Targeted Duration Controlled Grazing – The Effects of Timing of Grazing on Nitrate Leaching and Treading Damage.

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Jay Howes

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ABSTRACT

Duration controlled (DC) grazing is successfully employed for two main reasons: to reduce N leaching and to protect pastures and soils from treading damage in wet conditions. These two objectives are currently very important for the New Zealand (NZ) dairy industry and this will only continue to increase with changing environmental expectations and legislation. However, while there have been a number of studies showing the benefits of DC grazing, there has not been any detailed research into the means to modify or improve the management of DC grazing systems. Therefore, the overall objectives of this research were to further the understanding of the advantages of targeted cow standoff from pastures during the late-summer to early-winter period and its effect on nitrate (NO_3^-) leaching, and to identify the relationship between soil water deficit (SWD), grazing duration and treading damage (related to standoff in winter to early spring).

Two experiments were conducted on a fine textured Tokomaru silt loam soil at Massey University's Dairy 4 Farm near Palmerston North, Manawatu, New Zealand. One experiment was conducted to investigate the interaction of grazing duration and SWD on soil damage and pasture production, while the other experiment compared NO_3^- leaching under a standard dairy grazing system and a grazing system that used targeted DC grazing (i.e. during late-summer to early-winter).

Irrespective of drainage season and grazing treatment, the greatest NO_3^- concentrations in drainage occurred in the first seven to eight drainage events, which equated to the initial 50 to 100 mm of drainage. The majority of N losses following this were in the form of total organic nitrogen (TON). The average reductions in NO_3^- and TN leaching following targeted DC grazing in the summer to early winter periods of 2015 and 2016

were 28% and 20% respectively. The uniform return of slurry contributed to the DC treatment maintaining similar pasture production to the standard grazing treatment. Compared with year-round DC grazing, targeted DC grazing could be relatively inexpensive and so is likely to be a good mitigation option for N leaching in many cases, particularly on free draining soils where treading damage is uncommon.

Treading damage can be easy to observe; however, it can be time consuming to measure and even more difficult to quantify in a spatially aware manner. Therefore, two new and contrasting methods of assessing treading damage were developed, namely, the *visual scoring* method and the *pugometer*. The advantage of the pugometer is that it can automatically capture spatial variability rapidly, which no current method is able to do.

Only minimal treading damage and no reduction in pasture production was associated with cows grazing pasture at SWD > 2 mm, and this SWD appears to be a critical value, which farmers on fine textured soils, like the Tokomaru silt loam, could use to schedule grazing to protect soils and pastures from pugging damage. However, due to the need to maintain pasture quality there will be numerous occasions when the pasture on farms practising DC grazing will need to be grazed at a SWD < 2 mm. A modelling exercise revealed that up to 60% of a farm with standoff facilities could be damaged in an average season. While the damage inflicted on pastures may look unsightly, this may have little influence on overall accumulated (annual) pasture production. However, when the SWD was less than 2 mm, there were short-term losses in pasture production of approximately 500 to 1000 kg DM/ha under the grazing regimes studied here (i.e. 4- or 8-hour grazing duration and single and repeat damage events). If there is a need to graze in wet conditions (at or near saturation), then short durations (up to 4 hours) are recommended. Targeted DC grazing management provides the opportunity to achieve improved

environmental outcomes, and the effectiveness of targeted DC grazing as a multi-purpose tool is not undermined by the need to graze in wet conditions.

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For anyone who looks back and regrets things they could have done in the past

"You can't go back and change the beginning, but you can start where you are and change the ending".

C.S. Lewis

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1 GENERAL INTRODUCTION

1.1 Background

New Zealand (NZ) is heavily dependent on pasture-based agriculture, particularly the dairy sector, to generate export receipts. The dairy sector accounts for 29% percent of export earnings and contributes $7.8 billion dollars (3.5%) to NZ's gross domestic product (NZIER 2017). Due to the temperate nature of NZ's climate, dairy farmers can practise year-long outdoor grazing (Laurenson et al. 2017) and don't need to house cows for extended periods. This makes the typical New Zealand dairy farm a predominantly pasture based grazing system (Monaghan et al. 2008), with the advantage of an international image that is perceived as "clean and green" and that it is achieved at a lower cost, compared to mostly housed dairy systems in some other countries (Holmes et al. 2007). However, while the ability to graze year-round has been seen as a major advantage for the dairy industry, it might also be seen as a major contributor to some of the major challenges that the industry faces, in particular environmental and animal welfare concerns.

Sustainable and productive dairy farms in NZ are dependent upon the maintenance of high-quality pasture (Menneer et al. 2005). However, with the practice of year-round grazing on dairy farms, there will be times of the year when soils are wet and more prone to pasture damage from animal treading (Horne & Hooper 1990). Treading damage is an unwanted consequence of year-round grazing, but historically it has been considered to be 'part and parcel' of winter and spring pasture management in most areas of NZ (Betteridge et al. 2002). However, this damage has become more of a concern in recent years due to the recognition that it limits a farm's ability to maintain high-quality, productive pastures (Betteridge et al. 2002) and, therefore, reduces farm productivity and/or profitability. DairyNZ has estimated that treading damage could be costing dairy farmers on wet soils as much as $1000/ha/y (DairyNZ 2019b). Just as importantly,

treading damage can also be detrimental to the environment and the public perception of animal welfare (MfE 2019).

Year-round grazing, associated with weather patterns that generate drainage and/or overland flow, creates nutrient and pathogen losses to waterways that can pollute receiving waters, potentially tarnishing NZ's perceived international "clean green" image (Foote et al. 2015). It is widely accepted that agricultural, non-point source pollution is a leading cause of water quality degradation in NZ (Hamill & McBride 2003; Hoekstra et al. 2007). One of the principal impacts of dairy farming on water quality degradation is the nitrogen (N) leached from cow urine patches (Menneer et al. 2005). With increasing public awareness of the dairy sector's influence on water quality, all regional councils will be introducing stringent regulations around the loss of N from agricultural enterprises by 2025 (MfE 2019). The dairy industry in NZ is under constant scrutiny and some major dairying areas (e.g. Canterbury, Waikato and Southland) may be required to decrease N leaching to water by 50 – 60% (MfE 2019). Therefore, identifying and developing or improving options to mitigate N leaching losses from dairy farms is of utmost importance to the dairy industry and the wider agricultural science community. Accordingly, there is increasing interest in the use of structures/standoff facilities, such as free stall barns, which are used to stand cows off pasture using a practise called duration controlled grazing (DC). There are two important advantages that result from DC grazing. Firstly, the N in excreta is captured, while cows are on the standoff facility, and can be returned as effluent at much lower rates and more uniformly than those associated with urine patches. Secondly, the greater flexibility in grazing management means that cows can be stood off paddocks for long periods to protect wet soils and pasture from treading damage. However, research to date has concentrated on evaluation of the concept of DC grazing and there has had been

little work on the details of the management of DC grazing or how this might be practised and improved.

DC grazing to reduce N leaching

The use of DC grazing has been demonstrated to substantially reduce nitrate (NO_3^-) leaching from NZ dairy farms (Ledgard et al. 2006), with year round DC grazing decreasing NO_3^- leaching on average by ca. 50% (Christensen et al. 2018b) . However, some studies have demonstrated that confining the practice of DC grazing to just the late summer/autumn period can still achieve substantial reductions in N leaching. For example, Monaghan and De Klein (2014) measured a reduction of N leaching of 41% with autumn DC grazing, indicating, a 'critical period' for the most efficient DC grazing. This 'critical period' has been identified as the late summer-autumn period (Shepherd et al. 2010; Vogeler et al. 2010; Shepherd et al. 2011), where an accumulation of nitrate in the dry soil can lead to significant amounts of N in winter drainage. Therefore, management options used to mitigate N leaching to waterways should target this critical period in order to achieve the greatest reduction per unit of time in standoff. However, the literature related to DC grazing in this critical period is limited to modelling exercises (Vogeler et al. 2010), or to small plot scale trials that used artificial urine to simulate cow urine spots (Shepherd et al. 2011). There is a need for a study in this critical period that uses a standoff facility, such as a free stall barn, and grazing cows to quantify the actual effect of targeted DC grazing in this late summer/autumn on N leaching to water.

1.2 DC grazing to protect pastures from pugging damage.

It is widely recognised that treading damage results in poor pasture utilisation on the day of grazing and a reduction in pasture growth rates subsequent to the grazing event (Drewry 2006). These reductions in pasture growth have been shown to be extremely

variable (0 – 88% reduction reported in the literature) and are highly dependent on soil water deficit, as well as grazing intensity, grazing duration and soil type. Most published literature report the impact of one (severe) treading damage event. In reality, multiple treading damage events may occur to paddocks on dairy farms that are rotationally grazed through autumn, winter and spring. There has, however, been no investigation into the effect of repeat damage in a single season and the effects on short and long-term pasture production. In addition, the majority of the literature focuses on one grazing event at one particular soil moisture content, usually field capacity or saturation and, therefore, there is very little research information about the relationship between SWD and grazing duration (i.e. with regards to soil damage and pasture production). Furthermore, these studies (Blackwell 1993; Nie et al. 2001; Drewry 2003; Menneer et al. 2005) often employ large stocking rates and prolonged grazing periods. In comparison, grazing management on many dairy farms is relatively sophisticated with farmers attempting to more accurately match pasture supply with animal requirements and minimise grazing time and treading damage. Given this, the relevance of historic treading research to modern dairy production systems is not clear. Therefore, little is known of the consequence, if any, of treading damage on pasture production on a well-managed dairy farm, which might practise some form of standoff.

While most forms of treading damage to pasture can be observed, they still need to be quantified. The extent or severity of treading damage can be assessed using a number of methods such as the roller chain (Saleh 1993), depth of pug and visual scoring method (Tuñon et al. 2014; Little et al. 2015). However, the ability of these methods to assess treading damage, and their relative merits, have not previously been compared or reported. While the methods mentioned above are relatively simple and somewhat successful, they are not without limitations. As such, no quick and reliable method has

been developed that is capable of assessing the variability in the extent and severity of treading damage, in a quantitative manner, on areas that range from small (plot or part-paddock) to large (paddock or whole-farm) scales. Any such method will need to be sensitive enough to discern the spatial variability in treading damage that can occur both between and within paddocks and this technique should be able to capture or record this information in an automatic and spatially aware manner. Therefore, there is a need to develop a new method of measuring pugging damage in the manner described above.

1.3 Aims and objectives

The overall objectives of this thesis were to further our understanding of the major advantages of standoff to drainage water quality and soil and pasture protection, and to help refine or improve the management of standoff. More detailed objectives are given in each chapter and alluded to in the description of the thesis structure below. Two hypotheses were developed to help guide the general direction of the thesis.

Hypothesis 1: *Even on farms with extensive standoff facilities, it will often be necessary to graze pasture in wet conditions (i.e. near saturation) in order to maintain pasture quality, but providing that these grazings are confined to relatively short periods (i.e. four hours) the associated treading damage will have a relatively small effect on pasture production and will not undermine the overall efficacy of DC grazing management.*

Hypothesis 2: *While large reductions in N leaching have been achieved under year-round DC grazing, substantial reductions in N leaching can also be achieved when duration controlled grazing is only practised during the late-lactation period (i.e. critical period).*

1.4 Thesis structure

This thesis comprises seven chapters including this general introduction chapter and a review of literature (Chapter 2). Chapters 3-6 report on the research experiments conducted in this study. Each of the four research chapters have their own introduction, materials and methods, results and discussion, and conclusions sections. The main findings of the research chapters are discussed in a final summary in Chapter 7.

- Chapter 2 is a review of the literature, which summarises the relevant research literature and identifies gaps in existing knowledge and establishes the research objectives.
- Chapter 3 is a research paper published in the *Journal of Soil Research* (Howes et al. 2018), which compares methods used for pugging measurement and describes a new method, developed for pugging research. This chapter develops recommendations for monitoring the extent and severity of treading damage on pastoral farms.
- Chapter 4 quantifies the relationship between soil moisture, grazing duration and the intensity of treading damage. It also measures the effect of repeated treading damage on the soil surface. Importantly, this chapter identifies the critical soil moisture deficit at which severe treading damage is likely to occur. This contributes to guiding grazing management on farms with standoff facilities.
- Chapter 5 investigates the effect of treading damage at different soil moisture levels and grazing durations on pasture production. It also investigates the effect of repeat treading damage on pasture production and helps clarify the critical soil moisture deficit at which treading is likely to adversely impact on pasture growth.

- Chapter 6 quantifies the effect of using targeted DC grazing, which is confined to the summer/autumn period, on NO_3^- leaching.
- Chapter 7 provides an overall conclusion of the results presented in the research chapters, discusses the implications of the research, and makes recommendations for future research.

2 LITERATURE REVIEW

2.1 Introduction

Given that there are two distinct issues mentioned in the introduction (Chapter 1), this review of literature is divided into two sub chapters Part 1 - The effects of cattle treading on soil properties and pasture growth, and Part 2 – Mitigations to reduce nitrogen leaching to water. Part 1 reviews the literature on the effects of cattle treading damage on soil properties and pasture growth and utilisation, including the mechanisms of soil failure, the effects on soil physical properties, soil recovery and pasture growth and utilisation. Grazing management to limit soil damage is also considered. Part 2 reviews water quality issues in NZ, the nitrogen cycle in pastoral systems, the causes of N leaching and finally mitigations used to reduce N leaching.

2.2 Use of terminology

In this thesis, the term "treading" is defined as the physical action of cattle hooves on soil and pasture. The resulting damage by cattle treading is called "treading damage". The term treading damage covers any range of severity of damage to both soil and pasture.

2.3 Part 1: The effects of cattle treading on soil and pasture

2.3.1 The processes of treading damage

2.3.1.1 Physical processes of soil failure

The grazing animal is capable of exerting ground pressure comparable and /or greater to that of agricultural machinery (Greenwood & McKenzie 2001; Bilotta et al. 2007). The force imposed on the soil by a grazing animal is a function of the animal's weight and the area of contact between the animals hooves and the soil surface (Patto et al. 1978). The static dairy cow can exert up to 200 kPa on the soil (Di et al. 2001). The dynamic load of a dairy cow in motion can increase up to 400 kPa (Climo & Richardson

1984). These pressures can cause stress to plants and reduce growth through two main mechanisms: 1) directly, by reducing the plant's ability to function through fragmentation, crushing and/or burial of plant organs (Menneer et al. 2005); 2) indirectly, through three types of damage to soil. Treading damage to soil can be grouped under three headings: compaction; pugging; and poaching (Greenwood & McKenzie 2001).These three terms describe the different types of treading damage that can occur under different soil moisture contents, all of which have different effects on the soil (Bilotta et al. 2007).

Soil compaction is defined as the compression of an unsaturated soil body resulting in a reduction of the fractional air volume (Hillel, 1980). Soil compaction occurs when the load of the grazing animal is greater than the load-bearing capacity of unsaturated soil (Bilotta et al. 2007). The potential for grazing animals to cause soil compaction has been clearly identified (Edmond 1958 ; Gradwell 1965). This potential is dependent on soil texture, organic matter and soil water content (Mapfumo & Chanasyk 1998). Soil compaction leads to decreased: root penetrability, soil aeration, gas diffusion (Asady & Smucker 1989), and nutrient and water availability (Scholefield & Hall 1985; Asady & Smucker 1989), all of which have been observed to decrease root growth and development (Scholefield & Hall 1985; Asady & Smucker 1989; Houlbrooke et al. 1997).

Soil pugging is described as the process by which livestock tread on soft wet soil and create deep hoof prints (Drewry 2006). Pugging causes plastic deformation of the soil at high soil moisture contents when the animal hoof weight exceeds the bearing capacity of the soils, leaving hoof imprints and uneven pasture surfaces (Patto et al. 1978). A bearing capacity of 700 kPa has been mentioned as the minimum value required to

prevent pugging of soil (Climo & Richardson 1984). The hoof imprints created by pugging can influence soil water dynamics, particularly infiltration rate, and plant growth. For any given soil, pugging usually occurs at higher soil moisture contents compared with those that cause compaction (Bilotta et al. 2007).

Poaching describes the slurry-like soil conditions that occur on saturated, or near saturated soils, when trampled by livestock (Drewry 2006). Poaching is a type of plastic deformation which, like pugging, occurs when the load that animals exert on saturated soil exceeds the load-bearing capacity of the soil (Patto et al. 1978). However, poaching is more likely to occur at the highest soil moisture levels and under prolonged grazing and/or high stocking rates. The slurry-like conditions associated with poaching of pasture are not produced immediately upon treading of wet soils, but only after a progressive loss of soil strength due to continuous and/or repeated treading (Scholefield & Hall 1986). Poaching can be extremely disruptive to plant growth and can have grave consequences for soil hydrology (Bilotta et al. 2007). Poaching is not a common term in New Zealand and is more likely to be referred to as ‘severe pugging’ (Horne 2019, pers comm).

2.3.1.2 Soil moisture

The water content of a soil, important for plant growth, also directly affects soil strength and, therefore, the way a soil responds to an imposed load (Greenwood & McKenzie 2001). For example, during wet periods in winter and spring, the type and extent of soil damage at the time of grazing is largely determined by soil moisture content (Laurenson & Houlbrooke 2016). Soil moisture content can be described in a number of ways including by the term soil water deficit (SWD). The SWD is defined as the amount of water, expressed in mm of precipitation, required to replenish soil water to field capacity

(Herbin et al. 2011). The SWD under pastures is routinely modelled or calculated using variations on a soil water mass balance (Schulte et al. 2005) rather than measured directly. The exception here would be the commonplace use of sensors to identify the SWD as an aid to irrigation scheduling. However, the use of probes to identify the SWD to help winter management is not straightforward as grazing decisions at this time of year revolve around relatively small deficits e.g. 2 to 5 mm developing in the very surface soil (e.g. 0 to 5 cm) which probes are often not capable of monitoring reliably.

In dry soils (large SWD), treading damage to the soil is unlikely to occur as the particles are interlocked and there is frictional resistance to movement and deformation (Hillel 2003a). However, as soils wet and approach field capacity, moisture reduces these frictional forces (Marshall & Holmes, 1979), allowing compaction to occur under grazing (Betteridge et al. 2003). When soils are wetter than field capacity, i.e. saturated or nearly saturated, plastic deformation, rather than compaction, will occur during grazing (Climo & Richardson 1984). This trend is explained by reference to the relationship between soil moisture content and soil strength, i.e. as the soil water content increases then the soil loses strength or, in other words, the resistance to penetration decreases (Figure 2.1).

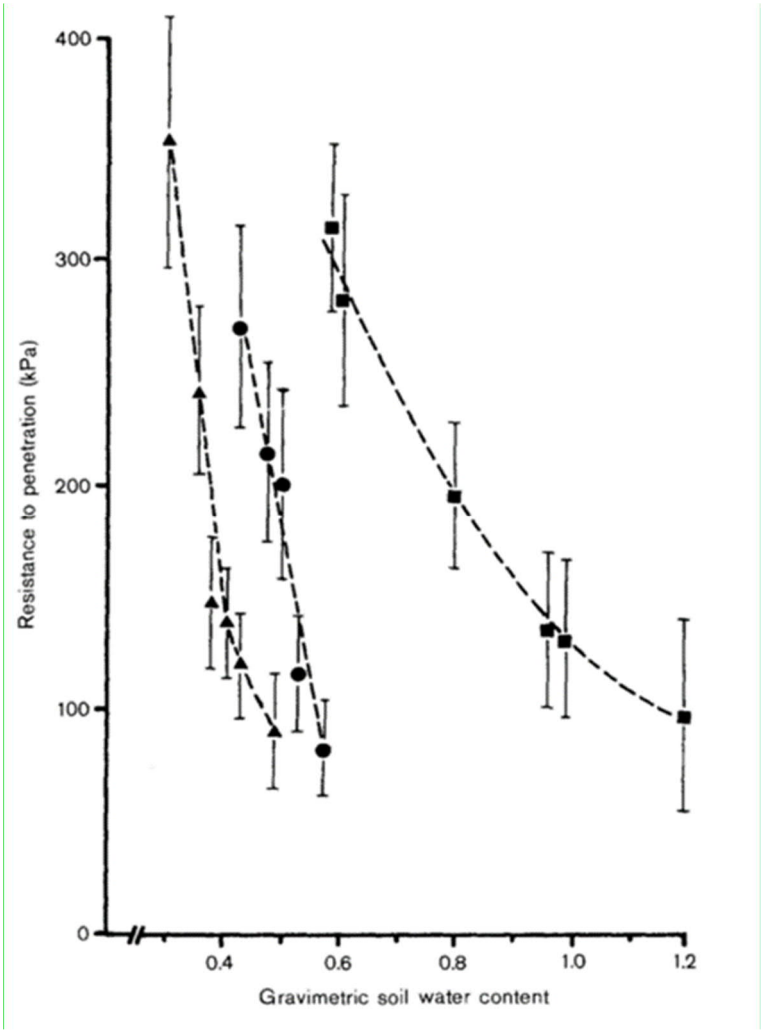

Figure 2.1 Relationship between resistance to penetration and soil water content for three soils in the Manawatu. Ramiha silt loam (■), Manawatu fine sandy loam (▲) and Tokomaru silt loam (●) taken from Climo and Richardson (1984).

As the susceptibility of a soil to treading damage depends on its moisture content, damage also varies with soil type (Hewitt & Shepherd 1997), hence, treading damage is a greater problem for some soils than others (Scholefield & Hall 1985). Climo and Richardson (1984) investigated three contrasting soil types with different susceptibilities to treading damage. The soils studied were: a well-drained Ramiha silt loam with high levels of organic matter, a well-drained Manawatu fine sandy loam with comparatively low organic matter content, and a poorly drained Tokomaru silt loam. All

three soils in this study showed an inverse relationship between soil water content and soil strength, and all three soils are likely to be damaged when saturated (Fig.1). However, the length of time a soil remains very wet will depend on factors that influence drainage rate and evapotranspiration. Drainage rate varies with differences in soil texture and structure. The well-structured, free draining Ramiha soil is rarely saturated, and thus the potential for damage is low. Due to the vulnerability of the structure of the surface of the Manawatu soil, the movement of water through the topsoil can be restricted meaning that this soil will be saturated under heavy rainfall more often than the Ramiha soil. However, the free draining nature of the rest of the coarse soil profile means that this window for potential soil damage is relatively narrow. In contrast, the fine textured Tokomaru soil, through which water moves slowly, will remain susceptible to damage for prolonged periods after rainfall.

2.3.1.3 Grazing intensity

Animal grazing and treading, particularly in wet conditions, can affect pasture yield directly through leaf burial in mud, crushing, bruising, and a reduction in dry matter production (Ledgard et al. 1996; Nie et al. 2001). Grazing intensity (stocking rate) affects the severity of treading damage (Nie et al. 2001; Menneer et al. 2005). Nie et al. (2001) reports on a series of treatments of varying pugging severity (no pugging, light, medium and heavy) imposed with a range of stocking rates during winter. The medium and heavy pugging treatments reduced pasture yield in the following spring by 40-42%, with the light pugging having no effect on pasture yield. Menneer et al. (2005) reported that annual pasture production under moderate and severe pugging treatments (imposed at 4.5 cows/100m^2 for 1.5 and 2.5 hours respectively) was reduced by 21% and 45%, respectively. Brown and Evans (1973) reviewed the work of the late D.B. Edmond, on sheep treading. The authors reported that herbage yields were reduced by up to 63% for

high sheep stocking rates, particularly in wet conditions. The results of the studies mentioned above imply that limiting grazing intensity is likely to reduce the severity and impacts of treading damage on pasture utilisation and subsequent recovery and growth.

2.3.2 The effects of treading on the soil surface

2.3.2.1 Soil surface roughness

Cattle treading results in hoof indentations that may penetrate or rupture the soil surface (Scholefield & Hall 1985; Bilotta et al. 2007). Thus, the measurement of soil roughness is an indicator of treading damage to soil and is usually a good indication of the deterioration in soil surface conditions. Four techniques for measuring surface roughness are: the depth of pug method (Nie et al. 2001; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015), the pin and profile meter method (Davies & Armstrong 1986; Betteridge et al. 1999), the more frequently used roller chain method (Nie et al. 2001; Pande et al. 2002; Drewry et al. 2003; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015) and the Visual scoring method (Sheath & Carlson 1998; Nie et al. 2001; Zegwaard 2006; Little et al. 2015). A comparison of untrodden, lightly trodden and heavily trodden areas by Pande et al. (2002) showed significant increases in the surface roughness as measured by the roller chain method.

Using the depth of pug method and roller chain, Tuñon et al. (2014), found a linear relationship between hoof imprint depth ($p < 0.001$) (Table 2.1) and the level of damage inflicted on soil. This suggests that soil surface roughness can be a good quantitative measure of the intensity of treading damage to soil.

Table 2.1 Hoof imprint depths and surface roughness (measured as proportion of chain reduction when placed on the soil surface) of plots allocated to one of four treading damage treatments: control (C, no damage), light damage (L), moderate damage (M) and severe damage (S) in Experiments 1 and 2. Taken from Tuñon et al. (2014)

		Treatments				
	Date	C†	L	M	S	s.e.m.	Sign
Experiment 1							
TD 1 (spring 2009)							
Hoof print depths (cm)	21 Mar 09		$3{\cdot}6^{a}$	$4{\cdot}8^{b}$	$5{\cdot}8^{c}$	0·89	***
Surface roughness	19 Mar 09		$0{\cdot}06^{a}$	$0{\cdot}08^{ab}$	$0{\cdot}13^{b}$	0·001	***
Experiment 2							
TD 2 (autumn 2009)							
Hoof print depths (cm)	5 Nov 09		$3{\cdot}3^{a}$	$8{\cdot}8^{b}$	$13{\cdot}3^{c}$	0·87	***
Surface roughness	5 Nov 09		$0{\cdot}02^{a}$	$0{\cdot}10^{b}$	$0{\cdot}14^{c}$	0·002	***
TD 3 (spring 2010)							
Hoof print depths (cm)	9 Apr 10		$3{\cdot}3^{a}$	$5{\cdot}8^{b}$	$7{\cdot}9^{c}$	0·88	***
Surface roughness	9 Apr 10		$0{\cdot}04^{a}$	$0{\cdot}07^{b}$	$0{\cdot}10^{c}$	0·002	***

s.e.m. = standard error of the mean; TD = treading date.Within rows, means not showing a common superscript differ sig cantly ($P < 0{\cdot}05$). †Not subjected to treading damage. ***$P < 0{\cdot}001$.

2.3.2.2 Bare ground

An increase in the area of bare ground within a pasture can be caused by several processes such as plant pulling, and plant death due to physical damage from treading and burial. The areas of bare ground associated with treading is likely to be dependent on soil type and livestock class. Cattle treading is well known to increase the area of bare ground in pasture (Elliott et al. 2002a). This happens as cattle press herbage into the soil and bury pasture under remoulded soil, (Nie et al. 2001). Higher stocking densities during grazing can also result in greater herbage death, and therefore, a greater occurrence of bare ground (Warren et al. 1986). A study by Drewry et al. (2003) reported bare ground values following cattle treading were higher for clay soils (48% of soil surface) compared with a free-draining soil (26%) which had been subjected to a longer period of treading at the same stocking density. The modelling of inter-rill erosion from hill clay/silt loam soils suggested bare ground may be as much as 70% after severe cattle treading (70 cows ha^{-1}, treading for up to 3 days) (Elliott et al. 2002a). However, the creation of bare ground is not confined to just wet soils, as severe animal treading

(compaction) of dry soil resulted in long-lasting open spaces within the sward (Kelly 1985). Areas where bare ground has formed due to treading activity are more susceptible to further treading damage than are those with pasture cover (Betteridge et al. 1999), thus this can become a self-perpetuating problem. However, bare ground resulting from treading can typically be halved after 2 months from initial treading damage (Elliott et al. 2002a)

2.3.3 The effects of treading damage on soil properties

Pugging will detrimentally affect soil structure in wet conditions. Badly pugged soils will result in poor structure such as surface caps, platy structure, or increased clods of massive structure, whereas compaction can result in increased bulk density and reduced porosity (McLaren & Cameron 1996; Bilotta et al. 2007).

2.3.3.1 Soil dry bulk density and total porosity

Treading damage by cattle is known to increase soil bulk density. For example, in six contrasting soil types (clayey to silty/sandy loam), untrodden soils had on average 13% lower soil dry bulk densities when compared to severely trodden soils (Singleton et al. 2000). Differences of 21.6 % in soil dry bulk density of a sandy loam have been reported between lightly trodden and severely trodden areas (Mulholland & Fullen 1991). However, Gradwell (1968) showed little change in bulk density, but a large change in macroporosity in his treading trial. It has been suggested that macroporosity may serve as a better indicator of the structural impedance (compared to bulk density) most likely to affect plants due to treading, (Greenwood & McNamara 1992).

Macroporosity has been shown to decrease with cattle treading (Drewry et al. 1999; Singleton & Addison 1999; Di et al. 2001). Macroporosity has been described by Drewry et al. (2001) as the best indicator for soil compaction because it has shown the

best relationship between the effects of treading and relative pasture yield. The macroporosity of a healthy soil depends on the soil type and physical condition, but a macroporosity percentage of 15-20 in non-compacted, well-structured soils would be deemed appropriate (Drewry et al. 2001; Betteridge et al. 2003). Soil macroporosity of less than 10% may restrict soil aeration to a level that can have detrimental effects on grass growth and relative pasture yield (Climo & Richardson 1984; Drewry & Paton 2000b; Drewry et al. 2001). Both decreases in total porosity and macroporosity are linked to a reduction in hydraulic conductivity (impeding water movement within a soil) (Warren et al. 1986; Proffitt et al. 1993). This is particularly relevant to macropores, as they are the primary pathway for rapid water movement within a wet soil (Beven 1980).

2.3.3.2 Hydraulic Conductivity

Hydraulic conductivity is defined as the flux (rate of flow of water through a volume of soil) subject to a unit gradient (Hillel 2003b). Hydraulic conductivity varies with soil water content and is commonly measured under saturated and unsaturated conditions. Saturated hydraulic conductivity is measured when all the soil pores are filled with water, including preferential flow pathways such as earthworm burrows (Zachmann et al. 1987). Saturated flow may vary over time and may have rapid and spatially variable flow rates due to the chemical, physical and biological processes in the soil (Hillel 2003b). Unsaturated flow is said to occur when the larger soil pores are no longer contributing to flow. Water flow under unsaturated conditions is slow compared with that of a saturated soil: as the majority of soils are unsaturated most of the time, unsaturated water flow is most common (McLaren & Cameron 1996). As unsaturated hydraulic conductivity is not affected by large preferential flow pathways it is less spatially variable, and so it has been suggested to be a better indicator of structural change than that of soil dry bulk density (Mulholland & Fullen 1991).

Treading can decrease pore volume and modify the pore size distribution, thereby reducing the hydraulic conductivity. Individual hoof prints may result in smearing of soil, sealing the soil surface and slowing infiltration rates (Abdul-Magid et al. 1987). Reductions in saturated flow rates due to treading, are largely attributed to the destruction of preferential flow pathways (such as earthworm burrows) (Drewry et al. 2003). Treading has been reported to decrease hydraulic conductivities for a range of soil types (Greenwood et al. 1997; Drewry et al. 2002). Free-draining soils tend to have smaller differences in hydraulic flow rates between cattle treading treatments than gleyed soils (Singleton et al. 2000).

2.3.4 Natural recovery of soils

Natural recovery of soils after severe animal treading damage can be slow and full recovery is not always observed. Often natural recovery is attributed to inherent soil processes such as shrinking and swelling of clays, freezing and thawing (Koenigs 1963), root growth and earthworm activity (Abdul-Magid et al. 1987; Hewitt & Shepherd 1997). Earthworms are important in pasture soils that have excessive compaction (Haynes et al. 1995), as earthworms can burrow through soil with a penetration strength up to 3.5 MPa (Dexter 1987). However, after severe treading Cluzeau et al. (1992) found that earthworm populations were up to 85% lower in trodden than untrodden areas. Treading, therefore can diminish the potential recovery rate of soil from earthworm activity (Edmond 1963).

Research by Greenwood et al. (1998), Drewry and Paton (2000b), and Drewry et al. (2003) has focused on recovery of soil with grazing exclusion. Some evidence of recovery within months after soil compaction was found, but recovery back to pre-damage conditions takes longer (Greenwood et al. 1998; Elliott et al. 2002a). Short-term

recovery (over 21-weeks) of a Te Kowhai silt loam and Kereone silt loam soil, after a one-off severe cattle treading event followed by grazing exclusion was monitored by Drewry et al. (2003). This study reported that both soils were detrimentally affected by cattle treading and recovered by natural processes over a five months period, with improvements in saturated hydraulic conductivity being most rapid, probably because of earthworm activity. Some recovery of hydraulic conductivity after grazing exclusion has been reported after 30 days (Warren et al. 1986), while others report that full recovery (to pre-damage levels) of hydraulic conductivity can occur after six months (Elliott et al. 2002a).

The magnitude of compaction during spring, and natural recovery of soil physical properties during summer and autumn, were quantified on a Pallic soil intermittently grazed during rotational grazing by dairy cows (Drewry et al. 2004). Bulk density recovered well and decreased to 0.9 g/cm^3, during the summer autumn period. Soil macroporosity also recovered markedly during the same period and increased from 12.5% to 18%. Possible reasons for this recovery of physical condition in summer and autumn in temperate environments includes increased cracking and activity of soil fauna (Drewry et al. 2004). The recovery of macroporosity is important for pasture production after treading. Betteridge et al. (2003) showed that for each 1% increase in macroporosity the relative spring pasture production in Waikato and Otago increased by 1.8% (Drewry et al. 2002).

Soil conditions in areas excluded from grazing are different to those included in a continuous grazing rotation. Soils in a continuous grazing rotation receive regular treading damage and, therefore, have slower natural recovery (Greenwood & McNamara 1992). Recovery that has taken place in soils under rotational grazing is

often offset by the effect of renewed treading (Greenwood & McNamara 1992). Given that natural recovery of soil is slow and renewed treading offsets recovery, soils under grazed pastures will always likely have some soil damage due to animal treading. However, as soil recovery over the summer-autumn period after treading (Drewry et al. 2004) improves pasture production potential, it is less likely there will be treatment differences in pasture yield over the whole growing season (Houlbrooke et al. 2009).

2.3.4.1 Mechanical recovery

Recovery of damaged soils may be ameliorated by mechanical means (McLaren & Cameron 1996). Shallow mechanical loosening of soil (also called ripping, sub-soiling or aerating) is especially effective in reducing compaction (Burgess et al. 2000; Drewry et al. 2000; Drewry & Paton 2000a). The use of shallow mechanical loosening with conventional tines and wing-shaped tines increased macroporosity volume by 50%, and saturated hydraulic conductivity and air permeability by 200 % on a sheep grazed Waikiwi silt loam (Drewry & Paton 2000a). Despite improvements to soil conditions following mechanical loosening, herbage growth may not be immediately enhanced (Chapman & Allbrook 1987). The lack of pasture response (to mechanical loosening) has been attributed to dry soil conditions at the time of shallow mechanical loosening (Burgess et al. 2000; Drewry et al. 2000), although long-term responses of the sward to more favourable soil conditions after mechanical loosening should eventually improve herbage growth (Burgess et al. 2000).

2.3.5 The effects of treading on pasture composition and growth

2.3.5.1 Botanical composition

The botanical composition of a pasture can be susceptible to change following animal treading as less treading-tolerant species are replaced with more tolerant, but possibly

less desirable, species. Germination of volunteer species in bare ground may result in change to the composition of the sward. *Poa annua* (annual poa) is often present in grazed swards as the result of its prolific seed production and colonisation abilities (Kemp et al. 1999), and it is very often found occupying spaces created by treading activity.

Severe cattle treading can also decrease *Trifolium repens* (white clover) content. This was reported by Ward and Greenwood (2002), when cattle grazing on a soil susceptible to pugging damage resulted in the elimination of clover from the sward. Furthermore, moderate and severe cattle treading has been shown by Menneer et al. (2001) to decrease the clover content of the sward by 38 and 65% respectively, and these reductions were greater than those recorded for *Lolium perenne.* This indicates that clover is more susceptible to the negative effects of treading than grass. The loss of clover from the sward and the long term effect on pasture production and therefore milk production was modelled by Menneer et al. (2001). The authors estimate that 10 years after a moderate or severe treading damage event, it was predicted that a decrease in N_2 fixation, soil organic N and grass growth, could result in a loss in milk production of 21% and 54%, respectively, on a whole farm basis.

2.3.5.2 Sward tiller density

Tiller density measurement has been used worldwide for many years as an indicator of the agronomic status of swards in forage studies (Matthew et al. 1996). Tiller density is defined as the number of individual grass tillers per given area, and is an important indicator of sward vigour (Mitchell & Glenday 1958). As treading by hooves results in the crushing of grass, tiller density can provide an indication of plant damage (Brown & Evans 1973). Low tiller density is an indication of low plant vigour, hence, low annual

herbage production (Edmond 1958). A field study of tiller response to cattle treading showed there was a reduction in tiller numbers of 54% and that this was linked to a 56% decrease in herbage growth rate (Pande, 2002). Pande et al. (2000) reported a 36% decline in grass tiller densities seven weeks after cattle treading on a Tokomaru silt loam soil.

2.3.5.3 Pasture production reduction and recovery after treading

Pasture recovery following cattle treading tends to be more rapid than soil physical recovery, suggesting that tiller dynamics and plant growth may be better indicators of sward damage than soil conditions (Betteridge et al. 2002). The reported interval of time for pastures to recover (Table 2.2) varies greatly from 48 to > 365 days. From a grazing management perspective, the ultimate measure of treading damage to pasture is the reduction in subsequent pasture production. The reduction in pasture production attributed to treading varies widely across different studies, from 0% to 88% (Table 2.2). These reductions in pasture production most likely reflect the differences in severity of treading damage owing to variations in key factors, such as soil type, soil moisture content, above ground pasture density, stocking rates (grazing intensity), duration of grazing, and season of the year (Table 2.2) (Patto et al. 1978).

