dairy Farm One and PCRU.



Figures 3.12: Mean soil penetration resistance (Mpa) measured under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg), diverse pasture and contemporary management (Div-Con), and standard pasture and regenerative management (Std-Reg) on Tokomaru silt loam at PCRU in 2023 and 2024.



Figures 3.13: Mean volumetric water content (%) measured from 0-15cm depth under standard pasture and contemporary management (Std-Con), diverse pasture and regenerative management (Div-Reg), diverse pasture and contemporary management (Div-Con), and standard pasture and regenerative management (Std-Reg) on Tokomaru silt loam at PCRU in 2023 and 2024.

3.7 Discussion

The baseline soil physical property measurements collected in 2023 and 2024 provide important insights into the initial conditions across the WHP farmlets early in the trial. No statistically significant differences can be seen between the different treatments at this time. This is not unexpected given that changes in soil physical properties in response to management can take several years to manifest, particularly in terms of bulk density (Drewry, 2006d; Schipper et al., 2014). As the diverse pasture swards and regenerative grazing practices are implemented over multiple seasons, differences between the treatments may start to emerge (Cartmill & Donaghy, 2024).

The consistently lower bulk density values observed on the PCRU farmlet compared to the Dairy Farm One site likely reflect inherent differences in soil texture between the two locations. The Tokomaru silt loam soil at PCRU has a finer texture compared to the coarser-textured Recent soils at Dairy Farm One. This aligns with established soil physics principles that finer-textured soils with higher clay content typically have lower bulk densities than coarser sandy soils (Houlbrooke et al., 2011). The lower penetration resistance values measured at PCRU further support this, as finer-textured soils generally offer less mechanical impedance to probe insertion during moist conditions. These inherent soil differences are important to document early in the trial and will need to be accounted for when evaluating treatment effects over time.

Higher bulk density and penetration resistance values observed at 5-10 cm compared to 0-5 cm depth (Figures 3.5-3.12) likely reflect surface accumulation of organic matter, greater root density, and biological activity in the top few centimetres of the soil profile, typical of soils under pasture (Schipper et al., 2007). Monitoring changes in bulk density and penetration resistance down the soil profile will be important for assessing the influence of diverse pastures and regenerative management over time.

Spatial variability

The high standard deviations observed in both the bulk density and penetration resistance measurements, particularly at Dairy Farm One, highlight the inherent spatial variability in soil physical properties. This variability likely stems from the alluvial nature of the Recent soils, with localised differences in texture, and uneven animal treading patterns contributing to heterogeneity at the paddock scale. While this variability presents challenges for detecting statistically significant treatment effects, it also underscores the importance of the intensive sampling approach adopted in this study. The use of multiple measurement points along transects helps capture this variability and provides a more robust characterisation of soil conditions across the experimental plots. Additional replication of treatments could be considered to help address the relatively high natural variation of the sandy Recent soils on Dairy Farm One.

Influence of soil moisture

The high variability in penetration resistance on Dairy Farm One (Figures 3.8 and 3.10) suggests that soil moisture content at the time of measurement is influencing the results. Wetter soils generally have lower penetration resistance (Drewry et al., 2022). Unfortunately, moisture content was only assessed from 0-15cm depth at the time of sampling, which limits our ability to interpret the penetration resistance results down the soil profile. The sandy Recent soils on Dairy Farm One vary in texture both laterally across the floodplain and vertically down the profile, reflecting individual flood deposition layers that have accumulated over time. These vertically stacked flood layers vary in texture and may be influencing moisture content and penetration resistance down the profile.

Rangitikei loamy sand had slightly lower volumetric water content at 0-15cm depth in both 2023 and 2024 compared to the Manawatu sandy loam (Figures 3.9 and 3.11). This likely reflects the sandier nature of the Rangitikei loamy sand, which is somewhat excessively well drained (Cowie, 1978). In contrast, the Tokomaru silt loam had slightly higher volumetric water content compared to the Rangitikei loamy sand or Manawatu sandy loam from 0-15cm depth in 2023 and 2024, likely reflecting higher clay content in the topsoil and the blocky, silty clay loam subsoil that restricts drainage (Climo and Richardson, 1984).

The soil water balance data from Dairy Farm One (Figure 3.2) demonstrates that 2023 was a typical wet winter with soil profiles reaching field capacity in early June, while 2024 was characterised by a dry start to winter. Soil profiles did not reach field capacity in 2024 until late July, followed by flood events in August 2024. WHP soil sampling targets moist conditions in winter on an annual basis. TDR measurements from 0-15 cm depth demonstrate that soils had similar volumetric water content in the topsoil between 2023 and 2024, however, the subsoil was likely drier in 2024. This could influence the results and demonstrates a weakness in our sampling methodology, which should include the measurement of volumetric water content down the profile alongside resistance to penetration.

Implications for plant growth

Typical bulk densities for Manawatu fine sandy loam topsoil (0-10 cm) under long-term grass range from 1.1-1.2 g/cm^3 (New Zealand National Soils Database, SB10034). Typical bulk density for Manawatu loamy sand topsoil (0-15 cm) under a kiwifruit orchard is 1.38 g/cm^3 (McAuliffe, 1985). Previous average bulk densities for Tokomaru silt loam topsoil under pasture are 0.99 ± 0.12 (0-5cm) and 1.18 ± 0.03 (5-10cm), respectively (Heng, 1991). The bulk density values measured in this study were broadly consistent with typical ranges reported previously for similar soil types. However, relatively high bulk densities measured in this study on Dairy Farm One, likely reflect the impact of compaction under dairy landuse.

All bulk densities measured in this study were below 1.6 g/cm^3, which is the threshold commonly associated with restricted root growth (McKenzie et al., 2004). Similarly, penetration resistance values were predominantly below the 2 MPa threshold commonly associated with root growth restriction (Bengough et al., 2011), suggesting that soil strength is unlikely to be substantially limiting pasture growth at present. Although some subsurface measurements at Dairy Farm One approached 3 MPa, these values are not uncommon in grazed pastoral systems and may reflect localised compaction or naturally dense alluvial layers.

Volumetric water content values were also consistent with winter conditions near field capacity for the respective soil textures, with the finer-textured Tokomaru silt loam retaining more moisture than the coarser Rangitikei loamy sand. Overall, the baseline measurements suggest that soil physical conditions at both sites are within expected ranges for intensively managed pastoral systems.

3.8 Conclusion

This study provides valuable baseline data on soil physical properties across the WHP farmlet trials at Massey University in the first two years of the programme. The penetrometer and bulk density measurements taken in 2023 and 2024 establish initial conditions against which future changes can be assessed as the treatments progress. The results demonstrate that no statistically significant differences in bulk density or penetration resistance exist between the pasture and management treatments after the initial two years. This is not unexpected given changes in soil physical properties in response to management can take several years to manifest.

The consistently lower bulk density and penetration resistance values observed at PCRU compared to the Dairy Farm One likely reflect inherent differences in soil texture. The finer-textured Tokomaru silt loam soil at PCRU has a naturally lower bulk density compared to the coarser-textured Recent soils at Dairy Farm One. This aligns with established soil physics principles. The lower penetration resistance at PCRU further supports this, as finer-textured soils generally offer less mechanical impedance when moist. High variability in bulk density and penetration resistance on Dairy Farm One highlights the inherent spatial heterogeneity of soil physical properties in these alluvial landscapes. This underscores the importance of the intensive sampling approach used in this study to adequately characterise the treatments.

While clear treatment differences have yet to emerge, these baseline measurements provide a solid foundation for evaluating the impacts of diverse pastures and regenerative grazing on soil physical quality over the course of the WHP. Continued monitoring will be essential for understanding how management-induced changes translate into effects on plant growth, animal production, and environmental outcomes.

CHAPTER FOUR: TREADING DAMAGE CASE STUDY

Chapter Four describes cattle treading damage under contemporary vs regenerative management and standard vs diverse pasture on Massey University's Dairy Farm One. Soil physical properties were assessed pre and post-grazing during saturated conditions to assess treading damage under different grazing practices and pasture types. The results from this work will be submitted as a journal article intended for publication in the New Zealand Journal of Agricultural Research.

Chapter four captures thesis objective 3 by investigating the influence of diverse pasture and regenerative management practices on key soil physical indicators. Key discussion points include:

- Bulk density, moisture content, and resistance to penetration are measured pre-grazing and post-grazing during saturated conditions to assess compaction.
- A pugometer developed by Howes et al. (2018) is used to quantify treading damage post-grazing and is linked with observations made during visual scoring.
- Rising plate metre measurements are undertaken pre and post-grazing to assess any influence on treading damage.
- Comparisons are made between contemporary and regenerative management and standard and diverse pasture treatments.

This chapter details soil physics measurements to assess the influence of pasture diversity and regenerative management on treading damage and links this research to other work done around New Zealand.

Calves on Massey University's Dairy Farm One farm in August 2024. Calf jackets are being used to provide extra warmth.

Assessing treading damage under regenerative versus contemporary dairy grazing and diverse versus standard pastures in New Zealand

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4.1 Abstract

This study investigates the short-term impacts of dairy cattle grazing on soil physical properties under two contrasting management systems at Massey University's Dairy Farm One farm in New Zealand. We compare soil physical properties between a regeneratively managed diverse pasture and a contemporary managed standard pasture before and after a grazing event under saturated soil conditions in Spring 2024. Both paddocks display evidence of soil compaction and pugging after grazing, but with notable differences in magnitude and spatial distribution. The contemporary managed paddock exhibited a greater increase in resistance to penetration and bulk density compared to the regeneratively managed paddock. Visual scoring and pugometer measurements revealed distinct spatial patterns of pugging damage that correspond to the timing of rainfall, antecedent soil moisture conditions and the location of troughs, shelter belts and gateways in the paddock, which influence animal behaviour. Higher pre and post-grazing pasture covers are associated with less pugging damage. However, repeat analysis and long-term monitoring are required to quantify the influence of higher pre and post-grazing pasture covers and diverse versus standard pasture swards on treading damage and post grazing pasture and soil recovery.

4.2 Introduction

Treading damage on dairy farms can negatively impact production and overall farm profitability. Leaf crushing, plant burial, and root damage can directly affect pasture growth and utilisation (Cartmill & Donaghy, 2024). Increased bulk density and decreased macroporosity can also indirectly restrict plant growth, reduce soil water infiltration and increase water runoff, heightening the risk of nutrient and pathogen loss to freshwater.