Table 2.2 Effect of cattle treading damage on pasture production from field trials in the literature.

Management	Yield		Difference % in DM production	Time frame	Soil moisture %	Stocking rate	Soil type	Repeat damage conducted in a single year	Region	Reference
	Not treaded	Treaded								
Wet soil daiy cow treading	8126 lb DM/acre/yr	8553 lb DM/acre/yr	5% increase	365 days	Field capacity	60 cow/acre 24 hrs	Te Kowhai silty clay loam	No	New Zealand	Campbell (1966)
				365 days		120 cow/acre 24 hrs				
(3 year mean)		8163 lb DM/acre/yr	0%							
Wet soil bullock treading	12,066 kg DM/ha/yr	11,279 kg DM/ha/yr	7% decrease	356 days	Saturation	2 bullocks/ha	Meduim texture and good structure	No	Ireland	Mullen et al. (1974)
(3 year mean)		10,179 kg DM/ha/yr	10% decrease	365 days		6 bullocks/ha				
Dry soil dairy cow treading conducted over 3 years	Year 1, 16.4 t DM/ha/yr	15.4 t DM/ha/yr	6% decrease	356 days	> 40 mm	25-35 cows/plot/ 8 hrs	Lemnos loam, a typical red-brown earth	No	Australia	Kelly (1985)
	Year 2 16.7 t DM/ha/yr	15.2 t DM/ha/yr	10% decrease	365 days						
	Year 3, 19.1 t DM/ha/yr	16.8 t DM/ha/yr	13% decrease	365 days						
Winter dairy cow grazing	2030 kg DM/ha	1980 kg DM/ha	2% decrease	120 days	N/a	3.7 cows/ha on a 120 day winter rotation	Stratford fine sandy loam	No	New Zealand	Thomson and Laurence (1992)
Dairy cow treading	59 kg DM/ha/day	33 kg DM/ha/day	44% decrease	48 days	Saturation	150 cows/ha 36 hrs	Tokamaru Silt loam	No	New Zealand	Pande et al. (2000)
Moderate dairy treading	8168 kg DM/ha/yr	6456 kg DM/ha/y	21% decrease	1 year for both treatments	Saturation	450 cows/ha for 1.5 hrs	Te Kowhai silt loam	No	New Zealand	Menneer et al. (2001)
Severe dairy treading	8168 kg DM/ha/yr	4526 kg DM/ha/yr	45% decrease			450 cows/ha for 2.5 hrs				
Moderate dairy treading			52 % decrease	100 days	Saturation	450 cows/ha for 1.5 hrs	Te Kowhai silt loam	No	New Zealand	Menneer et al. (2001)
Severe dairy treading			88% decrease			450 cows/ha for 2.5 hrs				

Management	Yield		Difference % in DM production	Time frame	Soil moisture %	Stocking rate	Soil type	Repeat damage conducted in a single year	Region	Reference
	Not treaded	Treaded								
Light dairy cow treading	9366 kg DM/ha	8717 kg DM/ha	7% decrease	August -Nov	Gravametric moisture content 30%	67 cows/ha for 7 hrs	Brown Chromosol	No	Australia	Nie et al. (2001)
Moderate dairy cow treading		5475 kg Dm/ha	41% decrease			33 cows/ha for 7hrs				
Severe dairy cow treading		5632 kg DM/ha	40% decrease			267 cows/ha for 7 hrs				
Dairy cow 3 hrs block grazing (3 year mean)	3457 kg DM/ha/yr	2555 kg DM/ha	26% decrease	July-Sept	53-83%	240-350 cows/ha	Te Kowhai silt loam	No	New Zealand	Drewry (2003)
Dairy cow 12 hrs block grazing (3 year mean)		2685 kg DM/ha	22% decrease							
Dairy cow treading 3 hrs (3 year mean)	3000 kg DM/ha	1900 kg DM/ha	37% decrease	8 weeks	65%	300 cows/ha	Te Kowhai silt loam	No	New Zealand	Zegwaard (2006)
Dairy cow treading 9 hrs (3 year mean)		2150 kg DM/ha	29% decrease							
Dairy cow treading 24 hrs (3 year mean)		1550 kg DM/ha	49% decrease							
Dairy cow treading 3 hrs (3 year mean)	1800 kg DM/ha	1500 kg DM/ha	17% decrease	8 weeks	71%	300 cows/ha	Te Kowhai silt loam	No	New Zealand	Zegwaard (2006)
Dairy cow treading 9 hrs (3 year mean)		1150 kg DM/ha	27% decrease							
Dairy cow treading 3 hrs (3 year mean)		900 kg DM/ha	50% decrease							

Management	Yield		Difference % in DM production	Time frame	Soil moisture %	Stocking rate	Soil type	Repeat damage conducted in a single year	Region	Reference
	Not treaded	Treaded								
Dairy cow treading 3 hrs (3 year mean)	1650 kg DM/ha	1800 kg DM/ha	0% decrease	8 weeks	81%	300 cows/ha	Te Kowhai silt loam	No	New Zealand	Zegwaard (2006)
Dairy cow treading 9 hrs (3 year mean)		750 kg DM/ha	55% decrease							
Dairy cow treading 24 hrs (3 year mean)		600 kg DM/ha	64% decrease							
Dairy cow treading 3hrs (3 year mean)	13.3 t DM/ha/yr	13.3 t DM/ha/yr	0%	Sept-Apr	(35% of penetrometer readings were greater than 2 cm depth)	65 cows/ha	Pukemutu silt loam	No	New Zealand	Houlbrooke et al. (2009)
Dairy treading on three differennt farm systems (mean of three farm systems)	10.5 t DM/ha/yr	9.45 t DM/ha/yr	10% decrease	1 year	n/a	1.8 cow/ha	Poorly drained gley soil	No	Ireland	Phelan et al. (2013)
Spring dairy cow treading 20 min	3,471 kg DM/ha	3,724 kg DM/ha	7% increase	70 days	Saturation	n/a	Free draining acid brown earth	No	Ireland	Tuñon et al. (2014)
Spring dairy treading 40 mins	3,471 kg DM/ha	3,612 kg DM/ha	5% increase	70 days						
Spring dairy treading 120 mins	3,471 kg DM/ha	2,971 kg DM/ha	15% decrease	70 days						

Some of the studies in Table 2.2 suggest that there may be some initial benefit to light treading damage with several authors reporting small increases (5 – 7%) in pasture production (Campbell 1966; Tuñon et al. 2014). However, the short and long-term effects of severe treading damage as reported in the literature appear to be quite varied. For example, Campbell (1966) examined treading by dairy cows while grazing autumn-saved pasture in late winter over three years. There was no evidence that a single treading in late winter, repeated on the same plots in three consecutive years, had any cumulative effect on annual pasture production. There was no more than a 10% reduction (for the three years) in pasture production over the spring period following the grazing. This trend is also reported by Tuñon et al. (2014) who showed that a severe treading event in late winter caused an initial 15% reduction in herbage mass after 70 days, yet annual pasture production was not affected. The literature suggests that initial damage does not always seem to have long-term effects on pasture production. However, this is not surprising given that soil recovery over the summer-autumn period after treading (Drewry et al. 2004) improves pasture production potential, so it is less likely that treading will result in large reductions in annual pasture yield (Houlbrooke et al. 2009).

The negative effect of treading damage on short-term reductions in pasture production is clearer. Several authors report short-term decreases in pasture production following treading damage without any long-term reduction in pasture production. For example, Pande et al. (2000) showed a reduction in pasture production of 50% in the following 49 days after severe treading damage. Menneer et al. (2001) also reported that the largest decrease in pasture production (88%) from severe winter grazing of wet soils was observed during the first 100 days after treading. However, interestingly, this author

reports that the effect of such severe treading on the annual pasture production only resulted in a 19% reduction.

It appears (Table 2.2) that short and long term damage should be considered separately when analysing the effects of treading damage (Tuñon et al. 2014). Most published literature measures the impact of one treading damage event (Table 2.2). In reality, multiple treading damage events may occur to paddocks on dairy farms that are rotationally grazed through autumn, winter and spring. There has, however, been no investigation into the effect of repeat damage in a single season and the effects on short and long-term pasture production. In addition, the majority of the literature focuses on one grazing event at one particular soil moisture content, usually field capacity or saturation. Furthermore, these studies often employ large stocking rates and prolonged grazing periods. In comparison, grazing management on many dairy farms is relatively sophisticated with farmers attempting to more accurately match pasture supply with animal requirements and minimise treading damage. Given this, how relevant is the historic treading research to modern dairy production systems? A key question would be "what is the effect of treading damage on pasture production on a well-managed dairy farm, which might practise some form of standoff"?

2.3.6 Environmental effects of treading

2.3.6.1 Sediment and runoff

Severe treading damage by cattle can increase sediment runoff from relatively flat land to waterways (Sheath & Carlson 1998; McDowell et al. 2005). Hard grazing regimes may also increase sediment runoff from farmed hill-country to waterways, and more so for cattle grazed than for sheep grazed areas. A three years study on undrained soils in Southland by Smith and Monaghan (2003) reported that N and P losses via overland

flow showed that most losses occur in late winter and spring as a consequence of soil treading damage and the moist soil conditions at these times of the season. Treading damage during the grazing of winter brassica crops, which is practised in some areas of the South Island (NZ), increased sediment runoff by 25% compared to untrodden croplands (McDowell et al. 2003). Sediment runoff from grazed pasture also tends to have elevated levels of microbial pathogens (sourced from faeces), which adversely affects water quality (Nguyen et al. 1998).

2.3.7 Beneficial effects of treading

Until this point, this literature review has only covered detrimental effects of treading damage. However, there are a number of beneficial effects from treading such as suppression of weeds, which favours the development of *Lolium perenne* (perennial rye grass) pasture swards, and reductions in the population of pasture pests. Moderate cattle treading was suggested by Harker et al. (2000) to suppress broad-leaved weeds. Furthermore, moderate treading damage without considerable plant burial or death, may favour development of swards of treading tolerant plants such as *Lolium perenne* (perennial rye grass) (Kemp et al. 1999). Treading has the beneficial effect of reducing sward damage by *Costelytra zealandica* (New Zealand grass grub) invasion on some soils (Betteridge et al. 2003). Cattle treading and pasture rolling in late-July/early-August decreased New Zealand grass grub populations by 69%, whilst treading in October further decreased populations by 92% (Atkinson & Slay 1994). Treading activity also has the beneficial effect of breaking-up sod-bound swards or those with thatch build-up, such as for *Pennisetum clandestinum* (Kikuyu grass) dominated swards common in Northland, New Zealand (Langer 1984).

2.3.8 Grazing management to limit treading damage

2.3.8.1 Standoff (on/off grazing)

Research has shown that cows can eat up to 80% of their allocated feed within a four-hour period (Thomson & Laurence 1992; Judd 1994; Christy 1996; Kennedy et al. 2009; Christensen et al. 2018a). With the inclusion of supplementary feed there was no effect animal production (Kennedy et al. 2009; Kennedy et al. 2011). Therefore, livestock can potentially be removed from pasture after shorter periods of grazing when there is a high risk of treading damage (Bilotta et al. 2007). Given this, reducing grazing time on wet soils should be seen as an effective management tool to protect pastures (Nie et al. 2001). However, the reported effects of reduced grazing time on soil properties and pasture production in the literature varies, and there may or may not be advantages to these reduced periods of grazing. For example, a three year study by Drewry (2003) in the Waikato comparing different grazing regimes found that a three-hour grazing treatment (during wet soil conditions) resulted in better soil physical quality than a conventional grazed control (un-restricted grazing). However, this was not reflected in greater pasture production. This result is mirrored in a three year trial in Southland by Houlbrooke et al. (2009). This trial compared a three-hour restricted spring grazing treatment on a wet Pallic soil against a conventional grazed control. These authors reported no significant difference in total or cumulative pasture production and soil physical condition over the three-year period between the restricted and conventional grazing treatments. These two studies show little benefit to soils and pasture from restricted grazing. However, other studies hint that there is a benefit to restricted grazing. For example, an Australian study of restricted grazing by Christy (1996) compared the effect of a range of grazing durations on wets soils. The author reported pasture production following 2, 4 and 12 hours of grazing; as grazing duration increased, the reduction in pasture production was

19, 28 and 40%, respectively, for the following two months. This suggests an advantage to shorter grazing events on wet soils. However, there was no assessments of the severity of pugging damage caused by these different grazing times. A similar NZ study by Thomson and Laurence (1992) showed that, compared to a non-damaged mown control, a four hour restricted grazing event on wet soils in July resulted in no reduction in pasture production over a subsequent four month period, suggesting a potential benefit of standoff.

2.3.8.2 Grazing at a safe soil moisture content

Studies such as those of Climo & Richardson, (1984) and Zegwaard (2006) are good illustrations of the manner in which soil texture, structure and SWD interact to influence the reaction of soil to grazing. The SWD at which soil is prone to treading damage is sometimes called the threshold SWD or critical water content (CWC) (Laurenson & Houlbrooke 2016). This threshold value can vary depending on a number of factors, including soil type, infiltration rate, drainage rate, previous damage and natural spatial variability. (Climo & Richardson 1984; Laurenson & Houlbrooke 2016).

A study by Zegwaard (2006) looked at the impacts of 'one-off' treading events by cattle on a soil susceptible to treading at gravimetric soil moisture contents (GSM) of 65%,71% and 81% (no SWD was reported). Treading caused more damage at the greater GSM content than at the lowest GSM content. When the GSM was >71%, a three-hour grazing caused a total decline of 1,100 kg DM ha^{-1} in pasture productivity. However, Zegwaard (2006) suggested that at lower soil GSMs, a grazing of > 3 hours is unlikely to cause a significant decline in pasture productivity.

In an Irish study, Herbin et al. (2011) investigated the effect of treading by dairy cows at different SWD on key soil health indicators (bulk density, soil shear strength,

penetration resistance and total porosity). The target SWD treatments were 0, 5, 10 and 20 mm. They found that the degree of damage was directly dependent on SWD, with the negative impact of grazing on soil health indicators increasing at smaller SWDs. Piwowarczyk et al. (2011) also used SWD to predict treading damage. Two contrasting Irish soils were analysed for changes in bulk density under grazing over a range of estimated SWDs (0, 5, 10 and 20 mm). The change in bulk density from simulated hoof compression was linearly related to SWD (R^2 0.90 to 0.99), leading to the conclusion that SWD can be used to predict when soils are likely to be at risk of damage from grazing animals.

While the research of Herbin et al. (2011) and Piwowarczyk et al. (2011) suggests that incorporating the SWD into grazing management could help to predict potential impacts of treading damage on soil quality, the SWD range that they investigated is not sufficiently fine or detailed to offer much by way of practical help to grazing management in New Zealand. At SWD values of 10 and 20 mm, nearly all soils will be very firm and have adequate strength to support the heaviest of grazing animals. Even at a SWD of 5 mm, most soils would be able to sustain grazing for relatively long periods. Therefore, the New Zealand dairy farmer would be much more interested in the effects of grazing at SMD values between 0 and 5 mm.

A number of studies have been conducted in New Zealand to quantify the effects of grazing soils with relatively small deficits. Laurenson et al. (2014) investigated the effects of grazing dairy cows on soils with three SWD ranges in the South Island, NZ. The treatments were: if SWD > 6 mm then there was no restriction to grazing; if 6 > SWD > 2 mm then cows could graze 13 hours/day; and if SWD < 2 mm there was no grazing on paddocks and cows were stood off pasture. They found that grazing pasture

for 13 hours/day at SWDs between 2 mm – 6 mm had minimal negative effect on soil properties or pasture production.

In another New Zealand (Otago) study by Laurenson and Houlbrooke (2016), the susceptibility of two intact soils (North and South Otago Pallic soils) to compaction was assessed in the laboratory using the Proctor test and Plastic limit test. The threshold SWD in the top 100 mm of each of these soils was 2.8 and 1.0 mm, respectively. However, given the large spatial variation in soil properties that could be expected under field conditions, they recommend that farmers should use a SWD of at least 3 mm as a guide to scheduling grazing to avoid soil compaction.

Generally, pastoral farmers are aware that treading damage impacts on pasture growth (Laurenson & Houlbrooke 2016). Therefore, identification of critical SWDs would help farmers to avoid grazing events likely to lead to soil physical damage and reductions in pasture performance (Kerebel et al. 2013). In other words, given that wet soil is the precursor to treading damage and that there is a threshold SWD at which treading damage can be expected, the use of the SWD could be a valuable management tool (Herbin et al. 2011; Kerebel et al. 2013). Although there have been some preliminary studies in New Zealand, there are limited guidelines or management frameworks incorporating threshold SWD values to enable farm managers to schedule grazing and make decisions that are likely to decrease the incidence and severity of treading damage (Laurenson et al. 2014).

2.3.9 Tools for measuring treading damage

Because cattle treading can result in hoof indentations that penetrate or rupture the soil surface (Scholefield & Hall 1985; Bilotta et al. 2007), measurements of soil roughness or disruption may be used as indicators of the severity of treading damage to soil. Four

means of measuring treading damage in this manner are: the *depth of pug* method (Nie et al. 2001; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015), the *pin and profile meter* method (Davies & Armstrong 1986; Betteridge et al. 1999), the more frequently used *roller chain* method (Nie et al. 2001; Pande et al. 2002; Drewry et al. 2003; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015) and the *Visual scoring* method (Sheath & Carlson 1998; Nie et al. 2001; Zegwaard 2006; Little et al. 2015). These four techniques mentioned above are reviewed in Chapter 3 and therefore, will not be expanded upon here.

2.4 Part 2: Reducing nitrogen leaching to water

2.4.1 Nitrogen Water Quality Issues relating to New Zealand Agriculture

2.4.1.1 Nitrogen

Nitrogen (N) is a naturally occurring chemical element and is an essential nutrient for plant growth. The quantity of N cycling in pastoral systems is greater than that for other nutrients; furthermore, it is more mobile and labile than other nutrients and is highly susceptible to leaching from the root zone (Ledgard et al. 1999). Nitrogen can be present in water in a number of forms: nitrate (NO_3^-), nitrite (NO_2^-), ammoniacal (NH_3) and organic N (HorizonsRegionalCouncil. 2013). Of these different forms, NO_3^- is of most concern to water quality. Nitrate is an anion and a highly mobile form of N; it is formed via nitrification, where ammonium is converted to NO_3^- by bacteria (McLaren & Cameron 1996).

Due to high water solubility of NO_3^- and NZ's negatively charged soils (hence poor anion retention capacity), nitrate readily enters groundwater with drainage through the process of leaching (McLaren & Cameron 1996). Nitrogen leaching, the removal of N

from the soil in drainage water, can involve organic N such as particulate and dissolved forms, but the predominant form of N leached is NO_3^- (Di & Cameron 2002). The amount of N leached from the soil depends on the concentration of NO_3^- in soil solution, and the volume of water draining through the soil. In New Zealand, drainage mostly occurs in late autumn, winter and early spring. For leaching to occur, there must be mass flow of water through the soil profile. Therefore, the more water that flows through the soil, the more NO_3^- is leached.

2.4.1.2 Nutrient Loading

Intensive agriculture is known to emit significant amounts of N, which is recognised as a major cause of water quality degradation in many regions of New Zealand (Ledgard et al. 1999; Hamill & McBride 2003). Nitrogen can enter water bodies relatively quickly, through fluvial transfer processes, particularly in dissolved forms in subsurface drainage (Gregg et al. 1993). In recent years, the negative environmental impact of agriculture on water quality has grown due to increased farm productivity (MinistryfortheEnvironment 2018). Furthermore, due to the relative prosperity of the dairy industry there has also been a move away from low-intensity to high-intensity land use, i.e. the conversion of sheep and beef farms to dairy (MinistryfortheEnvironment 2018). The net effect of intensified land use and production is the increase in nutrients loads that enter waterways (Ledgard et al. 2006). These increased nutrient loads lead to accelerated nutrient enrichment (eutrophication) of waterways (MinistryfortheEnvironment 2018).

Eutrophication is the contamination of lakes, rivers and underground aquifers with the growth of algal blooms from nutrients such as N and phosphorus (P) entering waterways, usually from concentrated urine patches (particularly dairy cows) and to a

lesser extent fertilisers (McLaren & Cameron 1996). These uncontrolled algal blooms not only degrade the visual quality of waterways, but also deplete oxygen in the water to levels which are unsustainable for aquatic life (McLaren & Cameron 1996). Plants only produce oxygen during the day when photosynthesising, but the processes of respiration and decomposition that consume oxygen, occur night and day. The result of excessive plant growth leads to dramatic drops in oxygen levels at night, leaving fish and other aquatic creatures unable to breathe. Oxygen is also consumed when these plants die and are broken down by bacteria (McLaren & Cameron 1996). Plants and algal blooms also block water flow and remove habitat for native organisms. Aquatic invertebrates and fish exposed to NO_3^- may be smaller, reach maturity later, be less successful in reproduction, or may even die at extremely high exposure levels (HorizonsRegionalCouncil. 2013). Benthic cyanobacteria or blue green algae from eutrophication is also becoming an increasing issue with respect to water quality, as several of the cyanobacteria species are known to produce natural toxins which pose a threat to human and animal health when consumed, or after contact with contaminated water (HorizonsRegionalCouncil. 2013).

When setting acceptable NO_3^- levels for ground water, human health is of primary concern. The World Health Organisation (WHO) established the current drinking water standard advisory level of 11.3 ppm NO_3^- on the basis of human health risks due to NO_3^- consumption (McLaren & Cameron 1996). Although there have been studies that attempted to link NO_3^- consumption to stomach cancer, childhood diabetes and other secondary medical problems, findings are inconclusive (Addiscott & Benjamin 2004). Only methemoglobinemia, (also known as infant cyanosis or blue-baby syndrome) has been proven to result from ingestion of water containing high nitrate concentrations (McLaren & Cameron 1996). Because of the links made between NO_3^- in drinking water

and medical problems, and considerable media attention, world and national organisations have created guidelines for drinking water quality.

2.4.1.3 Inefficiencies of Nitrogen cycling in grazed pasture systems

There are two major inefficiencies in the cycling of N in grazed pasture systems, which can lead to an excess of NO_3^- in soils. These are: the way ruminant animals partition dietary N into urine, and the high concentration of excreted N in urine patches (Haynes & Williams 1993), mostly in the urea form (Petersen et al. 1998).

2.4.1.4 Ruminant Partitioning of N into Urine

The forages eaten by the dairy cow provide sugars, which are used by microbes as an energy source for their own growth and end products for the cow. Forages also contain protein which provides dietary N in the form of amino acids and proteins that are then utilised by the microbes also for their own reproduction and end products for the cow (Moran 2005). Dietary N requirements for ruminants has been recognised for over a century (Pacheco & Waghorn 2008).

Dietary N consumed by a ruminant is in either the rumen degradable protein (RDP) form or the rumen un-degradable protein form (RUP). About 20% of the dietary N consumed by the dairy cow is RUP, which consists of some RDP that escapes rumen fermentation and other dietary N not degraded by rumen microbes due to their structural properties. The RUP is hydrolysed in the intestine and is then partitioned either into milk or into faeces (Figure 2.2).

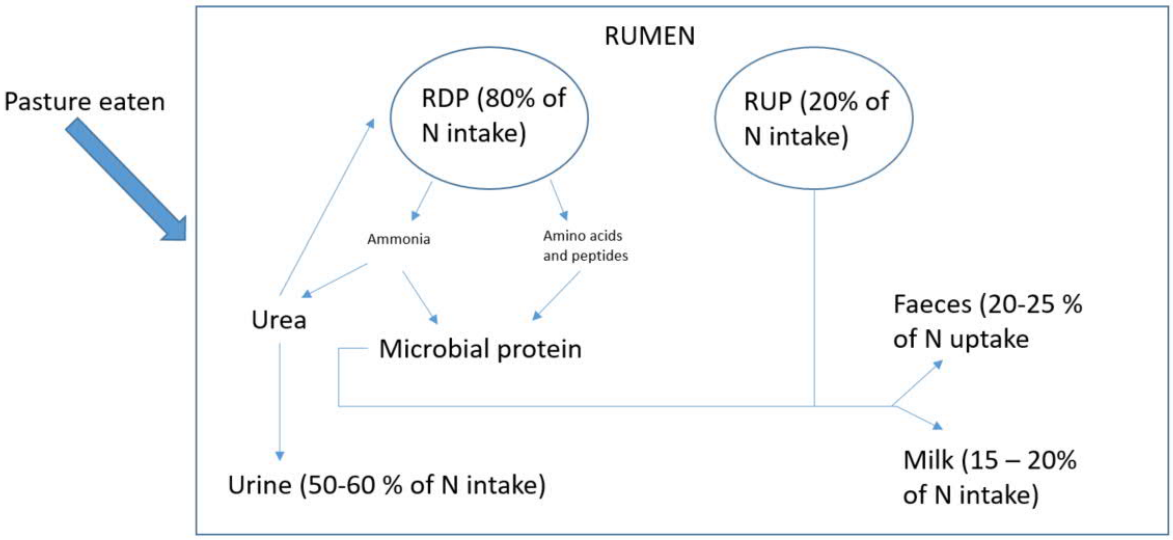

Figure 2.2 Schematic representation of nitrogen flows in the rumen relative to 100% of the total N eaten in fresh pasture. Adapted from (MacRae & Ulyatt 1974; Leng & Nolan 1984; McDonald et al. 2002; Pacheco & Waghorn 2008).

The other 80% of dietary N is RDP. The RDP is degraded by microbes in the rumen to amino acids, peptides, and ammonia. The microbes then re-synthesize microbial protein from degraded protein. This process results in an upgrading of forage protein to microbial protein that has higher levels of essential amino acids and greater biological value than plant protein (Shirley 1986). However, the rumen has a limited capacity to convert Dietary N to microbial protein and if the nutritional requirements for N are exceeded then this has no value to the animal (Pacheco & Waghorn 2008). The nutritional requirements for N are usually expressed as a crude protein percentage (Pacheco & Waghorn 2008).

Crude protein is equal to the N concentration of a plant times 6.25 and is given as a percentage e.g. 25% CP. Crude protein includes all compounds containing N as part of their structure. For grazing animals fed on temperate forages, dietary CP concentrations exceeding 20 % (3.25% N) of dry matter (DM) are always surplus to requirements, even for lactating dairy cows (Pacheco & Waghorn 2008). Therefore, when CP in feed

exceeds 20% the microbes are unable to convert it into microbial protein, and consequently excessive ammonia may accumulate in the rumen. The excess ammonia produced has no nutritive value and is converted to urea in the liver (50 – 60% of N intake) (Figure 2.2). The N in excess of requirements has to be disposed of, mostly as urinary N. Kebreab et al. (2001) reported that urinary N output is correlated with increasing N intake. When the protein content of the diet is increased, the concentration of N in urine rises exponentially while only minimal N is partitioned into faeces and milk (Figure 2.3). The excess N ingested by the cow that is partitioned into urinary N is deposited onto the ground in a urine patch as the predominant N-containing compound urea. Urea is rapidly converted to NO_3^- and is at high risk of leaching into waterways (Haynes & Williams 1993).

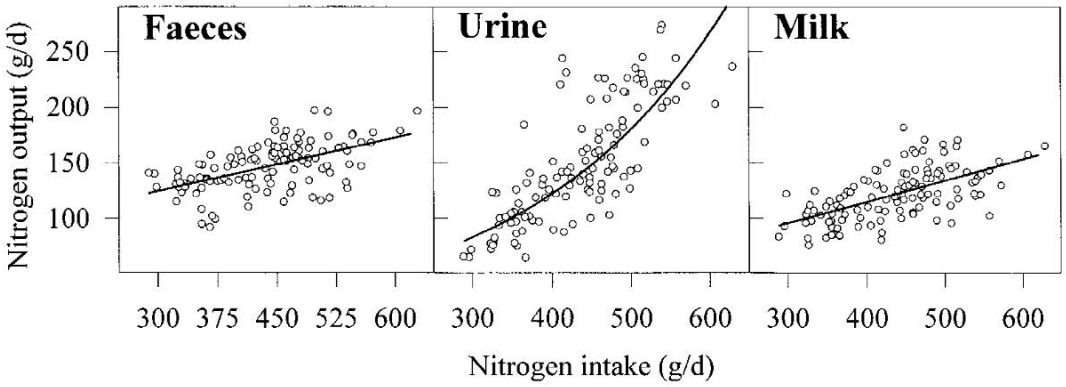

Figure 2.3 Relationship between total N intake and faecal, milk and urinary N outputs, taken from (Kebreab et al. 2001).

2.4.1.5 The Urine Patch

In NZ grazed pastoral systems, animals graze pasture year-round on a daily basis and excrete urine back onto pasture in patches. The area of these patches depends on the volume of urine excreted. The number of urine patches deposited depends on the frequency of urinations (driven by stocking rate, feed and water intake) (Pleasants et al. 2007). Nitrogen losses occur predominantly under animal urine patches (Ledgard &

Menner 2005; Selbie et al. 2015). This causes an uncoupling of the N cycle as the grazing animals removes N in herbage across a large area. However, the animal deposits it back to a small area in very high concentrations via the urine patch (Schnyder et al. 2010). Ruminant animals (cattle, sheep and deer) urinate on average 8-12 times each day (Haynes & Williams 1993). The area affected by urine can often be easily observed in the field as green patches of increased pasture growth. A urine patch can be defined as the surface area of soil that is wetted by urine excreted by an animal in a single event (Selbie et al. 2015). This wetted area may receive up to 5 mm equivalent depth over a 0.2-0.4 m^2 area (Jarvis et al. 1995). The 'average' dairy cow urine patch is described by Haynes and Williams (1993) as 2 L of 10 g N/L urine returned to a surface area (wet) of 0.2 m^2. This corresponds to a urine patch-loading rate of 1000 kg N ha, a figure that is commonly used in the literature. However, this rates is actually quite varied (Selbie et al. 2015), and the urine N loading rate of a dairy cow actually varies from 400 to over 1000 kg N ha^{-1} (Haynes & Williams 1993; Jarvis et al. 1995; Di & Cameron 2002), which is primarily governed by the amount of N ingested by the animal.

The distribution of the urine patch on a grazed area is non-uniform, with high spatial variability (Selbie et al. 2015). The variability is greatly influenced by animal congregation (beneath trees and hedges, around gateways and water troughs) and stock management (day vs. night paddocks), type of animal and the stocking rate (Haynes & Williams 1993; Pleasants et al. 2007). Like the N loading rate of a urine patch, the coverage of the urine patch is also extremely varied. This variability of coverage can be seen in a review by Selbie et al. (2015), who report the estimates of coverage in the literature range from 4% to 29% of the soil surface annually.

While the N partitioning in the rumen and the concentration of N in the urine patch are the main causes of high N in soils and thus N leaching, it is when it is deposited during the grazing season that determines the flux of nitrogen in drainage.

2.4.2 The timing of N losses and a critical period for N accumulation

Numerous authors have reported that the quantity of NO_3^- leached under pasture is strongly related to the amount of urinary N deposited in late summer to autumn that is not utilised by the pasture, i.e., the fraction that remains in the soil at the commencement of drainage (Cuttle & Bourne 1993; Thompson & Fillery 1997; Decau et al. 2003; de Klein et al. 2006; Shepherd et al. 2010; Vogeler et al. 2010; Shepherd et al. 2011; Cichota et al. 2013; Monaghan et al. 2016; Christensen et al. 2018b). The urine deposited in spring and summer appears to have less effect on the quantity of leaching. In other words, these studies show that the N deposited between late summer and autumn is the N that is most susceptible to leaching from winter drainage, and in doing so, identify the 'critical period' for N accumulation in the soil. The importance of the late summer-autumn period is due to the accumulation of mineral N in the soil prior to the commencing of the drainage season. Factors that influence this accumulation are: lactating cows depositing concentrated N in urine patches on to dry soil coupled with low denitrification rates, summer drought reducing pasture growth and N uptake, and episodic summer rains pushing mineral N lower in the root zone (Shepherd et al. 2011; Snow et al. 2011).

The influence of N uptake by pasture prior to winter drainage has been investigated in overseas studies in England and France. The English study by Cuttle and Bourne (1993) reported on the effect of urine applied to grasslands during different periods of the

growing season. The authors showed that the amount of N remaining in the soil at the start of the drainage season was directly related to the time of the year that the urine was deposited. Of the N deposited in late spring and early summer, 5-13% remained in the soil profile before winter drainage, while from late summer onwards 30-50% of the urine N deposited was still present in the soil in late autumn. A French study by Decau et al. (2003) on contrasting soil types reported that the N leaching potential of deposited urine increased with proximity to winter drainage. There was a seasonal effect as N leaching losses were greatest for autumn, intermediate for summer and smallest for spring-applied urine irrespective of soil type. The contribution of the direct urine to leaching amounted to 1 to 2% in spring, 8 to 15% in summer, and 15 to 29% in autumn.

The critical period for NO_3^- accumulation in New Zealand conditions was evaluated by Shepherd et al. (2010). Artificial urine was applied to separate plots at monthly intervals from March to August. A single application of urine was applied at a rate of 800 kg N/ha to individual plots at the start of each month. Drainage started in late May, and there was a highly significant effect of application time on NO_3^- leached. During the drainage period the following losses were reported (kg NO_3^- /ha): 332 (March applied); 264 (April applied); 306 (May applied); 233 (June applied); 76 (July applied); 12 (August applied). The indication from this experiment is that the N in the urine deposited in March is as great or at higher risk of NO_3^- leaching as for urine deposited in May. While the results are only from one season and one soil type in the Waikato region, they clearly demonstrate the risk posed by NO_3^- accumulation in the soil leading up to the drainage period as reported by the overseas studied mentioned above.

A follow-up study by Shepherd et al. (2011) looked to test the hypothesis that summer urine deposition can be a greater source of NO_3^- leaching than later urine depositions

leading up to winter drainage. Artificial urine (800 kg N/ha), replicating a cow's urine patch, was applied to separate replicated plots at monthly intervals from February to July 2010. There was a significant ($P < 0.01$) relationship between time and rate of urine application on the amount of NO_3^- leached during the winter drainage period. Nitrate leaching increased approximately linearly for the urine applications from February to May. Leached NO_3^- values for the February and May applications were 317 and 445 kg N/ha respectively, showing that the contribution to NO_3^- leaching from urine deposited in February can be significant. These results show that while the May application of urine lead to the highest loss of N, the total N lost during the drainage season would be significantly higher due to the accumulation of nitrogen in the soil from the previous grazing events. However, the authors state that further work is required to test if this relationship holds for other regions within New Zealand where climate and pasture growth patterns will differ.

The effects of NO_3^- accumulation in the soil over the late summer - autumn period is also documented by Christensen et al. (2018b). They present NO_3^- leaching data from a study comparing year-round grazing and duration controlled grazing in the Manawatu, NZ. During 2009, there were two distinct drainage periods. The first drainage period was unusual for the Manawatu region and consisted of three drainage events in late summer/early autumn, with the second, more typical, drainage period starting in mid-May. Concentrations of NO_3^- in the February drainage were up to 14.6 mg/L. However, when the typical drainage season started, NO_3^- concentrations in drainage water had further increased up to 20.6 mg/L. The inference here is that NO_3^- had accumulated in the soil between the drainage events in February and May. This demonstrated that grazings during the late summer and autumn period are an important source of NO_3^- accumulation in the soil, which in turn is a major contributor to NO_3^- losses in the

drainage season (Cuttle & Bourne 1993; Decau et al. 2003). This is further confirmed by a modelling study under NZ conditions by Vogeler et al. (2010). The authors used the APSIM (Agricultural Production System Simulator) model to determine risk indicators of N leaching from urine patches. The simulation compared six different soil types over a range of annual rainfall scenarios (600 – 1200 mm). The authors state that the month of urine deposition directly affects the amount of NO_3^- leached, with a higher risk observed from January to April and a lower risk observed between May and December.

2.4.3 Mitigations used to reduce N leaching

Given the patterns for drainage and urine deposition on farms, there are implications for N management. More specifically, the challenge is to develop mitigations that can operate within a farm to decrease N loss from the urine patch without compromising farm productivity or profitability. Accordingly, there are numerous research projects undertaken by animal scientists, soil scientists and agronomists to identify methods to mitigate NO_3^- loss to water. Some methods seek to either reduce the amount of N consumed by the cow, or manipulate the cow's diet so it partitions more N into milk protein and less into urine (Kebreab et al. 2001; Ledgard et al. 2006; Higgs et al. 2013). There are also other methods being investigated that do not manipulate the animal's diet, but rather grazing and or farm management; these can include options such as, salt supplementation (Ledgard et al. 2007) animal selection (Woodward et al. 2011) and on off grazing (Monaghan et al. 2016; Christensen et al. 2018b).

2.4.3.1 Feeding Supplements

The feeding of supplements is a common practice by NZ dairy farmers to fill feed gaps experienced during winter and summer sessions. Supplements, depending on what they

are, have different N contents (CP protein), protein degradability and energy values. A study by Kebreab et al. (2001) compared four different types of supplements all with relatively low protein concentrations, but different energy sources, to quantify which was the best at reducing the output of urine N from dairy cows. The energy sources were sugar beet pulp (Fibre), barley wheat (high starch), maize silage (starch) and molasses (sugar). The starch based maize silage had the lowest N output and a higher milk N output when compared to the other supplements in the experiment. The lower urinary N observed with the maize supplement is explained by the fact that maize protein is more slowly degraded in the rumen (Beever et al. 2000). Protein degradability is important as the more slowly protein is degraded in the rumen then the more likely protein is to be absorbed in the small intestine and thus less N will be partitioned to urine and more to faeces and milk. Maize silage has good metabolisable energy (ME) levels, with low crude protein contents and a high percentage of starch. However, with such a low CP % content, maize silage can only be used as a supplement, and would need to be fed with pasture, as at approximately 8% CP (Burke et al. 2000) maize would be below the CP requirement of a lactating cow.

2.4.3.2 Mixed forages

The New Zealand dairy industry has traditionally been based on perennial ryegrass (*Lolium perenne*)/ white clover (*Trifolium repens*) pasture. The CP content of these traditional pastures varies naturally throughout the grazing season, but they are characterised by a crude protein (CP) content typically above 20% of dry matter (DM) (Litherland & Lambert 2007). The high solubility of this protein, results in a large proportion of dietary N being excreted in the urine (Tamminga 1992). Mixed forage pastures with lower CP content have been identified as a way to reduce N losses to the environment under dairy cow grazing. A study by (Woodward et al. 2012) compared a

standard perennial ryegrass/white clover pasture (RYE) with a mixed pasture (MIX) of ryegrass/clover, chicory (*Cichorium intybus*), plantain (*Plantago lanceolata*) and lucerne (*Medicago sativa*). The MIX treatment had a higher milk solid yield and more N partitioned to faeces, but most importantly, significantly less N partitioned to urine (29%) vs. the RYE (43%), and an increase in N being partitioned into milk (23% vs. 15%). This partitioning improved the N use efficiency of the dairy cows grazing the MIX. This experiment has shown that there could be opportunities to improve N use efficiency and reduce urinary N output by feeding mixed pasture to dairy cows.

2.4.3.3 Condensed Tannins (CT)

The options to reduce urinary N excretion discussed so far involve feeding diets with low CP. However, diverting dietary N away from urine to faeces is also a method that can be used to reduce urinary N. Condensed tannins (CT) present in lotus species are able to divert dietary N from urine to faeces as well as increasing MS production in dairy cows (Woodward et al. 2009). Condensed tannins bind to plant proteins in the rumen, effectively protecting them and. reducing the breakdown of the plant protein to ammonia by rumen microflora. This partitions more N to faeces and milk (Jacobs & Woodward 2010). In a study by Woodward et al. (2009) cows were fed a ryegrass based pasture diet with increasing levels of birdsfoot trefoil (*Lotus corniculatus*). The results of this trial showed that, as the proportion of Lotus fed in the dairy cow diet increased (from 0 to 45%) then so did the amount of N partitioned into milk (16 -21%) and faeces (29 – 37%), while at the same time the partitioning of N to urine declined (49-34%). Forages containing CT do not have a major role in New Zealand farming because management practices have not been developed to properly graze them, and dry matter yields from lotus species are much lower than from ryegrass-dominant pasture (Waghorn et al. 1998).

2.4.3.4 Cultivar Selection

There have been studies undertaken using different cultivars of perennial ryegrass to reduce the amount of N that is partitioned into urine by the dairy cow. Perennial ryegrass diploids with elevated concentrations of water-soluble carbohydrates (WSC), commonly known as 'high-sugar grasses', were developed by the Institute of Grassland and Environmental Research (IGER) who have been working to increase the readily available metabolisable energy (ME) content of grass forages (Parsons et al. 2011). These grasses are also promoted as a tool for increasing the N use efficiency of livestock, offering prospects for increasing milk and meat production whilst decreasing N losses to the environment. The hypothesis is that high sugar grasses (HSG) will increase the supply of metabolisable energy to the rumen microbial population; this will increase the supply of protein to the animal in the form of microbial protein thereby increasing N use efficiency (Parsons et al. 2011). Improved assimilation of dietary N into rumen microbes results in greater microbial flow to the small intestine and therefore an increased supply of protein to the ruminant (Edwards et al. 2007), and hence this will reduce the proportion of N eaten that is returned to the soil in the form of urine (Miller et al. 2001).

2.4.3.5 Salt Supplementation

Another potential option to reduce the concentration of N in cow urine patches is to increase the number of times the cow urinates, thereby diluting the concentration of urinary-N. This can be achieved by adding a diuretic such as salt (NaCl) to a cow's diet. Research by Ledgard et al. (2007) has shown that supplementing dairy cows on a pasture diet with salt reduced the N concentration in their urine by increasing the water intake of the animals. The animals urinated more frequently, which, combined with the lower N concentration in the urine, resulted in lower rates of N application in urine patches. Preliminary modelling of these results suggested that N leaching losses could be reduced

by up to 30%. There were no adverse effects of salt on cow live weight or feed intake. Daily water intake increased as salt ingestion increased. Similarly, supplementing with salt significantly increased cow urine volumes by approximately 2- and 3-fold respectively, compared to the non-salt control treatment.

2.4.3.6 Animal Selection

Reducing the number of cows (reducing stocking rate) is an obvious way of reducing urinary N load to pastures. This would often mean a reduction in production and thus income, which would be unacceptable to many farmers. However, this measure can be financially advantageous if the reduction in cow numbers is accompanied by a sufficiently large increase in per animal production (de Klein et al. 2010). This can be a double edge sword as an increase in per cow performance will require higher levels of dry matter intake per cow, which in turn increases N excretion levels per cow (de Klein et al. 2010). However, farmers who have low breeding worth (BW) and/or production worth (PW) cows may be able to reduce their stocking rate (SR), but increase or maintain production by using cows with better genetics (better BW/PW). Selecting cows with a high BW and/or PW can have not only a positive effect on production and profitability, but can also increase the proportion of dietary N retained in milk (Rotz 2004). In a study by Woodward et al. (2011) high BW/PW cows partitioned less N into urine and more into milk than low BW/PW cows, thus lower concentration of N in urine would be expected.

2.4.3.7 Nitrification Inhibitors

In recent times, nitrification inhibitors (NI) like dicyandiamide (DCD) have been used to reduce N leaching, particularly from urine patches (Di & Cameron 2005). NI are recommended to be applied twice yearly, in the autumn and late winter. Large decreases

in N leaching (up to 55%) have been reported in cooler areas of NZ, like Southland (Monaghan et al. 2009). However, NI like DCD were withdrawn from use on NZ dairy farms when traces of this chemical appeared in milk products.

2.4.3.8 Grazing management

An obvious solution to the risk of N loss from urine patches is to exclude cows from grazing pasture and adopt a 'European/North American' type system where feed is imported or 'cut and carried' to the herd, which is housed indoors or on feedlots. However, this type of system is an expensive option due to the level of infrastructure needed and the cost of imported feed. In addition, the NZ dairy industry relies on farmers producing high quality milk products at a low cost, which means that it needs to take advantage of the pasture-based grazing system provided by NZ's temperate climate. Therefore, the management of grazing time i.e. reducing the amount of time dairy cows graze pasture is one way to reduce the quantity of urine patches deposited on the paddock while still taking advantage of the NZ pastoral grazing model (Monaghan et al. 2007; Oudshoorn et al. 2008). Grazing management schedules which target the amount of urinary N deposited, or modify the timing of deposition, have been shown to be highly effective ways of reducing NO_3^- loss to the environment with reductions of up to 60% being reported in the literature(Chadwick et al. 2002; de Klein et al. 2006; Ledgard et al. 2006). Furthermore, restricting the time cows graze pasture is used in conjunction with standoff facilities where the deposited urine and dung can be collected as effluent. This effluent can then be spread back on the farm evenly, at concentrations that better match plant requirements (de Klein 2001; Christensen 2013).

Management systems, which retain pastoral grazing, but limit the time cows spend grazing paddocks can be separated into two categories:

1. The ‘nil’ grazing system, where cows are stood off pasture for a certain period of the year, and feed is ‘cut and carried’ and brought directly to them in a standoff facility (de Klein et al. 2000).
2. An ‘on/off’ grazing system, which retains most of the features of pasture-based grazing but limits the time cows spend grazing paddocks. This kind of system is often called ‘duration controlled (DC) grazing’. Under a DC regime, cows spend a fixed period grazing per day; the rest of the time they are housed in a standoff facility where they receive supplementary feed (Christensen et al. 2018a).

As noted, the nil grazing system is most commonly found in European and North American dairy systems (de Klein 2001) where long cold winters cause extended periods of snow and freezing conditions and/or no pasture growth that necessitates the need for cows to be kept indoors and fed on imported feeds (Chadwick et al. 2002).

A two year farmlet study in Taranaki by Chadwick et al. (2002) compared an ‘all-year grazing’ system to a ‘strategic feed-pad’ system where cows were stood off pasture for four months during late-autumn and winter. The ‘all-year grazing’ system had NO_3^- leaching of 29 kg N/ha/yr, whereas, the ‘strategic feed-pad’ system only leached 14 kg N/ha/yr., i.e. a 50% reduction in NO_3^- leaching. Modelling by de Klein et al. (2000) investigated the effects of nil grazing on N losses to water. The study modelled a nil grazing system where cows were kept off paddocks from April to August, and then they conventionally grazed paddocks from September to March. During the period of nil grazing, pasture was ‘cut and carried’ and fed to the cows on a standoff facility. The nil grazing system showed a potential to decrease N leaching by 35 – 50%. The model suggested that there would be a 5% increase in pasture production from the strategic even spreading of captured excreta, together with the protection of soils. The nil grazing system was initially reported to be a financially feasible option with a positive return on

capital for an average NZ dairy farm. However, de Klein (2001) states that the potential advantages of nil grazing systems could be outweighed by the adverse consequences of a greater use of machinery traffic. Secondly, clover relies on areas in the pasture with low N status (non-urine and dung patches) to maintain a presence in the sward and so the even return of excreta may result in a reduction in the clover content of pastures (de Klein 2001). Clover is an integral part of New Zealand's low-cost pastoral systems, and so a major restriction on its growth and activity could have implications for the viability of this kind of system (de Klein 2001).

Furthermore, in a three year study comparing a conventional grazing system and a nil grazing system, Monaghan et al. (2016) found that the N loss in subsurface drainage from the nil grazing system exceeded that measured in the conventional treatment. The authors suggested that the most probable explanation for this unexpected result was the high rates and application timings of fertiliser N inputs to the nil treatment. The N fertiliser was applied at high rates so as to replace the large amounts of N removed in the pasture herbage that was cut and removed. Given this, and the fact that most areas of NZ experience milder autmum/winters compared to Europe, a DC grazing system may be more suitable for NZ dairy farms that need to reduce N leaching.

The purpose of a 'DC' grazing system is to reduce the number of urine spots deposited on pasture, while still allowing year-round grazing of pasture. The main advantage of this type of system is that it offers the farmer the ability to utilise pasture on a year-round basis, while still being able to reduce NO_3^- leaching to water. In a typical NZ conventional grazing system, cows are milked in the morning and then put out to graze pasture for a period (6 – 8 hours) until the afternoon milking when they are returned to pasture for the rest of the afternoon/evening (10 - 14 hours). The 'DC' system utilises

the same daily pattern of milking followed by periods of grazing. However, the grazing periods are shortened to a fixed grazing period of circa 4 hours per grazing. Dairy cows have been shown to be able to consume up to 80% of their daily requirement from two 4-hour grazings per day (Thomson et al. 1993; Draganova et al. 2010; Kennedy et al. 2011; Christensen et al. 2018a). Therefore, cows in a DC system can still obtain the majority of their feed intake from pasture, with the remaining coming from supplementary feed provided during the standoff period.

A two-year farmlet trial (Waikato, NZ) investigating the environmental impacts of the intensification of dairy farming systems was undertaken by Ledgard et al. (2006). The trial consisted of a 'control' farmlet that ran 3.0 cows/ha, used 170 kg N fertiliser/ha/year and grazed pasture year-round. The control was compared to six other intensive dairy systems. The comparison of interest was a 'stand-off' system, which was similar to the control; however, the difference was that cows spent 18 hours per day on a standoff pad from mid-May to early–July. The control farmlet had an average annual NO_3^- leaching loss of 50 kg N/ha and the average for the standoff farmlet was 37.5 kg N/ha, which was 25% lower than the control. This study showed the benefits of reducing the time cows spend on pasture. However, the standoff period was only implemented during the period when cows were not lactating (winter). Therefore, it could be expected that further reductions could be achieved by extending the standoff period to other months.

A three-year plot scale study of year-round DC grazing was undertaken by Christensen et al. (2018a) and Christensen et al. (2018b). The study compared a standard grazed (SG) system and a DC grazed system. The SG treatment plots had a grazing duration of 8 hours for day-grazings and 13 hours for night-grazings. The DC plots had a grazing duration of 4 hours for both day and night grazings. All plots were grazed on the same

day with the same average stocking rate, set according to pasture cover. The average annual NO_3^- leached was reported for the SG system at 14 kg/N/ha, compared to 6.7 kg /N/ha for the DC system i.e. a 48 % reduction. Christensen et al. (2018b) has provided quantitative evidence that year-round DC grazing significantly reduces N loss to water when compared to a SG system. However, implementing a year round DC system means increasing standoff time and this in turn increases the cost (capital and maintenance) of standoff facilities and creates new management challenges, particularly for effluent management (Hedley et al. 2014). Furthermore, modelling suggests that due to the investment required in infrastructure, additional feed and labour to hold cows off-paddock for long periods of time (i.e. days) for the purposes of avoiding soil treading damage could reduce farm profitability of DC compared to SG systems (Beukes et al. 2013b; Laurenson et al. 2016; Laurenson et al. 2017). Therefore, it could be presumed that the same conclusion can also be made for a year-round DC system.

An important finding from the study by Christensen et al. (2018b) was that the quantity of NO_3^- leached in drainage was strongly related to the quantity of late summer and autumn-deposited urinary N that was not taken up by pasture. The urine deposited during spring and early summer grazings was estimated to have had less effect on the leaching load. Given these findings and the discussion above on the critical period of NO^-_3 accumulation, scheduling DC grazing at certain times of the year, namely autumn (Christensen et al. 2018b) may be a more efficient way to reduce NO_3^- leaching. This is where a more low cost option (i.e. retro-fit free-stalls to a dairy farm's existing uncovered feed pad) (Hanly et al. 2014) could be used to save on capital expenditure, while still achieving significant reductions in NO_3^- leaching.

The effect of DC grazing over autumn on NO_3^- leaching was studied in Southland NZ by Monaghan et al. (2016). The three-year study was a plot scale trial on a poorly drained Pallic soil. It compared a "normal" grazing system with a DC system, where the cows grazed pasture for only three hours/day during March, April and May, with the rest of the day spent on a feed pad. The 'normal' grazing system had an annual average NO_3^- loss to water of 17 kg N/ha compared with the 10 kg N/ha that leached from the DC system i.e. a 41% reduction ($p < 0.05$). This decrease was greater than that reported by Ledgard et al. (2006), suggesting the later lactation season is critical to the impact on N leaching. Taken together, Monaghan et al. (2016) and Christensen et al. (2018b) results suggest that a shorter period of DC grazing targeted at the late summer to autumn is highly effective at reducing NO_3^- losses to water on dairy farms. However, these results need to be taken in context, i.e. they are only from two areas of NZ and would need replicating to see if similar reductions can be obtained in other regions, where climate and pasture growth patterns will differ (Shepherd et al. 2011). Furthermore, the authors state that more research is needed to fully consider some of the practical implications associated with having cows off pasture for extended periods. One of these implications, which is not addressed by Shepherd et al. (2011) is the collection, storage and re-application of cow urine and dung as effluent, and the effect on pasture production.

2.4.3.9 The effect of DC grazing on pasture production

While it has been shown that reducing the grazing duration of the dairy cow will reduce NO_3^- losses to water, the decrease is predominantly down to less urine being deposited onto pasture. However, there is a concern that a reduction in excreta return will reduce the quantities of nutrients available for pasture growth (Ledgard et al. 1982). Replacement nutrients may have to be added through fertiliser to maintain pasture

growth (Christensen et al. 2018a). As discussed earlier, DC grazing is usually used in conjunction with standoff facilities where urine and dung deposited on these areas can be collected as effluent. Therefore, given the concern mentioned above, excreta captured from the standoff should be returned to pasture to maintain nutrient balance in the system (Monaghan et al. 2008). Uniform reapplication of the excreta as slurry, at lower concentrations of nutrient (particularly N) per unit surface area than found in dung and urine patches, should improve the efficiency of nutrient use (Monaghan et al. 2010).

Modelling by de Klein (2001) reported that an increase in DM production of 2-8% could be expected when a DC grazing system was compared to a conventional grazing system. However, a plot scale study in the Manawatu by Christensen et al. (2018a) showed no such advantage, and even a reduction in pasture production when comparing a DC system with a conventional system. In the Christensen et al. (2018a) study, both the DC grazing and conventional system received the same amount of nutrients from fertiliser. Therefore, the major difference in nutrient addition to the plots is that slurry was spread on the DC plots at a rate to compensate for the reduction in dung and urine returned by the grazing animal (as described by Christensen et al. (2018a)). It must be noted that the slurry returned to the DC plots was a slurry analogue (mixture of feed pad bunker material and farm dairy effluent), and not actual slurry from a standoff area. Average pasture accumulation across all three study years was 14327 kg DM ha/yr. for the conventional treatment which was greater than the 12813 kg DM ha/yr. grown on the DC treatment ($p < 0.05$). Interestingly, there was no statistical difference in average pasture accumulation between the two treatments in the first and third years of the study. However, in the second year of the trial, the 20% reduction in pasture accumulation on the DC plots, relative to the conventional plots, was significant. The reason for these differences was that slurry was applied in the first year of the trial (to DC plots) but not

in the second year of the trial. It was therefore concluded that a single application of slurry was not sufficient to increase pasture accumulation, or even maintain pasture production on a bi-annual basis, and that a critical part of practising DC grazing is that nutrients removed from pasture in cow dung and urine collected in the standoff facility should be returned in a timely fashion to the pastures from which they originated.

2.4.4 Summary of the literature

This review of the literature has demonstrated that livestock grazing, and in particular dairy cow grazing, can have negative impacts on soil physical properties, drainage water quality and pasture production. As agricultural technology has developed and economic pressures have increased, the trend has been for intensification of production, causing greater potential for pasture damage and degradation of New Zealand's waterways.

The literature clearly demonstrates that reductions in NO_3^- leaching under DC grazing can be substantial, with year-round DC grazing reducing nitrate-N leaching by 50%. Some studies have shown that shortening the grazing duration to just the summer - autumn period can still achieve substantial reductions in NO_3^- leaching. Duration controlled grazing in summer and autumn, the 'critical period,' can reduce NO_3^- leaching by up to 40%. Nitrate accumulates in the dry soil in the late summer-autumn period, which results in significant amounts of N in winter drainage. Therefore, DC options used to mitigate NO_3^- leaching should target this critical period to achieve the greatest reduction per unit of time in standoff.

The treading damage literature shows that soil and pasture damage from grazing is linked to the soil water content at the time of grazing. There is a wealth of literature on

grazing very wet soils that shows that grazing for prolonged periods at high stocking rates can result in severe treading damage and a marked reduction in pasture growth with reductions up to 88% being reported. Pastures seem to recover from cattle treading more rapidly than soil physical properties do, suggesting that plant growth may be a better indicator of sward damage than soil conditions. Having said this in the literature, the reported interval of time for pastures to recover varies greatly from 48 to > 365 days. However, there seems to be more evidence to suggest that reductions in pasture production from treading tends to be a short-term problem rather than an annual one. Removing livestock or reducing the time spent grazing on wet soils can be an effective management tool to protect pastures and mitigate the detrimental effects of treading damage.

There are, however, limitations in the literature that need addressing, these include:

1. While targeted DC grazing has shown the potential to reduce NO_3^- leaching, there has been minimal field trials conducted to quantify this effect.
2. The one study of DC grazing targeted to the critical period of summer- autumn found in the literature (Monaghan et al. 2016) is for one area of NZ (Southland) and would need replicating in other areas of NZ to see if similar reductions can be obtained, where climate and pasture growth patterns differ (Shepherd et al. 2011).
3. Monaghan et al. (2016) state that further research is needed to fully consider some of the practical implications associated with having cows off pasture for extended periods. One of these implications, which is not addressed by Monaghan et al. (2016) is the collection, storage and re-application of cow urine and dung as effluent, and the effect on pasture production.

4. With regards to treading damage, further research is required to determine the relationship between soil moisture and treading duration on short- and long-term pasture productivity.
5. The majority of the literature only reports the effects (on pasture production) of a single, severe treading event, whereas, in an actual grazing system, some paddocks on the farm may be subjected to repeated treading damage i.e. damaged in the winter and then again in spring. Therefore, this needs to be further investigated.
6. It is well known that the intensity of treading damage is linked to the soil water content at the time of grazing. However, what is less well known is the soil moisture content criteria for safe grazing on fine textured soils.
7. The extent or severity of treading damage can be assessed using a number of methods (*roller chain, depth of pug, visual scoring*). However, the ability of these methods to assess treading damage, and their relative merits, have not previously been compared.
8. A review of the literature on the measurement of treading damage suggests that there is currently no tool available that is able to measure treading damage in a spatially explicit manner.
9. The effects of short duration grazing in 'wet' conditions and the effect on short- and long-term pasture production needs further investigating, as there are conflicting results in the literature.
10. There is no study that investigates the area of a farm that could potentially be damaged during the winter/spring period.

3 THE PUGOMETER: AN EVALUATION OF A NEW TOOL FOR ASSESSING TREADING DAMAGE AND COMPARISONS WITH OTHER METHODS

3.1 Abstract

Treading damage inflicted by grazing animals degrades soil physical quality, increases sediment and nutrient loss to water, and reduces pasture yield. The extent or severity of treading damage can be assessed using a number of methods (*roller chain, depth of pug, visual scoring*). However, the ability of these methods to assess treading damage, and their relative merits, have not previously been compared. Four methods of measuring treading damage are compared in this study including the three methods mentioned and a new tool called the *pugometer*, which was developed to measure treading damage in a spatially explicit manner. These comparisons were conducted on three paddocks at Massey University's Dairy 4 farm near Palmerston North, Manawatu, New Zealand. The paddocks had sustained treading damage of varying levels during grazing in wet conditions. Treading damage inside a quadrat (0.6 m x 1.0 m) was assessed at 25 sites using four methods. The pugometer was also used to capture the spatial variation of treading damage at the paddock scale and to assess the recovery of pug marks.

All four methods were able to identify varying degrees of treading damage competently with strong correlations between them. Therefore, the selection of the most appropriate method to assess treading damage will depend on the circumstances. The *visual scoring* method was the quickest and simplest method to perform over a large area and so could be employed easily by a farmer. In contrast, while the *pugometer* took twice as long to measure treading damage on the same area, it provided a quantitative measure of the spatial variability of treading damage and so would be a useful research tool. The *depth of pug* and *roller chain* methods are reliable but much more time consuming and therefore are only practicable as research tools for small plot studies. Following a treading event, the pugometer was able to monitor the recovery of surface roughness in a spatially explicit and rapid manner.

3.2 Introduction

Treading damage of paddocks by grazing livestock degrades soil quality and increases the losses of nutrients and pathogens in surface runoff (Drewry et al. 2003; Kurz et al. 2006). Intensive pugging events can also cause considerable damage to pasture, which can result in large reductions in pasture utilisation and yield (Horne & Hooper 1990; Nie et al. 2001; Menneer et al. 2005; Phelan et al. 2013; Tuñon et al. 2014). While these effects of treading damage have been researched, accurate but practicable methods to measure or assess the magnitude and extent of treading damage have proved to be more elusive. Land managers require a quick and simple procedure for assessing the severity of treading damage, while researchers need a more spatially aware and quantitative measurement of the extent of pugging damage.

Cattle treading can result in hoof indentations that penetrate or rupture the soil surface (Scholefield & Hall 1985). Thus, measurements of soil roughness or disruption may be used as indicators of the severity of treading damage to soil. Four means of measuring treading damage in this manner are; the *depth of pug* method (Nie et al. 2001; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015), the *pin and profile meter* method (Davies & Armstrong 1986; Betteridge et al. 1999), the more frequently used *roller chain* method (Nie et al. 2001; Pande et al. 2002; Drewry et al. 2003; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015) and the *Visual scoring* method (Sheath & Carlson 1998; Nie et al. 2001; Zegwaard 2006; Little et al. 2015).

The *depth of pug* method typically involves measuring (with a ruler) the depth of 20 pug marks randomly selected within a given area. This method has been used on research trial plots ranging in area from 55 to 300 m^2 (Nie et al. 2001; Zegwaard 2006; Tuñon et

al. 2014; Little et al. 2015). The ruler is placed in the deepest part of each hoof imprint and the length to the field surface, i.e. the lip of the hoof depression, is measured. The average depth of pug in the area of interest is calculated and reported.

The *roller chain* method was originally developed by Saleh (1993) to measure soil surface roughness caused by wind and soil erosion and tillage processes. More recently the chain technique has proved to be a useful means of measuring treading damage (Nie et al. 2001; Pande et al. 2002; Drewry et al. 2003; Zegwaard 2006; Tuñon et al. 2014; Little et al. 2015). The *roller chain* method utilises the ability of the chain to closely follow the micro-contour or outline of the damaged, disrupted soil. As soil surface roughness increases (treading damage becomes more severe), the distance between the two ends of the chain, measured at the soil surface, decreases. While there is no published standardised index to interpret chain measurements (Zegwaard 2006), a number of attempts have been made to correlate the percentage reduction in chain length to other indicators of treading damage. Zegwaard (2006) compared the percentage reduction in chain length to an arbitrary index of soil damage which was based on roughness classes of 1-5. Zegwaard (2006) assigned chain length reductions of 0-5 % to the roughness class of 1 (slightly rough) while chain length reductions > 20% were classified as 5 (extremely rough). However, most studies tend to use the *roller chain* method solely as a way to quantify a trend of increasing or decreasing soil damage, rather than attempting to establish a set index or categories of treading severity (Nie et al. 2001; Tuñon et al. 2014).

The *visual scoring* method uses treading damage criteria based on one or more of the following: a series of photos illustrating the range of treading damage, pugging depth,

the percentage of bare ground, or percentage of an area damaged (Sheath & Carlson 1998; Nie et al. 2001; Zegwaard 2006; Little et al. 2015). *Visual scoring* methods can be performed at either: a quadrat (Nie et al. 2001), small research plot (Zegwaard 2006; Little et al. 2015) or paddock scale (Sheath & Carlson 1998). The *visual scoring* method needs to be undertaken by a practiced user who is familiar with the particular criteria used to gauge treading damage. Depending on the type of criteria, the user will need to walk/stand and observe areas of interest and record the subjective measure of the treading damage observed.

The *pin and profile* method was first designed and used for cultivation studies by Kuipers (1957). This method uses a number of metal pins which are held within a metal frame and lowered onto the damaged soil. As the pins drop, they 'mirror' an image of soil micro-contour that can be measured for height or graphed manually by tracing the pin heights on a white board behind the pins. This forms a visual image and a measurement of treading damage.

All the methods discussed above have been reported to be effective in measuring the degree and intensity of pugging damage. For example, studies such as Nie et al. (2001), Tuñon et al. (2014) and Little et al. (2015) report that *depth of pug, roller chain* and *visual scoring* methods have been able to measure a wide range of pugging damage ($p < 0.01$ to 0.05). The *pin and profile* method has been used in a grassland treading study in England by Davies and Armstrong (1986) and in a study of treading damage in New Zealand hill country by Betteridge et al. (1999). Both these studies were able to differentiate their treading treatments according to the intensity of damage using this method. However, this particular method while accurate, has been criticised as being too impractical for routine use in the field, being labour intensive and time consuming

(Saleh 1993; Ward & Greenwood 2002; Thomsen et al. 2015). Therefore, the *pin and profile* method is not commonly used to measure treading damage.

The three more common methods (*depth of pug, visual scoring and roller chain*) are all able to characterise the severity of treading damage, but to the best of the authors' knowledge they have not been directly correlated against each other. However, there have been studies that investigated the correlation between *pin and profile* method and the *roller chain* method on cultivated and/or rain damaged plots (Saleh 1993; Jester & Klik 2005; Thomsen et al. 2015). These studies have shown strong agreement between the two methods with R^2 values of 0.76 – 0.96.

While the methods discussed above are relatively simple and somewhat successful, they are not without their limitations. As such, no quick and reliable method has been developed that is capable of assessing the variability in the extent and severity of treading damage, in a quantitative manner, on areas from the small (plot or part-paddock) to large (paddock or whole-farm) scale. Any such method will need to be sensitive enough to discern the spatial variability in treading damage that can occur both between and within paddocks and this technique should be able to capture or record this information in an automatic and spatially aware manner. To this end, a new tool called the *pugometer* has been developed to help better quantify treading damage.

The objectives of this paper are to describe the *pugometer* and compare it with the three most commonly used methods for assessing pugging damage. On the basis of this comparison, a series of recommendations will be developed to guide the selection of the most appropriate technique to employ to gauge the extent of treading damage in a range of situations. The use of the *pugometer* will also be demonstrated in a small study of the rate that surface roughness, associated with treading, recovers.

3.3 Material and methods

3.3.1 Experimental procedure and site details for the comparison of methods

The experiment was conducted on three paddocks at Massey University's Dairy 4 farm near Palmerston North, Manawatu, New Zealand (NZMS 260, T24, 312867). The paddocks have flat topography (c. <3% slope). The soil in the paddocks is Tokomaru silt loam, which is classified as an Argillic-fragic Perch-gley Pallic Soil (Hewitt 2010). A detailed description of soil physical properties is provided by Scotter et al. (1979a). The soil is naturally poorly drained and consists of a weakly to moderately developed brown, silt loam A horizon to a depth of 250 mm, a weakly developed, grey, strongly mottled, clay loam B horizon to 800 mm and a C horizon of highly compacted, palegrey, silt loam fragipan, which acts as a natural barrier to drainage (Scotter et al. 1979a; Shepherd 1984). Therefore, this soil is subject to seasonal water logging and thus susceptible to treading damage. All paddocks are mole and pipe drained and grow a mixed sward of perennial ryegrass (*Lolium perenne)* and white clover (*Trifolium repens*). The three paddocks were chosen because they had recently (within two days) been grazed in relatively wet conditions and this grazing had resulted in a range of levels of treading damage.

The assessment of treading damage was conducted using four different methods: *visual scoring (VSM), roller chain, depth of pug* and the *pugometer*. Five areas, representative of each of the VSM scores, 1-5, were identified across the three paddocks. This gave a total of 25 sites. At each of the twenty-five sites, a 0.60 m^2 (0.6 m x 1.0 m) quadrat was placed on the ground in an area where the damage was very consistent with the visual score for the site. Treading damage was measured in each of the 25 quadrats using the

depth of pug, reduction in *roller chain* length and *pugometer* methods. The shorter sides of the quadrat were marked so that it could be used to define three 1 m transects, each 0.2 m apart. The reduction in *roller chain* length and *pugometer* measurements were made along these transects. There was a total of 75 transects measured over the 25 quadrat placements. The time taken to perform 10 measurements of each method was recorded.

3.3.2 A comparison of methods to quantify the severity of treading damage

3.3.2.1 Visual scoring method

The *VSM* was developed by constructing a catalogue of treading damage on Massey University's Dairy 4 farm over the winter/spring of 2014. This follows the procedure described by Little et al. (2015) and Zegwaard (2006). A log was kept of a wide range of treading events over two winter/spring periods. This log recorded a description of damage, example photos of damage and the location of the damage on a farm map. The visual indicators of treading damage were observed by two persons along with the description of the damage. From the catalogue, five levels of damage were identified. The categories varied according to visual depth of indentations in the soil, the presence of hoof smears (where the hoof of the animal had slid across the soil surface), and the degree of surface disruption. The *VSM* scale goes from a score of one, which denotes minimal treading damage to a score of five which describes severe treading damage. The *VSM* developed here is categorised by the extent and severity of damage according to a five-point scoring system outlined in Table 3.1 The visual damage score, increasing from levels 1 to 5, with score criteria and a close-up photo of each score level.

Following development, the *VSM* was used to assess treading damage on the farm, a plot scale research trial, and as part of the study reported here. Treading damage to an area is characterised by comparing the state of the surface soil and pasture with the series of reference photos and the description of the *VSM* scores (Table 3.1). If the area of damaged pasture has two different levels of damage, then an intermediate score can be assigned to reflect this e.g. if the area observed has approximately 40% of score 2 damage and 60% of score 3 damage then the area could be scored slightly in favour of the 3 category, say as a 2.6. However, the experimental areas were chosen that represented a single score level, and thus no intermediate score was recorded in this trial.

Table 3.1 The visual damage score, increasing from levels 1 to 5, with score criteria and a close-up photo of each score level.

Damage score	Score criterion	Close up
1	Minimal indentations of soil: no hoof smears or surface disruption	
2	Slight indentations of soil: some hoof smears: very minimal surface disruption	
3	Medium indentations of soil: some hoof smears medium surface disruption	
4	Deep indentations of soil: deep hoof smears: medium surface disruption	
5	Very deep indentations of soil: deep hoof smears: intense surface disruption	

3.3.2.2 Roller chain method and chain index

The roller chain (L1) used in this experiment was 1 metre in length and made of individual links that were 22.85 mm in length. The chain measurements were performed along the three transects of the quadrat. Starting at the top left mark on the quadrat, the chain was laid along the ground with care taken to ensure that it followed the outline of the pug marks across the transect line. The horizontal distance covered (L2) was then measured: this distance decreases as soil damage increases. As the difference between L1 and L2 is related to the degree of treading damage, values obtained using the chain method are presented as a chain length percentage reduction (CLPR), which is the percentage difference between the effective length (L2) and the actual length (L1) i.e. CLPR = (L2÷L1) x 100. The chain was then repositioned at the other end of the same transect (top right-hand side) and the same process was performed. The two measures along the transect are then averaged and recorded in sequential order. This process was then repeated along the other two transects in the quadrat to provide a total of six measurements that were averaged to also give a single quadrat mean value.

3.3.2.3 Measured depth of pug

As the quadrat used in this experiment was relatively small (0.60 m^2), the *depth of pug* method was modified slightly. In other studies, the depth of 20 randomly selected pug marks is measured. As there were fewer than 20 individual pug marks in each quadrat, the depths of the three deepest and three shallowest pug marks in each quadrat were measured. The depth of the pug mark was measured at the front of the pug mark using a 30 cm ruler. The depth of the six measured pugs for each quadrat was then recorded and averaged to give a mean depth of pug in the quadrat.

3.3.2.4 Pugometer

In order to quantify the magnitude and spatial variability of treading damage, a new tool called the *pugometer* was developed. The *pugometer* (Figure 3.1and Figure 3.2) is a prototype device that has been designed on the concept of the pin and profile meter described by Kuipers (1957). The *pugometer* is a mobile, handheld, global positional system (GPS) enabled, electronic surface roughness meter, which is used to quantify treading damage. The main advantages of this apparatus are that it can quickly give a quantitative measure of the severity of treading on a given area and the results can be mapped using geographical information system (GIS) software to illustrate the spatial variation in treading. The *pugometer* is an alternative to more traditional measures of soil surface roughness, such as the *roller chain* method or the *depth to pug* method.

The *pugometer* consists of ten stainless steel pins (0.6 cm diameter) fitted inside an aluminium frame at a spacing of 5 cm. Each of the pins has a plastic reflecting disk set on the top of it to face an infrared sensor (Model = Sharp GP2D120). The measurement is based on the intensity of the reflected light, the more emitted light the sensor detects, the nearer the disk is assumed to be. The pins slide up or down to conform to soil surface irregularities, with each pin measuring the distance between the bottom of the device and the soil surface. The further the sensor is from the reflecting plate then the deeper the pug mark being measured. The pins can slide up to 10 cm, i.e. they can detect pug marks to this depth. As the inferred sensor used is most accurate for depths of 0 to 10 cm, this was selected as the range of measurement depths. The dimensions and weight of the *pugometer* are as follows: length 53 cm; height (from bottom of *pugometer* to the top of the handle) 76 cm; width of 5 cm; with a weight of 2.9 kg, thus making it small and light enough for prolonged usage.

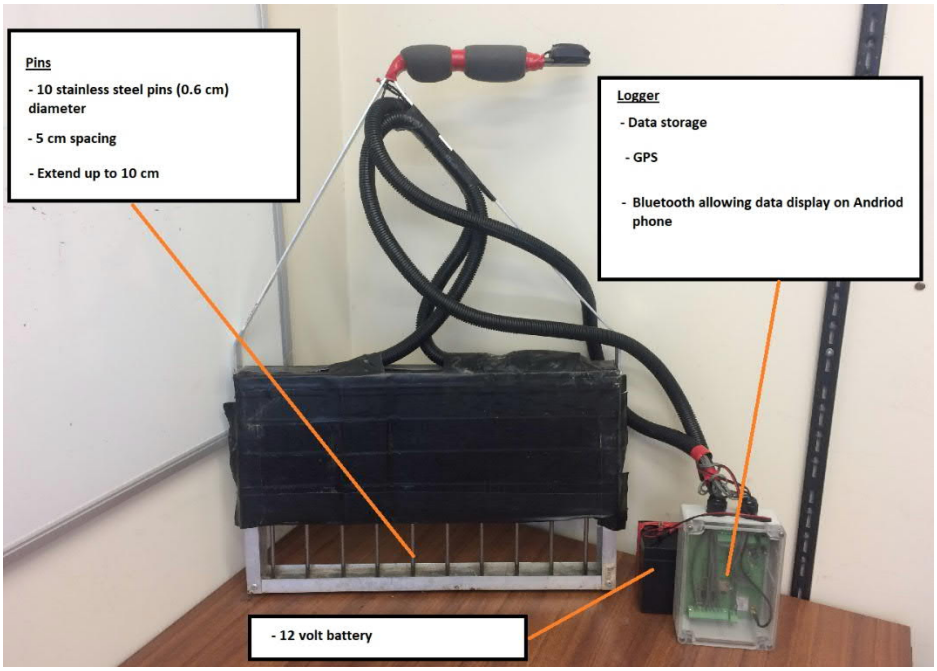

Figure 3.1 The pugometer, battery and data logger.