Soils are most vulnerable to treading damage during wet conditions when they lose strength and can undergo plastic deformation (Guo et al., 2024). Pugging occurs at high soil moisture content, where pressure from cattle hooves causes deformation and remoulding of the soil. While compaction occurs at lower moisture contents and tends to be a gradual process that occurs over years. Both processes can occur together; however, the risk of pugging increases with greater soil water content. Soil naturally repairs over time as drying cracks, roots and soil organisms create new pore spaces (Dexter, 1991). However, a severely damaged paddock can take several years to repair, leading to reduced pasture production and increased costs if mechanical intervention is required (Drewry, 2006).

In New Zealand, dairy farming generally involves intensive year-round grazing with no cow housing. This increases the potential for soil surface and pasture damage to occur during winter and early spring. The extent of treading damage is influenced by animal type and size, stocking rate, grazing duration and pasture cover (Wall et al., 2012). Management strategies to minimise pugging can include standing cattle off pasture during wet periods, however, this needs to be carefully balanced due to increased costs, supplementary feed and the influence on pasture growth rates.

Regenerative management practices are advertised as a way to improve soil health, plant and animal nutritive quality and reduce animal stress and dependence on agricultural chemicals. Common practices include maintaining higher pasture covers and post grazing residuals, grazing less frequently at a higher stocking intensity and aiming to increase soil carbon (Teague

& Kreuter, 2020). This has been suggested by practitioners to protect and enhance soil physical properties such as structure and porosity. There is also anecdotal evidence that incorporating deeper rooting species such as chicory into the sward will help develop soil structure and deepen topsoil. However, currently we lack research on the influence of regenerative management and diverse pastures on soil physical properties, particularly from a New Zealand pastoral perspective where soils have relatively high carbon, and the scope to increase this may be limited. Furthermore, the influence of regenerative management and diverse pastures on potential treading damage and soil physical properties is poorly understood (Drewry, 2006d).

This study aims to address this gap by investigating the influence of a single spring grazing event on a coarse-textured, saturated soil under contemporary versus regenerative management and standard versus diverse pasture in Palmerston North, New Zealand. The investigation forms a case study as part of the seven-year Whenua Haumanu Programme (WHP) into both contemporary and regenerative farming. The main aim of this work is to compare management and pasture types to assess if there is any difference in the pattern or severity of treading damage. Measurements are taken pre- and post-grazing to assess soil moisture, resistance to penetration, bulk density, and pasture covers. The depth and intensity of pugging damage is assessed using a visual scoring system and a pugometer developed by Howes et al. (2018).

4.3 Study area

The study was carried out from September to October 2024, with the approval of Massey University's animal ethics (MU22/17).

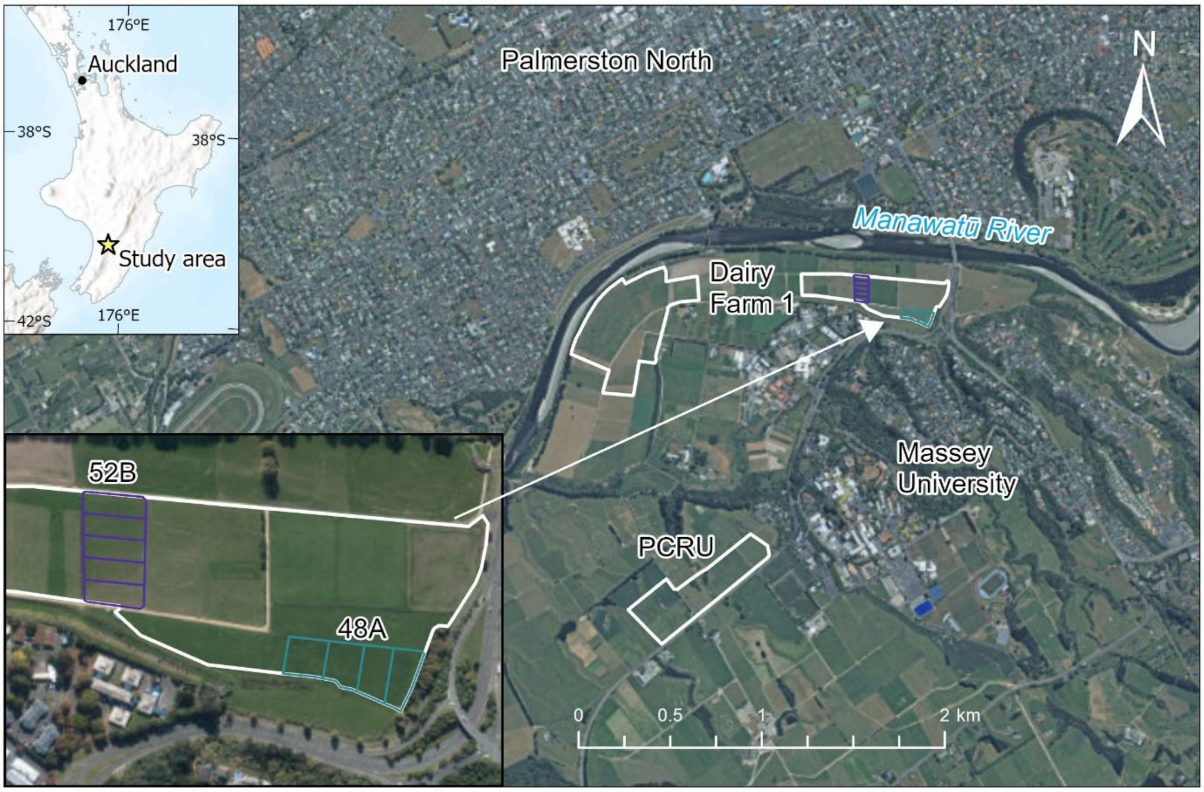


Figure 4.1: Paddock 52B and 48A in Palmerston North, New Zealand.

The study area comprises Paddocks 48A and 52B on Massey University's Dairy Farm One, located in the lower North Island of New Zealand (Figure 4.1). Dairy Farm One borders the Manawatū River and occurs within the Palmerston North City boundary. It is located approximately 35 metres above sea level and receives an average annual rainfall of between ~900-1000 mm(NIWA, 2024). Average monthly soil temperatures at 10 cm depth range from 9.7°C in July to 20.1°C in January (NIWA, 2024). The farm is located on the Manawatū River floodplain and consists of flat to undulating river terraces underlain by gravel alluvium. The soil parent material overlying the alluvium has built up over the last ~2000 years of floodplain deposition. Floods occur every ~10-20 years, with the last major flood event occurring in 2004, during which time up to 30 cm of sediment was deposited across the farm.

Paddocks 48A and 52B are underlain by Manawatu sandy loam, a well-drained Weathered Fluvial Recent Soil (RFW) developed in sandy alluvium over gravel. The soil has good physical properties with an estimated Profile Available Water (PAW) of 100vmm measured from 0-64 cm depth using a network of Time Domain Transmission (TDT) probes. Limitations include relatively low organic matter content due to the position on an active floodplain where the soil is subject to ongoing addition of river alluvium over time. Leaching risk is high due to the free draining nature of the soil and the presence of a shallow gravel aquifer connected to the Manawatū River. From a management perspective, the soil has a low vulnerability to structural damage, pugging, and waterlogging.

WHP is a seven-year project funded through MPI to assess the suitability and relevance of regenerative agriculture to New Zealand, taking our climate, soils and management systems into consideration. The project is exploring contemporary and regenerative farming practices across both standard (ryegrass and white clover) and diverse pastures (multi species of grasses, herbs and legumes) on several research sites at Massey and Lincoln universities and is currently in year 4 of the trial.

Massey University's Dairy Farm One is a 120 ha (effective) commercial dairy farm that operates a low-input pasture-based system with minimal supplementary feed and milks approximately 250-300 cows once a day throughout the season. The Whenua Haumanu trial uses approximately 36 hectares of Dairy Farm One, which has been subdivided into three farmlets: standard pastures under contemporary management (Std-Con), diverse pastures under regenerative management (Div-Reg), and diverse pastures under contemporary management (Div-Con).

The WHP dairy farmlets are run as self-contained units, each consisting of 13 farmlets ranging from 0.6 to 1.2 ha with a total area of ~12 ha. Contemporary farmlets are managed in alignment with DairyNZ recommendations (DairyNZ, 2021), while the regenerative farmlet adopts a range of alternative practices including longer rest periods between grazing, higher post-grazing pasture mass, reduced synthetic fertiliser inputs, and the use of amendments that aim to support soil microbial function

Each farmlet has its own herd of cows, which are balanced by breed (jersey, friesian, and crossbred) and breeding worth and are milked once-a-day all season (Table 4.1 and 4.2).

Supplementary feed is bought in as required but all farmlets target a system 1 configuration where 100% of feed is grown on farm. Culling of empty cows and drying-off from mid-lactation onward is governed by decision rules according to feed availability and animal body condition, which can result in variations in stocking rate and lactation status within farmlets from February through May each year.

Standard pasture includes a traditional mix of Italian ryegrass (*Lolium multiflorum*), perennial rygrass (*Lolium perenne*), white clover (*Trifolium repens*), and red clover (*Trifolium pratense*). Diverse pasture includes the traditional pasture species together with phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*), tall fescue (*Lolium arundinaceum*), and prairie grass (*Bromus willdenowii*); herbs including plantain (Plantago lanceolata) and chicory (*Chicorium intybus*); a range of clovers including white, red, crimson (*Trifolium incarnatum*), persian (*Trifolium resupinatum*), subterranean (*Trifolium subterraneum*), balansa (*Trifolium michelianum*); and other legumes such as lucerne (*Medicago sativa*).

Table 4.1: Cow breed in the Std-Con and Div-Reg farmlets between 14-18th September 2024.

Treatment	Holstein-Friesian	Jersey	crossbred
Std-Con	10	10	10
Div-Reg	8	8	8

Table 4.2: Characteristics of the Std-Con and Div-Reg farmlets between 14-18th September 2024.

Farmlet	Pasture management system	Area (ha)	Number of cows	Stocking rate (cows/ha)	Rotation length (days)
Std-Con	Standard pasture under contemporary management	~12	30	2.5	40
Div-Reg	Diverse pasture under regenerative management	~12	24*	2	60

*Note between 14-18th September 2024 two cows were still to calf in the Div-Reg farmlet so only 22 cows were in the milking herd when they grazed paddock 52B for this study.