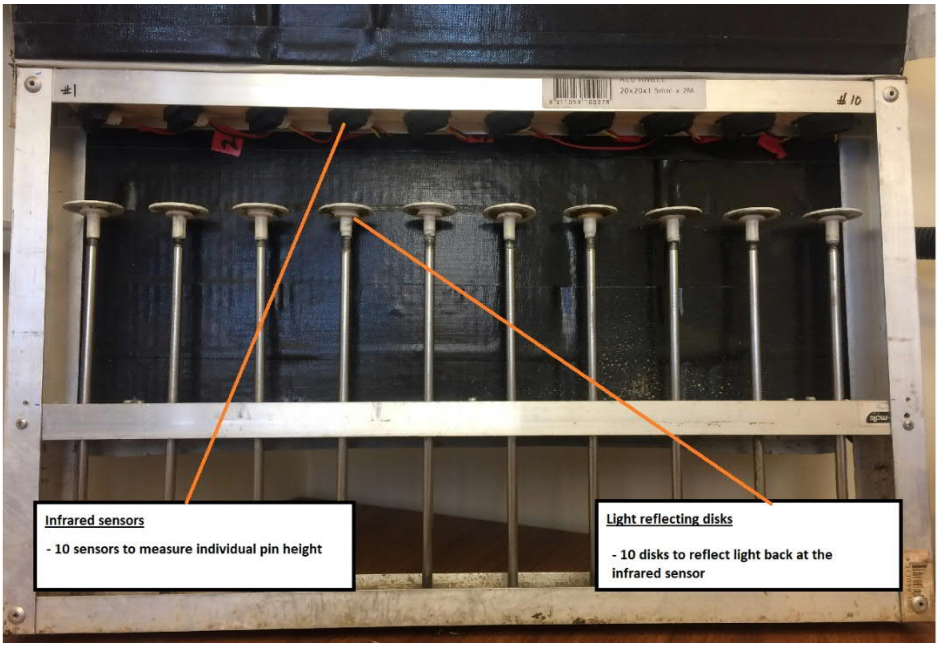

Figure 3.2 The pugometer with upper pin cover folded up, exposing the inferred sensors and light reflecting disks.

As the sensors measure the reflected intensity of light, which is recorded as a voltage, these readings need to be calibrated to a measure of distance. Therefore, a calibration

curve was created that converted light intensity to a measure of centimetres. This was developed by positioning the *pugometer* flat on the ground, so all the pins were retracted in the device and a measurement was taken. Then 1 cm (in height) blocks where placed at either end of the *pugometer* so each edge of the device could rest on them and the pins would drop 1 cm to the ground surface. A reading was taken and recorded for each of the ten pins. The height of the blocks was increased to 2 cm above the ground to allow the pins to drop 2 cm. Again, a reading was taken and recorded. This process was repeated a total of ten times so at the final measure, the *pugometer* was elevated 10 cm and the pins had dropped 10 cm. Each of the ten pins was then individually calibrated to report light intensity as centimetres of pin drop.

There is a separate data logger that is connected to the *pugometer* by electrical wires. This data logger unit includes a recording secure digital (SD) card chip, Bluetooth chip and GPS circuit board. The data logger can be carried in a bag so that the only part of the device being held in the hands of the user is the *pugometer* itself. The apparatus is operated by firstly lifting the device and then positioning it on the soil. Once the device is resting on the soil, a button on the device handle is pushed to make a measurement recording. The voltage reading is displayed on an Android phone via Bluetooth technology, as well as being recorded on the SD card in the data logger unit. The GPS location is also recorded each time the button is pressed. The device is then lifted and repositioned as many times as the user wishes. With data from multiple positions, a detailed picture of the extent of treading damage emerges.

For the measurement comparison experiment, four equally spaced readings were made with the *pugometer* along the same 1-meter long transects used for the *roller chain* method. The four measures were averaged for each transect. As for the *roller chain* method, this procedure was repeated for three transects per quadrat, which were

averaged to provide a single mean value for each quadrat. This process was repeated for all twenty-five experimental sites.

3.3.3 Experimental procedure and site details for the pugometer demonstration

The demonstration was performed on a paddock on Massey University's Dairy 4 farm. This paddock was chosen because it had four areas of contrasting treading damage as a result of strip grazing in-calf heifers at an average stocking rate of 215 hd/ha over a four-day period (15^{th} – 18^{th} July). A photo of the paddock was taken by an un-manned aerial vehicle (UAV) after grazing (Figure 3.3). The first grazing was conducted in the rain and then the soil dried over the next 3 days. The strips were grazed first at the top end of the paddock (strip grazing 1) and lastly at strip grazing 4. The seven individual transects were identified and marked, with fencing standards, at intervals of 7.5 m so that the transects could be identified for later measurements. The seven transects started 10 meters from the paddock entrance ways and ended at the edge of a gully in the top left-hand corner of the paddock. The side of the paddock that included the gully was excluded from the experiment so that all measurements were made on the same topography.

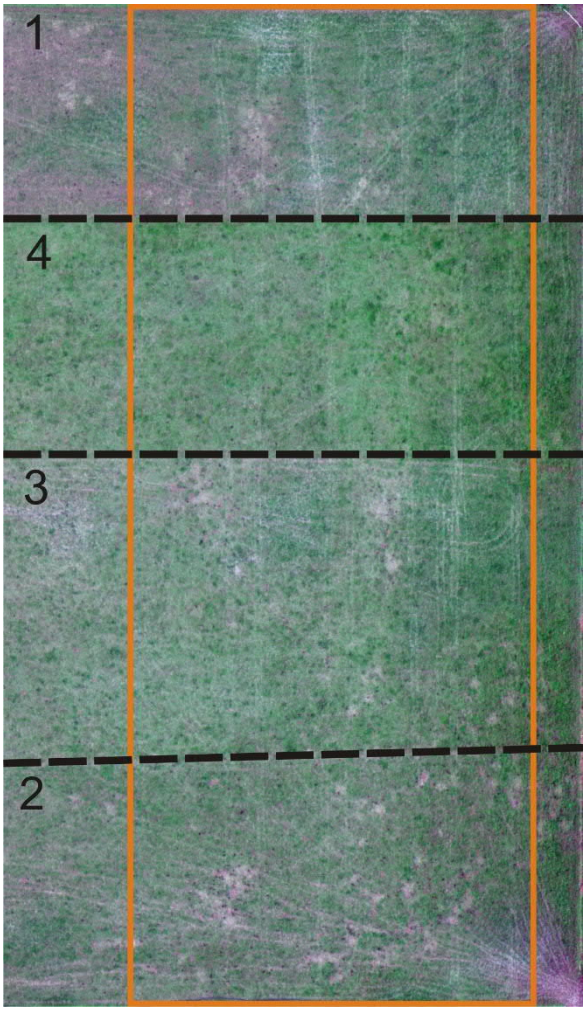

Figure 3.3 The areas of the paddock that were allocated to the four strip grazing events (numbered 1-4). The area of the seven measurement transects used is also shown in the orange box. The entrance ways are at the top and bottom right-hand corners of the paddock. One end of the badly damaged gully is seen in the left side of Strip grazing 1.

The damaged area within each strip was visually scored using *VSM* on 19th July, which was one day after the final grazing. The *VSM* scores were 5, 3, 2, 1 for strip grazing 1, 2, 3, and 4, respectively. *Pugometer* measurements were made at approximately every 4th pace along each transect, which gave approximately 36 measurements/transect. This was carried out on 22nd of July, which was four days after final grazing. In order to evaluate the potential of the *pugometer* to characterise recovery from treading damage, surface roughness along the transects was re-measured at 49 and 104 days after the first

grazing events. Once all measurements had been recorded, the data was imported into Arc 10 GIS software and maps revealing the spatial variability in treading damage were generated.

3.3.4 Statistical analysis

The software SAS (Statistical Analysis System, version 9.2: SAS Institute., Cary, NC US) was used for all statistics in this chapter. Two-variable regression (linear) was carried out and presented with the coefficient of determination (r^2) for the comparisons of *Pugometer*, *roller chain*, *depth of pug*. As the *VSM* is a subjective measurement, linear regression could not be used to compare this method with the other three methods, thus all analysis comparing the *VSM* used Analysis of Variance ANOVA,

3.4 Results

3.4.1 A comparison of methods

That assessment of treading damage can be laborious and time consuming is a common perception amongst both researchers and farmers. Therefore, the time taken to complete an assessment of treading damage is an important feature of any particular method. The approximate time taken to use each of the techniques compared here is presented in Table 3.2. The fastest measurement of pugging damage was the subjective *VSM,* as it has only one measurement and takes only the time required to observe the area and then manually record the *VSM* score. Each area was easily viewed and a *VSM* score decided upon within a period of 20 seconds. The *pugometer* was the second fastest method even though it had the greatest number of measurements per quadrat. Each *pugometer* measurement took only approximately five seconds. The average time to measure a quadrat with the *pugometer* was 60 seconds. The *depth of pug* was the third fastest method, taking a total of 90 seconds to complete a quadrat, with the average time taken to identify and measure each individual pug being approximately 15 seconds. However, while the deepest pugs in a quadrat were easily identifiable, the three shallowest took slightly longer and increased the average time taken.

Table 3.2 Approximate time to complete measurements in a quadrat including recording the result.

Method	# Measurements taken in a quadrat	Time taken per measurement (secs)	Total time to complete a quadrat (secs)
Pugometer	12	5	60
Depth of pug	6	15	90
Roller chain	6	90	540
Visual scoring	1	20	20

The slowest method was the *roller chain* method, which at 540 seconds/quadrat was very time consuming compared to the other methods. The reason for this length of time was due to care needed to ensure that the chain was moulded to the contour of the soil surface before the reduction in chain length could be measured and then manually recorded. These results highlight the advantage of rapid techniques such as the *pugometer* and *VSM* methods. However, the *pugometer* has the added advantage of automatically recording a spatially defined, quantitative value.

The complete set of *pugometer* measurements (75 transect points from 25 areas) are compared with the corresponding values obtained using the *roller chain* method in Figure 3.4. A significant positive correlation was found between the two methods (R^2 = 0.72, $p < 0.01$ n = 75). At lower levels of treading damage, there was very good agreement between the *roller chain* reductions and *pugometer* values. However, the differences between the two methods were generally larger at higher levels of pugging i.e. values above approximately 20% reduction in *roller chain* length and a 3.5 cm *pugometer* score.

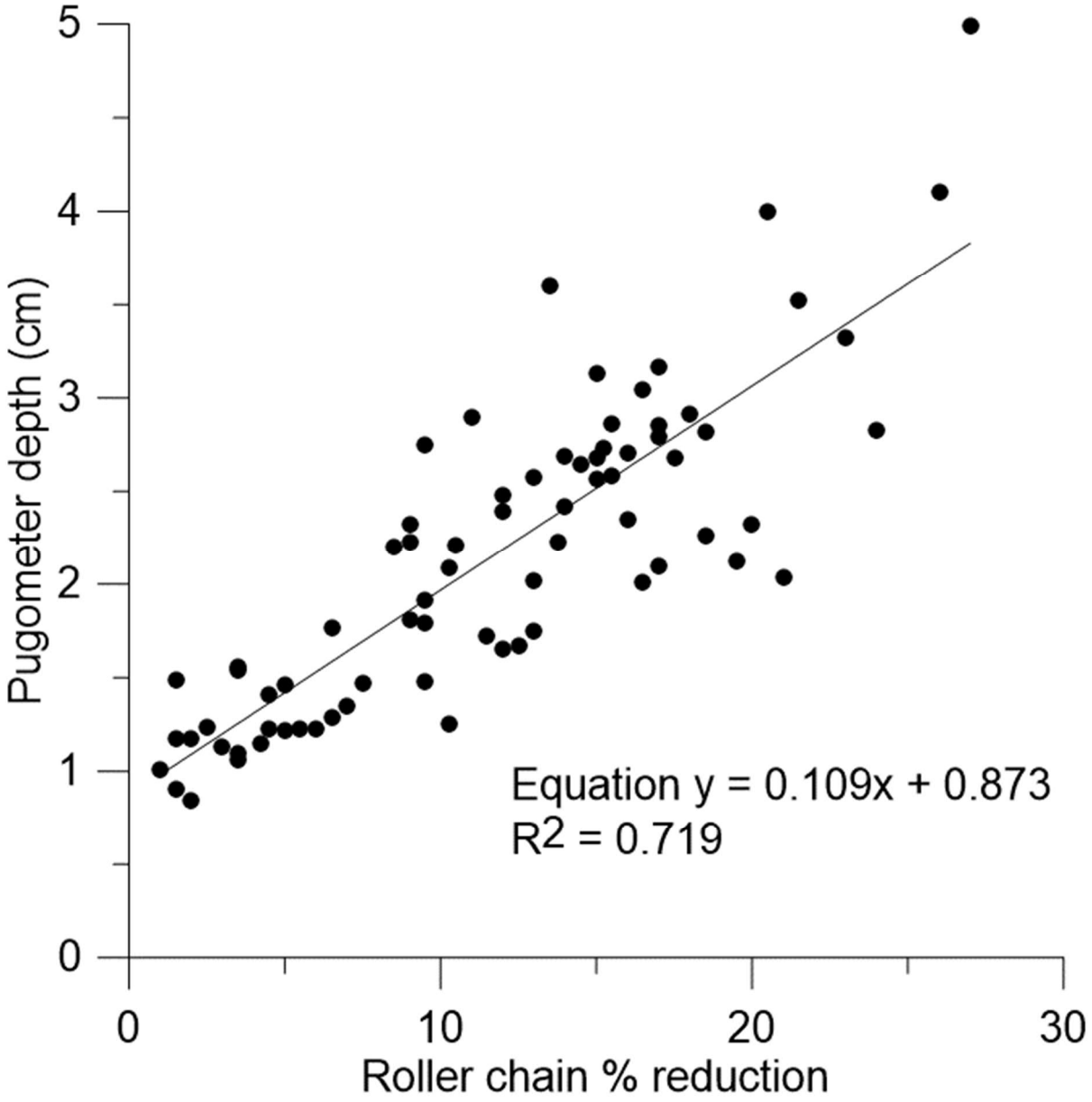

Figure 3.4 Linear regression comparing 75 individual measurements made by the pugometer and roller chain methods.

There was a strong positive correlation between the average values obtained for the quadrats using the *pugometer*, *roller chain*, and *depth of pug* methods (Figure 3.5). In all three comparisons, the strongest relationship was between the *depth of pug* and the *roller chain* methods ($R^2 = 0.871$, $p < 0.01$, $n = 25$), and between the *pugometer* and the *roller chain* method ($R^2 = 0.867$, $p < 0.01$, $n = 25$). This comparison at the quadrat level suggests much better agreement between the *pugometer* and *roller chain* methods than

that which was observed when the values for the transects were compared above (Figure 3.4) presumably as a consequence of averaging the values across the three transects for an overall quadrat value.

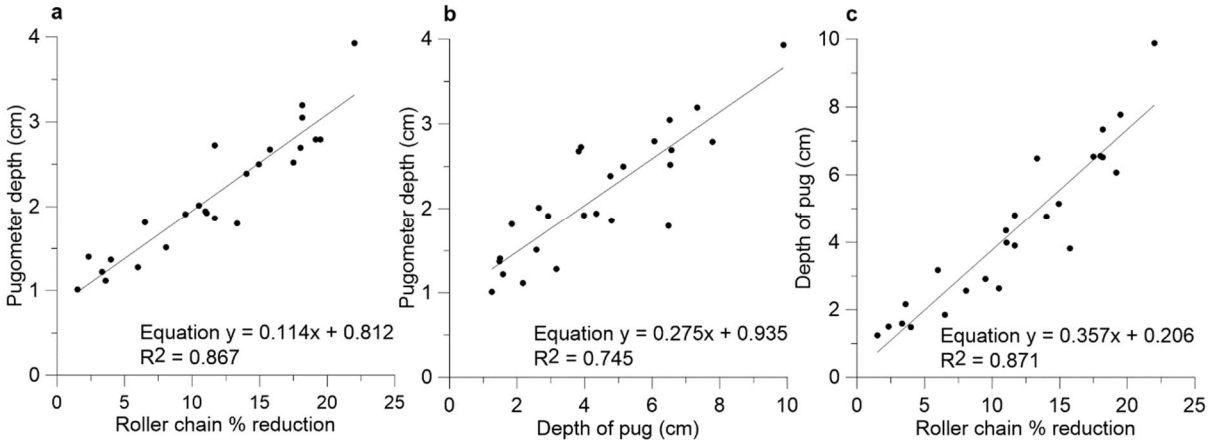

Figure 3.5 Linear regression comparing a) pugometer vs. the roller chain % reduction; b) pugometer vs. depth of pug; and c) depth of pug and roller chain % reduction.

The *pugometer* and the *depth of pug* method has the lowest correlation coefficient (R^2 = 0.745, $p < 0.01$, n = 25). There are two possible explanations for this. Firstly, the infrared sensors used in this prototype *pugometer* restrict the length of the steel rods to 10 cm. Accordingly, pug marks greater than 10 cm would only be recorded as 10 cm by the *pugometer*. Secondly, the *pugometer* has ten steel rods that are separated by 5 cm spacings. Therefore, the pins will not necessarily coincide with the deepest part of the pug mark, which is often the front of the pug. If the pugometer pins routinely missed the bottom of the pug mark, then its values will not be as strongly correlated to the depth of pug method which measured the deepest part of the pug mark.

The *roller chain*, *pugometer* and *depth of pug* methods are compared to the subjective measurement of the *VSM* in Figure 3.6.

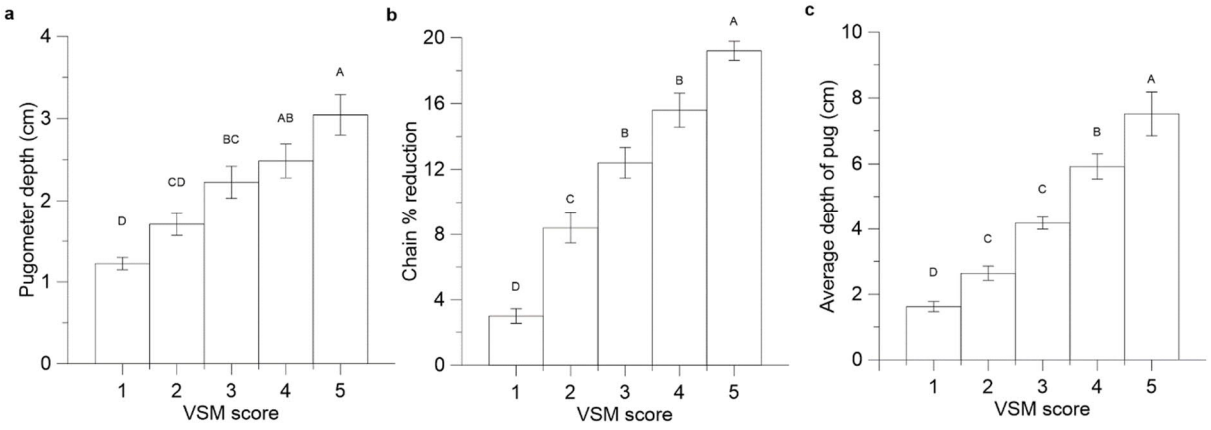

Figure 3.6 Anova analysis comparing the VSM scores (1-5) against: a) pugometer; b) roller chain % reduction; c) depth of pug. Values with the same letter are not significantly different (P < 0.05), with error bars showing the standard error of the mean.

There was a significant positive relationship ($p < 0.0001$) between the *VSM* and the *roller chain*, *pugometer* and *depth of pug* methods (Figure 3.6). All three methods are able to clearly identify a difference (ANOVA, $p < 0.05$) between the levels of treading damage as assessed by the *VSM* scores with at least one score difference between them, i.e. 1 vs. 3 or 2 vs. 4 etc. However, all three methods found it more difficult to significantly discriminate between consecutive *VSM* scores. Values for the *roller chain* method were the closest match to *VSM* scores, and it was able to significantly ($p < 0.05$) distinguish between all *VSM* scores except between a score of 3 and 4.

3.4.2 Use of pugometer to assess treading damage

The GIS interpolated data as recorded by the *pugometer* provides a graphic illustration of the spatial variation in treading damage (Figure 3.7). The area grazed during the wettest soil conditions is clearly identified as having a higher degree and extent of treading damage (top section; Figure 3.7). Damage associated with cow and vehicle traffic through the gateway is also clearly identified in the bottom right hand side of Figure 3.7. The *pugometer* also suggests that three of the strips sustained relatively little treading damage apart from some poorly drained areas in the central part of the right-hand side of the paddock. This points to the relatively quick drying of the surface soil so long as the mole-pipe drainage system is fully operational.

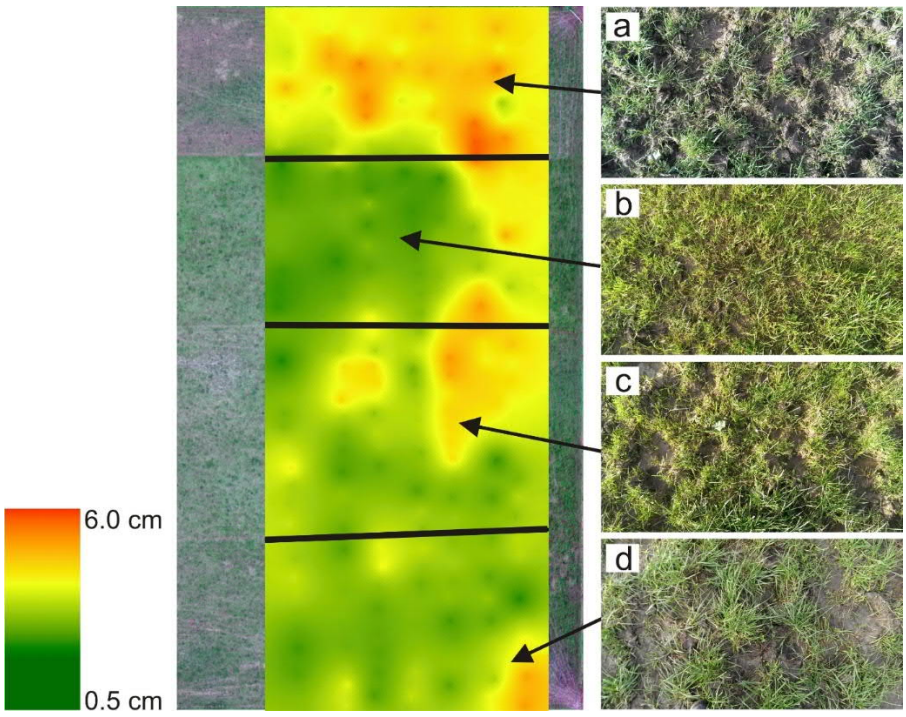

Figure 3.7 Interpolated data from pugometer measurements. A comparison of the assessment of treading damage as made by the pugometer and VSM. Photos showing actual damage with each photo having a VSM score, A = 4, B = 0.5, C = 3, D = 2.

Treading damage across the four grazing strips was also assessed using the *VSM*. A series of GPS referenced *VSM* scores, and accompanying photos, are shown in Figure 3.7. Photo A shows a treading damage score of 4, which was also identified by the *pugometer* as an area of high level of soil damage. Photo B shows a score of 0.5 indicating that there were minimal imprints on the soil surface, which again agrees well with the *pugometer* assessment. Photos C and D show *VSM* scores of 3 and 2 respectively, and the *pugometer's* evaluation of these intermediate levels of treading damage. It is noteworthy that there is no easy way to illustrate the variability in treading damage across the area using the *VSM* scores.

While aerial photography (Figure 3.3) could be used to identify and quantify damage at a paddock and farm scale, in this study it was only able to capture some of the more extreme treading damage (i.e. *VSM* scores of > 4). More detailed methods of photo analysis were outside the scope of this paper and were not investigated but could be employed to characterise treading damage in the future.

It has been observed that the surface roughness, associated with treading damage, can recover quickly (Sheath & Carlson 1998), with reports of recovery times between 87 to 165 days, depending on the characteristics of the soil (Elliott et al. 2002b). Factors that contribute to recovery include wetting/drying processes, rainfall induced erosion, earthworm activity and cattle hooves scuffing and knocking raised lumps of soil to fill hollows (Singleton & Addison 1999). This experiment evaluated the use of the *pugometer* to monitor the recovery of treading damage, as measured by reductions in soil surface roughness. Figure 3.8 shows the *pugometer* assessments of recovery from treading damage in the strips at intervals of 49 and 104 days after the initial wet soil grazing. It would appear that even the relatively severe surface roughness had

disappeared after a period of 104 days and it was unlikely that further grazings did any more damage. It is important not to read too much into this value of 104 days as this recovery period was unique to this treading event. The main point here is that the *pugometer* allowed this information to be collected rapidly, i.e. in less than half an hour per measurement period and, therefore, will be a useful tool for more comprehensive studies of the recovery of surface roughness following treading damage. None of the methods previously discussed are able to provide and automatically record this level of spatial detail within a comparable timeframe.

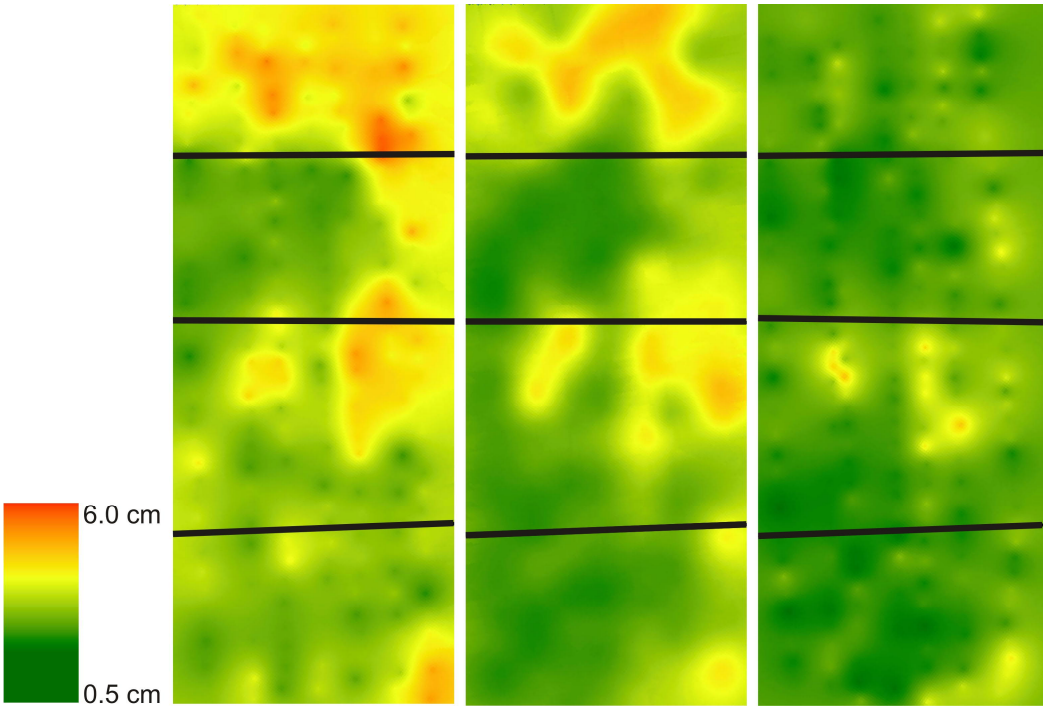

Figure 3.8 Treading damage as assessed by the pugometer after the initial grazing damage occurred (left), 49 days after initial wet grazing (middle) and 104 days after initial wet grazing (right).

3.5 Discussion

3.5.1 Comparison of the four methods

Treading damage, as inflicted on soil by grazing animals during wet periods, is difficult to quantify on a large scale, particularly in a quantitative way for research purposes. In the first instance, surface roughness is most commonly used as an indicator of the extent of treading damage. While multiple methods to quantify surface soil roughness have been compared on tilled arable land (Thomsen et al. 2015), the current study is the first known comparison conducted on grazed dairy pastures. In this study, three existing but contrasting methods and one new technique for measuring treading damage were evaluated over a range of damage levels.

All four methods were able to quantify treading over the range of damage levels observed in this study. Despite the marked differences between the methods, the measurements that they generated were strongly correlated, i.e. there was strong agreement between methods in their assessment of treading damage. Perhaps this is unsurprising given that three of the methods are commonly used to measure treading damage. However, the newly developed *pugometer* produced similar results to the other methods tested in this paper is a useful new finding.

At a detailed level, the *pugometer*, *roller chain*, and *depth of pug* methods all compared well against the subjective *VSM* method. However, these other methods were not able to differentiate between consecutive *VSM* scores (i.e. one score unit). Although the *VSM* is subjective, it is a rapid, practical and reliable method for assessing soil damage up to a paddock scale and in the human eye, it employs one of the most powerful instruments known. The score card presented in Table 3.1 provides guidance to help provide consistency and reduce variation between different users.

One of the biggest differences between the methods is the time taken to conduct measurements and record them. When comparing the methods at the quadrat level, the slowest method is the *roller chain*, as the chain has to be laid out along the soil and moulded into the indentations in the soil before the length is measured and recorded. The *depth of pug* method is slightly quicker than the chain, but neither method is practical for measuring treading at a paddock scale. Like the *VSM*, the *pugometer* provides a rapid method for assessing treading up to the paddock scale, but the latter has the advantage of being able to automatically record spatial variation in soil damage across an area. This is useful because treading damage can be highly variable, even within the same paddock (Figure 3.7). This can be due to a range of reasons some of which have already been mentioned and include: paddock breaks being grazed on different days with varying soil moisture conditions, variation in drainage across a paddock, different soils types, and differences in cow traffic and animal behaviour.

To illustrate the differences in the time and number of measurements it would take to conduct the four different methods over a larger area than a quadrat, the following example is used. Take a hypothetical square 100 m x 100 m area (1-hectare), which has been badly damaged by grazing cows. Table 2 suggests that the *VSM* is the fastest method. If a walking pace of 3 km/hr is used to walk a 'M' shaped transect, approximately 500 m would be covered in 10 minutes. The total time to complete the *VSM* would be 10 minutes. To cover the same transect using the *pugometer*, a reading would be taken at every 4th pace (approximately 4 m): this would give 125 readings and take 20 minutes to complete (10 minutes to walk the area plus 10 minutes to complete the readings). For this larger area, the *depth of pug* and *roller chain* methods could be performed at random or representative points on this same transect. If there is the same 20-minute period allowed (like the *pugometer*) for the *depth of pug* method, and it takes

10 min to walk the transect then there would be time to measure the depth of pug marks in seven quadrats. As it takes 90 secs to complete a *roller chain* measurement then this method would only be able to take seven measurements in 10 minutes. This reduction in sample size limits the ability of these two slower methods to accurately quantify spatial variability. Whether the reduction in sample size would affect the correlation of the depth to pug and chain methods with the *pugometer* and *VSM* or give reliable estimates of treading damage over a larger area was not investigated in this study.

One of the advantages of the *pugometer* is that the large number of measurements and the GPS functionality allows the user to characterise the spatial variability in treading damage. While the *VSM* is more limited in its ability to record spatial detail, it can still be a practical tool for farmers to record soil damage.

Given that all methods are reasonably accurate and in agreement then the choice of method for assessment of treading damage will depend on the context and scale. For small scale research plots, where spatial variability is low, and the number of measurements required is relatively small, all four techniques could be considered as acceptable methods. In large scale plots and paddock research areas, larger numbers of measurements may be required to capture spatial variability. In these situations, both the *VSM* and the *pugometer* would be feasible options. At a farm management level, where farmers often want to quantify pugging damage quickly (to make decision such as whether to continue grazing paddocks in wet conditions or stand cows off), the *VSM* method would be most appropriate given that the farmer could undertake a simple paddock walk (similar to a pasture walk) to easily and quickly determine the degree of damage on an area without the use of any apparatus. For paddock or farm scale research, where a good record of the spatial variation in pugging damage is important, the use of the *pugometer* would be advantageous.

3.5.2 Demonstration of the use of the pugometer at scale.

As noted above, an important advantage of the *pugometer* is that it can describe treading damage over a large area relatively quickly and the GPS technology allows the automatic capture of spatial variability. These features mean that the *pugometer* can be used to study some aspects of treading damage in detail and answer questions such as those related to recovery time.

The *pugometer* was effective at recording and identifying the spatial variability in treading damage across a paddock caused by grazing different parts of a paddock at different soil moisture contents. The greatest treading damage resulted when grazing occurred on the day it was raining, and the soil was saturated. The extent of damage declined over successive grazing events as the soil dried. The *pugometer* was also able to quantify increased treading damage on more poorly drained parts of the paddock and areas with higher cow and vehicle traffic. It was also used to track the recovery of soil surface roughness. This one-off set of measurements obtained with the *pugometer* showed that surface roughness recovery after a wet soil treading event was similar to values reported in the literature.

This work has attempted to provide guidelines to help in the selection of the most appropriate method to assess treading damage. It recognises that the requirement of farm managers differs from researchers and, to this end, has introduced a new tool, the *pugometer*, for use in paddock-scale research. The methods compared here all equate the severity of treading damage to the degree of surface roughness. However, there is much more to treading damage, including its impact on soil properties and processes and pasture utilisation, regrowth and species composition. In the future, it will be important to attempt to relate the severity of treading damage as assessed by the methods

used in the present study to soil and pasture characteristics. An obvious example would be to develop relationships between VSM and *pugometer* scores with likely pasture growth rates following a treading event. As mentioned above, the *pugometer* also lends itself to studies of the recovery rate of surface roughness following treading damage.

3.6 Conclusion

This study presents three established methods of measuring treading damage and introduces and demonstrates a new tool called the *pugometer*. This study is to the best of the author's knowledge, the first that directly compares the common methods of measuring treading damage on dairy pastures. All methods were strongly correlated and were able to identify varying levels of treading damage. However, which method is the best choice for assessment of treading damage depends on the circumstances. For small scale research plots, where spatial variability is low, and the frequency of measurements is relatively small, all four techniques could be considered as acceptable. For large plots and paddock scale research the *visual scoring* method and *pugometer* would be most appropriate. However, the advantage of the *pugometer* in this case is that it can capture spatial variability rapidly and automatically. This was demonstrated by its practical ability to track the recovery of surface roughness following a wet soil treading event.

4 TREADING DAMAGE TO SOILS UNDER DURATION CONTROLLED GRAZING: THE EFFECTS OF SOIL WATER DEFICIT AND GRAZING DURATION

4.1 Introduction

Treading damage is commonplace across most areas of New Zealand in winter and spring and presents a major challenge to grazing management (Betteridge et al. 2002), particularly on soils with impeded drainage, fine textured soils and/or soils in regions with frequent rainfall. It is widely recognized that severe treading damage, associated with the grazing of very wet soils for long periods degrades soil structure and damages pasture. Treading damage is also detrimental to the wider environment, and the farm's economic performance (Singleton & Addison 1999; Betteridge et al. 2002; Ward & Greenwood 2002; McDowell et al. 2003; Beukes et al. 2013b).

Cattle treading results in hoof indentations that may penetrate or rupture the soil surface (Scholefield & Hall 1985; Bilotta et al. 2007). Given this, the measurement of soil roughness has been shown to be an indicator of treading damage to soil and is usually a good measure of the deterioration in soil surface conditions (Pande et al. 2002; Tuñon et al. 2014; Little et al. 2015).

Farmers can minimise treading damage by standing cows off pastures when soils are wet (i.e. small soil water deficits; SWD) (Laurenson et al. 2014). However, the number of days of standoff required on farms that are vulnerable to treading damage can be very large. Ideally, following standoff, grazing should only resume when larger SWDs have developed and the soil has enough strength to support the grazing cow. However, regular grazing is required during winter and spring to control pasture cover and the long-term quality of the sward. This can create tension between the need to frequently house cows to protect soils and pasture from treading damage, and the need to routinely graze to control pasture covers. On occasions, this requirement to graze is likely to necessitate the grazing of very wet soils for short durations. In these cases, the management of pasture quality takes priority over the risk of severe treading damage.

A cow can consume approximately 80% of the offered feed in the first four hours of a grazing period (Kennedy et al. 2011), with the remaining grazing time being used mostly for rumination, walking and standing (Draganova et al. 2010). Given this, if increasing pasture covers compel farmers to graze their herd during wet periods in winter and spring, they should do so for approximately 4 hours a day for non-lactating cows, and for 4 hours following both the morning and afternoon milkings for lactating cows.

The majority of treading studies involving grazing duration have used longer grazing intervals of up to 24 hours (Singleton & Addison 1999; Singleton et al. 2000; Betteridge et al. 2002), but relatively few studies have investigated the effects of treading damage inflicted during shorter grazing intervals of 4 hours or less. When compared to longer grazing durations, shorter grazing intervals (on/off grazing) have been reported to reduce the negative effects of treading damage (Drewry 2003; Houlbrooke et al. 2009). However, the treading studies above have only considered grazing that was conducted on very wet soils, and therefore the relationship between treading damage and the SWD has not been comprehensively investigated.

The size of the SWD is a primary determinant of the severity of treading damage, and a number of studies have shown that the degree of damage is directly dependent on SWD. The negative impact of treading damage on soil health indicators increases when grazing occurs at a smaller SWD (Herbin et al. 2011; Piwowarczyk et al. 2011). However, as noted above, the relationships between treading damage and SWD reported in these studies are not sufficiently detailed to offer much by way of practical help to grazing management in New Zealand. The studies that have been conducted in New Zealand to quantify the effects of grazing soils with relatively small SWDs (Zegwaard 2006; Laurenson et al. 2014; Laurenson & Houlbrooke 2016) suggest that a SWD between 0 and 5 mm would be of more interest to New Zealand farmers.

There are a number of questions and gaps in the literature related to the management of dairy cow grazing in wet conditions. These mostly relate to identifying the range of SWDs for which cows should be removed and stood off pasture and, therefore, when grazing can recommence. The most appropriate grazing duration on wet soils is another important consideration. The identification of critical SWDs, which avoid damage to soil and pasture, would be of great value to farmers seeking to minimise damage to the soil resource and to optimise pasture utilisation and production (Kerebel et al. 2013). There is little information available to help farmers identify critical SWDs, and therefore it is very difficult to make grazing management decisions for wet conditions (Laurenson et al. 2014).

Furthermore, many studies focus on a single, severe treading event, whereas in an actual grazing system, some paddocks on the farm may be subjected to repeated treading damage. This will happen when a paddock is grazed during a wet period in winter and then again, coincidently, during a wet period in spring. In wetter than average years, this will be a common occurrence. Soil that has been subjected to treading damage once, may be more susceptible to subsequent damage as the infiltration and drainage characteristics of the soil are likely to be negatively impacted by the initial damage (Greenwood & McKenzie 2001). Therefore, repeat treading may exacerbate both soil damage and the reduction in pasture production compared to a single treading event.

Given that soil moisture levels (and SWD) during winter/spring will be dependent on how wet the season has been, the area of a farm damaged in any one year could be expected to vary greatly as does seasonal rainfall. However, there is no literature currently available that has investigated the area of a farm that could be potentially damaged during a grazing season.

To address these questions, a series of treading experiments was conducted on a mole and pipe drained, fine textured soil over the consecutive grazing seasons of 2015/16 and 2016/2017. In addition, the DairyNZ Whole Farm Model (WFM) was used to estimate the area of a farm that would be damaged when using on/off grazing protocols using results from the conducted treading trials.

The objectives of these treading trials were:

i. to identify the relationship between the severity of treading damage to the surface soil and the SWD at the time of grazing,

ii. to quantify the effect of grazing duration on the severity of treading damage to the surface soil,

iii. to identify the impact of a repeat treading damage (i.e. spring damage on an area that was damaged during winter) on the severity of treading damage to the surface soil, and

iv. to contribute to a major gap in the literature in regard to the area of a farm that could be potentially damaged, even when standoff grazing is practised.

Important outputs of this research will be the identification of the critical SWD (range) at which grazing will result in acceptable levels of treading damage (i.e. ‘safe’ grazing), and guidelines for grazing management of wet soils on farms with standoff facilities.

4.2 Materials and Methods

4.2.1 Trial site

The experimental site was located in a 3.2 ha paddock (Figure 4.1) on Massey University's No. 4 Dairy Farm near Palmerston North, Manawatu, New Zealand (NZMS 260, T24, 312867). The site has flat topography (c. <3% slope), and receives an average annual rainfall of approximately 930 mm (NIWA 2016). The soil is the Tokomaru silt loam, classified as an Argillic-fragic Perch-gley Pallic Soil. This soil has poor natural drainage. However, nearly all the paddocks on this dairy farm, including the present research site, have mole and pipe drainage.

Figure 4.1 An aerial view of the trial paddock showing the experimental area within the black outline, and the four experimental blocks separated with orange lines, with block numbers.

4.2.2 Soil fertility and fertiliser application

The background soil fertility of the site (Table 4.1) is at or close to optimum for ryegrass clover pastures (FertResearch 1999). Sulphate of ammonia fertiliser was applied (October) to the experimental area at a rate of 180 kg/ha (37 kg/ha Nitrogen and 43 kg/ha Sulphur) in the first grazing season of the experiment (2015-2016). No fertiliser was applied in the second grazing season (2016-17).

Table 4.1 The background soil fertility for the trial area (sample taken 2014)

pH	Olsen P	SO_4	K	Ca	Mg	Na	CEC	Wt/vol
	µgP/g	µgS/g	me/100g	me/100g	me/100g	me/100g	me/100g	g/ml
5.7	37.9	13.8	0.39	7.7	1.60	0.23	16	0.89

4.2.3 The Experimental area

The paddock (Figure 4.1) was sectioned off into a 2 ha experimental area that was separated into four blocks (Figure 4.1) and, in turn, each block was divided into seven plots. Each plot was 20 m x 30 m giving 28 plots, each with an area of 600 m^2. The blocks were separated by two alleyways (Figure 4.1), which were used to guide cows onto treatment plots. All of the plots were fenced individually, and all fences were electrified.

Once all the experiments had been completed for a grazing season, fences were then removed, and all the plots were grazed as one paddock (i.e. as part of the farm's normal grazing rotation). However, grazing of the site was managed to ensure that the only treading damage was the planned experimental treading damage.

The treading treatments were carried out using lactating Friesian x Jersey dairy cows (of mixed ages, not heifers; the range of cow live weights was 470-550 kg). The cattle used in the experiments had previously been used in similar sized experimental plots, and

therefore their behaviour was not likely to be greatly modified by placing them on the plots. Once cows were allocated to plots, they were initially observed for atypical grazing behaviour (i.e. jumping around, bullying other cows etc.). If such behaviour was observed, then the offending cow was removed from the experimental plot and replaced with another cow.

4.2.4 The treatments

Four SWD ranges were compared in this study (Table 4.2) These SWDs were selected based on results reported in the literature and from on-farm experience. The SWD targeted and studied here are as follows: 0 mm and raining, so the soil is at saturated or near saturated conditions (Herbin et al. 2011); 0 to 2 mm (Laurenson et al. 2014), which is approximately one to two days after saturation in winter and spring; 2 to 4 mm (Laurenson & Houlbrooke 2016); and > 4 mm, which is a deficit already recognised by farm staff as resulting in safe grazing. This latter treatment might be thought of as the Control as very little treading damage occurs at this SWD. This treatment corresponds to the ideal winter/spring grazing where there would be minimal visual damage and, therefore, this is the benchmark against which other treatments are compared.

Table 4.2 The treatments of the treading trial

Treatment I.D (SWD mm: Grazing duration hr)	Soil moisture target	Treatment grazing time (hrs)
0mm:4hr	Saturated	4
0mm:8hr	Saturated	8
0-2mm:4hr	Soil moisture deficit 0 – 2 mm	4
0-2mm:8hr	Soil moisture deficit 0 – 2 mm	8
2-4mm:4hr	Soil moisture deficit 2 – 4 mm	4
2-4mm:8hr	Soil moisture deficit 2 – 4 mm	8
Control	Soil moisture deficit > 4 mm	8

Soil water deficit treatments of 0 mm, 0-2 mm and 2-4 mm, each had two grazing intervals of four and eight hours (Table 4.2). The 4-hours grazing treatment corresponds to the grazing duration employed in a farm system with a cow house or similar standoff facility when high pasture covers necessitate grazing in wet conditions. The 8-hours treatment corresponds to the grazing period between morning and afternoon milkings and/or the time that cows often need to spend on paddocks on farms where the only standoff facility is a hard surface (e.g. feed pad) with limited capacity for cow lying. The Control treatment is only to be grazed at a 'safe grazing' SWD and only with an eight-hour grazing interval.

4.2.5 Experimental design and treatment allocation

The trial was conducted over two consecutive grazing seasons (2015-2017). There were two experiments in each season. Experiments 1 (2015) and 3 (2016) (Table 4.3) measured the effects of SWD and grazing duration on a single winter treading damage

event (S sub-treatments Table 4.3). Experiments 2 (2015) and 4 (2016) quantified the effects of SWD, grazing duration on treading damage, plus the effect of a repeat or second damage event in spring (D sub-treatments Table 4.3).

Before each treatment was grazed, the SWD on the day of grazing was estimated using a soil water balance described by Scotter et al. (1979c), and grazing was undertaken if the SWD was within the target SWD range for that treatment (Table 4.3).

Table 4.3 The soil water deficit (SWD) and the date of grazing treatments. S = one grazing at treatment SWD, D = two grazings at treatment SWD.

	Experimental grazing dates			
Target Soil moisture deficit (mm)	0 **0mm:4hr & 0mm:8hr**	0 – 2 **0-2mm:4hr & 0-2mm:8hr**	2 – 4 **2-4mm:4hr & 2-4mm:8hr**	> 4 **Control**
Experiment 1 2015				
Actual SWD (mm)	0[a]	0.7	2.7	4.5
Grazing Date	29/07	31/07	13/08	29/08
Experiment 2 S sub treatment (2015)				
Actual SWD (mm)	> 4	> 4	> 4	> 4
Grazing Date	02/10	02/10	02/10	02/10
Experiment 2 D sub treatment (2015)				
Actual SWD (mm)	0[a]	0.7	2.5	n/a
Grazing Date	23/09	25/09	26/09	n/a
Experiment 3 (2016)				
Actual SWD (mm)	0[a]	1.2	2.3	4.9
Grazing Date	13/08	16/08	10/08	12/08
Experiment 4 S sub treatment (2016)				
Actual SWD (mm)	> 4	> 4	> 4	> 4
Grazing Date	25/09	25/09	25/09	25/09
Experiment 4 D sub treatment (2016)				
Actual SWD (mm)	0[a]	1	n/a	n/a
Grazing Date	28/09	29/09	n/a	n/a

a – the soil was at or near saturation during the grazing of these treatments

4.2.6 The Experiments

4.2.6.1 Experiment 1

In Experiment 1, there were four replicates of each treatment. Each replicate was randomly allocated to one of the four blocks in the experimental area (Figure 4.2). The plots were grazed at a stocking rate of eight cows/plot (134 cow/ha) aligned with an initial pasture cover of approximately 2300 kg DM/ha and a residual cover of approximately 1600 kg DM/ha, which corresponds to a pasture allocation of approximately 5.5 kg DM/cow. This stocking rate also reflects standard grazing practice at that time of year for the dairy farm the experiment was conducted on, when cows are receiving approximately 2/3 of their diet as fresh pasture and the remainder as maize and grass silage. This stocking rate was used for the rest of the trial (Experiments 1-4). Experiment 1 began on the 29th July 2015, when treatments 0mm: 4hr and 0mm:8hr were grazed. The other treatments were grazed as the appropriate SWD was attained. The last grazing, the Control treatment, was conducted on the 29th August 2015, which ended Experiment 1.

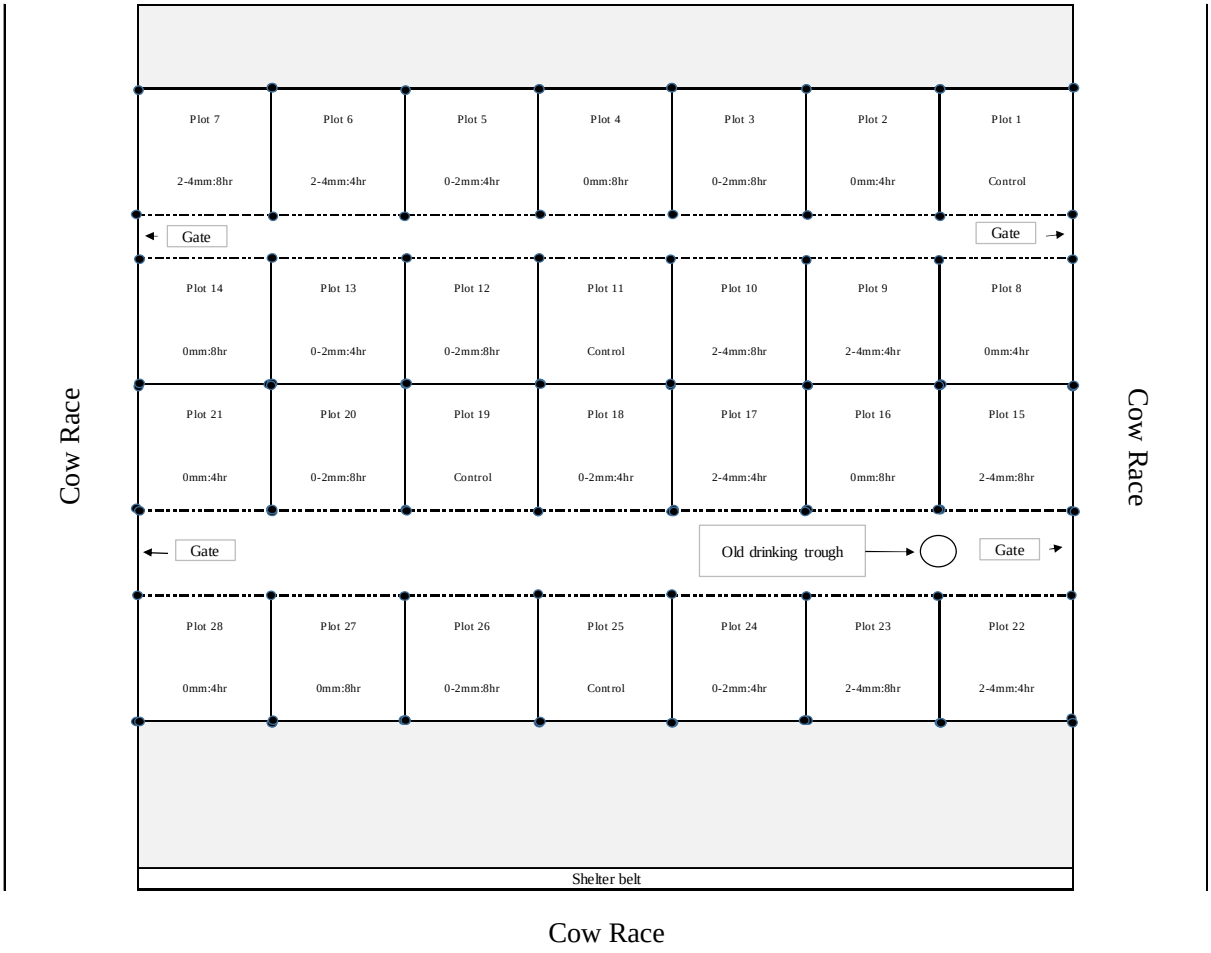

Figure 4.2 The grazing treatment plots as allocated for Experiment 1 (2015). Each plot is 600 m^2 and treatments were allocated according to a randomised block design.

4.2.6.2 Experiment 2

On 10 September 2015, the treatment plots (600 m^2) from Experiment 1 were split into twin 300 m^2 plots (Figure 4.3). Dividing the plots in this manner allowed a comparison of the effects of a single treading event (i.e. July to August) with repeated spring damage (i.e. grazed in July to August and then again in the spring). Therefore, in Experiment 2, there were a total of 56 plots (Figure 4.3).

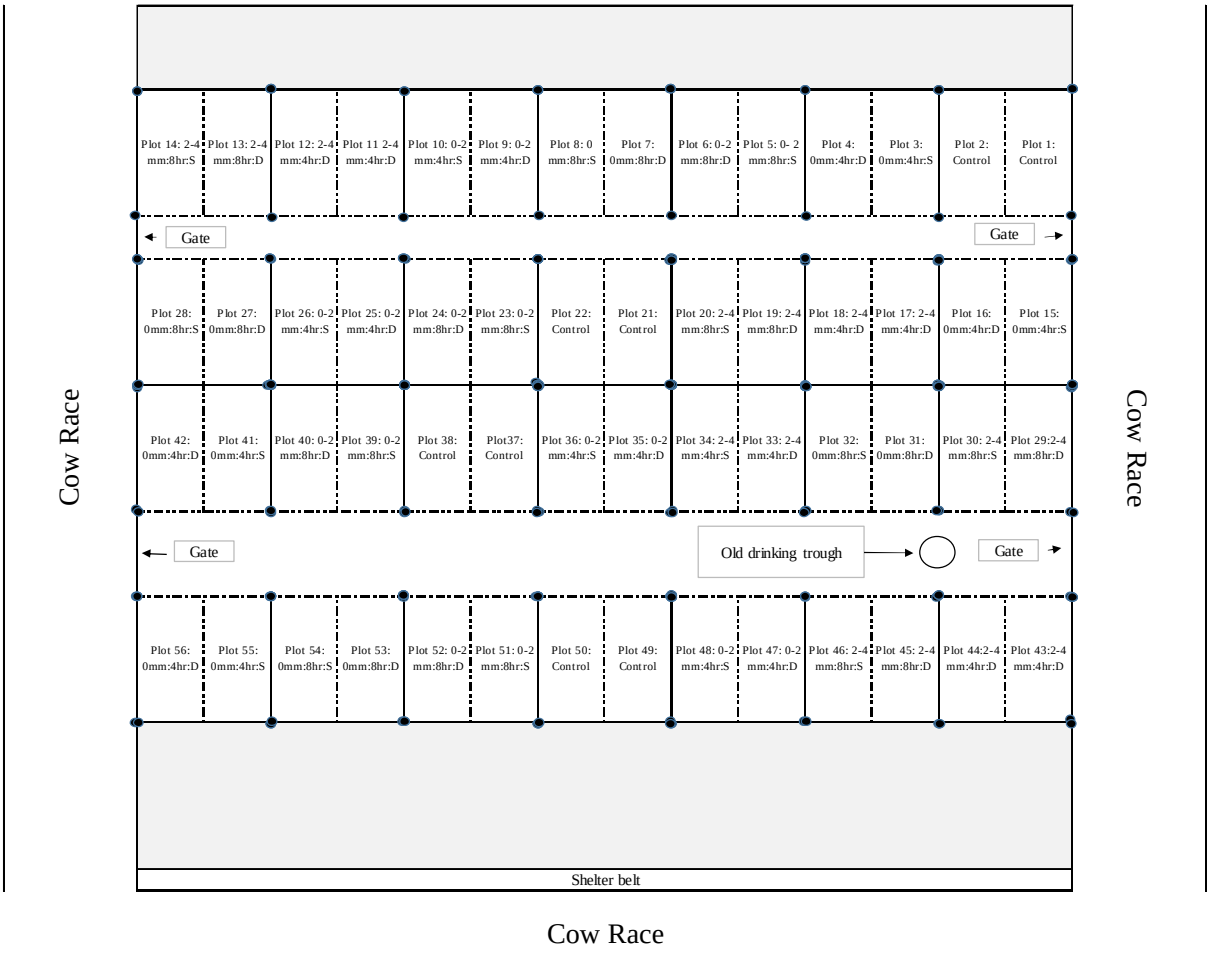

Figure 4.3 Experiment 2 treading trial (2015-16) map showing the larger plots from Experiment 1 split into twin 300 m^2 plots. S = one grazing at treatment SWD, D = two grazings at treatment SWD.

All plots were re-grazed at the same equivalent-stocking rate as used for Experiment 1 (i.e. at four cows per 300 m^2 plot). One of the twin plots was re-grazed at the same SWD treatments as Experiment 1, while the other twin plot was grazed at optimum conditions (SWD > 4 mm). In this manner, the single treading damage versus double treading damage comparison was established.

The split plots are now identified by their original treatment identification (Table 4.2) and a new sub treatment letter, either an 'S' or 'D', was introduced. 'S' denotes plots that had single treading damage (i.e. all subsequent grazings for the year occurred when SWD was > 4). 'D' denotes the smaller plots that had double treading damage.

Experiment 2 started with the first grazings (treatments 0mm:4hr:D and 0mm:8hr:D) on the 23 September 2015 and the second grazings occurred as the SWD reached their target treatment values. Experiment 2 finished on 2 October 2015 with the grazing of the Control and S sub-treatments. Plots were then deconstructed, with markers left in the ground to identify each treatment area, and the experimental area was left open for grazing (only at a SWD > 4 mm) at a stocking rate and duration dictated by the farm's grazing round. There were eight further non-treatment grazing events up to the end of the first year of the study on 29 July 2016.

4.2.6.2.1 Changes to experimental procedures for the 2016-17 grazing season

Site preparation and the experimental period for Experiments 3 and 4 differed from the first two experiments due to an unforeseen event. The last grazing of the trial area in the 2015/16 year (in June 2016), occurred at an estimated SWD of only 3 mm, immediately after a rain event. While this led to mostly minimal treading damage, a few areas sustained more severe damage. There is a risk that such unplanned events will occur in large research studies that are integrated into normal farm operations, despite all care being taken by the researchers. The trial plots were assessed for their suitability for use in Experiments 3 and 4 using the visual scoring method (VSM) and the pugometer (Howes et al. 2018). In each of the four trial blocks, five of the 300 m^2 plots had significantly ($p < 0.05$) more damage than the other plots in the block. Therefore, these plots (five in each block) were excluded from the experimental design for the 2016-17 grazing season (Figure 4.4).

4.2.6.3 Experiment 3

There were four replicates of each treatment in Experiment 3 (as for Experiment 1) and each replicate was randomly allocated to one of the four blocks (Figure 4.4). However, there were two plots with 0mm:8hr treatments and two plots with 0-2mm:8hr treatments.

The reason for this is that when Experiment 4 commenced, one of each of these 0mm:8hr and 0-2mm:8hr plots in each block became the D sub treatment for Experiment 4 (Figure 4.4).

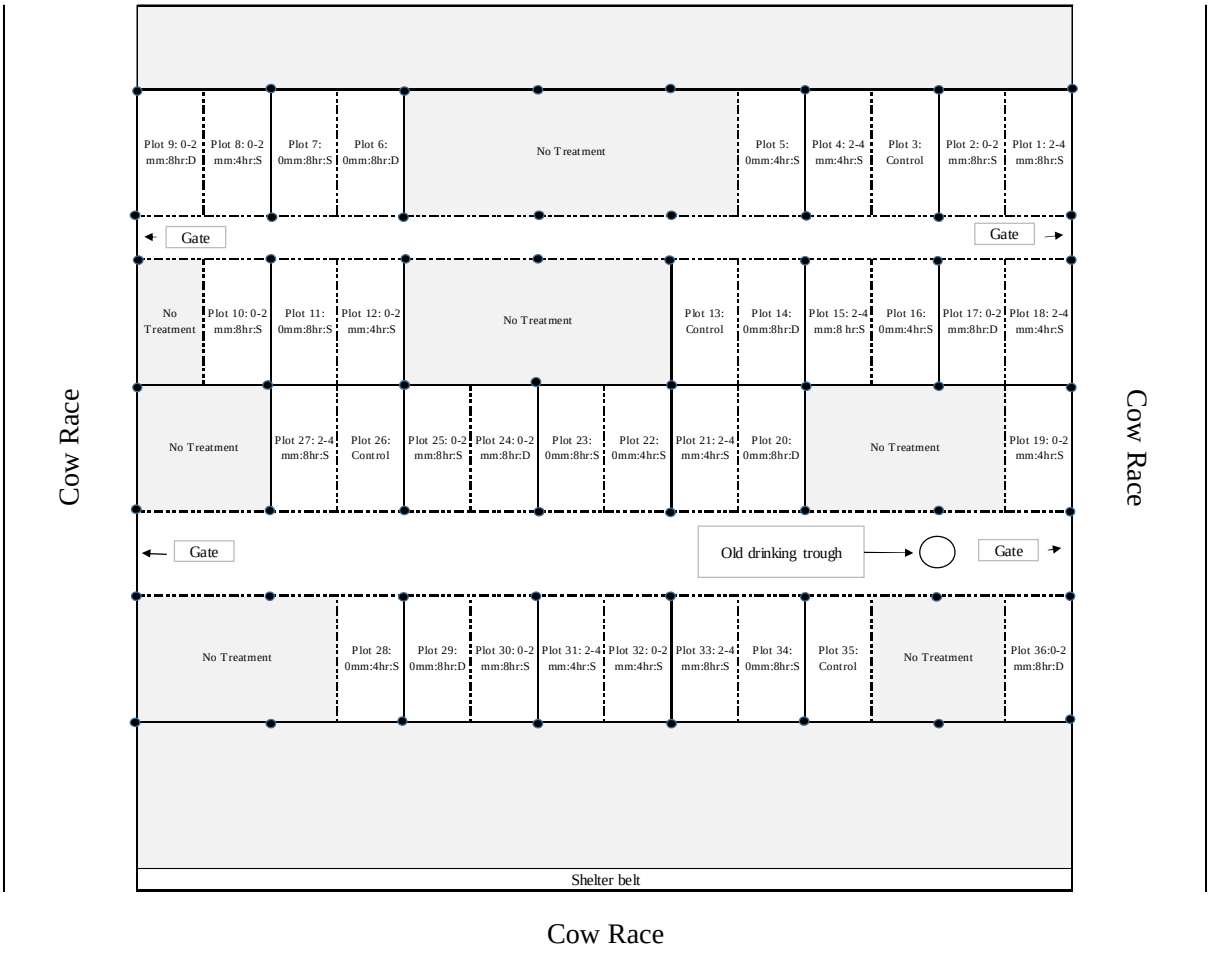

Figure 4.4 Experiments 3 and 4 treading trial (2016-17) map, showing treatment plots in a random configuration. Treatments with an S are damaged only once at treatment SWD, D = two grazings at treatment SWD.

The stocking rate in Experiment 3 was the same as that used in the previous two experiments. Experiment 3 began on the 10th August 2016, when treatments 2-4mm:4hr and 2-4mm:8hr were grazed. The other treatments were grazed as the appropriate SWD was attained. The last grazing treatments of 0-2mm:4hr and 0-2mm:8hr were conducted on 16th August 2015.

4.2.6.4 Experiment 4

Because of the decrease in the number of plots available, Experiment 4 (investigating the effect of repeat damage) had fewer treatments than Experiment 2. Therefore only the 0mm:8hr and 0-2mm:8hr treatments were imposed (re-damaged) and designated with the 'D' sub-treatment (Figure 4.4). These two treatments were selected, as they were the only D sub-treatments that were significantly different to the Control treatment in Experiment 2 in 2015/16.

The S sub-treatments were grazed on the 25th September 2016 (SWD > 4 mm). The D sub-treatments (0mm:8hr:D and 0-2mm:8hr:D) were grazed on the 27th and 29th September 2016, respectively. However, due to a period of dry weather that caused SWDs to increase, all eight of the D treatment plots had to be irrigated to saturation to enable the imposition of these grazing treatments. All plots had in excess of 10 m^3 of water applied to ensure saturation (i.e. approximately equivalent to 33 mm application depth). The 0mm:8hr:D treatments were grazed as soon as the irrigation ceased, with the 0-2mm:8hr:D treatments given time to drain and grazed when the SWD was estimated to be 0-2 mm.

Once Experiment 4 was finished, the trial area was deconstructed, and the paddock was grazed as part of the farm's normal rotation. There were ten further non-treatment grazing events up to the end of the experimental period on 9 August 2017.

4.2.7 Field Measurements

Throughout the experimental process, a series of field measurements were undertaken to measure soil moisture, susceptibility to damage, and severity of damage. The apparatus and methods used are described below.

4.2.7.1 Time-Domain Reflectometry (TDR)

A TDR (model: 6050X3K1b Mini Trase) was used to record the volumetric soil moisture content to a depth of 10 cm in the experimental plots at the time of the grazing treatments. The TDR probes were inserted into the ground at twelve random points across each treatment plot. The twelve readings were then averaged to give the soil moisture of each plot.

4.2.7.2 Penetrometer

Immediately prior to each grazing event, a Rimik electronic CP40 II Cone Penetrometer was used to assess the vulnerability of each plot to treading damage by mimicking the depth the hoof of a mature dairy cow would penetrate (equivalent to exerting a pressure of 350 kPa) under the pre-grazing pasture cover and soil moisture conditions (Scholefield & Hall 1986). The penetrometer used a 75 kg load cell and a 333 mm^2 penetration cone. The penetrometer was inserted into the soil at approximately 10 random points across the plots. As the penetrometer is pushed down into the soil, it records the tensile strength of the soil at 1 cm intervals to a depth of 20 cm. The cone is pushed into the soil until it reaches a tensile strength of 350 kPa; this penetration depth is recorded. In addition, the percentage of these readings greater than 2 cm is also presented. Betteridge et al. (2003) reported that, over a broad range of soil types, if 30% or more of the penetrometer readings penetrate the soil by 2 cm or more, then the soil is susceptible to pugging damage.

4.2.7.3 Visual scoring method

A visual scoring method (*VSM*) was used to quantify treading damage post-grazing. The method used was similar to the *VSM* described in Howes et al. (2018). After a treatment grazing, two experienced users of the *VSM* method walked across each treatment plot

and assessed the treading damage before agreeing on the treading damage score (1-5). Similar types of VSMs have been used in other treading research trials (Nie et al. 2001; Zegwaard 2006; Little et al. 2015; Fransen et al. 2017).

4.2.7.4 Pugometer

The *Pugometer,* as described by Hanly et al. (2016) and Howes et al. (2018), was also used to quantify the severity of treading damage. Sixty random measurements were taken post-grazing on each plot. These sixty measurements were then recorded and averaged to give a pugometer treading damage score for each plot.

4.2.7.5 Depth of pug and number of pugs

The *depth of pug* method, as described by Howes et al. (2018), was used to quantify treading damage severity. A 0.72 m^2 quadrat (0.6m x 1.2m) was randomly placed ten times within each plot and the three deepest and the three shallowest pugmarks were identified, and their depths were measured. These six measurements were averaged to give the average depth of pug print for the plot. The number of pugs (per m^2) in a plot were counted at the same time and in the same quadrat area of soil used to assess the depth of pug. This method involved identification of pugmarks by observation and physical identification on the soil surface. The number (#) of pugs in a quadrat was recorded and expressed as #pugmarks/m^2.

4.2.8 The DairyNZ Whole Farm Model (WFM)

DairyNZ's WFM was used to identify the percentage area of a model farm (an analogue of Massey University's No.4 dairy farm) that is damaged by treading over a range of years. As noted in the introduction, this is a gap in the literature, and modelling is the only practical way to identify the variation in the extent of treading damage. The model

was run using the results from the treading experiment reported in this chapter i.e. the SWD deemed to enable safe grazing of soils.

4.2.8.1 Model farm

The scenario used for this modelling exercise was based on No.4 dairy farm, Massey University (Table 4.4) and, where possible, the inputs used in the model were aligned to the management practices of No.4 dairy farm Massey University.

Table 4.4 No.4 Dairy Farm Massey University

	No.4 Dairy Farm
Milking platform area (ha)	188
Stocking rate (cows/ha)	2.7
Cow Breed	KiwiX
Planned start of calving	15 Jul
N fertilisation (kg/ha/yr)	75
Crop grown on the platform	Turnips
Crop proportion of platform (%)	6
Supplements imported	Grass silage, maize silage
Supplements made	Grass silage
Effluent irrigated proportion of milking platform (%)	25

4.2.8.2 Whole Farm Model (WFM)

The DairyNZ WFM has been used in New Zealand to model farm management strategies for a range of pastoral dairy systems (Beukes et al. 2008; Beukes et al. 2013a; Beukes et al. 2013b; Laurenson et al. 2016; Laurenson et al. 2017). A full description of the WFM can be found in Beukes et al. (2013a). In brief, the model framework represents a ryegrass/white clover mixed pasture-based dairy farm. The model operates

on a daily time step and at a spatial scale of individual paddocks. As the WFM simulates daily farming practices and activities, it is therefore a very complex modelling program and so, depending on computer processor power, a single full-scale scenario could take in the region of 12 to 72 hours to complete. Therefore, due to the number of scenarios that had to be conducted during this modelling exercise (ca. 250), it was decided to run the WFM at a 10% scale of the actual model farm and then to extrapolate results so that they represented full size farms (P.Buekes pers comm). This enabled the relatively quicker modelling (this still required many days of actual modelling to complete).

4.2.8.3 Animal characteristics

For the simulations conducted in this modelling exercise, the cow breed was Friesian Jersey cross (KiwiX), with a mean live weight of 475 kg. Feed intake is determined by metabolic demand from 'Molly' which is a mechanistic and dynamic model within the WFM that simulates critical elements of cow digestion and metabolism (Hanigan et al. 2009).

4.2.8.4 Climate and soil water deficit (SWD)

The pasture-soil model in WFM (Romera et al. 2009) is climate-driven using either weather data provided by the National Institute of Water and Atmospheric Research (NIWA) or a user-defined climate pattern. A standard soil water balance is used to determine actual SWD on any one day (Beukes et al. 2013b). Available soil water holding capacity, daily rainfall/irrigation and daily potential evapotranspiration are all user-defined inputs.

4.2.8.5 Standoff policy and grazing management

Grazing management was modelled by the consideration of several factors. Paddocks were grazed rotationally in accordance with a specified rotation length. Pasture regrowth

after grazing was determined by herbage mass (residual) which, in turn, was simulated as a function of the feed demand of the herd, grazing hours, and the herbage allowance on any given day. Grazing duration was determined by the standoff policies explored here. Cows were stood off when the SWD was less than the critical SWD (when pasture damage is expected on the soil type on the model farm). The critical SWD used in this modelling exercise was obtained from the results of the treading experiments outlined in this chapter. However, there was also another trigger used for the standoff policy. This was based on the average pasture cover kg/ha on the farm at the time of grazing. This was introduced to reflect the requirement to control pasture cover, and to investigate the conflict between standoff for soil and pasture protection and the need to graze wet paddocks in order to control pastures covers (i.e. for pasture quality and pasture growth rates). Therefore, if the SWD was below its critical value and the average pasture cover (APC) was below its critical amount then no grazing would occur until the SWD reached a safe grazing value. The critical value of 2000 kg/DM/ha was used as this was the rule adhered to by the staff of No.4 dairy. However, if the SWD was less than its critical value but the APC was above its critical value, then 4 hr grazing would need to be implemented (with the rest of the daily time on a stand-off area receiving supplementary feed). When cows were stood off pasture, the daily feed requirement comprised grass and maize silage. The number of days that the SWD was below safe grazing, and therefore the amount of deferred grazing implemented (in hrs/month) was identified using the WFM. This was implemented for a 34 year period (1981-2016) to produce a table (Table 4.10) showing the wettest year to the driest years as characterised by the number of standoff days per year. The wettest years are therefore those with the greatest number of standoff days recorded and the driest years are vice versa.

4.2.8.6 Silage cutting policy

Annual pasture production (APP) was based on typical No.4 dairy farm production levels. SWD and climatic conditions are used to predict daily pasture growth rates, which also account for the effect of shading (due to high pasture mass) on growth. As part of a pasture conservation policy, silage was made when pasture surpluses occurred. Conservation paddocks were cut when pasture herbage mass exceeded 3500 kg DM/ha.

4.2.8.7 Soil damage frequency

The WFM represents the effect of treading (i.e. pugging) damage on pasture as a percentage loss in regrowth potential following grazing of a paddock below the user defined critical SWD. In the WFM the loss of pasture growth potential is a function of stocking density (animals/ ha) and grazing duration (h/day) based on the model of Betteridge et al. (2003). Grazing in wet conditions therefore triggers a reduction in pasture growth in the model i.e. if the SWD is less than the critical value and the APC is above the trigger point then cows would have to graze for 4 hrs and a damage event is recorded.

4.2.8.8 WFM outputs

The outputs from the WFM are user-defined and extensive. The results of simulations are presented in raw data form. Therefore, the questions asked in this modelling exercise are not answered directly by the WFM model, rather the raw data has to be manipulated using software such as Microsoft Excel, with specific, complex algorithms developed to achieve this.

4.2.9 Statistical analysis

The software SAS (Statistical Analysis System, version 9.2: SAS Institute., Cary, NC US) was used for all statistics in this chapter. Mean treatment field measurements (TDR,

pugometer, depth of pug etc) were tested for normality and transformed if necessary, before being subjected to an Analyses of Variance ANOVA. Analyses of Variance was used (for all field measurements) to determine differences between treatments (having experiment treatment SWD criteria as a blocking factor), and was used to derive the Least Significant Differences (LSD) of the means of treatment plots where significance differences are measured with a p value of <= 0.05. The ANOVA considered experimental structure, where the within-plot variability was included with the within-treatment (treatment replication) variability.

4.3 Results

4.3.1 Climate

The annual rainfall for 2015/16 and 2016/17 was 1446 and 1391 mm, respectively, both of which are well in excess of the mean annual rainfall of 930 mm for Palmerston North. The wet nature of the winter and spring of both years is illustrated by the very small SWDs for these periods (Figure 4.5). In both years, the soil profile had rewet to field capacity by late autumn and did not start to accumulate large deficits until November. Mean daily air temperatures of 8.8, 9.8 and 10.7 ^{o}C were measured for July, August and September in 2015, respectively, which were the months the grazing treatments were imposed. The mean daily temperature for July, August and September in 2016 were 9.7, 9.8 and 12.3 ^{o}C, respectively.

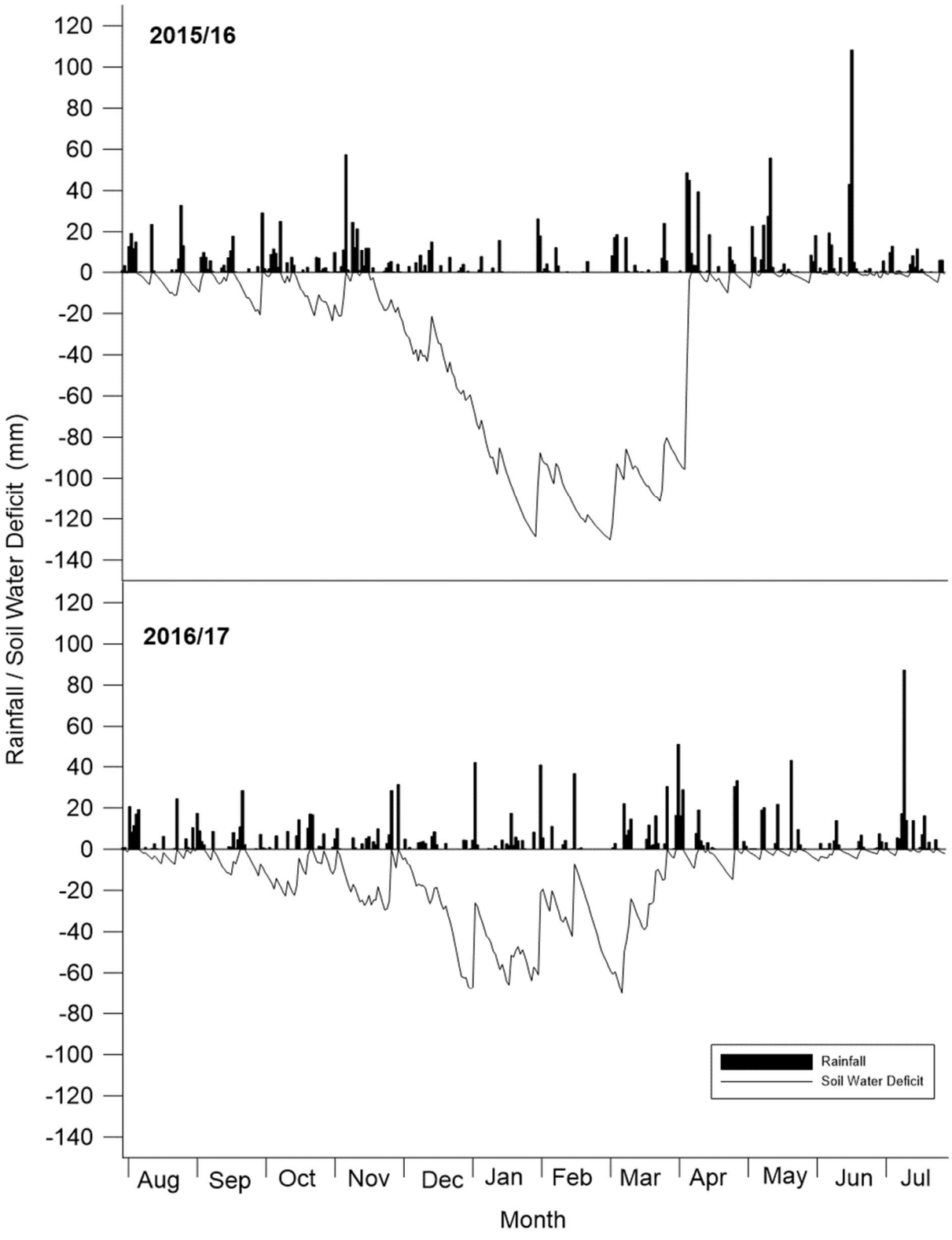

Figure 4.5 Daily rainfall (mm) and soil water deficit (mm) at No. 4 Dairy Farm for seasons 2015/16 and 2016/17.