4.4 Experimental setup

This study was carried out between September and October 2024 in Paddocks 48A and 52B of the Dairy Farm One which are under Std-Con and Div-Reg treatments, respectively. Paddock selection was based on the need to fit in with the farmlet rotations and align with a time of saturated soil conditions (spring) and rain forecast for upcoming grazing. The number of cows in the Std-Con and Div-Reg herds differed at the time due to the Div-Reg farmlet running a lower stocking rate (Table 4.2) and late calving cows that were still excluded from the Div-Reg herd.

Paddock 48A (Std-Con) was divided into 4 breaks with milking occurring daily at 8:30am, followed by allocation of a fresh break and pasture. Cows were able to use a trough located in Break 1 with an additional trough becoming available in Break 4 on the final day of grazing. This influenced animal traffic across Breaks 2 and 3 during grazing. An exclusion zone was located in Break 2 and was fenced off from stock. This area was excluded from the break area calculations and together with the troughs and a shelterbelt along the eastern side of Break 4 had an influence on animal behaviour. Cows entered Break 1 on 14/09/2024 and grazed the paddock over 4 days until 17/09/2024. During this time approximately 34.6mm of rain occurred on already saturated soil (Table 4.3).

Paddock 52B (Div-Reg) was divided into 5 breaks grazed between 14/09/2024 and 18/09/2024, with cows given a fresh break and pasture daily following milking (Table 4.2). Cows were back fenced to prevent them from walking back across previous breaks, with electric fencing used to create a lane and allow access to the troughs located in Break 1 and 3, respectively. An exclusion zone, located in Break 4, was fenced off from stock and together with a shelterbelt along the western side of Breaks 1-5 had an influence on animal behaviour. Back fencing meant that even although the Div-Reg farmlet was running a lower stocking rate than the Std-Con farmlet at the time, the stocking density or number of cows per break area was higher in the Div-Reg farmlet for Breaks 2-5. This aligns with regenerative management where cows enter a break with higher pasture cover, graze at higher density and leave higher residuals than under contemporary management. During grazing of Paddock 52B (Div-Reg), approximately 36mm of rain occurred on already saturated soil.

Table 4.3: Characteristics of paddock 52B and 48A breaks in Spring 2024.

Treatment paddock	Break No.	Date grazed	Area (ha)	No. of cows	Rainfall (mm)	SWD* (mm)	Average wind Direction (degrees)	Average wind Strength (km/hr)	Min air-temp (°C)	Max air-temp (°C)
Std-Con 48A	1	14/09/24	0.24	30	20.8	0	236 (SW)	3.5	10.4	13.7
	2	15/09/24	0.23		0.2	0.4	194 (SSW)	3.7	9.2	15.2
	3	16/09/24	0.25		4.8	0	236 (SW)	5.3	8.9	14.3
	4	17/09/24	0.26		8.8	0.1	159 (SE)	2.5	6.3	9.2
Div-Reg 52B	1	14/09/24	0.24	24**	20.8	0	236 (SW)	3.5	10.4	13.7
	2	15/09/24	0.21		0.2	0.4	194 (SSW)	3.7	9.2	15.2
	3	16/09/24	0.22		4.8	0	236 (SW)	5.3	8.9	14.3
	4	17/09/24	0.21		8.8	0	159 (SE)	2.5	6.3	9.2
	5	18/09/24	0.22		1.4	0.5	210 (SW)	7.2	1.7	12.3

*SWD – Soil Water Deficit measured by a network of Time Domain Transmission (TDT) probes from 0-64cm depth located in adjacent farmlets.

**Note there are 24 cows in the Div-Reg farmlet with a stocking rate of 2 cows ha^{-1} but two cows were still to calf and so were separate from the milking herd at the time of grazing.

Pre-Grazing Measurements:

Prior to the grazing, measurements were taken on the 12th and 13th of September 2024 across Paddock 48A (Std-Con) and 52B (Div-Reg), respectively. Measurements were taken along a 50 m transect line established in each break (Figures 4.2 and 4.3). Transects were located away from troughs, gateways and exclusion zones to minimise the influence of enhanced treading damage associated with those areas. Transect start and end points were marked using handheld GPS and tape measure.

Intact soil cores were taken in five positions (0 m, 12.5 m, 25 m, 37.5 m, 50 m) along each transect to determine bulk density and volumetric water content. The cores were taken to a depth of 20 cm by driving a stainless-steel corer with an inside diameter of 50 mm vertically into the soil using a post rammer. The core was then extruded using a push rod and cut using a PVC cutting template into 0-5cm, 5-10 cm, 10-15 cm, and 15-20 cm depth increments.

Intact soil samples were weighed in the Massey University soil physics laboratory before being oven-dried at 105ºC overnight and weighed again to determine bulk density and gravimetric water content. Bulk density was used to convert gravimetric into volumetric water content.

Resistance to penetration was measured at 30 points along each transect to a maximum depth of 50 cm. Measurements were taken using a CP40-II penetrometer, which records the force required to insert the cone into the soil at regular depth intervals.

Average pasture covers were measured using a plate meter by taking 30 measurements along each 50 m transect.

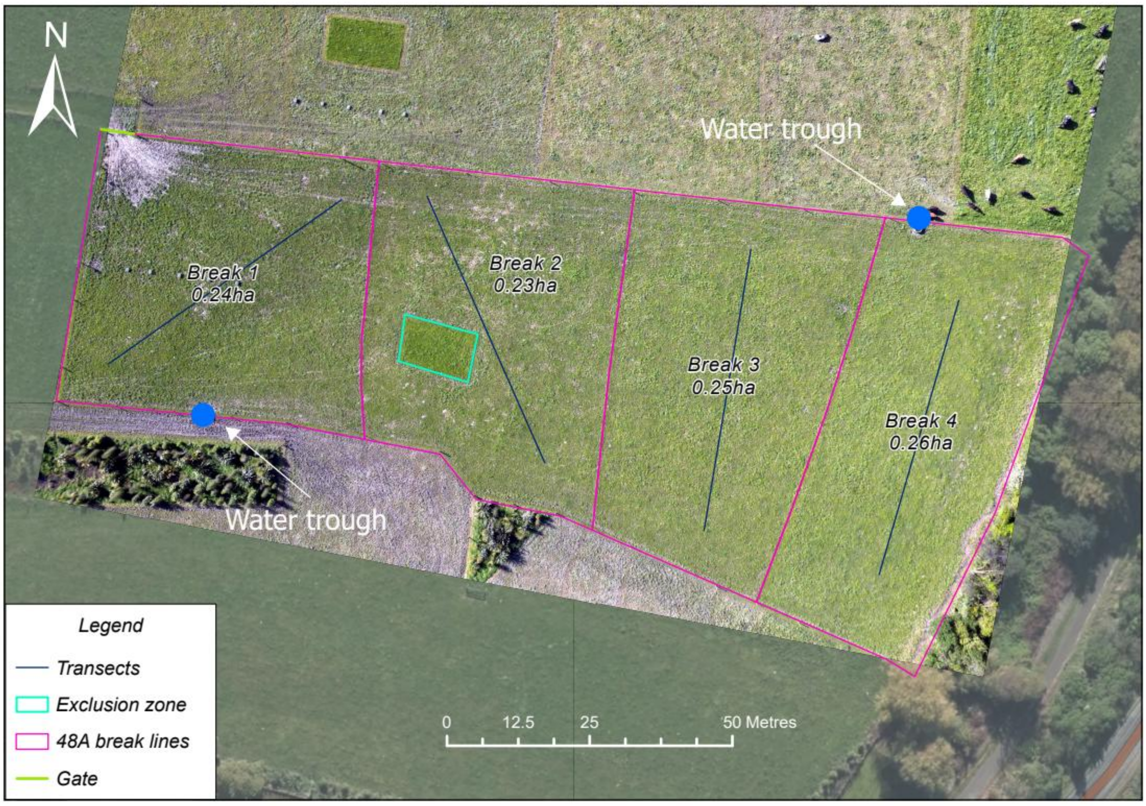


Figure 4.2: Transect locations in Paddock 48A (Standard pasture and contemporary management) of Dairy Farm One.

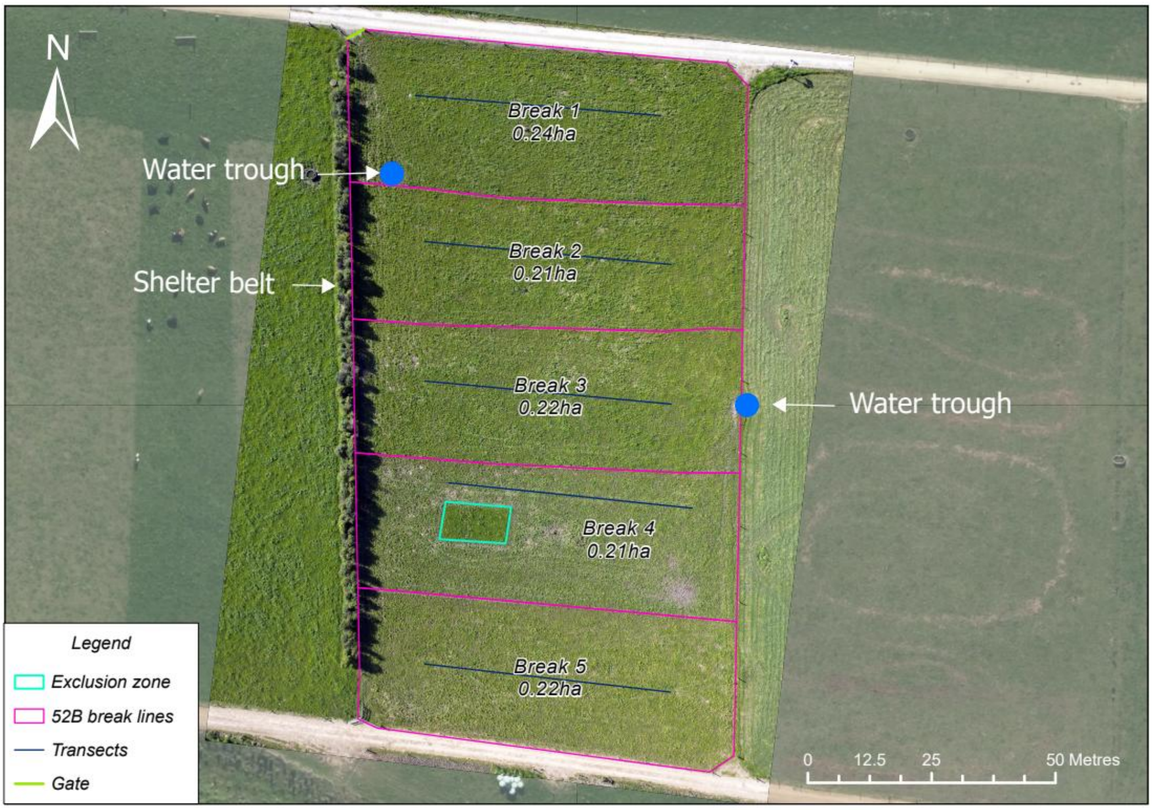


Figure 4.3: Transect locations in Paddock 52B (Diverse pasture and regenerative management) at Dairy Farm One.