4.3.2 Pre-grazing soil moisture and penetrometer

The measurements of pre-grazing soil water content (Table 4.5) show that the grazing treatments were imposed at different soil moisture conditions as planned. Given the narrow range of soil moisture contents investigated in this study (i.e. 0 mm, 0-2 mm, 2-4 mm and > 4 mm SWD), this was not an insignificant achievement. The penetrometer measurements lend this claim further support, although this data is more variable and the differences between treatments are less obvious.

Table 4.5 Mean values of soil moisture content and resistance to penetration at the time of the grazing treatments for all experiments.

Mean pre-grazing soil measurements	Soil Water deficit				
	0 mm	0 – 2 mm	2 – 4 mm	> 4 mm	LSD
Experiment 1 (2015/16)					
Soil water content TDR (%)	55.5 [a]	53.0 [a]	47.5 [b]	46.0 [b]	4.6
Penetrometer depth (cm) to 350 kPa	2.13 [a]	0.47 [b]	1.72 [a]	1.46 [ab]	0.85
% of penetrometer measures > 2 cm	46 [a]	8 [b]	38 [a]	35 [a]	21
Experiment 2 (2015/16)					
Soil water content TDR (%)	56.8 [a]	50.7 [b]	43.6 [c]	39.2 [d]	3.7
Penetrometer depth (cm) to 350 kPa	3.88 [a]	3.7 [a]	2.76 [ab]	1.93 [b]	1.48
% of penetrometer measures > 2 cm	87[a]	80 [a]	70 [a]	52 [b]	21
Experiment 3 (2016/17)					
Soil water content TDR (%)	55.8 [a]	50.0 [b]	48.3 [c]	45.6 [d]	0.93
Penetrometer depth (cm) to 350 kPa	2.22 [a]	2.01 [a]	1.19 [b]	1.93 [a]	0.67
% of penetrometer measures > 2 cm	55 [a]	56 [a]	34 [b]	56 [a]	17
Experiment 4 (2016/17)					
Soil water content TDR (%)	53.5 [a]	49.0 [b]	n/a	n/a	0.8
Penetrometer depth (cm) to 350 kPa	3.2 [a]	2.7 [a]	n/a	n/a	1.8
% of penetrometer measures > 2 cm	75 [a]	70 [a]	n/a	n/a	37

Within row means not showing a common superscript differ significantly ($p < 0.05$)

LSD = Least significant difference

The volumetric soil water contents of the 0 mm SWD treatments (corresponding to a saturated or near saturated soil) over the four experiments were very similar, ranging from 53.5 to 56.8%, with a mean value of 55.4%. Subsequent drainage and

evapotranspiration resulted in a decrease in the soil moisture content and an increase in the SWD. For Experiments 2, 3 and 4 (Table 4.5) the volumetric water content was very often significantly different between all treatments. However, the penetrometer data was not strongly correlated with soil moisture. The average depth (cm) at which the penetrometer insertion recorded a soil tensile strength of > 350 kPa decreases, as does the percentage of penetrometer insertions greater than 2 cm, as the SWD increases. The two most striking differences in 'depth of penetration' are for the 0-2 mm treatment in Experiment 1 (0.47 cm) and the 2-4 mm treatment in Experiment 3 (1.19 cm). However, both of these values are very different to the corresponding values (1.46 – 3.88 cm) recorded for the other treatments, and as there is no reason to explain these marked discrepancies, it is suggested that an error occurred in either the measurement or the recording of these values.

4.3.3 Treading damage – Experiments 1 and 2 (2015-16)

For Experiment 1, all measurements of treading severity (Table 4.6) showed a trend of decreasing damage as SWD increased. The 0 mm and 0 – 2 mm SWD treatments generally incurred significantly more ($p < 0.05$) damage than the Control treatment. The largest significant differences were between the Control treatment and the 0mm:4hr and 0mm:8hr treatments. All post-grazing measurements of the severity of treading damage showed a significant difference between the 0mm:8hr treatment and all other treatments, which is expected given that the 0mm:8hr treatment had the combination of the wettest soil (0 mm) and longest grazing duration (8 hr). There were no significant differences between the 2-4mm:4hr treatment and the Control treatment. However, according to the 'number of pugs' technique, grazing for 8 hours at the 2-4 mm SWD (i.e. the 2-4mm:8hr treatment) significantly increased the severity of treading damage (Table 4.6).

Table 4.6 Mean post-grazing soil damage measurements for Experiment 1 (2015-16).

Measurement	Soil moisture deficit							
	0 mm		0 – 2 mm		2 – 4 mm		> 4 mm	LSD
	Grazing treatment							
	4 hr	8 hr	4 hr	8 hr	4 hr	8 hrs	8 hr (Control)	
VSM	3.0 ^{b}	4.4 ^{a}	2.0 ^{c}	2.9 ^{b}	1.8^{cd}	2.5 ^{bc}	0.9 ^{d}	1.0
Pugometer (cm)	2.3 ^{a}	3.3 ^{c}	2.2 ^{a}	2.2 ^{a}	1.9 ^{b}	1.9 ^{b}	1.9 ^{b}	0.2
# of pugs (per m^2)	20 ^{bc}	27 ^{a}	20 ^{bc}	25 ^{ba}	16 ^{c}	23 ^{ba}	17 ^{c}	5.8
Avg. depth of pug (mm)	48 ^{b}	68 ^{a}	50 ^{b}	49 ^{b}	39 ^{c}	39 ^{c}	32 ^{c}	8.0

Within row means not showing a common superscript differ significantly ($p < 0.05$)

LSD = Least significant difference

The post grazing measurements for the D sub treatments in Experiment 2 (2015-16) are shown in Table 4.7. Data for the 'number of pugs', and the 'average depth of pug' for the 0-2mm:4hr:D, 0-2mm:8hr:D, 2-4mm:4hr:D and 2-4mm:8hr:D plots is not available.

Table 4.7 Mean post-grazing soil damage measurements for Experiment 2 (2015-16).

Measurement	Soil moisture deficit							
	0 mm		0 – 2 mm		2 – 4 mm		> 4 mm	LSD
	Grazing treatment							
	4 hr (D)	8 hr (D)	4 hr (D)	8 hr (D)	4 hr (D)	8 hr (D)	8 hr (Control)	
VSM	3.1 ^{b}	4.9 ^{a}	2.0 ^{cb}	3.1 ^{b}	1.1 ^{cd}	2.4 ^{b}	0.6 ^{d}	1.3
Pugometer (cm)	2.6 ^{b}	3.7 ^{a}	2.2 ^{c}	2.3 ^{bc}	2.1 ^{c}	2.2 ^{c}	2.1 ^{c}	0.4
# of pugs (per m^2)	18 ^{a}	24 ^{b}	n/a	n/a	n/a	n/a	18 ^{a}	5.5
Depth of pug mm	47 ^{a}	61 ^{b}	n/a	n/a	n/a	n/a	32 ^{c}	12

Within row means not showing a common superscript differ significantly ($p < 0.05$)

LSD = Least significant difference

All measurements of the severity of damage in Experiment 2 were similar to those recorded for Experiment 1. Again, all measurements showed a significant difference in treading intensity between treatment 0mm:8hr and all other treatments. As in Experiment 1, damage to the 0 mm SWD treatments was significantly greater than that of other treatments. It would seem that the 0 mm SWD treatments sustained significant damage relative to the Control treatment, while the 2-4 mm SWD treatments incurred little significant damage and the 0 - 2mm SWD plots were somewhere in-between, sustaining some damage but with less significant differences to the Control treatment.

4.3.4 Treading damage – Experiments 3 and 4 (2016-17)

The post-grazing measurements of the severity of treading damage for Experiment 3 (Table 4.8) are similar to those of Experiments 1 and 2 (Table 4.6 and Table 4.7). For all measurements of treading damage, the Control was generally significantly different to treatments 0mm:4hr, 0mm:8hr, 0-2mm:4hr, and not significantly different to 2-4mm:4hr and 2-4mm:8hr (i.e. the damage incurred was less severe as the SWD at grazing increased). However, unlike Experiments 1 and 2, only the VSM and average depth of pug measurements were able to show a significant difference between the 0mm:8hr treatment and all other treatments. Interestingly, the average ‘depth of pug’ and the pugometer methods suggested that there was less damage on the 0-2mm:8hr than the 0-2mm:4hr treatment.

Table 4.8 Mean post-grazing measurements of soil damage for Experiment 3 (2016-17).

Measurement	Soil moisture deficit							
	0 mm		0 – 2 mm		2 – 4 mm		> 4 mm	LSD
	Grazing treatment							
	4 hr	8 hr	4 hr	8 hr	4 hr	8 hrs	8 hr (Control)	
VSM	3.5 ^{b}	4.2 ^{a}	2.9 ^{c}	2.8 ^{cd}	2.3 ^{d}	2.9 ^{c}	1.3 ^{e}	0.6
Pugometer (cm)	2.8 ^{a}	2.9 ^{a}	2.4 ^{b}	2.1 ^{c}	1.7 ^{d}	1.9 ^{cd}	1.9 ^{cd}	0.3
# of pug (per m^2)	23 ^{bc}	27 ^{bac}	32 ^{a}	29 ^{bac}	23 ^{bc}	29 ^{bac}	24 ^{bc}	6.0
Avg. depth of pug (mm)	47 ^{b}	55 ^{a}	46 ^{b}	37 ^{c}	30 ^{cd}	34 ^{cd}	27 ^{d}	9.0

Within row means not showing a common superscript differ significantly ($p < 0.05$)

LSD = Least significant difference

In Experiment 4, as for the previous three experiments, there was a trend of decreasing treading damage with larger SWDs at the time of grazing (Table 4.9). The post-grazing measurements of treading severity on the Control plots were significantly different to the measurements for the 0mm:8hr:D treatments, but there were no significant differences between the Control and 0-2mm:8hr:D or between 0-2mm:8hr:D and 0mm:8hr:D treatments.

Table 4.9 Mean post-grazing soil damage measurements for Experiment 4 for the two D sub treatments and the Control.

Measurement	Soil moisture deficit			
	0 mm	0 – 2 mm	> 4 mm	
	Grazing treatment			
	8 hr (D)	8 hr (D)	8 hr (Control)	LSD
VSM	3.3 ^{a}	2.4 ^{ba}	1.3 ^{b}	1.4
Pugometer (cm)	2.9 ^{a}	2.2 ^{ab}	1.7 ^{b}	0.87
# of pugs (per m^2)	24 ^{a}	23 ^{a}	n/a	3.6
Avg. depth of pug (mm)	53 ^{a}	30 ^{b}	n/a	12

Within row means not showing a common superscript differ significantly ($p < 0.05$)

LSD = Least significant difference

4.3.5 Average pasture cover (APC) at grazing

A rising plate meter was used to measure APC of treatment plots pre grazing. For Experiments 2, 3 and 4, the pre-grazing APCs were generally similar for all treatments (i.e. relatively uniform across all plots), being an average of 2725, 1950 and 2803 kg DM/ha, respectively. For Experiment 1, there was a difference in APC on the day of grazing between the 0 mm and 0-2 mm SWD treatments (APC = 2271 kg DM/ha) and the 2-4 mm and > 4 mm SWD treatments (APC = 2538 kg DM/ha). This difference was due to the delay in the grazing of these latter two treatments by 2 - 4 weeks after the grazing of the former treatments.

4.3.6 The area of treading damage –the WFM

Thirty-four years of historic climate data for No.4 dairy farm (Massey University) was used to run 34 separate simulations i.e. 34 seasons (a season is the typical dairy farm season i.e. July to June). The years were ranked according to the number of standoff hours recorded by the model. Nine of 34 years were selected for discussion here (Table 4.10). In terms of annual standoff hours, these nine years represent the 3 wettest, the 3 driest and the three median years.

Table 4.10 Showing the driest to wettest seasons in sequential order according to annual standoff hours as predicted by the Whole Farm Model.

Climate Period	Annual Stand-off (Hours) to protect pastures
1997 - 1998	98
1987 - 1988	215
2014 – 2015	350
2003 -2004	730
1981 - 1982	783
2009 - 2010	788
2004 – 2005	1028
1994 – 1995	1151
1995 - 1996	1342

The three driest seasons (1997/98, 1987/88 and 2014/15) had minimal standoff hours compared to the wettest seasons. The wettest scenario (1995/96) had approximately 10 fold more standoff hours than the driest season (1997-98). Over the 34-year period, the median number of standoff hours as predicted by the WFM was in the region of 730 – 788 hrs or approximately 30 - 32 complete days of standoff.

The area of the farm (%) that is damaged is shown in Figure 4.6. As this model farm is assumed to have a well-managed and fully functional standoff system, treading damage only occurs on those days when the requirement to control average pasture cover necessitates grazing of a wet soil. In the driest season, the WFM predicts that 63% of the farm will receive no damage, with 26% receiving at least 1 damage event and a

further 11% receiving two damage events (Figure 4.6). Unsurprisingly, the wettest seasons have the lowest percentage area that does not receive damage (Approximately 90% of the farm area will be damaged); a small portion of the farm will be damaged 4 times. The median year shows approximately a third of the farm is predicted to not receive any damage. However, 62% of the farm will receive 1 – 2 damage events during the season. Therefore, even with the best practice of standing cows off pastures to protect soils there will be some periods when the need to manage the APC will overrule this desire and thus damage appears to be inevitable. However, the amount of damage will be seasonally dependent.

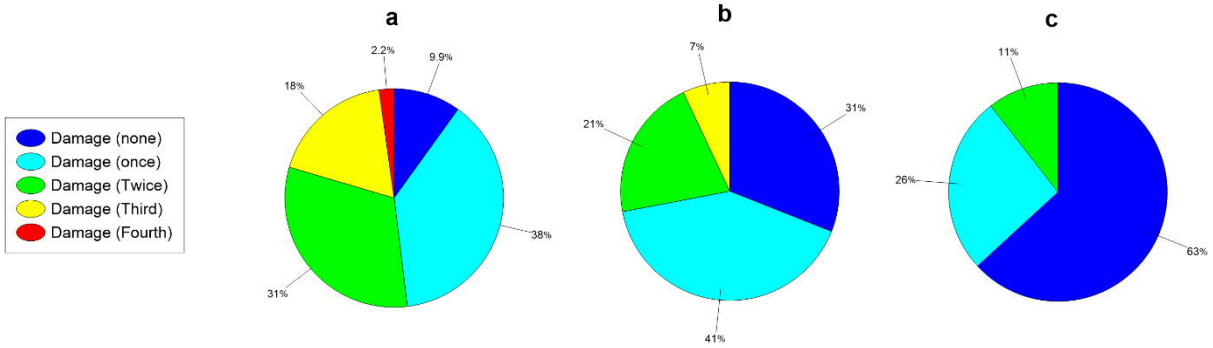

Figure 4.6 The percentage (%) area and the frequency of damage inflicted on the model farm damaged in the a) wettest , b) median and c) driest seasons.

4.4 Discussion

The SWD at the time of grazing appears to be the single largest determinant of the magnitude of treading damage. This relationship was identified by the measurement of surface soil disruption in this study. The results presented help identify a critical SWD where safe grazing can occur (on fine textured soils) and quantify the percentage area damaged over different seasonal events.

This chapter set out to compare the differences in treading damage intensity for grazings over a relatively narrow range of small SWDs. Therefore, it was important that grazings occurred at different soil moisture contents so that there was confidence that the treatments had been imposed as planned. A 2 mm change in SWD over the depth of a 100 mm probe equates to a 2% difference in the volumetric moisture content reading made by the TDR equipment. Given natural field variability in soil moisture content, some difficulties were anticipated in measuring this change. Fortunately, over the four experiments, the TDR measurements generally showed a significant difference ($p < 0.05$) in volumetric soil moisture content between the SWD treatments. The value for the volumetric soil water content at saturation measured here (mean value of the four experiments was 55.4%) compares well to other studies on this soil or soils of very similar texture in the Manawatu. For example, Hart et al. (1988) and Scotter et al. (1979b) measured values of 50.6% and 53% for saturated Tokomaru silt loam, respectively.

A penetrometer was also used to measure soil tensile strength at the time of grazing (Scholefield & Hall 1986; Betteridge et al. 2003). Penetrometer values tended to increase as the TDR data values for soil moisture content decreased; however, there was no significant difference in penetrometer readings between soil moisture contents. Given the marked differences in treading damage across the treatments, it is arguable

that penetrometers of the type employed here are not sensitive enough to discriminate between differences in the susceptibility of wet soils to treading damage. These penetrometers were initially developed to assess soil strength and identify compacted layers over a greater range of, mostly drier, soil moisture contents in tillage studies.

The level or intensity of treading damage, as measured during the four experiments using the four techniques, increased as the volumetric water content increased (i.e. the SWD decreased). All four methods used in this study showed that treading damage increased under grazing at wetter soil moisture contents.

In this trial, the average (of the four treading experiments) depth of pug at the different SWDs, was deeper than 30 mm, with the 0 mm SWD treatments averaging 54 mm pug depth, the 0-2 mm SWD averaging 45 mm and the 2-4 mm SWD averaging 35 mm. These pug depths are typical of the values reported for damaged soils in other studies. For example, Betteridge et al. (2003) reported that treading with cattle on a silt loam soil resulted in pug depths of 30 mm or more if the soil moisture content was high. Furthermore, Nie et al. (2001) on a clay loam soil reported pug depths of 20 mm, 36 mm and 43 mm for plots that were subjected to light, medium and heavy levels of treading damage, respectively. In comparison, Tuñon et al. (2014) reported pug depths of 33 - 36 mm for light damage, 48 – 88 mm for moderate damage and 58 – 133 mm for severe damage on a sandy loam soil.

All methods were in general agreement that the 0mm:8hr:S and 0mm:8hr:D treatments sustained significantly more soil damage than the other treatments. However, separating the damage intensity of other treatments was less straightforward. Even though there were consistent differences between 0-2 mm SWD treatments (0-2mm:4hr and 0-2mm:8hr) and SWD 2-4 mm treatments (2-4mm:4hr and 2-4mm:8hr), these were

generally not significant. Across all four experiments, there was a higher risk of significant damage for the 0 mm and 0-2 mm treatments (wetter) than for 2-4 mm and the Control treatments (drier). There did not seem to be any evidence of a compounding effect, or greater damage to the soil surface, on repeat damage of an area.

At drier soil moisture contents, treading damage severity decreased. As anticipated, the Control treatment (< 4 mm) had the lowest intensity of treading damage. The surface soil of the 2-4mm:4hr (S and D) treatment was generally similar to the Control with few significant differences between these two treatments.

Given the complexity of this type of research and the inherent variability of treading damage, the relationship observed here between the SWD at grazing and the severity of treading damage, as measured by damage to the soil surface, is strikingly consistent across all experiments. The results of this two-year study reveal that for fine textured soils, like the Tokomaru silt loam, a deficit of 2 mm is the critical value if treading damage to the soil surface is to be minimised. This critical value is similar to that reported by Laurenson and Houlbrooke (2016), who recommended that to minimise soil compaction on Pallic soils, a critical SWD of at least 3 mm should be used to schedule grazing. To put this critical value of 2 mm in perspective for farm management, given average daily evaporation rates, cows would need to be stood off from grazing for at least 4-5 days post saturation, in the cooler winter period (June – Aug). However, during the spring period (Sept –Nov), cows would only have to be excluded from grazing for 1 – 2 days.

Best management practice for farmers on fine textured soils includes standing cows off paddock when the SWD is small. However, while cows are standing off paddocks, the pasture will continue to grow. If cows stand off for prolonged periods, excessive pasture

length and poor pasture quality may become a problem. The analysis performed using the WFM showed that there may be times when soils are wet but the need to graze, in order to reduce pasture cover to control its quality, can override the requirement to protect the soil and pasture from treading damage. This research set out to investigate how this tension between the need to prevent treading damage and the requirement to graze in order to maintain long-term pasture quality should be managed. An obvious question here is – what area of the farm is likely to be damaged when DC grazing is practised in this manner. The results of the WFM analysis on the No 4 dairy farm analogue showed that substantial areas of the farm may be damaged, or in other words, even on farms with well-managed standoff facilities, treading damage is unavoidable. Even in the driest season, up to 30% of the farm could be damaged and in a wet year, approximately 90% of the farm area could be damaged.

However, if grazing is to be undertaken then grazing at deficits less than 2 mm should be avoided to minimise the risk of damage to the soil surface, and if grazings are undertaken under this critical level then significantly less damage to pastures and soils will be inflicted when grazing for shorter periods i.e. 4 hrs.

4.5 Conclusion

This study measured the treading damage associated with relatively short grazing durations on a fine textured soil. This duration controlled grazing is likely to be encountered on a farm where best management practices (BMP) for winter/spring grazing are followed including the use of some form of standoff. In addition to soil and pasture protection, these BMPs also include the requirement to graze regularly in winter and spring to maintain the longer-term quality of the sward. On occasions, this may necessitate the grazing of very wet soils. On a fine textured soil such as the Tokomaru silt loam, treading damage to the soil surface can be expected if cows graze when the

SWD is below a critical value of 2 mm, and this damage will be more severe at longer grazing durations (i.e. 8 hours in this study). Only minor treading damage was associated with grazing at SWD > 2 mm, and grazing interval had no significant effect on damage. There did not seem to be any evidence of a compounding effect, or greater damage to the soil surface, on repeat damage of an area. The WFM suggests that under BMP (i.e. DC grazing) the need to control pasture covers will result in the grazing of wet soils and the damage of relatively large areas of the farm, and in an average year, up to 60% of the farm area may be damaged.

The following Chapter (5) will investigate whether short duration grazing of wet soils and its associated treading damage to the soil, as observed in this chapter, has a similar effect on pasture production i.e. is the critical SWD level > 2 mm for soil surface damage also the critical value for pasture damage that affects regrowth.

5 TREADING DAMAGE TO PASTURE UNDER DURATION CONTROLLED GRAZING: THE EFFECTS OF SOIL WATER DEFICIT AND GRAZING DURATION

5.1 Introduction

Sustainable and profitable dairy farms in New Zealand are dependent on the maintenance of high-quality productive pasture swards (Menneer et al. 2005). However, there are times of the year, typically in winter and spring, when soils are wet and prone to damage from animal treading (Horne & Hooper 1990). Therefore, treading damage is commonplace across most areas of New Zealand in winter and spring and presents a major challenge to grazing management (Betteridge et al. 2002), particularly on soils with impeded drainage, fine textured soils and/or soils in regions with frequent rainfall.

It is widely recognized that severe treading damage, associated with the grazing of very wet soils for long periods, results in poor pasture utilisation at the time of grazing and a reduction in pasture growth rates subsequent to the grazing event.

Farmers can minimise treading damage by standing cows off pastures when soils are wet (i.e. small soil water deficit; SWD) (Laurenson et al. 2014). Ideally, grazing will only resume when a larger SWD has developed and the soil has enough strength to support the grazing cow. The number of days of standoff on farms that are vulnerable to treading damage can be very large. However, as explained in Chapter 4, regular grazing may be required during winter and spring to control pasture cover and the long-term quality of the sward. This can create tension between the need to frequently house cows to protect soils and pasture from treading damage, and the requirement to routinely graze so as to control pasture covers and maintain pasture quality. On occasions, this requirement to graze is likely to necessitate the grazing of very wet soils for short durations. In these cases, the management of pasture quality takes priority over the risk of severe treading damage.

A cow can consume approximately 80% of offered feed in the first four hours of a grazing period (Kennedy et al. 2011), with the remaining grazing time being used for rumination, walking and standing (Draganova et al. 2010). Therefore, four hours of grazing is sufficient time for cows to eat the offered pasture without affecting animal performance, including milk production (Kennedy et al. 2011). Given this, if increasing pasture cover compels farmers to graze their herd during wet periods in winter and spring, they can do so for approximately four hours a day for non-lactating cows, whereas lactating cows are more likely to graze separate areas for 4 hours following both the morning and afternoon milkings.

In pasture-based systems, reductions in pasture growth following treading have been found to be extremely variable with losses of 0 – 88% reported in the literature (Campbell 1966; Brown 1968; Watkin & Clements 1976; Curll & Wilkins 1983; Kelly 1985; Thomson & Laurence 1992; Ledgard et al. 1996; Menneer et al. 2001; Nie et al. 2001; Drewry 2003; Drewry et al. 2003; Zegwaard 2006; Tuñon et al. 2014; Laurenson et al. 2016). As this range implies, losses in pasture production following treading are dependent on a number of key soil and plant factors, including soil water content at grazing, soil type, grazing intensity, grazing duration, characteristics of the pasture sward, and season of the year (Patto et al. 1978; Drewry et al. 2008). Therefore, it is crucial to not only quantify the losses in pasture production post treading damage, but also to understand the interactions between the factors that contribute to the extent of these losses. Arguably, the three factors that feature most prominently in the farmer's day-to-day attempts to minimise treading damage are soil water content, grazing duration and grazing intensity.

The majority of treading studies involving grazing duration have used longer grazing intervals of up to 24 hours, but relatively few studies have investigated the effects of

treading damage inflicted during shorter grazing intervals of 4 hours or less. When compared to longer grazing durations, shorter grazing intervals (on/off grazing) have been reported to reduce the negative effects of treading damage on winter and early spring pasture production. However, these results are varied. For example, Thomson and Laurence (1992) reported that 4 hours "on/off" grazing resulted in no reduction in subsequent winter pasture growth compared to a 15% reduction for a 24-hour grazing treatment. Drewry et al. (2003) reported that grazing for 3 hours showed no advantage to pasture production compared to a 12-hour grazed treatment. In contrast, Christy (1996) measured a yield reduction of 28%, compared to a mown control, for the two months following 4 hours of grazing in West Victoria, Australia, and a 40% decrease following 12 hours of grazing (but no assessment of treading damage was made during this study). The treading studies described above have either only considered short-term pasture production and/or grazing was conducted on very wet soils, and so there has been no attempt to identify the relationships between the SWD and treading damage and pasture production post- treading.

There are several questions and gaps in the literature related to the management of dairy cow grazing in wet conditions. These mostly relate to identifying the range of SWDs for which cows should be removed and stood off pasture and, therefore, when grazing can recommence. The most appropriate grazing duration on wet soils is the other important consideration. The identification of critical SWDs which minimize damage to soil and pasture have been investigated and reported in chapter 4. However, it would be of great value to farmers seeking to optimise pasture production to know how grazing at SWD values less than the critical limit of 2mm (established in Chapter 4) will actually affect pasture production i.e. does the soil and pasture damage inflicted when grazing occurs at SWDs less than 2 mm (Chapter 4) translate into, or cause, reductions in pasture

growth post grazing. There is little information available to help farmers identify critical SWDs, and therefore it is very difficult to make grazing management decisions in wet conditions (Laurenson et al. 2014).

Furthermore, many studies focus on a single severe treading event, whereas in an actual grazing system, some paddocks on the farm may be subjected to repeated treading damage. Chapter 4 demonstrates how some areas of the farm may be damaged as many as four times in a wet year. This will happen when a paddock is grazed during a wet period in winter and then again, coincidently, during a wet period in spring. In wetter than average years, this will be a common occurrence. Soil that has been subjected to treading damage once, may be more susceptible to subsequent damage as the infiltration and drainage characteristics of the soil are likely to be impeded by the initial damage (Greenwood & McKenzie 2001). Therefore, repeat damage may exacerbate the reduction in pasture production compared to a single treading event.

To address these questions, a series of treading experiments was conducted on a mole and pipe drained, fine textured soil over the consecutive grazing seasons of 2015/16 and 2016/2017. The purpose of these experiments was to quantify the effect of the following factors on the extent and magnitude of treading damage (as described in Chapter 4):

i. the SWD at the time of grazing,

ii. the grazing duration, and

iii. repeat treading damage (i.e. spring damage on an area that was damaged during winter),

In Chapter 4 the effect of these three factors on soil damage was measured and discussed. The objectives of this chapter mirror those of the preceding study i.e.:

i. to identify the relationship between the SWD at the time of grazing and subsequent pasture production,

ii. to quantify the effect of grazing duration on pasture production post-treading, and

iii. to identify the impact of repeat treading damage (i.e. spring damage on an area that was damaged during winter) on pasture production,

An important output of this research will be the identification of the critical SWD at which grazing will ensure that pasture growth rates are not compromised by treading damage (i.e. 'safe' grazing), and give some guidelines for grazing management of fine textured soils on farms with standoff facilities.

5.2 Materials and Methods

5.2.1 Trial site, experimental area and treatments

The location, experimental area and design plus the treatments used in this trial have been described in detail in Chapter 4.

5.2.2 Field Measurements

5.2.2.1 Pasture production/accumulation

Pasture accumulation was estimated using the rising plate meter (RPM) method (Earle & McGowan 1979). The RPM used was a locally calibrated 'Jenquip' (Reid Line East RD5 Feilding New Zealand) folding plate pasture meter with a 'Farmworks' electronic pasture height recorder. Average pasture cover (APC) was estimated for each plot from 60 plate readings taken over an 'M' shaped transect. Following the imposition of grazing treatments, pasture accumulation was measured weekly until pasture production slowed due to large SWDs in summer. RPM measurements were taken directly after a grazing event (giving the post-grazing pasture mass) and immediately before the next grazing

(giving the pre-grazing pasture mass) – the difference between the post- and pre-grazing pasture mass represents pasture accumulation between consecutive grazing events. The total pasture accumulation over a period (season or year) was obtained by summation of the appropriate pasture accumulation data.

A single calibration equation was used:

$$\text{APC (kg DM/ha)} = \text{RPM} \times 140 + 500$$

This equation is the best fit for most situations and makes the data produced easier to interpret (Farmfact 2008). This equation has also been used by other researchers on Massey University's No. 4 Dairy Farm (Hendriks et al. 2016b; Christensen et al. 2018a)

All methods of measuring pasture have their inherent restrictions or challenges and it is therefore acknowledged that the RPM has potential limitations for measuring pasture mass on soils that have received treading damage. There is potential for the shaft of the RPM to be enter into a pug mark which could then give an incorrect reading of pasture height and therefore, there is potential for pasture mass to be overestimated on damaged soils. However, the rationale for using the RPM was: 1) it enabled the rapid collection of a very large number of pasture measurements over treatments plots, which would reduce the spatial variability that would be expected if slower more labour intensive methods were used. For example, it is estimated that time and personnel constraints would allow only two or three quadrat cuts to be made per plot.3) Other techniques such as the pasture cut method may have given even less reliable measurements of pasture accumulation. Initial experimentation with the pasture cut method revealed that it was very difficult to harvest all of the buried pasture, and even if it could be teased out of the mud, it was covered with soil which needed to be removed before drying and weighing. 4) even if there were some measurements where the shaft of the RPM entered

into pug marks the number of measurements taken per plot should have ‘smoothed’ this error. 3) any such error associated with the use of the RPM would only affect the initial pasture measurements (post grazing). As subsequent measurements are made on the same damaged soil, the RPM should be able to measure the relative difference in pasture height between grazings. 5) the RPM is a commonly used technique in treading damage research in both New Zealand and other countries (Zegwaard 2006; Tuñon et al. 2014; Laurenson et al. 2016)

5.2.2.2 Changes to pasture production measurement experimental procedures for the 2016-17 grazing season.

An unscheduled grazing event and pasture topping (not communicated to research staff) occurred one week before a scheduled grazing. This precluded the measurement of the pre- and post-grazing pasture covers associated with this grazing event. Therefore, pasture production in the 2016-17 grazing season was only measured up to 08/02/2017 (182 days).

5.2.3 Statistical analysis

The software SAS (Statistical Analysis System, version 9.2: SAS Institute., Cary, NC US) was used for all statistics in this chapter. Mean treatment pasture accumulation was tested for normality and transformed if necessary, before being subjected to an Analyses of Variance ANOVA. Analyses of Variance was used to determine differences between treatments having experiment treatment SWD criteria as a blocking factor) and was used to derive the Least Significant Differences (LSD) of the means of treatment plots where significance differences are measured with $p = 0.05$. The ANOVA considered experimental structure, where the within-plot variability was included with the within-treatment (treatment replication) variability.

5.2.4 Average pasture cover (APC) at grazing

For Experiments 2, 3, and 4, the pre-grazing APCs when treatments were imposed were generally similar for all treatments (i.e. relatively uniform across all plots), having the average of 2725, 1950 and 2803 kg DM/ha, respectively. For Experiment 1, there was a difference in APC on the day of grazing between the 0 mm and 0-2 mm SWD treatments (APC = 2271 kg DM/ha) and the 2-4 mm and > 4 mm SWD treatments (APC = 2538 kg DM/ha). This difference was due to the delay in the grazing of these latter two treatments by 2 - 4 weeks after the grazing of the former treatments.

5.2.5 The relationship between SWD at grazing and pasture accumulation

5.2.5.1 Pasture accumulation for Experiments 1 and 2

The SWD at the time of grazing appears to be the single largest determinant of the magnitude of treading damage. This relationship was identified by the measurement of surface soil disruption in the first part of this study (Chapter 4). Therefore, it was important to identify if this SWD at the time of grazing also affected accumulated pasture production (APP), compared to grazing at lower SWD.

The APP following grazing at the treatment SWDs for the grazing seasons of 2015-16 and 2016-17 are presented in Figure 5.1 and Figure 5.2, respectively. These figures only consider the relationship between SWD at grazing and post-grazing pasture growth, and so post-grazing pasture accumulation for all treatments associated with a particular SWD have been averaged. This was regardless of whether they were for 4 hours or 8 hours grazing duration or single or double damage treatments. As there was no repeat damage treatment at the 2 – 4 mm SWD in Experiment 4, the accumulated pasture yields for the SWD, in Figure 5.2, only include the single damage treatments. This range in

treading damage severity might be expected on dairy farms where paddocks would be grazed at a range of SWDs, durations, and single versus repeat damage events.

In general terms, the relationship between SWD at grazing and APP post-grazing was simple and clear. For the 365-day period following the start of Experiment 1 (29/07/2015), mean total accumulated pasture yields were 8884, 8663, 9719 and 9461 kg DM/ha for the 0 mm, 0-2 mm, 2-4 mm and > 4 mm (Control) SWD treatments respectively (Figure 5.1).

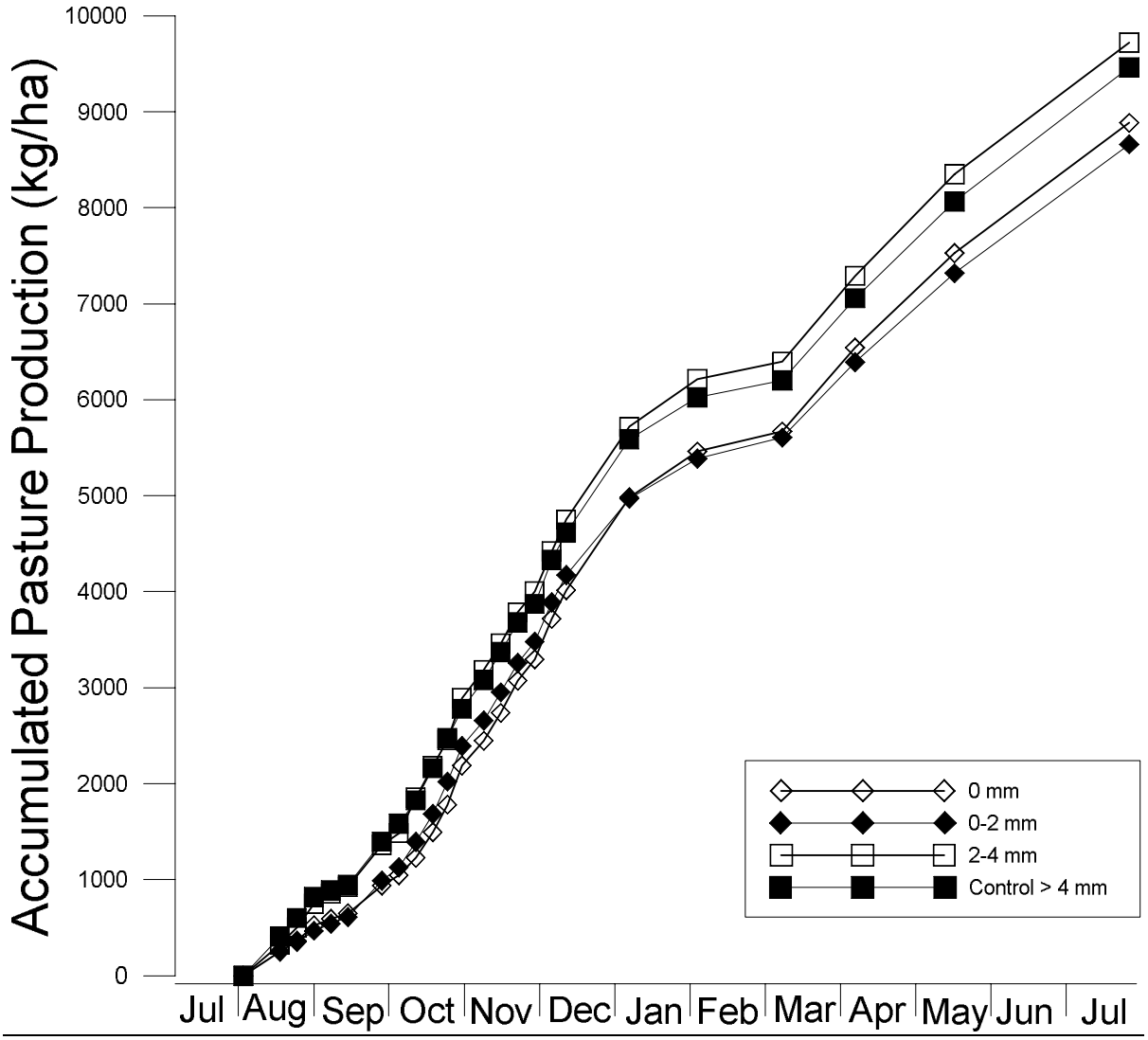

Figure 5.1 Accumulated Pasture Production for Experiments 1 and 2.

While there were differences in annual pasture production between the SWD treatments, only the mean total APP for the 0 – 2 mm SWD treatment was significantly lower (800 kg DM/ha, $p < 0.05$) than the Control treatment. Interestingly, APP on the 0 mm SWD plots (i.e. the 'wettest' treatment), was only significantly lower than the Control until 7/3/2016, with a difference in APP of approximately 550 kg DM/ha at that date. This reduction lasted approximately 222 days. The mean APP on both the 0 mm and 0-2 mm SWD treatments were significantly lower ($p < 0.05$) than the 2-4 mm SWD treatment. These differences were 835 and 1056 kg DM/ha, respectively. Mean APP on the 2-4 mm SWD treatment was not significantly different to that on the SWD > 4 mm treatment (Control) at any stage. The trends described above are illustrated in Figure 5.1, where the 2 - 4 mm and > 4 mm SWD treatments are grouped together as were the 0 mm and 0 - 2 mm SWD treatments. The distinct separation between the two groups of treatments increases as the grazing season progresses (Figure 5.1). These differences in APP between the two groups of SWD treatments reflect the manner in which the measures of soil damage clustered the 0 and 0 -2 mm SWD treatments together, and the 2-4 mm and >4 mm treatments together.

5.2.5.2 Pasture accumulation for Experiments 3 and 4

Experiment 3 began on 10/08/2016, but due to an incomplete data set, measurements are only presented for the period ending on 08/02/2016 (day 182 of the trial). The mean total accumulated pasture yields for this period were 5970, 5852, 6246 and 6300 kg DM/ha for the 0 mm, 0-2 mm, 2-4 mm and > 4 mm (Control) SWD treatments, respectively (Figure 5.2).

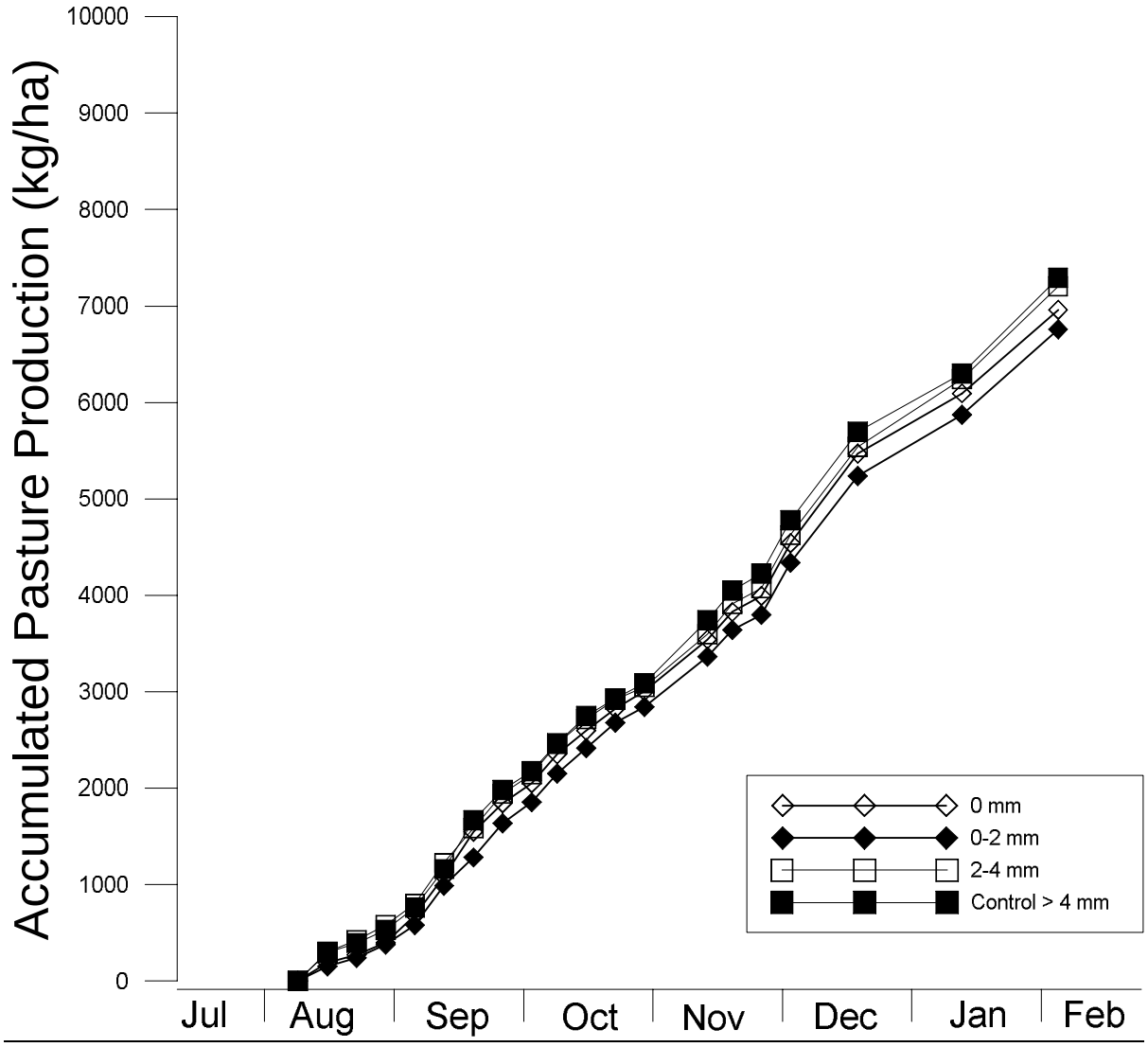

Figure 5.2 Accumulated Pasture Production for Experiments 3 and 4.

The differences in accumulated DM production between the SWD treatments in Experiments 3 and 4 are not as pronounced as they were in Experiments 1 and 2. This may be an effect of the first grazing in 2016-17 being a month later than in 2015-16. Pasture accumulation on the 0 mm and 0 – 2 mm SWD treatments were only significantly lower than the > 4 mm treatment (Control) for approximately 35 days (approx. 200 kg DM) and 83 days (approx. 300 kg DM) following grazing, respectively. While the significant differences in pasture accumulation between the treatments are not as large or as prolonged in 2016-17 as those in 2015-16, it is worth noting that these differences occurred during the period of peak lactation, when high quality pasture

supply is critical to maintain peak milk solids production per cow. There was no significant difference in DM accumulation between the 2 – 4 mm and > 4 mm (Control) SWD treatments at any time. While there was no significant difference between the 0 mm SWD and 0 – 2 mm treatments, surprisingly the pasture accumulation on the wetter 0 mm treatment tended to be greater. This matches the results of Experiments 1 and 2.

The SWD treatment shows very similar trends in both Figure 5.1 and Figure 5.2, which show that the APPs for the two drier SWD treatments are separated from the APPs of the two wetter SWD treatments. However, the gap between the two groups in Figure 5.2 is not as pronounced as in Figure 5.1, and is relatively constant over time. Over the four experiments, the differences in DM accumulation between the drier (> 2 mm) SWD and wetter (< 2 mm) SWD treatments correspond well with the differences in the intensity of treading damage reported in Chapter 4. In other words, inspection of this aggregated data suggests that it is clearly preferable for farmers to wait until a SWD of greater than 2 mm is reached before grazing paddocks.

5.2.6 The effects of SWD, grazing duration and repeat damage on pasture accumulation

5.2.6.1 Experiments 1 and 2 (2015-16)

The effects of SWD, grazing duration and repeat damage treatments on APP for the two grazing seasons are presented in Figure 5.3 - Figure 5.8. In 2015-16, the mean APP for all treatments followed the same general trend as the Control treatment (Figure 5.3 - Figure 5.5). Pasture accumulated rapidly during the spring period, followed by a period of slower accumulation from early January until early March, when APP increased more rapidly until the end of the measurement period. At the end of the measurement period (29/07/2016), there was no significant difference in mean annual APP between the Control and any of the other treatments. Although not significantly different, the greatest

differences in mean annual APP between treatments and the Control was 1369 (14% decrease) and 1113 (12% decrease) kg DM/ha for 0mm:8hr:D and 0-2mm:8hr:D treatments, respectively. This is not surprising as these two treatments incurred the greatest treading damage (8 hrs grazing, double damaged at a small SWD). A comparison of the spread between treatments (part B of Figure 5.3 - Figure 5.5) again suggests that the damage incurred by pasture during grazing at a deficit of 2 mm or greater is quantitatively different to the damage inflicted when grazing occurs at smaller deficits.

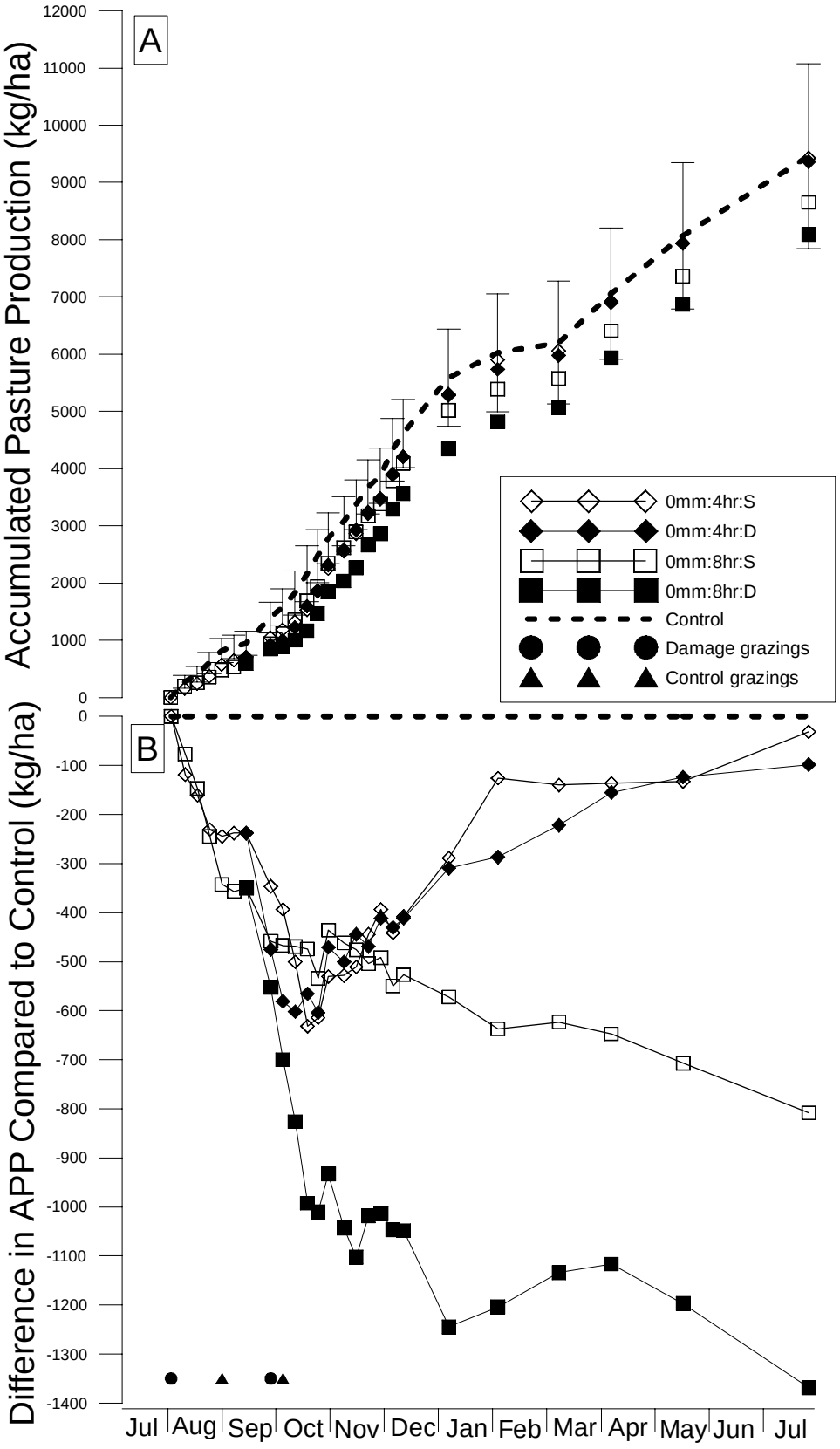

Figure 5.3 Accumulated pasture production (APP) for the 0 mm SWD treatments. A: APP for Experiments 1 and 2 (the 2015/16 grazing season), and B: difference in APP between treatments and the Control. Grazing events are also shown. LSD bars $p < 0.05$.

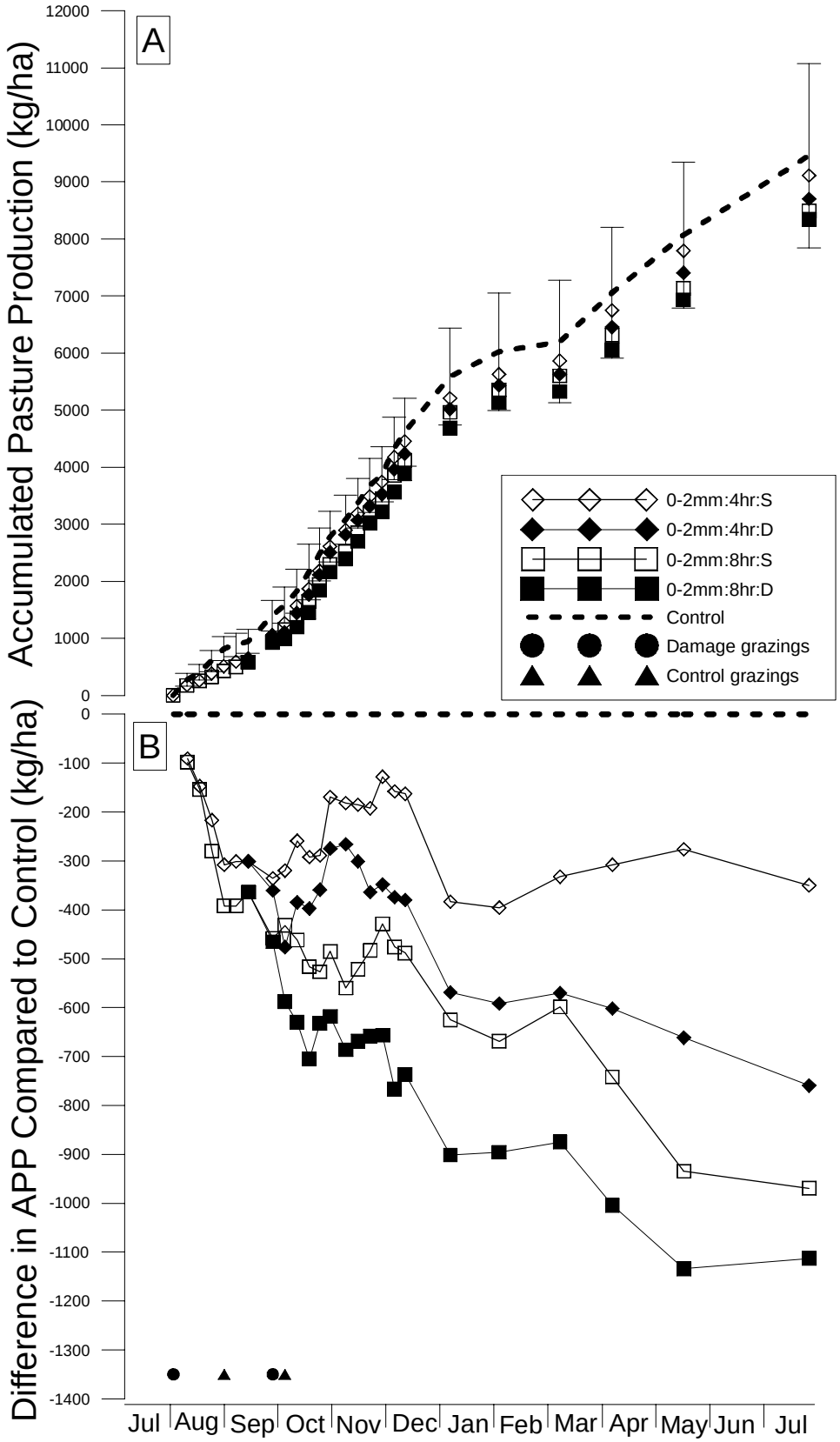

Figure 5.4 Accumulated pasture production (APP) for the 0-2 mm SWD treatments. A: APP for Experiments 1 and 2 (the 2015/16 grazing season), and B: difference in APP between treatments and the Control. Grazing events are also shown. LSD bars $p < 0.05$.

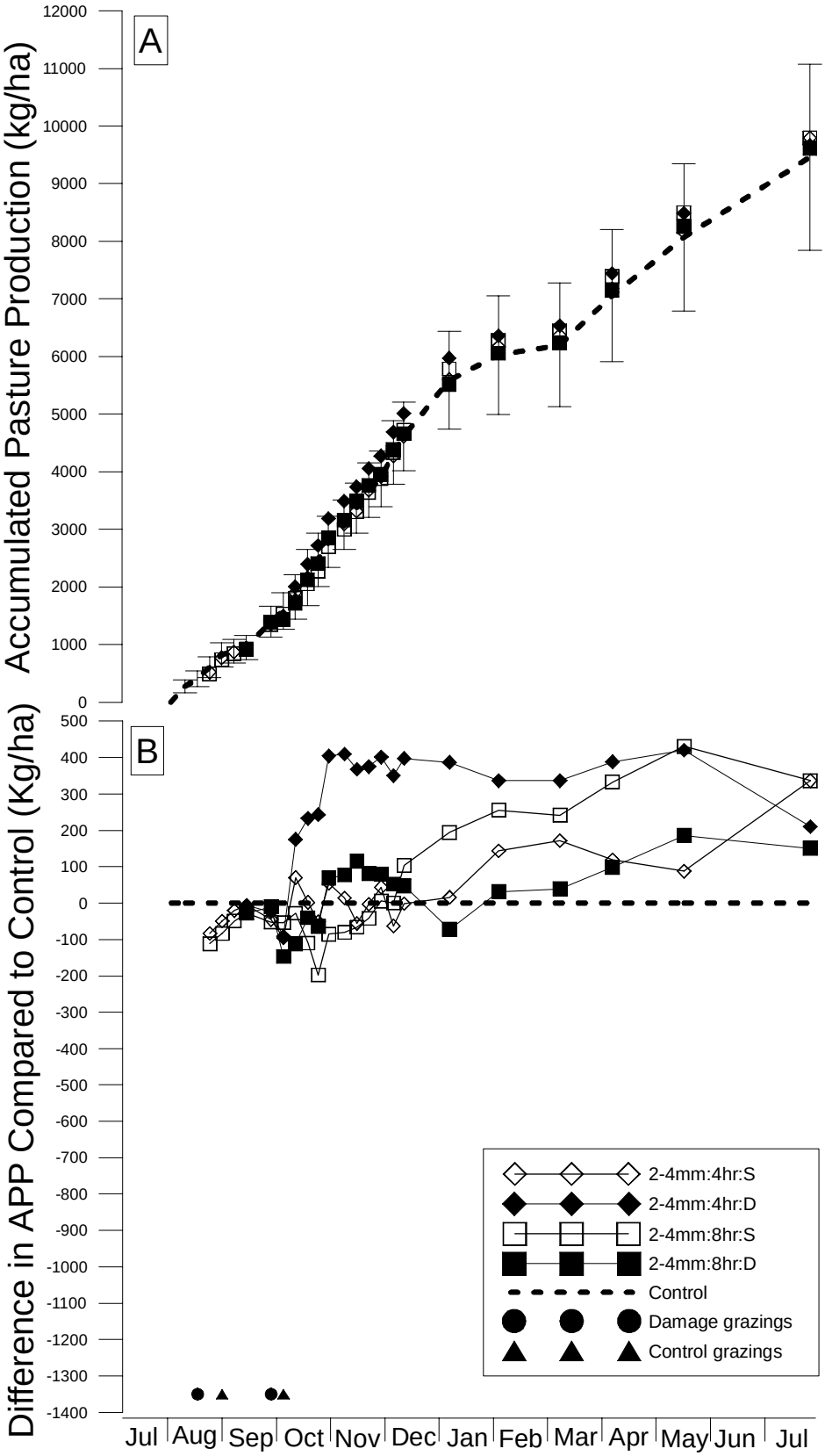

Figure 5.5 Accumulated pasture production (APP) for the 2-4 mm SWD treatments. A: APP for Experiments 1 and 2 (the 2015/16 grazing season), and B: difference in APP between treatments and the Control. Grazing dates are also shown. LSD bars $p < 0.05$.

Having established that there were very few consistent significant differences between any of the 0, 0-2 and 2- 4 mm treatments themselves, attention will now be focused on differences between these treatments and the Control. Pasture production differences between the undamaged Control and treading damaged pasture are of most interest to farmers. A farmer needs to know what the yield penalty caused by grazing at small SWDs is likely to be.

Although there were no significant differences between the annual APP of any of the treatments and the Control, there were differences in APP between treatments and the Control for the period immediately after the treatment grazings. The magnitude of these differences and their duration are shown in Table 5.1.

Table 5.1 A summary of the effects of the treading treatments on the duration of significant reductions in APP (accumulated pasture production) and the magnitude of these reductions.

Treatment	Days that treatment was different[a]	Reduction in APP[b] (kg DM/ha)	Treatment	Days that treatment was different[c]	Reduction in APP[d] (kg DM/ha)
0mm:4hr:S	106	511 (15%)	0mm:4hr:D	106	445 (13%)
0mm:8hr:S	127	550 (13%)	0mm:8hr:D	222	1134 (18%)
0-2mm:4hr:S	64	320 (20%)	0-2mm:4hr:D	71	385 (21%)
0-2mm:8hr:S	113	483 (13%)	0-2mm:8hr:D	159	901 (16%)

a, c The days that the APP of the treatment was significantly different ($p < 0.05$) to the APP of the Control. *b, d* the reduction in APP, relative to the APP of the Control, for the period that these APPs were significantly different (i.e. *a* and *d*). The reduction in APP, relative to the Control is also expressed as a percentage.

Post grazing Experiment 1, there was an immediate significant ($p < 0.05$) reduction in APP for all of the 0 and 0 – 2 mm treatments (Figure 5.3 and Figure 5.4) relative to the Control. There was an initial reduction in APP following grazing of the 2-4mm:4hr:S and 2-4mm:8hr:S treatments, but this decrease was negligible, and the APP of these treatments was not significantly different to the Control at any time during the grazing season. The duration of this reduction in APP for the wetter treatments relative to the Control, was similar (except for 0-2mm:4hr:S). The period of significant differences in APP was approximately 106, 127, 64, 113 days for 0mm:4hr:S, 0mm:8hr:S, 0-2mm:4hr:S and 0-2mm:8hr:S, respectively ($p < 0.05$). The reductions in APP (at the harvest made on these dates) were also similar at approximately 511 (15% reduction), 550 (13% reduction), 320 (20% reduction) and 483 (13% reduction) kg DM/ha for treatments 0mm:4hr:S, 0mm:8hr:S, 0-2mm:4hr:S and 0-2mm:8hr:S, respectively. For the wetter treatments, the APP for the 8 hr grazing treatments was significantly lower than the Control APP for longer than was the case for the 4 hr treatments. This difference was approximately 20 days longer for the 0mm:8hr:S than for the 0mm:4hr:S treatments, and 49 days longer for the 0-2mm:8hr:S than for the 0-2mm:4hr:S treatments. If the number of days of reduced APP and the reduction in APP are averaged according to grazing duration over the two wetter grazing treatments, it would appear that the average penalty to APP of a single treading damage of 4 hrs (0mm:4hr:S, 0-2mm:4hr:S) and 8 hrs (0mm:8hr:S, 0-2mm:8hr:S) duration lasts approximately 85 and 120 days and is of the order of approximately 415 and 516 kg DM/ha, respectively. While this may not be a large amount of pasture, this loss of approximately 500 kg DM/ha over this 85-120 day period (Aug – Oct) coincides with early lactation on a typical New Zealand dairy farm, when grass growth is particularly valuable and,

therefore, any reduction in pasture production could impact more directly on milk production, cow health and profit than at any other time of year.

Interestingly, the effect of repeat damage (D) on the APP of the wetter treatments was more varied than was the case for the earlier single damage event (Figure 5.3 and Figure 5.4). The decrease in APP relative to the Control following the second damage event was 0, 584, 63 and 418 kg DM/ha for the 0mm:4hr:D, 0mm:8hr:D, 0-2mm:4hr:D and 0-2mm:8hr:D treatments, respectively (Table 5.1). These differences between APP for the Control and the 0mm:8hr:D, 0-2mm:4hr:D and 0-2mm:8hr:D treatments were significant for 95, 7 and 46 days, respectively. Clearly, at the second damage event, grazing duration had the greatest impact on APP with the 8 hours grazing having a much larger adverse impact on APP than the 4 hour grazing. The impact of the second 8 hour grazing treatments on APP at the smaller deficits was similar to the effect measured after the first grazing event (i.e. 400 to 600 kg DM/ha). It is not clear why the impact of the 4 hour grazing at the second event was much smaller than at the first grazing.

When the single damage treatment is compared with the double-damaged treatment over the entire year then, as stated above, there were no significant differences between the annual APP values at any of the SWDs. However, as for the first grazing event, there were significant differences in APP between the Control and some of the double damage treatments immediately after grazing. After the repeat damage event, the 8 hour grazing of the 0 mm and 0-2 mm SWD treatments began to separate noticeably from the Control (Figure 5.3 and Figure 5.4), with both of the wetter D sub treatments showing a significant decrease in APP compared to the Control ($p < 0.05$). The significant effect ($p < 0.05$) of double damage on APP lasted approximately 222 and 159 days for 0mm:8hr:D and 0-2mm:8hr:D treatments, respectively. The differences in APP were

1134 (18% reduction) and 901 (16% reduction) kg DM/ha for treatments 0mm:8hr:D and 0-2mm:8hr:D, respectively ($p < 0.05$).

As seen in these values and in Table 5.1, the repeat damage of 4 hours duration on the 0 and 0 – 2 mm treatments in spring had essentially no effect on APP. There was no further reduction in APP, relative to the Control, on the 0mm:4hr:D and 0-2mm:4hr:D treatment plots as a consequence of the repeat damage. In other words, the APP of 0mm:4hr:D and 0-2mm:4hr:D treatments is very similar to the APP of the 0mm:4hr:S and 0-2mm:4hr:S treatments. Like their single damaged twin treatments, the double damaged 2-4mm:4hr:D and 2-4mm:8hr:D treatments showed no significant difference to the Control at any time.

As noted above, the repeat 4-hour grazing event had much less impact on APP than the first winter event. In contrast, the data presented in Table 5.1 suggests that the second 8-hour grazing event at 0 and 0 – 2mm SWD had a similar effect on APP as the first grazing i.e. approximately 500 kg DM/ha. Interestingly, there was no compounding effect on APP because of repeat damage i.e. the impact of the second damage event (a loss of approx. 500 kg DM/ha) was similar to that of the first damage event (approx. 500 kg DM/ha). This finding mirrors the lack of a compounding effect of repeat damage on the measures of soil treading damage to the surface soil reported in Chapter 4.

If the effects of damage are averaged over the two different grazing durations for the 0 and 0-2 mm SWD treatments (0mm:4hr:D, 0-2mm:4hr:D and 0mm:8hr:D, 0-2mm:8hr:D), it would appear that the average penalty to APP of a repeat damage at four and eight hours grazing duration is approximately 415 and 1017kg DM/ha, respectively. This lasts for approximately 89 and 190 days (i.e. 0mm:4hr:D, 0-2mm:4hr:D and 0mm:8hr:D, 0-2mm:8hr:D), respectively. When comparing the average APP of double

damage (D) and single damage (S) of the wetter treatments to the Control, the penalty to APP at the four hours grazing duration lasted only 4 days longer with double damage (0mm:4hr:S, 0-2mm:4hr:S = 85 days; 0mm:4hr:D, 0-2mm:4hr:D = 89 days) with no difference in APP (0mm:4hr:S, 0-2mm:4hr:S = 415 kg DM/ha; 0mm:4hr:D, 0-2mm:4hr:D = 415 kg DM/ha). In contrast, the significant penalty to APP, relative to the Control, on treatments that were double damaged with the eight hours grazing duration lasted 50 days longer (0mm:8hr:S, 0-2mm:8hr:S = 120 days; 0mm:8hr:D, 0-2mm:8hr:D = 170 days) with a difference in APP of 501 kg (0mm:8hr:S, 0-2mm:8hr:S = 516 kg DM/ha; 0mm:8hr:D, 0-2mm:8hr:D = 1017 kg DM/ha).

These results must be interpreted in the context of the timing of these damage events. If a paddock on a dairy farm suffers repeat treading damage, then it is likely that the first event will occur in winter and the second grazing will be in spring. Therefore, superimposed on the effect of repeat damage is the influence of seasonal conditions. This study would be typical in that the second damage occurred during the mid-spring, a period of peak pasture production, whereas the first damage happened in winter when pasture growth rates were much slower.

5.2.6.2 Experiments 3 and 4 (grazing season 2016/17)

As with Experiments 1 and 2 (2015/16), all treatments in Experiments 3 and 4 followed the same general APP trend as the Control (Figure 5.6 - Figure 5.8). There was rapid accumulation during the spring period that continued through to early February, which was the end of the measurement period (08/02/2016). There was no temporary levelling off in APP in early summer (Part A Figure 5.6 - Figure 5.8) as seen in the 2015/16 grazing season. This was most probably due to the unseasonably wet period experienced in the Manawatu that summer (2016/17), which saw 331 mm of rainfall between January and March and a maximum SWD of only 68 mm. As for Experiments 1 and 2, at the

end of the 2016/17 grazing season (day 182), there was no significant difference between the APP of any of the treatments and the APP of the Control.

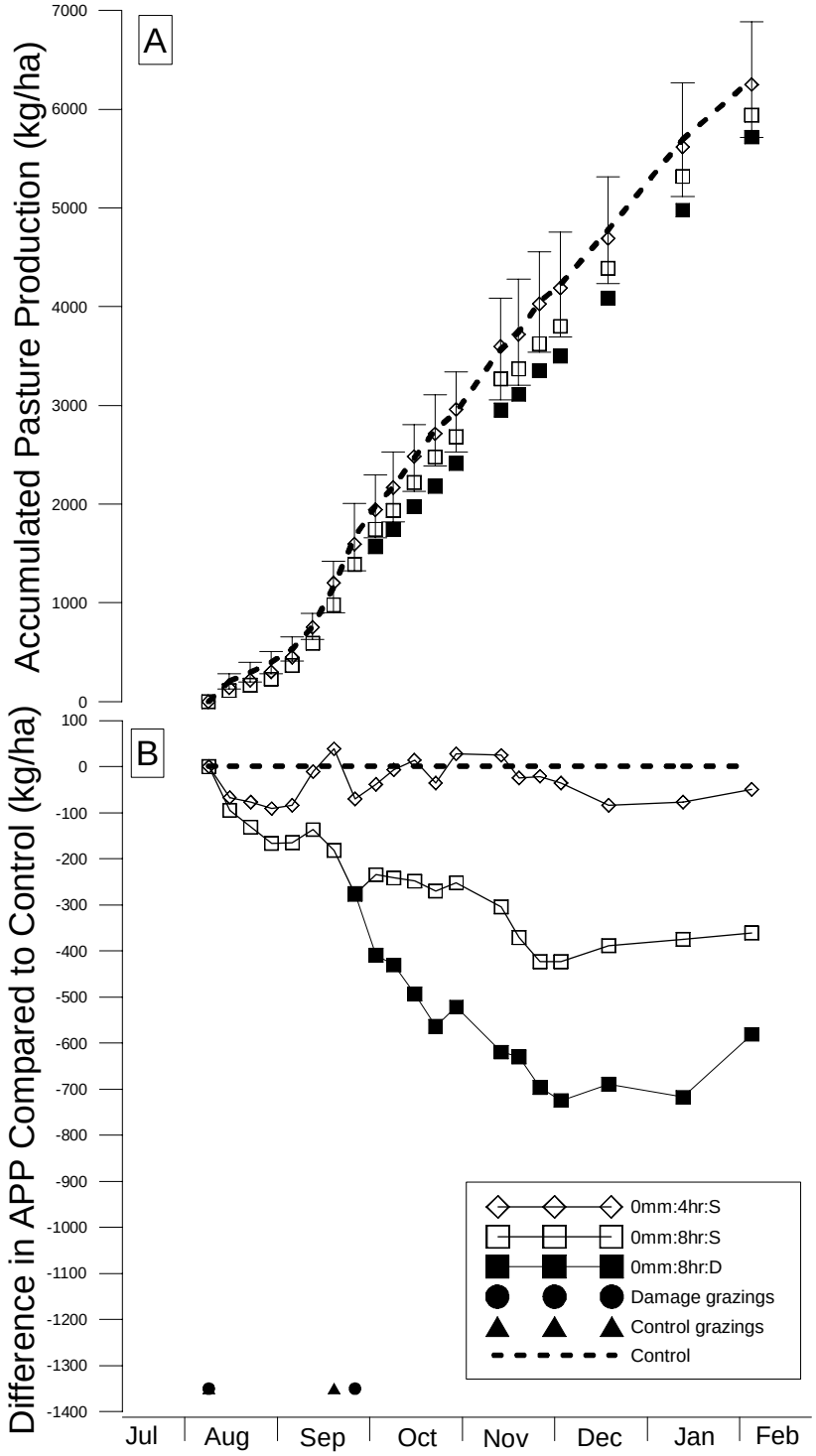

Figure 5.6 Accumulated pasture production (APP) for the 0 mm SWD. A: APP for Experiments 3 and 4 (the 2016/17 grazing season), and B: difference in APP between treatments and the Control. Grazing events are also shown. LSD bars p <0.05.

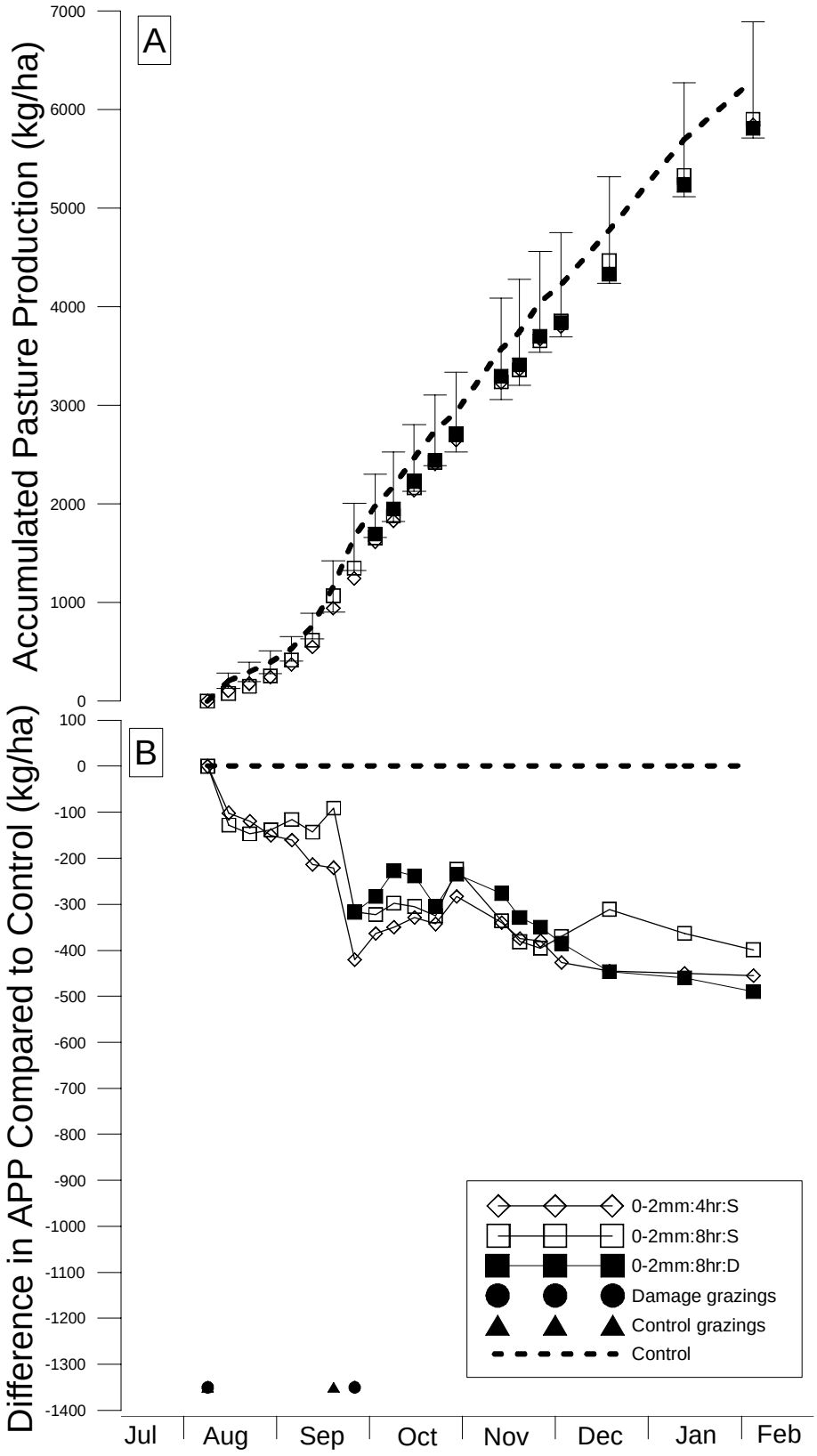

Figure 5.7 Accumulated pasture production (APP) for the 0-2 mm SWD. A: APP for Experiments 3 and 4 (the 2016/17 grazing season), B: difference in APP between treatments and the Control. Grazing events are also shown. LSD bars p <0.05.