Post-Grazing Measurements:

Due to ongoing rain and saturated soil conditions between the 20th and 27th of September, the post-grazing measurements were delayed and conducted on the 1st and 2nd of October 2024, approximately 12 days following grazing. This was done to minimise the risk of deformation when taking soil cores and ensure the pre and post grazing measurements were taken at a similar moisture content.

Intact soil cores, penetrometer and plate meter measurements were taken along the 50 m transects following the same protocol as pre grazing measurements. In addition, visual scoring was conducted on 24/09/2024 to assess the severity and distribution of treading damage according to the method of Sheath and Carlson (1998) (Table 4.4). A DJI Mini Pro 3 with a 48 MP camera was used to take high-resolution photography of the grazed areas on the 25th of September 2024, approximately 5 days after grazing (Figure 4.2 and 4.3).

A pugometer developed by Howes et al. (2018) was also used to assess the spatial distribution of pugging damage. The pugometer measurements were taken between the 1st and 2nd of October, approximately 12 days following grazing. Measurements were taken every 1 m along the transect between paddock fence posts located approximately 5 m apart. This allowed an average of 942 pugometer measurements to be taken per break to capture the magnitude and spatial variability of treading damage.

The pugometer data was written to a CSV file and imported into the ArcGIS Pro software. The point data was then interpolated using Inverse Distance Weighting (IDW) to create a map showing the spatial variability of the treading damage. IDW was selected as the most appropriate interpolation method by using cross-validation statistics and visual comparison.

The visual scoring system used to assess post-grazing treading damage in this study is outlined in Table 4.4. The scoring method uses a 5-point scale where higher scores indicate more severe damage. The scoring system evaluates three main types of damage indicators: Soil indentations progress from minimal at score 1 to very deep at score 5, indicating how much the soil surface has been compressed or depressed. Hoof smears appear starting at score 2 and become deeper at higher scores, suggesting visible marks left by animal hooves dragging across the soil surface. Surface disruption ranges from none at score 1 to intense at score 5, representing overall disturbance to the soil structure and surface integrity.

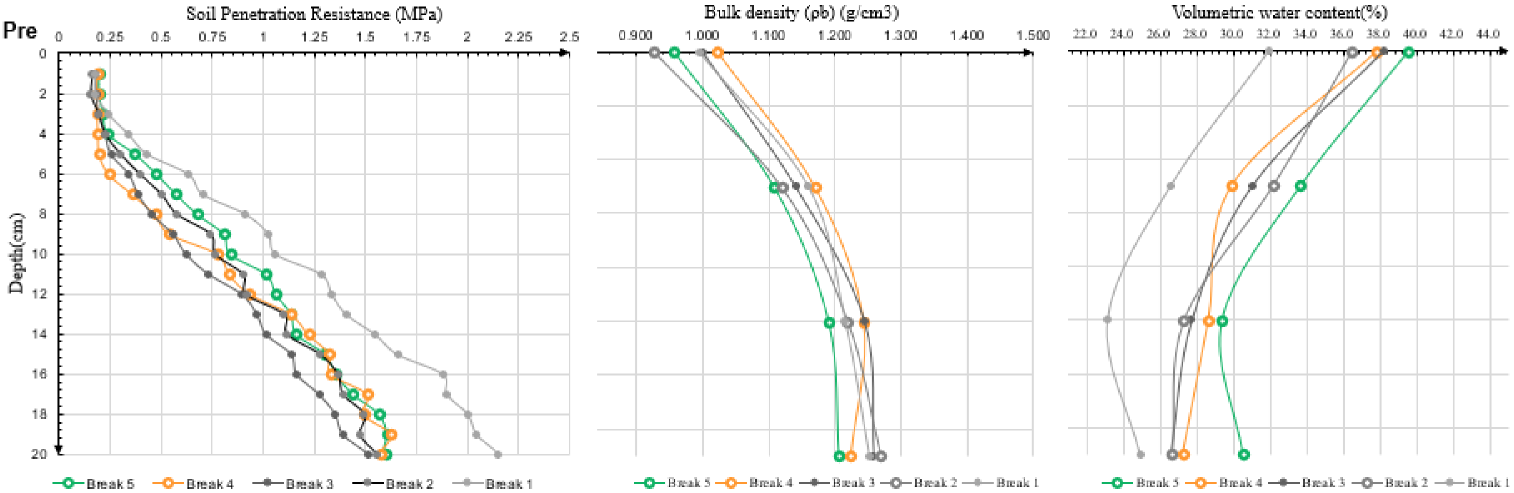
Table 4.4: Visual scoring method used for post-grazing assessments of treading damage in Paddock 48A and 52B. See Appendix C for visual scoring maps.

Damage score	Score criterion	Photo
<1	Minimal indentations of soil: no hoof smears or surface disruption	 Paddock 48A (Std-Con) Break 2
2	Slight indentations of soil: some hoof smears: very minimal surface disruption	 Paddock 52B (Div-Reg) Break 3
3	Medium indentations of soil: some hoof smears medium surface disruption	 Paddock 52B (Div-Reg) Break 4

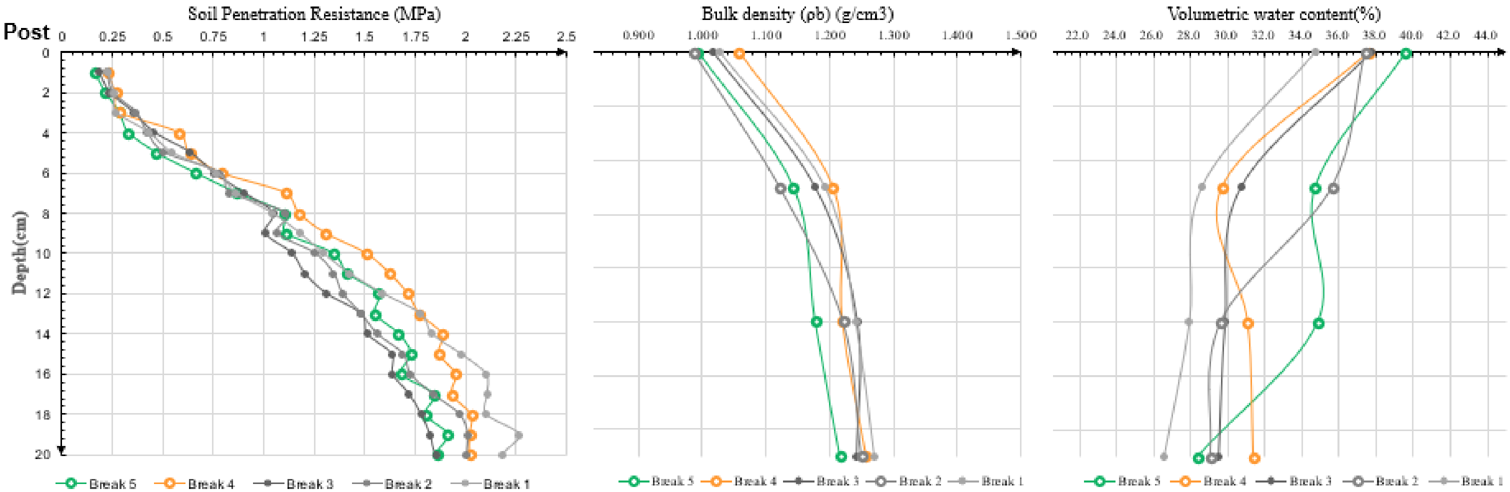
4	Deep indentations of soil: deep hoof smears: medium surface disruption	 Paddock 48A (Std-Con) Break 4
>5	Very deep indentations of soil: deep hoof smears: intense surface disruption	 Paddock 52B (Div-Reg) Break 4

4.5 Results

4.4.1 Paddock 52B (Diverse pasture and regenerative management)



Figures 4.4: Paddock 52B (Div-Reg) pre-grazing soil penetration resistance (MPa), bulk density (g/cm^3), and volumetric water content (%).



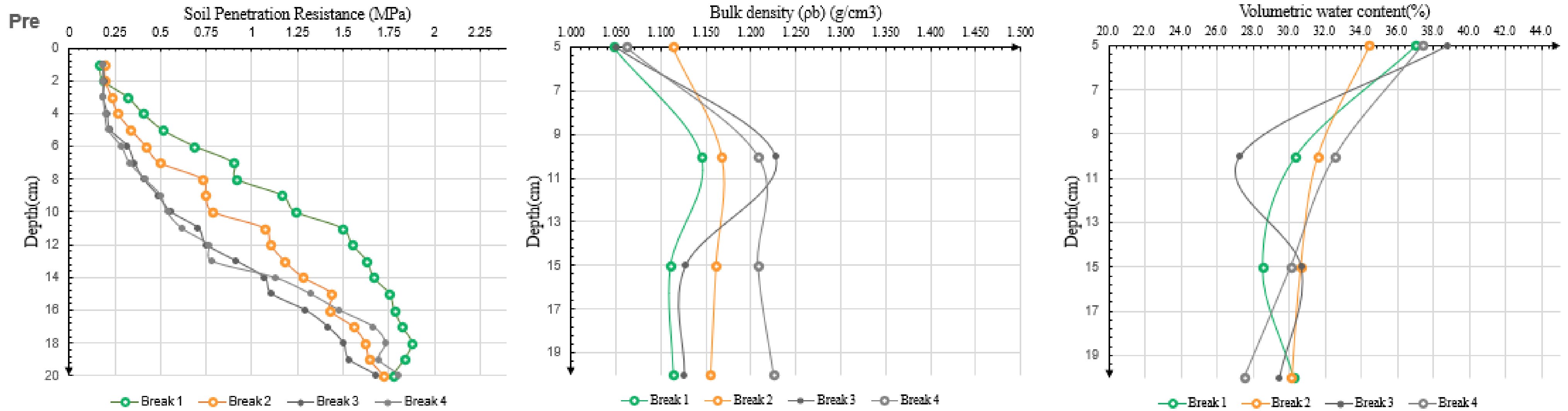
Figures 4.5: Paddock 52B (Div-Reg) post-grazing soil penetration resistance (MPa), bulk density (g/cm^3), and volumetric water content (%).

The soil penetration resistance values in Paddock 52B (Div-Reg) increased overall in the top 20 cm of the soil profile after the grazing event (Figures 4.4 and 4.5). After grazing, the overall penetration resistance was approximately 250 kPa higher than before grazing, with the average peak resistance reaching 2,264 kPa at 20 cm depth.

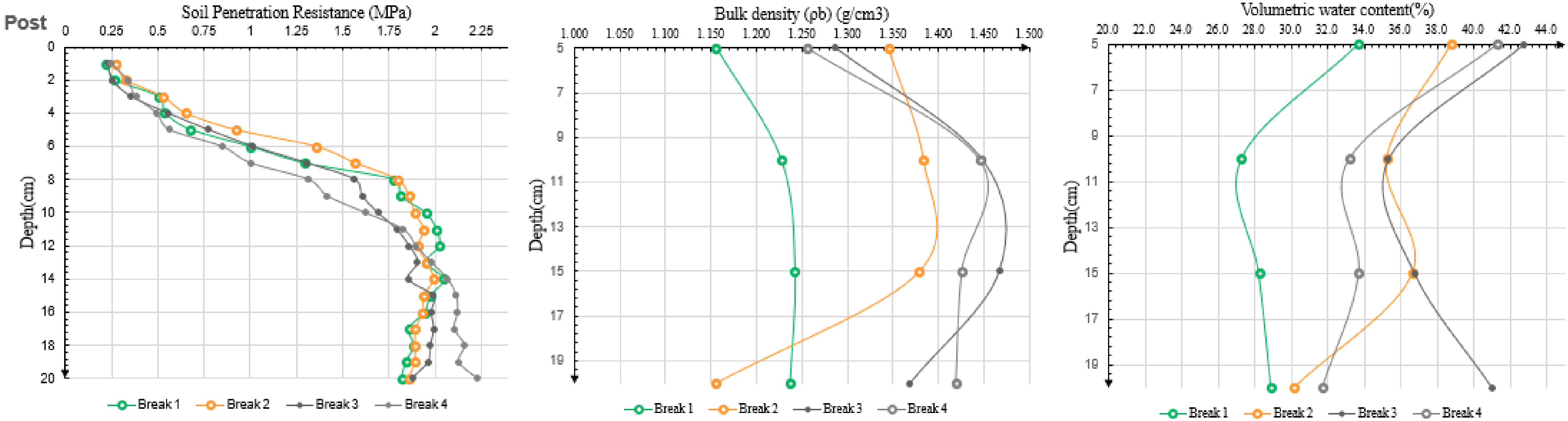
Volumetric water contents at the pre (1-2 days prior to grazing) and post-grazing (12 days post grazing) are similar, ranging from ~31.9-39.6% at 0-5 cm depth and decreasing down the soil profile to ~24.9-31.4% at 15-20 cm depth.

The bulk density values of Paddock 52B (Div-Reg) increased by an average of 0.05 g/cm^3 before and after grazing. This increase in bulk density is consistent with the observed trends in soil penetration resistance and indicates a positive correlation between these two soil physical properties.

4.4.2 Paddock 48A (Standard pasture and contemporary management)



Figures 4.6: Paddock 48A (Std-Con) pre-grazing soil penetration resistance (MPa), bulk density (g/cm^3), and volumetric water content (%).



Figures 4.7: Paddock 48A (Std-Con) post-grazing soil penetration resistance (MPa), bulk density (g/cm^3), and volumetric water content (%).

The soil penetration resistance data in Paddock 48A (Std-Con) showed notable changes in the top 20 cm of the soil profile after the grazing event (Figures 4.6 and 4.7), with the average maximum pressure at a depth of 0-20 cm increasing from 1.877 MPa before grazing to 2.228 MPa after grazing. Additionally, the slope of the penetration resistance profile became steeper after grazing, indicating higher average soil compaction from 0-10 cm depth.

Prior to grazing, there were some differences in penetration resistance across the four breaks in Paddock 48A (Std-Con). Break 1 showed the highest resistance, followed by Breaks 2, 3, and 4 in decreasing order. However, after grazing, these differences became less pronounced in the top 20 cm of the soil profile.

Volumetric water contents at the pre (1-2 days prior to grazing) and post-grazing (12 days post grazing) are similar, ranging from ~33.6-42.7% at 0-5 cm depth and generally decreasing down the soil profile to ~27.5-41.0% at 15-20 cm depth. There is high variability within the post-grazing volumetric water contents and Break 3 displays increasing moisture content down the soil profile. This higher variability and difference between pre and post-grazing volumetric water contents for Paddock 48A (Std-Con) could have some influence on the penetrometer data.

The bulk density in Paddock 48A (Std-Con) increased by an average of 0.2 g/cm^3 after the grazing event. This increase in bulk density is consistent with the observed trends in soil penetration resistance. Breaks 2, 3 and 4 display high variation in the post-grazing data, similar to the volumetric water content data.

4.4.3 Pugging damage assessment

A pugometer developed by Howes et al. (2018) was used to quantify the spatial distribution of treading damage across the breaks in Paddocks 48A (Std-Con) and 52B (Div-Reg). Work by Howes et al. (2018) shows a strong correlation between the pugometer, roller chain, depth of pug and visual scoring methods for assessing treading damage. Visual scoring was also completed across the entirety of both paddocks under the guidance of Professor David Horne to cross-validate the pugometer data. The pattern of treading damage illustrated by our visual scoring (Appendix C) is similar to the pugometer data presented in Figures 4.8 and 4.9. Maps showing the visual scoring assessment conducted on Paddock 48A (Std-Con) and 52B (Div-Reg) are included in Appendix C.

The pugometer data in Figures 4.8 and 4.9 show that the most severe treading damage in both paddocks was along Breaks 1 and 4. Treading damage is also concentrated around water troughs, shelter belts and gateways in both paddocks. The visual scoring noted evidence of pre-existing treading damage in Break 1 of both paddocks around gateways.

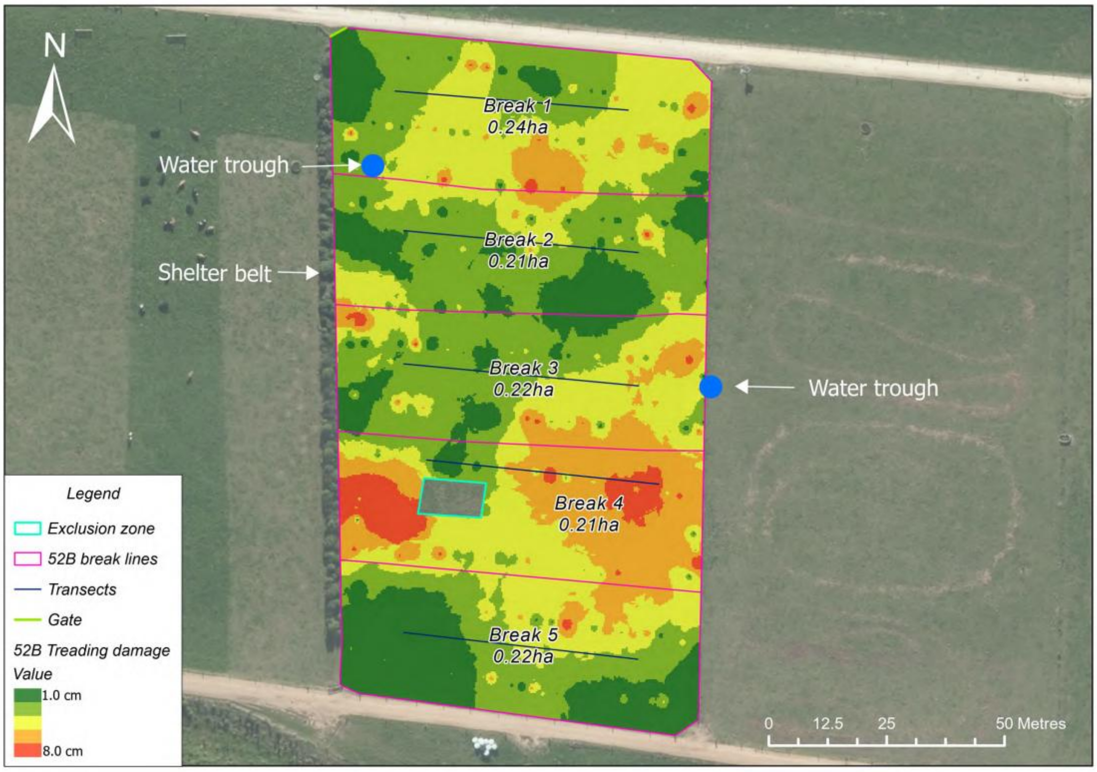


Figure 4.8: Paddock 52B (Div-Reg) post-grazing pugging damage measured by the pugometer.

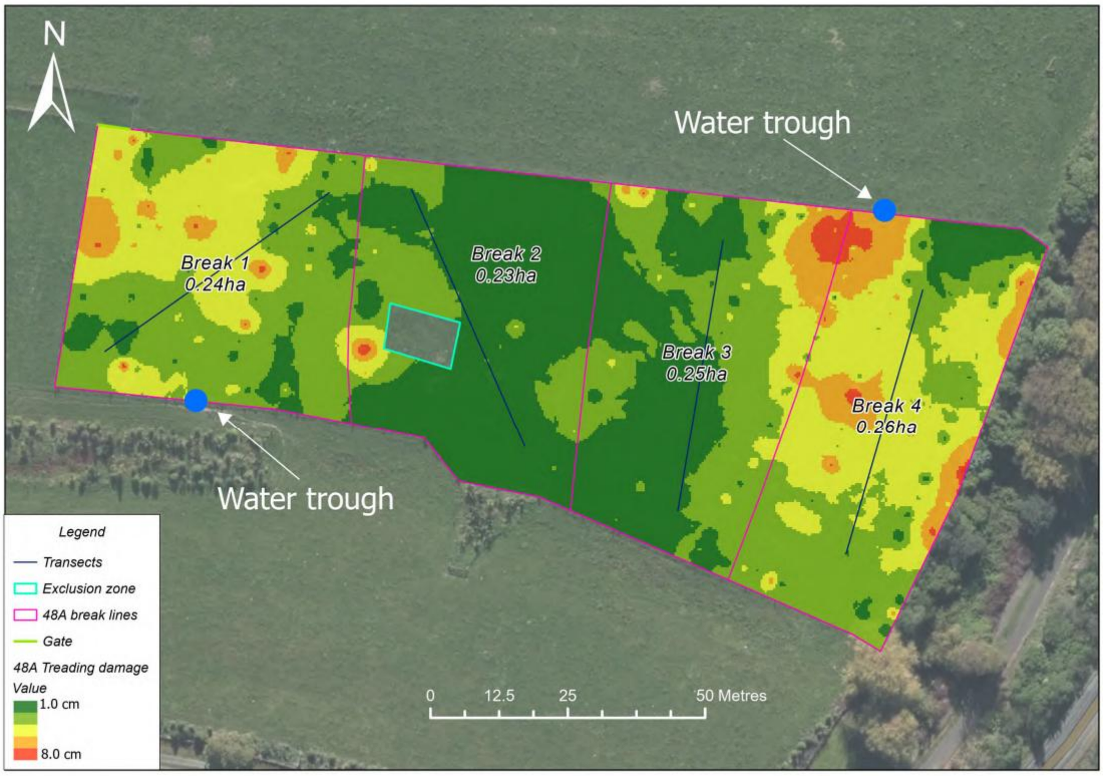


Figure 4.9: Paddock 48A (Std-Con) post-grazing pugging damage measured by the pugometer.

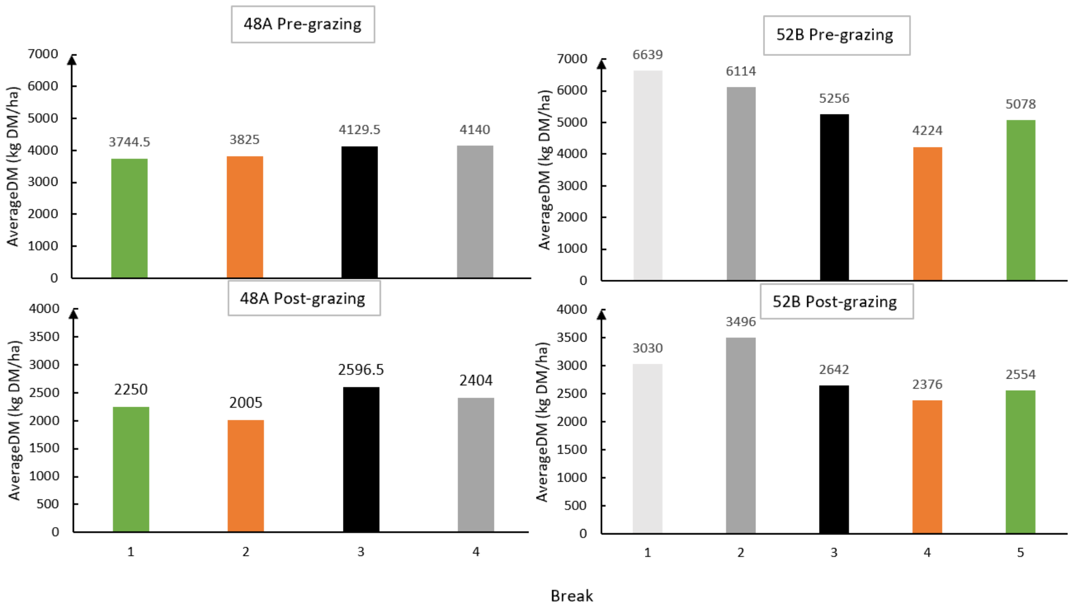


Figure 4.10: Paddock 48A (Std-Con) and 52B (Div-Reg) pre-grazing vs post-grazing pasture cover (kg DM/ha).

Figure 4.10 shows pre and post-grazing pasture covers across the breaks in Paddock 48A (Std-Con) and 52B (Div-Reg). Notably, pre-grazing pasture covers are higher at between 6,638 and 4,224 kg DM/ha in Paddock 52B (Div-Reg). Residual pasture is also higher in Paddock 52B (Div-Reg), with both pre and post-grazing pasture covers showing higher variability between breaks than Paddock 48A (Std-Con).

4.6 Discussion

Resistance to penetration and bulk density

Resistance to penetration increased in Paddock 48A (Std-Con) and 52B (Div-Reg) after grazing; however, the magnitude and pattern of change differed across the paddocks and down the soil profile. In Paddock 52B (Div-Reg), penetration resistance increased more uniformly down the soil profile to a depth of 20 cm, while Paddock 48A (Std-Con) exhibited a steeper and more pronounced increase in post-grazing penetration resistance with depth, reaching ~2 MPa by ~10cm depth. Although volumetric water content appears to have been in a similar range pre and post-grazing, even minor changes can influence penetrometer data (Gao et al., 2012). High variation in post-grazing volumetric water content for Paddock 48A (Std-Con) could reflect soil variation or potential errors introduced during field sampling and laboratory measurements.

The increase in pre and post-grazing bulk density (average of 0.05 g/cm³ in Paddock 52B (Div-Reg) and 0.2 g/cm³ in Paddock 48A (Std-Con)) and penetrometer data suggests topsoil compaction occurred under both treatments to 20 cm depth. Evidence of compaction is more evident for Paddock 48A (Std-Con). It appears that Break 1 in both paddocks had pre-existing levels of compaction, exhibited by relatively higher pre-grazing resistance to penetration and visual observations of compaction around gateways (Appendix C). In general, Paddock 48A (Std-Con) appeared to show signs of higher pre-existing compaction compared to Paddock 52B (Div-Reg), evidenced by relatively higher pre-grazing resistance to penetration and bulk density results. Pre and post-grazing bulk density and volumetric water content data for Paddock 48A (Std-Con) displays higher variation, potentially indicating some error in the analysis.

Pugometer, antecedent soil moisture and rainfall

The main pattern of pugging damage (Figures 4.8 and 4.9) is related to rainfall on the

14th and 17th of September 2024 (Table 4.3). Although this rainfall was minor, the soils were already at or near field capacity, and this additional rainfall corresponds well to Breaks 1 and 4 where the most severe pugging damage occurred in both paddocks.

The pugometer data demonstrates that up to 8 cm of pugging damage occurred across the two paddocks, concentrated in Breaks 1 and 4. Despite little to no visual signs of pugging damage in certain breaks, such as Break 2 in Paddock 48A (Std-Con) (Figure 4.9), high post-grazing penetrometer and bulk density data suggest soil compaction took place. This suggests that treading damage and soil compaction occurred differentially across the paddocks. Break 4 in both paddocks corresponds with the highest severity of pugging damage associated with 20.8 mm of rainfall on a soil already at field capacity (Table 4.3). This rainfall likely increased the soil moisture content towards its liquid limit, leading to greater pugging damage. Moving into Break 2, little to no rainfall over 24 hours allowed the soil to drain below the liquid limit. This allowed less pugging to take place, yet soil compaction still occurred as the soil was above the plastic limit.

Grazing management and animal behaviour

Both Paddock 52B (Div-Reg) and 48A (Std-Con) involved grazing the herd on each break for a day; however, Paddock 52B (Div-Reg) utilised back fencing to restrict cattle movement back across previously grazed breaks. This likely had some influence on the spatial distribution of treading damage in Paddock 52B (Figure 4.8). Any influence of back fencing is difficult to discern from the data gathered due to the main pattern of treading damage being related to the occurrence of rainfall on the 15th and 17th of September 2024 (Table 4.3).

In Paddock 48A (Std-Con), where no back fencing was used, animals could theoretically utilise a greater area during Breaks 2-4 compared to Breaks 2-5 in Paddock 52B (Div-Reg). However, despite this, cattle still rush into a new break to take advantage of the fresh allocation of feed and the influence of shelter, water troughs and gates appeared to exert a more important control on where animals were congregating, and treading damage was concentrated.

Although the two herds in Paddock 52B (Div-Reg) and 48A (Std-Con) treatments were balanced by breed (Table 4.1), the total number of cows in each herd differed by 8 at the time of this study, with a great proportion of cows in Paddock 48A (Std-Con). This difference reflects the higher stocking rate of 2.5 cows/ha under Std-Con compared to 2 cows/ha for Div-Reg. Two late calving cows from the Div-Reg herd were also excluded from the main milking herd at the time of grazing.

The pugometer results provide a valuable visualisation of the spatial patterns of pugging across the paddocks (Figure 4.8 and 4.9). This data demonstrates that pugging is not uniform across the paddocks but concentrates in preferred grazing areas and livestock movement corridors associated with water troughs, shelter belts and gateways (Donovan, 2024; Rodda et al., 2001). Moving forward, it will be beneficial to collect GPS collar data from each cow to ensure we can assess the pattern of animal movement across the paddock and how that relates to the pattern of treading damage.

The relationship between grazing behaviour and soil compaction and pugging has implications for grazing management strategies, suggesting that strategic placement of water sources, shade, and supplementary feed could help distribute animal impact more evenly across paddocks and potentially reduce localised soil damage (McKergow et al., 2016).

Pasture type and covers

Pre and post-grazing pasture covers were notably higher in Paddock 52B (Div-Reg) (Figure 4.10). Higher pasture covers likely provided additional physical protection to the soil, restricting treading damage (Gradwell, 1968; Nie et al., 2001).

The sharper increase in post-grazing resistance to penetration in Paddock 48A (Std-Con) treatment suggests that standard pasture systems under contemporary management may be more vulnerable to compaction during intensive grazing events, particularly when soil moisture conditions are suboptimal (Houlbrooke et al., 2011). However, further work is required to establish whether this is a trend through repeat analysis over multiple grazing events, including replication, collecting GPS collar data and attempting to balance the amount of cattle in each herd where practical.

Longer-term monitoring is required to evaluate the cumulative effects of these management systems over multiple grazing events and seasons and to assess soil and pasture recovery dynamics. In particular, the influence of higher pre and post grazing pasture covers and diverse versus standard pasture swards on treading damage and post grazing pasture and soil recovery is worth further investigation.

Management Implications

The contrasting responses of soil physical properties under regenerative versus contemporary management have some practical implications for dairy systems in New Zealand. Further work is required to establish whether treading damage and compaction is reduced under regenerative grazing management and diverse pastures; however, the overall increase in penetration resistance and bulk density in both systems indicates that even well-managed grazing during relatively wet conditions can result in some degree of soil compaction (Curran Cournane, 2010).

These findings support the value of adaptive management approaches that consider soil moisture conditions when planning grazing rotations (Donaghy et al., 2021). During periods of higher soil moisture, reducing stocking density or implementing shorter grazing periods could help minimise compaction effects (Greenwood & McKenzie, 2001). Additionally, the spatial variability in compaction and pugging highlights the importance of whole-farm planning that considers livestock movement patterns and identifies areas at higher risk of degradation (Monaghan et al., 2021).

4.7 Conclusion

This study compares soil physical responses to grazing under regeneratively managed diverse pasture versus contemporary managed standard pasture. Both paddocks displayed evidence of pugging and compaction associated with grazing during saturated conditions. Paddock 48A (Std-Con) displayed a greater increase in post-grazing resistance to penetration and bulk density associated with more treading damage. Notably, grazing pressure was higher in Paddock 48A (Std-Con). High post-grazing variation in bulk density and volumetric water content in Paddock 48A (Std-Con) may reflect soil variation or possible error introduced during sampling and analysis.

Pugometer data was used to assess the spatial distribution of pugging damage across both paddocks. Pugging damage is linked to the occurrence of rainfall events and the location of water troughs, shelter belts and gateways in the paddocks, which influence animal behaviour. Evidence of soil compaction is found in breaks where little to no pugging damage was observed. This suggests the soil had time to drain below the liquid limit, yet soil compaction still occurred as the soil was above the plastic limit.

Higher pasture covers likely provided additional physical protection to the soil, restricting treading damage. However, repeat analysis and longer-term monitoring is required to evaluate the possible advantages and disadvantages of diverse pastures and regenerative management on treading damage. In particular, the influence of higher pre and post grazing pasture covers and diverse versus standard pasture swards on treading damage and post grazing pasture and soil recovery is highlighted for further investigation.

CHAPTER FIVE: DISCUSSION

The findings from the research presented in this thesis elucidate the complex interactions between pasture type, management practices, and soil physical properties within the context of the Whenua Haumanu Programme (WHP). As detailed in Chapter 3, critical baseline data indicate that there are no statistically significant differences in soil physical properties between standard and diverse pastures or contemporary and regenerative management practices after the initial two years of observation. This lack of immediate distinction may be largely attributed to the time needed for management-induced changes to become evident, particularly concerning changes in soil structure.

Significant differences were found between the different soil types on the Dairy Farm One and the Pasture and Crop Research Unit (PCRU) farmlets, associated with changes in soil texture. Also, high variability was observed on Dairy Farm One reflecting the high natural variability of the sandy Recent soils on the Manawatū floodplain.

In contrast, the findings presented in Chapter 4 focus on more obvious, short-term changes in soil physical properties resulting from dairy grazing in wet spring conditions. Both regenerative (Div-Reg) and contemporary (Std-Con) management systems experienced increases in soil compaction following grazing; however, the extent and spatial distribution of these changes differed. Notably, the Std-Con paddock demonstrated a more pronounced increase in bulk density and resistance to penetration, indicating more soil compaction took place. This difference is possibly attributed to the lower cattle numbers and higher pasture covers in the Reg-Div paddock.

View west over the Manawatū River valley from Massey Universities Tuapaka Farm, 2023.

The research findings from Chapters 3 and 4 highlight the need for long-term research to fully clarify the relationship between pasture diversity, grazing management and soil health, and ultimately provide support for best practices in building sustainable agricultural systems in New Zealand.

Overall, the work presented in this thesis suggests that pasture type and management strategies play an integral role in influencing soil physical properties, particularly in New Zealand's diverse agricultural landscape. Repeated and long-term monitoring of soil physical properties is critical to elucidate the long-term impact of diverse pastures and regeneration practices, ultimately enriching the discussion on sustainable agricultural approaches and soil management strategies in New Zealand.

Interpretation of baseline soil physical data within the WHP

The absence of statistically significant differences in bulk density and penetration resistance between standard and diverse pastures, and between regenerative and contemporary management, is consistent with the early stage of the WHP. New Zealand studies have demonstrated that detectable improvements in soil structure under pastoral management often require prolonged periods of altered grazing pressure and pasture composition (Reganold et al., 1993; Drewry & Paton, 2005). The two-year monitoring period captured in this thesis should therefore be interpreted as an establishment phase rather than a test of long-term system performance.

Across both Dairy Farm One and the Pasture and Crop Research Unit (PCRU), soil type emerged as the primary driver of variability in soil physical properties. This finding aligns with New Zealand research showing that texture and soil order strongly influence bulk density, macroporosity and resistance to penetration under grazing (Houlbrooke et al., 2011; McDowell et al., 2013). Differences between the Manawatu sandy loam and Rangitikei loamy sand reflect inherent contrasts in texture, pore size distribution and drainage characteristics that strongly influence bulk density and penetration resistance. The high spatial variability observed on Dairy Farm One is typical of Recent alluvial soils on the Manawatū floodplain and highlights the importance of adequate replication and long-term monitoring when attempting to detect management effects in these landscapes.

Seasonal soil moisture conditions further influenced measurements. Penetration resistance and bulk density are highly sensitive to soil water status, and New Zealand studies consistently report higher compaction risk when grazing occurs at or above field capacity (Greenwood & McKenzie, 2001; Horne & Ross, 2013). Differences between sampling years align with rainfall patterns and soil moisture deficits, reinforcing that penetration resistance and bulk density measurements must be interpreted alongside contemporaneous soil water status. This finding supports established New Zealand literature emphasising soil moisture as a critical control on soil strength and susceptibility to compaction under grazing.

Short-term grazing impacts and treading damage under wet conditions

In contrast to the baseline analysis, the treading damage case study provides clear evidence of rapid soil physical change following grazing under saturated spring conditions. Both paddocks experienced increases in bulk density and penetration resistance after grazing, confirming that even well-managed dairy systems are vulnerable to compaction when soils are near or above the plastic limit. This response is well documented in New Zealand dairy systems, where treading damage and subsoil compaction frequently occur during wet spring grazing events (Houlbrooke et al., 2009; Curran-Cournane, 2024). confirming that even well-managed dairy systems are vulnerable to compaction when soils are near or above the plastic limit. These results are consistent with New Zealand studies demonstrating that pugging and compaction can occur independently, with compaction developing even where visible pugging is limited.

The greater post-grazing increase in soil strength and bulk density observed in the Std-Con paddock indicates a higher susceptibility to compaction under the specific conditions encountered. This response is likely driven by a combination of higher grazing pressure, lower post-grazing pasture cover and animal congregation around infrastructure such as gateways and water troughs. The spatial patterns identified using pugometer measurements reinforce the role of livestock behaviour in concentrating damage, a factor repeatedly highlighted in New Zealand dairy research, particularly around gateways, troughs and shelter areas (Monaghan et al., 2021; Donaghy et al., 2021).

In comparison, the Div-Reg paddock exhibited less severe and more spatially restricted damage. Higher pre- and post-grazing pasture covers likely provided greater physical protection to the soil surface, reducing direct hoof–soil contact and dissipating treading forces. Similar protective effects of higher herbage mass on soil physical condition have been reported under New Zealand grazing conditions (Houlbrooke et al., 2006; Drewry et al., 2008). While these results should not be interpreted as definitive evidence of regenerative management benefits, they suggest plausible mechanisms through which pasture cover and grazing intensity may moderate soil damage during wet periods.

Implications for regenerative and contemporary pastoral systems in New Zealand

Taken together, the findings suggest that short-term differences between regenerative and contemporary systems are unlikely to be detected using bulk density and penetration resistance alone, particularly on variable alluvial soils. However, the case study highlights that management decisions around grazing timing, stocking pressure and pasture cover can have immediate and measurable effects on soil condition, regardless of the broader system label.

For New Zealand dairy systems, this reinforces the importance of adaptive grazing management during periods of high soil moisture. Best-practice guidance and experimental evidence from New Zealand emphasise avoiding grazing on saturated soils, adjusting rotation length and stocking density, and protecting vulnerable areas to minimise long-term soil degradation (Greenwood & McKenzie, 2001; Donaghy et al., 2021). Strategies such as reducing stocking density, shortening grazing duration, maintaining higher residuals, or deferring grazing during extreme wetness are likely to be more influential for protecting soil structure than pasture species composition alone in the short term. These findings align with existing New Zealand guidance on minimising pugging and compaction risk under wet conditions.

Limitations and future research directions

Several limitations should be acknowledged. First, the relatively short monitoring period limits the ability to detect cumulative or legacy effects of regenerative management on soil physical properties. Second, inherent soil variability reduced statistical power, particularly on the Manawatū sandy loam. Third, differences in grazing pressure between paddocks constrained direct attribution of observed effects solely to management system.

Future work within the WHP should focus on continued long-term monitoring across multiple seasons and years, integration of soil physical data with biological indicators such as soil carbon and root distribution, and improved quantification of grazing pressure and animal movement. Repeated assessments of treading damage under contrasting seasonal conditions will be particularly valuable for identifying thresholds beyond which soil recovery is impaired.

CHAPTER SIX: CONCLUSION

Within the framework of the Whenua Haumanu Programme (WHP), this comprehensive study provides valuable baseline data on soil physical properties for farms with different pasture types and regenerative management models in New Zealand. The findings reported in this thesis for the first two years of the WHP provide an important reference for clarifying the complex relationship between pasture type, grazing management and soil physical characteristics.

The core conclusions of this study are as follows:

1. No statistically significant differences in soil bulk density or resistance to penetration were observed between standard and diverse pasture or contemporary and regenerative treatments after the first two years of the WHP. Changes in soil physical properties in response to pasture type and management may take longer to become apparent.
2. Significant differences were observed in soil physical properties between the Dairy Farm One and PCRU sites, reflecting differences in soil type. The finer-textured Tokomaru silt loam at PCRU exhibited consistently lower bulk density and penetration resistance values compared to the coarser Manawatu and Rangitikei soils at Dairy Farm One. This aligns with established principles of soil physics.
3. Seasonal fluctuations in soil moisture content were found to influence both bulk density and penetration resistance measurements, underscoring the dynamic nature of these soil physical properties.
4. The case study investigating short-term impacts of dairy grazing under saturated conditions on a regeneratively managed diverse pasture and a conventional standard

View of Massey Dairy Farm One and the Manawatū River from Te Motu o Poutoa, 2023.

pasture found evidence of pugging and soil compaction across both paddocks. The conventional standard paddock displayed a pronounced increase in bulk density and resistance to penetration, indicating more soil compaction took place. This difference is possibly attributed to the lower cattle numbers and higher pasture covers in the regeneratively managed diverse paddock.

These findings provide a critical baseline that will enable the assessment of long-term changes in soil physical properties as the Whenua Haumanu Programme continues. Continued monitoring and analysis of these parameters, alongside other soil health indicators, will be essential for elucidating the complex relationships between pasture diversity, grazing management, and sustainable agricultural outcomes in New Zealand. The insights gained from this research will inform decision-making by farmers, researchers, and policymakers as they work towards enhancing the productivity and environmental stewardship of pastoral farming systems.

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Appendix A – Bulk Density Sampling Protocol

0-5cm sample – sample from 3 positions along each transect:
1. Skin off surface vegetation, with spade, to expose soil.
2. Place bulk density core (5cm) sharp end down on soil and hammer in until almost flush with soil surface using a piece of wood on top of the corer. Try to keep movement of corer into the soil as straight as possible.
3. Place a spacer over corer rim and, using the wood again, drive the bulk density corer below the soil surface.

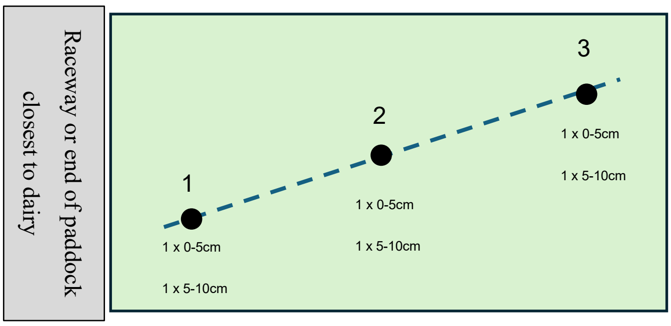
5-10cm sample – sample from 3 positions along each transect
1. Repeat the process above, except dig down to a depth of 5cm with a spade and create a flat soil surface.
2. Dig up the corer, making sure intact soil protrudes from each end.

1. Place in a plastic bag and carefully return to lab.
2. Wipe the corer of excess soil outside.
3. Trim the soil flush to the ends of the corer, if crumbling occurs fill the corer flush with soil. When crumbling is excessive (greater than 5%) don't continue with that sample.
4. Place corer and soil in a weighting tin or beaker or on a tin lid.
5. If required, weigh for gravimetric water content.
6. Place in oven at 105ºC until no further weight loss occurs.
7. Then weigh directly from the oven. This weight is Md.
8. Clean soil from corer and determine Mc (wt of the core and containers).

Formula: $$\rho_b \frac{M_d - M_c}{\text{volume of soil}}$$

$$\begin{aligned} \text{volume of soil} &= \text{internal volume of corer} \\ &= \pi r^2 h \\ &\sim 90\text{cm}^3 \text{ for std 5cm corer} \end{aligned}$$

Use vernier callipers to check, if required.



Figures 1: Bulk density sample plot of sampling points on the Transect

Appendix B – Penetrometer Sampling Protocol

Sampling Locations:

- Measurements taken at 6 points along each transect
- Maximum depth of 40 cm

2. Soil Conditions:

- VWC measured using Fieldscout Time-Domain Reflectometry (TDR) moisture sensor
- Moisture measured at 0-15 cm depth
- Measurements taken at two positions along each transect

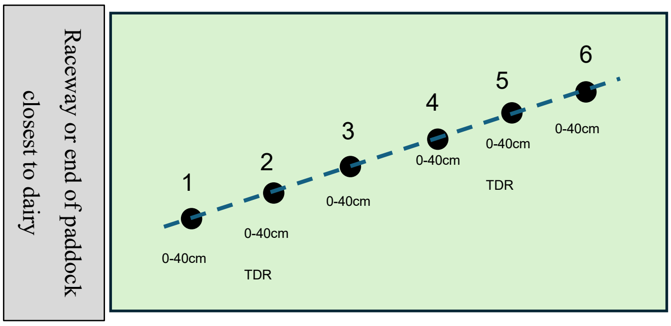
3. Transect Selection:

- In 2024, focused on two widespread soil types:
    - Manawatu sandy loam
    - Rangitikei loamy sand
- Total of 18 intensively monitored transects on Dairy Farm One
- Increased from 15 transects in 2023 to allow for better replication

4. Data Collection:

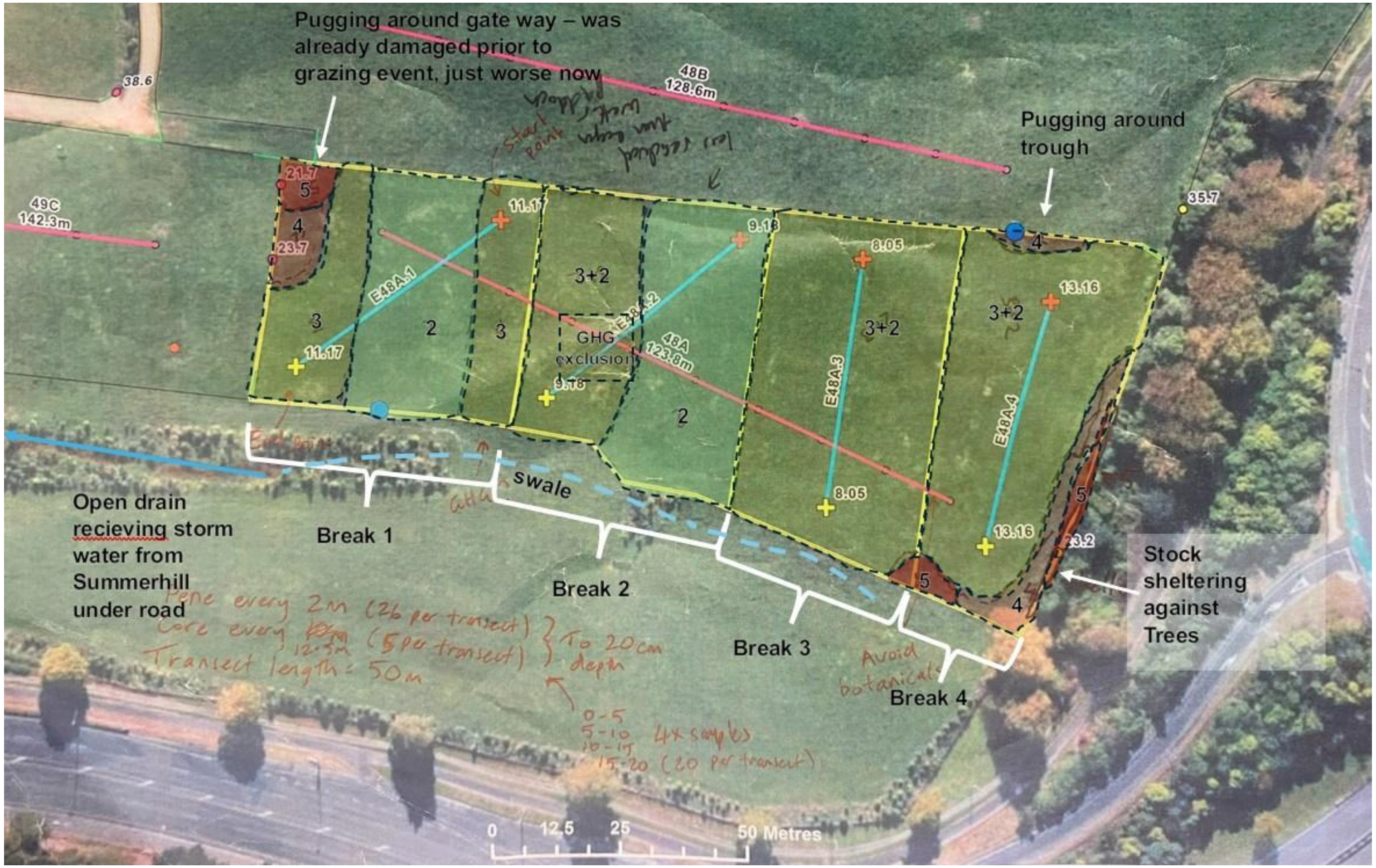
- Records soil penetration resistance in MPa
- Take measurements from surface (0 cm) to 40 cm depth
- Data collected at regular depth intervals
- Standard deviations calculated to assess variability

5. Results grouped by: Soil type, treatment type, depth intervals and year of measurement.



Figures 1: Penetrometer sample plot of sampling points on the Transect

Appendix C – Visual scoring of treading damage in paddock 48A and 52B



Pugged gateway prior to grazing, just got worse
Higher residuals
Generally best break of 48A or 52B
Generally worst break of 48A or 52B
Break 1
Break 2
Break 3
Break 4
Break 5
4+3
4+5 (post)
3+2
4 (post)
2+1
2 + little 3
4
3+4
4
3+4
GHG exclusion
5 (post)
5
4
2
E52B.5
E52B.4
E52B.3
E52B.2
E52B.1
15.4
14.81
14.27
13.69
13.19
52B 95.6m
54C 88m
29.9
25.8
26.5
32.1
24.8
29.1
28.5
0
12.5
25
50 Metres
Legend
Emily transect start points
Emily transect end points
Emily penetrometer transects
Intensively monitored transects revised 2024
No1 Dairy Line Features
Gate
Proposed Fenceline
Existing Fenceline
No1Dairy Point Features
Irrigation
Pole
Ponding
Power pole
Trough
Fences
Fifths_52B