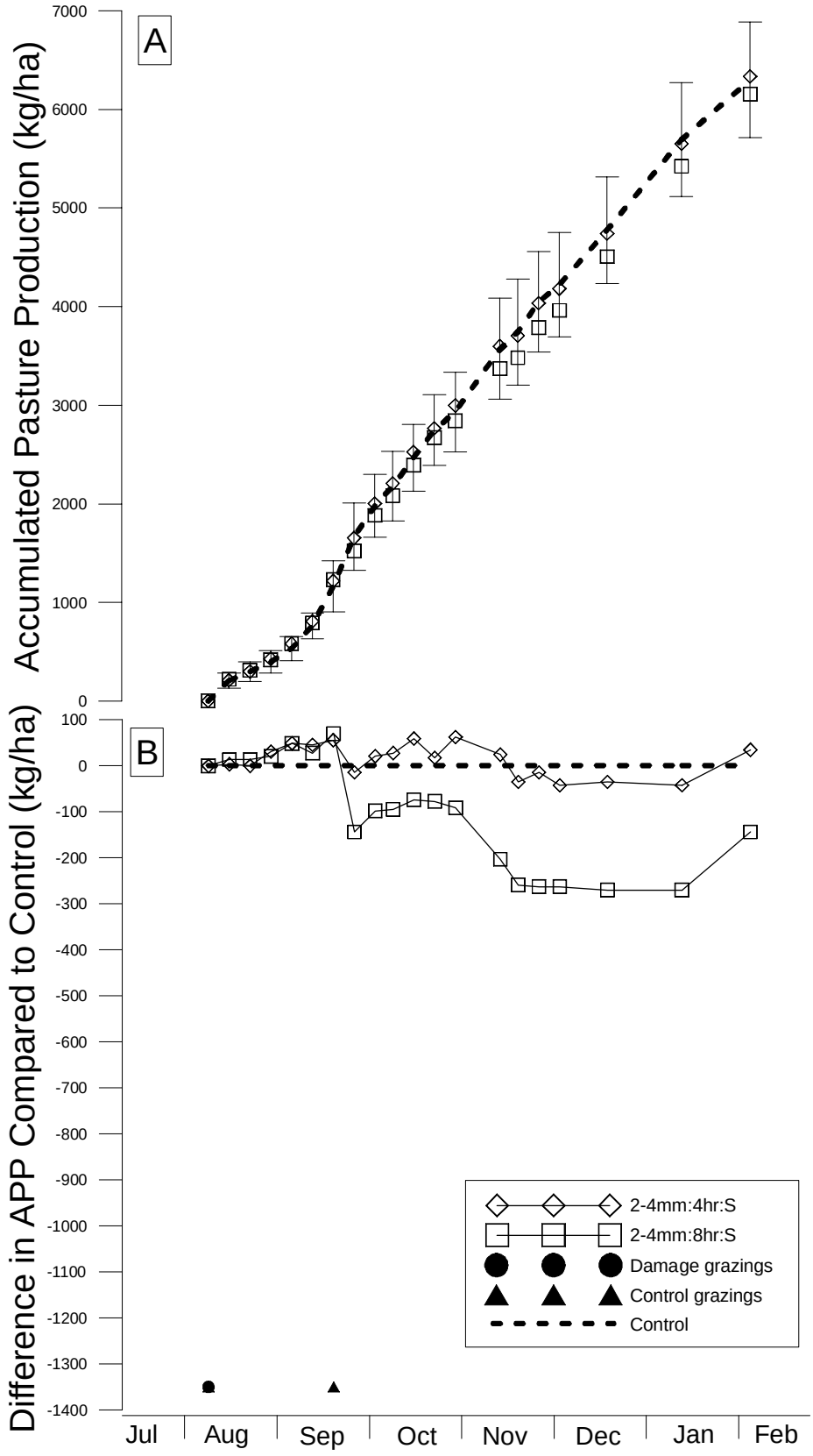

Figure 5.8 Accumulated pasture production (APP) for the 2-4 mm SWD. A: APP for experiments 3 and 4 (the 2016/17 grazing season), and B: difference in APP between treatments and the Control. Grazing events are also shown. LSD bars p <0.05.

In Experiment 3, it is interesting to note that at no time during the grazing season was the APP of the 0mm:4hr:S treatment significantly different to the Control and that the APP for the 0mm:8hr:S, 0-2mm:4hr:S and 0-2mm:8hr:S treatments were only significantly different to the Control for approximately 35 days ($p < 0.05$) (Figure 5.6 and Figure 5.7). This reduction in APP equated to 164 (21%), 214 (28%) and 144 (19%) kg DM/ha for treatments 0mm:8hr:S, 0-2mm:4hr:S and 0-2mm:8hr:S, respectively ($p < 0.05$). The drier 2-4mm:4hr:S and 2-4mm:8hr:S treatments showed a similar response to treading as in Experiment 1 (Figure 5.8), with there being no significant differences between the APP for these treatments and the Control. While the wetter treatments (0mm:8hr:S, 0-2mm:4hr:S and 2-4mm:8hr:S) had APP significantly different to the Control, there was no significant difference between the grazing durations (i.e. 4 hr vs. 8 hr) at any time.

When the reductions in APP for the two different grazing durations at the wetter treatments (0mm:4hr:S, 0mm:8hr:S, 0-2mm:4hr:S and 0-2mm:8hr:S) are averaged, the mean penalty to APP for a single damage event at four (0mm:4hr:S, 0-2mm:4hr:S) or eight hours (0mm:8hr:S, 0-2mm:8hr:S) grazing duration in late winter was approximately 154 kg DM/ha over a period of 35 days.

In Experiment 4, only the 0mm:8hr and 0-2mm:8hr plots received the D sub-treatment repeat damage. Following repeat damage, only the APP on the 0mm:8hr:D treatment was significantly less than the Control. This difference lasted for 103 days and amounted to 716 kg DM/ha (Figure 5.6).

5.3 Discussion

5.3.1 The effect of treading damage on annual pasture production

The objective of this research was to measure the effects of treading damage associated with best grazing management (i.e. moderate stocking rates and short grazing durations). This was not an investigation of the effects of the most severe forms of treading damage on pasture growth. Having said this, none of the grazing treatments and the associated levels of treading damage imposed in this study significantly affected annual pasture accumulation. Therefore, under best management protocols, the effects of treading damage may not be detected in measures of annual pasture production. However, the distribution of pasture across the seasons may be just as important, if not more important, than APP. Treading damage incurred here during grazing at deficits less than 2 mm did impact negatively on this distribution, which for winter and spring treading damaged soils resulted in loss of pasture production during peak lactation.

5.3.2 Pasture production following a single treading event in winter

The selection of 2 mm as the critical SWD for significant treading damage by dairy cattle is not limited to a consideration of the extent of physical damage to the soil surface (Chapter 4) but is also borne out by measurements of pasture accumulation following grazing. In other words, the effects of treading damage on APP also seemed to revolve around a critical SWD of 2 mm. At no time in any of the experiments was there a significant penalty to APP for grazing at SWD > 2 mm compared to the Control treatment at either of the grazing durations or for either single or repeat damage. There were, however, reductions in APP ($p < 0.05$) after a one-off winter treading event on plots that were badly damaged (i.e. the soil moisture deficit was less than 2 mm at grazing). In 2015-16, the winter grazing of both 4 and 8 hour grazing durations of the 0

mm and 0 – 2 mm treatments resulted in fairly consistent reductions in APP relative to the Control treatment. Following the grazing of these wetter treatments in winter, their APPs were significantly smaller than for the Control treatment for a period of 106 to 217 days, during which time APP was reduced by 320 – 550 kg DM/ha. The reduction in APP was slightly greater on the 8 hour treatments and this reflected the slightly greater soil damage associated with these treatments (Chapter 4). In comparison, the winter grazing of the wetter treatments in the 2016-17 season resulted in smaller decreases in APP (0 – 214 kg DM/ha over only approximately 35 days) relative to the Control treatment. As previously discussed, there is no good reason as to why the effects of winter treading should have been so different between the two years other than the fact that in the 2016-17 season this grazing occurred later in winter, and temperatures, and presumably growing conditions, were much improved on the previous year. The average percentage reduction in APP following the winter grazing of the wetter treatments in both years of 16% (approx. 400 kg DM) is very similar to treading damage results reported by Tuñon et al. (2014). Tuñon et al. (2014) showed that a severe treading event on a sandy loam soil in late winter caused an initial 15% reduction (approx. 500 kg) in APP. Reduced pasture growth rates lasted for 70 days, which is a shorter recovery period than that observed here (for 2015/16) in this trial. This could be attributable to a difference in soil type and/or climate.

5.3.3 Pasture production following repeated treading damage (double damage)

The effect on APP of the spring damage to the wetter plots was much more varied than the impact of the winter damage. Interestingly, as reported in Chapter 4, the surface soil damage at the second grazing was similar to the damage inflicted on the surface soil at the winter grazing. However, this damage did not translate into a negative impact on APP when the grazing duration was limited to 4 hours. The repeat 4 hour grazing at both the 0 and 0 – 2 mm SWD did not reduce APP to any marked extent in either year.

Only the repeat 8 hour grazing treatments at both of the small SWD treatments (0 mm and 0-2 mm) resulted in a reduction in APP in 2015-16 and only the 0mm:8hr:D grazing treatment in 2016-17 showed significant reductions in APP. The reduction in APP, relative to the Control treatment, associated with the second damage event for these three treatments was 584, 418 and 552 kg DM/ha, respectively. In very general terms, this reduction is similar to the reduction measured post winter grazing. Therefore, there did not appear to be any compounding effect of double damage, as might have been expected.

Given the prolonged period of wet soils in winter – spring and the short grazing rotation of a typical dairy farm at this time of year, there is likely to be a conflation of single versus double damage with winter versus spring grazing. This double treading damage, however, did not have a significant effect on the APP of the 4 hour grazing of wet soil in spring (i.e. double damage). This lack of effect is probably due to the more favourable growing conditions at this time of year when compared to the recovery of APP following winter damage.

5.3.4 The implications for grazing management

Best management practice for farmers on fine textured soils includes standing cows off paddock when the SWD is small. However, while cows are standing off paddocks, the pasture will continue to grow. If cows stand off for prolonged periods, excessive pasture length and poor pasture quality may become a problem. Therefore, there may be times when soils are wet but the need to graze, in order to reduce pasture cover to control its quality, overrides the requirement to protect the soil and pasture from treading damage. This research set out to investigate how this tension between the need to prevent treading damage and the requirement to graze in order to maintain long-term pasture quality should be managed. On the one hand, the results presented here suggest that grazing at deficits less than 2 mm should be avoided to minimise the risk of a short-term decrease in pasture production and damage to the soil surface. Although treading damage in winter may result in reductions in APP of only ca. 500 kg DM/ha, this is valuable pasture at a time when growth rates are slow and there is typically a feed deficit. Furthermore, if there is repeat damage in spring and cows are allowed to graze for 8 hours, as might well be the case for lactating cows, then a further approximately 500 kg DM/ha may be lost. On the other hand, if annual pasture production is the important consideration then the treading damage associated with grazing at deficits less than 2 mm for approximately four hours is unlikely to decrease annual pasture production. In other words, the relatively small impact on annual APP of grazing pastures for short durations when the SWD is at or near 0 mm is some consolation for farmers who are forced to graze in these conditions in order to protect future pasture quality.

If compelled to graze in the wettest conditions, it is beneficial to keep the grazing duration as short as practicable. There was some evidence that the shorter grazing period of 4 hours resulted in less damage and better pasture growth compared to the 8-hour

grazing duration, most notably if there is repeat damage in spring. The greater recovery rates from treading damage observed in spring suggest that grazing for 4 hours at this time of the year may not reduce APP. As this can be a wet time of the year, this may be good news for grazing management.

5.3.5 The long-term effect of treading damage on pasture production

While there were short-term reductions in seasonal APP from some of the treading treatments, there was no significant difference ($p < 0.05$) in annual APP between damaged and undamaged plots (i.e. treading damage in winter and/or spring did not affect the quantity of pasture grown over the entire year). In other words, the differences in pasture growth observed between some of the treatments post treading seem to disappear over the longer term (i.e. the year). This trend, however, is not surprising given that soil recovery over the summer-autumn period following treading (Drewry et al. 2004) can improve pasture production and mitigate the effects of winter-spring treading damage on annual pasture accumulation (Houlbrooke et al. 2009). The long-term or annual results of this trial coincide with the findings of other authors (on varying soil types, stocking densities and grazing intensities) who report initial short-term reductions (ca. 40 - 120 days) in pasture accumulation with no reductions in annual pasture accumulation (Campbell 1966; Menneer et al. 2001; Nie et al. 2001; Drewry 2003; Zegwaard 2006; Tuñon et al. 2014).

5.3.6 The effect of treading damage on the distribution of pasture accumulation

In this trial, the cycle of pasture growth following treading damage at SWD < 2 mm in winter could be summarised as follows. Immediately after a treading event (even if the grazing interval is as short as 4 hours), pasture growth rates are reduced in a marked

fashion. After this initial period of reduced growth (approximately 500 kg DM/ha over 100 days), the damaged pasture starts to recover until the growth matches, and possibly briefly exceeds, the growth on the undamaged areas. If there is a repeat damage event under an 8 hour grazing period, then there is likely to be a further reduction in APP of approx. 500 kg DM/ha. However, by the season's end, there is no difference in annual pasture accumulation as a result of winter and spring treading damage. While the 'compensatory' growth alluded to in the recovery phase above was not measured directly in this study, Ward and Greenwood (2002) also suggest that any such compensatory growth may be due to enhanced mineralisation of nitrogen in pugged areas. However, it is important to note that the results reported and discussed above and the 'cycle of treading damage' as outlined here reflect the degree of treading damage incurred in the trial conducted in the current study. More severe forms of treading damage, from longer grazing intervals and at greater stocking rates, may result in greater and more persistent reductions in pasture growth.

Rather than reducing total annual pasture yield, treading may reduce winter-early spring growth and increase late spring to early summer production. If this were the case, then the disadvantages of treading damage would then relate to the inefficiencies associated with a shortfall in pasture growth in late winter-early spring and more growth in late spring-early summer. Good pasture growth in late winter/early spring is important if the 'peak' lactation period is to be optimised (at a low cost). Therefore, if the cow diet is compromised by inadequate pasture growth, the cost of pasture damage could be high (i.e. having to replace 'lost' growth with supplements). In addition, if extra pasture is produced later in the lactation season (a time when surplus grass needs to be conserved), this might also incur a cost to harvest and place in storage. It is therefore misleading to

simply look at the long-term or annual effects of treading damage, when the short-term effects may have a greater impact on pasture production and farm profit.

5.3.6.1 The effect of treading damage on pasture accumulation at the farm systems level

The findings of this chapter can be laid alongside the results of the WFM analysis (Chapter 4) to gauge the likely magnitude of the penalty to pasture accumulation imposed by treading damage on a dairy farm with standoff facilities. In an average year on a 200 ha farm (on fine textured soil in the Manawatu) practising BMP with a four hour grazing duration on wet soils, pasture accumulation might be reduced by more than 69 t DM. In a wet year, treading damage may cost this farm system approximately 90 t DM in pasture accumulation. While in the larger context, this may not be a large quantity of pasture, much of this decrease occurs at a critical time when pasture growth rates are less then animal demand. Farmers need to understand the magnitude of this loss so that they can weigh its consequences and determine if ammeliorative measures, such as the purchase of more supplements to fill this gap in cow diet, are warranted.

5.4 Conclusion

This study measured the effects of the treading damage associated with relatively short grazing durations on a fine textured soil, such as likely to be encountered on a farm where best management practices (BMP) for winter/spring grazing are followed including the use of standoff. In addition to protecting soil and pasture from treading damage, these BMP's include the requirement to graze regularly in winter and spring to maintain the longer-term quality of the sward. On occasions, this latter condition may necessitate the grazing of very wet soils. On a fine textured soil such as the Tokomaru silt loam, treading damage to the soil surface and reductions in pasture production can be expected if cows graze when the SWD is below a critical value of 2 mm. Not

surprisingly, this mirrored the critical SWD for damage to the soil observed in Chapter 4. In other words, only minor treading damage and minimal decreases in seasonal pasture accumulation were associated with grazing at SWD > 2 mm. While there is a short-term reduction in pasture accumulation of approximately 500 kg DM/ha following winter grazing when the SWD is < 2 mm, there is unlikely to be an effect on the annual APP. If a paddock incurs repeat damage (i.e. damaged again in spring) then 4 hours grazing at this time of the year is unlikely to result in a further reduction in APP. However, grazing for 8 hours in spring when the SWD < 2 mm is likely to result in a reduction of another approximately 500 kg DM/ha. If compelled to graze in the wettest conditions, it is beneficial to keep the grazing duration as short as practicable. There was evidence that the shorter grazing period of 4 hours resulted in less damage compared to the 8-hour grazing duration.

The results of this study suggest that the need to occasionally graze in very wet conditions (at or near saturation) for short durations (up to 4 hours) in order to protect pasture quality need not undermine the usefulness or overall success of standoff practices.

6 TARGETED DURATION CONTROLLED GRAZING AS A TOOL TO REDUCE NITRATE LEACHING

6.1 Introduction

Dairy farming in NZ is predominately based on year round grazing of clover/ryegrass pasture (Monaghan et al. 2008). However, in this type of grazing system, large nitrate (NO_3^-) losses to water can occur under dairy cow urine patches (Cuttle & Bourne 1993; Haynes & Williams 1993). Grazing cattle harvest N in herbage before depositing between 70% to 90% of this ingested N back onto the pasture (Haynes & Williams 1993) in small patches at high concentrations i.e. at equivalent rates ranging between 400 and 1000 kg N/ha (Haynes & Williams 1993; Jarvis et al. 1995; Di & Cameron 2002; Selbie et al. 2015). These large quantities of N in urine patches exceed immediate plant requirements in the area of the urine patch (de Klein 2001), and thus the excess is susceptible to losses to water (de Klein & Ledgard 2001).

With increasing public awareness of the dairy sector's influence on water quality, more regional councils are introducing regulations which limit the loss of N from dairy farms (Monaghan et al. 2007). Many of the mitigations used by farmers target the major source of leached N, which, as described above, is urine excreted by dairy cows (Ledgard & Menner 2005; Selbie et al. 2015). Various management strategies and technologies have been reported to reduce N leaching from cow urine patches (Di & Cameron 2005; Monaghan et al. 2007; Christensen et al. 2018b). One such method is standing grazing animals off pasture, termed restricted or duration control (DC) grazing, which has been shown to be an effective strategy for reducing N losses on dairy farms (Christensen et al. 2018b).

Duration controlled grazing utilises standoff facilities, such as free stall barns, to decrease the time that cows spend grazing pasture. The two important advantages that result from DC grazing are: (1) the direct deposition of cow urine on pastures is significantly reduced due to the shorter time cows spend grazing on pasture (compared

to typical grazing management) (Christensen et al. 2018b); (2) the uniform spreading of the N which is captured in the effluent while cows are on the standoff facility, and which can be returned to pasture at much lower rates than those associated with urine patches (Monaghan et al. 2008). Furthermore, the uniform application of nutrients in effluent at lower concentrations of nutrient (particularly N) per unit surface area than those found in dung and urine patches, should also improve the efficiency of pasture nutrient use (Monaghan et al. 2010). However, the benefits of this (efficiency) to pasture production are not clear-cut. The DC grazing system (compared to a SG system) could have the potential to reduce pasture production by 20% as reported by Christensen et al. (2018a), or conversely, there may be the potential for an increase in pasture production by 20% as reported by de Klein (2001).

The use of year-round DC grazing, which involves cows spending ca. 4 hours on pasture at each grazing, has been demonstrated to substantially reduce N leaching by, on average, 52% (Christensen et al. 2018b). However, some studies have demonstrated that using a shortened grazing duration for only part of the year can still achieve large reductions in N leaching (de Klein et al. 2006; Ledgard et al. 2006). For example, de Klein et al. (2006) measured a reduction in N leaching of 41% with autumn DC grazing, while Ledgard et al. (2006) reported a 25% reduction in N leaching from a DC grazing period of late autumn to early spring. These results demonstrate that large reductions in N losses can be achieved using a shorter period of DC grazing, if this grazing is practised at the time of the year when it will have the greatest influence on N loss to water (i.e. the 'critical period').

A number of studies have found that the critical period is late-summer to early-winter (Shepherd et al. 2010; Vogeler et al. 2010; Shepherd et al. 2011), which is when an accumulation of N in the soil leads to significant amounts of N leaching when

subsequent drainage commences. Therefore, DC grazing should aim to target this critical period in order to achieve the greatest reduction per unit of time that cows spend in or on a standoff facility. However, the literature related to DC grazing in this critical period is limited to modelling exercises (Vogeler et al. 2010), or to small scale trials that used artificial urine to simulate cow urine spots (Shepherd et al. 2011), or trials that encompass only the autumn and winter seasons (de Klein et al. 2006; Ledgard et al. 2006; Beukes et al. 2017; Shepherd et al. 2017). Therefore, there is a need for a large-scale plot study of DC grazing of dairy cows, implemented over late-summer to early winter, to better quantify the effect of DC grazing, when confined to this period, on N losses to water and yearly pasture production. Accordingly, a grazed plot study was conducted over two years with the objective of quantifying the impacts of targeted (i.e. late-summer to early winter) DC grazing on pasture production and N losses in drainage water.

6.2 Methods

6.2.1 Trial site

This experiment was conducted from January 2014 to December 2015. The experimental area was located on a paddock at Massey University's Dairy No 4 Farm near Palmerston North, Manawatu, New Zealand (NZMS 260, T24, 312867). The paddock has flat topography (ca. <3% slope). The soil in the paddock is Tokomaru silt loam, which is classified as an Argillic-fragic Perch-gley Pallic Soil (Hewitt 2010). A detailed description of soil physical properties is provided by Scotter et al. (1979a). The soil is naturally poorly drained and consists of a weakly to moderately developed brown silt loam A horizon, to a depth of 250 mm. There is a weakly developed, grey, strongly mottled, clay loam B horizon to 800 mm, and a C horizon of highly compacted, pale grey silt loam fragipan, which acts as a natural barrier to drainage (Scotter et al. 1979a; Shepherd 1984). The paddock grows a mixed sward of perennial ryegrass (*Lolium perenne)* and white clover (*Trifolium repens*). Further details of the site are given by Houlbrooke et al. (2004).

6.2.2 Experimental design

The research area consisted of 14 separately fenced treatments. Each plot had an average area of 850 m^2/plot (Figure 6.1), and each plot had an isolated mole and pipe drain system. The mole channels were installed at a depth of ca. 0.45 m and at 2 m intervals, with drainage from the mole channels being intercepted by a collecting perforated pipe drain (0.11 m. diameter) at the edge of each plot. These pipe drains were installed perpendicular to the mole channels at a depth of ca. 0.60 m. Drainage water from these collecting pipes, at the edge of each plot, was directed to a nearby collection area where drainage-water monitoring, and sampling equipment was installed.

Figure 6.1 Layout of the fourteen experimental treatment plots (those marked with 'R' denote Duration-Controlled (restricted) grazed treatment, while unmarked plots correspond to Standard grazed treatment)

This experiment had two treatments: a standard grazed (SG) treatment and a DC treatment (Figure 6.1). There were seven replicates of each treatment. The SG treatment had a grazing duration between milkings of ca. 7 hours for day-grazings and ca. 12 hours for night-grazings (year-round). The DC treatment had a grazing duration of ca. 4 hours for both day and night grazings from mid-Feb to mid-July (3-4 grazings only), while the remainder of the year the DC treatments were grazed for the same grazing durations as described for the SG treatment. Christensen et al. (2018a) used the same SG treatment, however the targeted DC treatment imposed in the current study differed in an important way from that studied by Christensen et al. (2018a), where DC grazing was practised for the entire year. Time spent on races and at milking is likely to have been similar for both treatments.

All treatments were grazed on the same day with the same average stocking rate, which seasonally ranged from 12 to 18 cows per plot. The stocking rate was set according to pre-grazing pasture cover (average pre grazing cover was 2700 kg DM/ha), which was estimated using a rising plate meter (RPM), minus a target residual cover of 1700 kg DM/ha. Grazing for both treatments alternated between 'day' and 'night' to simulate standard farm practice. During the late-summer to early-winter period, cows were provided with a target pasture intake of 5 - 7 kg DM/cow for both treatments, with another 2 - 3 kg DM/cow provided from another source (i.e. turnips, maize silage). The SG treatment cows were fed their supplementary feed and then placed on the SG treatment plots to graze pasture. The DC treatment cows grazed their plots for 4 hours and were then housed and fed their supplement. In February, at the first DC grazing each year, turnips were fed to both treatments as part of the normal farm feeding policy. At this time, the DC treatment cows grazed treatment plots (4 hrs), and were then removed to graze their allocation of turnips before returning to a freestall barn, whereas the SG treatment cows were allocated turnips first and then put into the treatment plots for the SG grazing. Throughout the experimental period (2014 & 2015), cows were grazed only on the plots when the SWD was > 4 mm to protect plots from treading damage.

6.2.3 Pasture measurements and pasture accumulation estimations

Pasture accumulation was estimated using the RPM method (Earle & McGowan 1979). The plate meter used was a locally calibrated 'Jenquip' (Reid Line East RD5 Feilding New Zealand) folding plate pasture meter with a 'Farmworks' electronic pasture height recorder. Average pasture cover (APC) was estimated for each plot from 60 plate readings taken over an M-shaped transect. A single standard calibration equation was used to convert plate readings to APC:

$$APC\ (kg\ DM/ha) = RPM \times 140 + 500$$

This equation is the best fit for most situations and makes the data easier to interpret (Thomson et al. 2001; DairyNZ 2008). This approach has also been used by other researchers on Massey University's Dairy Farm No 4 (Hendriks et al. 2016a; Christensen et al. 2018a). Pasture accumulation between grazings was calculated by subtracting the post-grazing pasture mass at the previous grazing from the current pre-grazing pasture mass, while the DM intake by cows was estimated from the pre-grazing pasture mass minus the post-grazing pasture mass for the same grazing (Christensen et al. 2018a).

6.2.4 Soil fertility and fertilisers

All treatment plots were individually soil tested prior to the commencement of the experiment (Table 6.1). Fifteen soil cores from each plot, to a depth of 7.5 cm, were combined to make a single soil sample per plot. The samples were analysed for pH, Olsen P (mg kg^{-1} soil), sulphate sulphur (S) (mg kg^{-1} soil), and Quick test potassium (QT K), calcium (QT Ca) and magnesium (QT Mg). All soil test results were within or slightly above the recommended optimum for a soils of sedimentary parent material (FertResearch 1999), except for pH on both treatments, which were slightly under optimum.

Table 6.1 Soil test results for the trial site, averaged for both treatments (DC and SG grazing)

	pH		Olsen P (mg kg^{-1} soil)		Sulphate S (mg kg^{-1} soil)		QT K		QT Ca		QT Mg	
	DC	SG	DC	SG	DC	SG	DC	SG	DC	SG	DC	SG
Sept 2013	5.6	5.6	36	36	12	13	6.1	9.0	8.4	8.3	34	40

Both treatments received the same amount of nutrients from fertiliser (Table 6.2). Nutrients were applied in strategic additions of N and/or S fertilisers. The soil analysis (Table 6.1) suggest that no P or K fertiliser was required and this reflected nutrient management on Massey University's Dairy No 4 Farm at the time of the trial.

Table 6.2 Amount and timing of fertiliser applications to all treatment plots at the trial site.

Fertiliser	2014	2015
Urea (kg ha^{-1}) 46:0:0:0	70 (October)	
Ammonium Sulphate (kg ha) 21:0:0:24	176 (August)	176 (September)

6.2.5 Drainage sampling

Drainage water from each plot was measured separately by channelling flow through pipes into individual tipping-bucket flow meters located in sampling pits nearby. The flow rate of drainage water was measured with ca. 5 L tipping buckets. All tipping buckets were instrumented with data loggers to provide continuous measurements of flow rate. During each drainage event, a proportion (ca. 0.1%) of the drainage water from every second tip of the tipping-bucket flow meter was automatically collected to

provide a volume-proportioned, mixed sample for analysis. Drainage samples were filtered through a 0.45 μm filter within 12 hours of collection, and stored frozen until analysis. Filtered samples were analysed for nitrate (NO_3^-) and ammonium (NH_4^+) using colorimetric methods on a Technicon Auto Analyser (Blakemore et al. 1987). Total N (TN) and Total P (TP) concentrations of unfiltered samples were determined using the persulphate digestion method of Hosomi and Sudo (1986). Total organic N (TON) was estimated from the difference between TN and mineral N (NO^-_3 and NH^+_4). Drainage water NO^-_3-N and TN concentrations were multiplied by the measured drainage volumes for each sampling period to calculate the nutrient loads (kg/ha) that were leached.

6.2.6 Slurry application to the DC grazing treatment

For the duration of the experiment, slurry from an operating freestall barn was used. The freestall barn had a dedicated slurry collection pond that had been installed on Massey University's Dairy No 4 Farm, as part of the larger Pastoral 21 study conducted on the farm. The slurry from this pond was applied to the DC treatment at an application depth of ca. 6 mm/application using a Williams 'Elephant 5000' slurry tanker on the 31st July 27th November 2014 and 2nd April 6th November 2015. The depth of slurry application used in this experiment was based on previous experience with research conducted on these research plots. During application of the slurry, a series of plastic collection trays were placed on each plot to collect samples to measure application depth and provide samples for analysis of nutrient (TN, TP, NO^-_3, NH^+_4 and base cations) concentrations.

6.2.7 Statistical analysis

The software SAS (Statistical Analysis System, version 9.2: SAS Institute., Cary, NC US) was used for all statistics in this chapter. Mean treatment nitrate, total nitrogen

concentrations, mean treatment drainage events and mean treatment accumulated pasture production were tested for normality and transformed if necessary, before being subjected to an Analyses of Variance ANOVA. Analyses of Variance was used (for all measurements in this chapter) to determine differences between the DC and SG treatments (having experiment treatment as a blocking factor), and was used to derive the Least Significant Differences (LSD) of the means of treatment plots where significance differences are measured with a p value of <= 0.05. The ANOVA considered experimental structure, where the within-plot variability was included with the within-treatment (treatment replication) variability.

6.3 Results

6.3.1 Climate conditions and drainage

Annual rainfall was 916 and 1352 mm for the 2014 and 2015 years, respectively. The 2014 rainfall was similar to the Palmerston North long-term annual average of 900 mm (Chappel 2015). However, the 2015 season was considerably wetter than average.

There was no significant difference ($p > 0.05$) in average annual drainage depths between SG and DC treatments in either year. However, there was a significant difference in drainage ($p < 0.05$) between years, with 123 and 278 mm of drainage recorded in 2014 and 2015, respectively. The measured drainage events coincided with periods of zero soil water deficit (SWD) as predicted by the soil water balance model of (Scotter et al. 1979b) (Figure 6.2). The commencement and temporal distribution of the drainage also differed between the two years. The drainage season of 2015 was more prolonged than the 2014 season. The measured drainage depth in 2015 of 278mm, was most probably less than the actual drainage in that year. This was due to the very heavy

rainfall event on the 22nd and 23rd of June. This storm flooded the sampling pits and as a consequence the samplers were able to record only up to 63 mm of drainage. However, the soil water balance (SWB) predicted that this storm would have produced 151 mm of drainage (Figure 6.2). When this additional drainage is taken into account, the actual drainage for the 2015 year is likely to have been closer to 375 mm.

The measured drainage depth in 2014 was relatively small (123 mm), when compared to the average drainage depth of 340 mm recorded in a similar three-year trial over 2009-2011 by Christensen et al. (2018b). This small drainage total in 2014 is explained by the low winter rainfall which was only 125 mm for the period from June to August compared with the average of 180 mm for this period (Chappel 2015). The drainage season of 2014 began on 25th May. There were 16 drainage events, which mainly occurred in five groupings (Figure 6.2). The last drainage event was recorded at the start of December (early-summer, Figure 6.2). The size of drainage events in 2014 ranged from 2 to 15 mm (averaged across all treatment plots).

The drainage season began early in 2015 on the 14 April. There were 23 measured drainage events, which were predominantly grouped around the winter to early-spring period, with the last drainage event occurring in the middle of November (Figure 6.2). The size of measured drainage events ranged from 6 to 40 mm (averaged across all treatment plots).

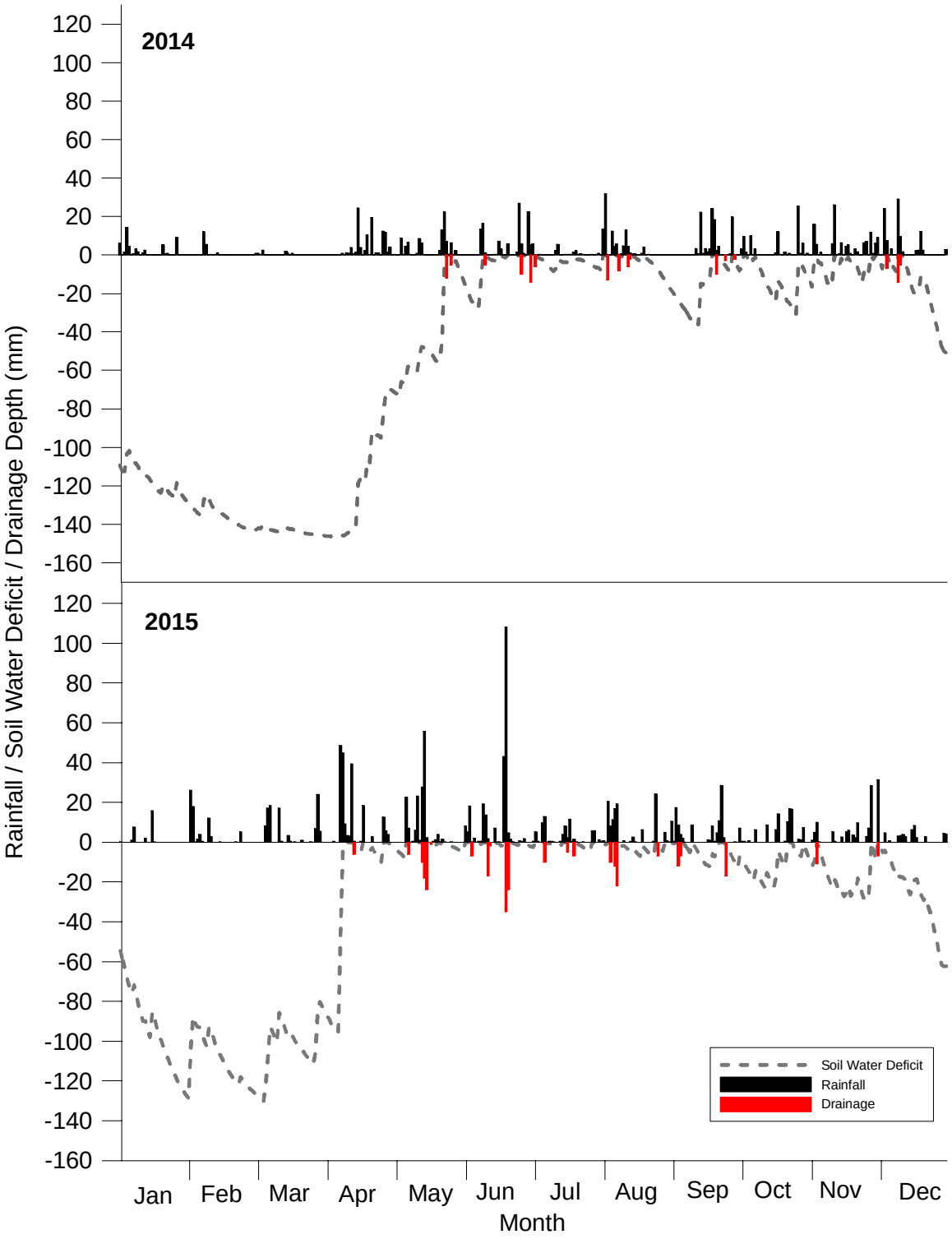

Figure 6.2 Measured mean drainage events for all DC and SG treatments, with rainfall and modelled soil water deficit.

6.3.2 Cow grazing hours and DC grazing events

The total number of grazings for each treatment and the total number of cow grazing hours/treatment plot over the two seasons in this study are shown in Table 6.3 and Table 6.4. Cow grazing hours can be defined as the total number of cows grazing a plot multiplied by the total hours of the grazing event e.g. 10 cows grazing for four hours = 40 cow grazing hours. Both seasons had nine grazing events.

The 2014 season had three DC grazing events, with the first grazing being in late February. The period between the first and second DC grazing was prolonged due to a long dry period (Figure 6.2), which limited pasture production and extended the return period of cows to treatment plots. Therefore, it was ca. 10 weeks (start of May) before there was enough pasture available to accommodate the second DC grazing. This delay pushed the third and final DC grazing into July (Table 6.3), which coincided with a dry cow grazing (an extended period of grazing). This resulted in the 2014 experimental season having 1 day and 2 night DC grazing events. The total cow grazing hours for the DC treatment was 903 cow hrs/year compared with 1256 cow hrs/yr for the SG treatment. This represents a 28% difference in annual cow grazing hours between the DC and SG treatments. The greatest differences between DC and SG grazings occurred during the night grazing events and during the dry cow grazing in June (Table 6.3). During the late-summer to earlier-winter period, the SG treatment had 541 cow grazing hours compared to 188 hours for the DC treatment (i.e. 353 cow grazing hours less than the SG treatment). This gave a reduction in grazing time of 65% for this critical period.

The 2015 season also had three DC grazings, the first of which was in February. However, due to favourable growing conditions during the autumn of 2015, the DC grazing period was shorter than in the previous year, finishing at the start of May (Table

6.4). The DC grazing period in 2015 involved 2 ‘day’ and only 1 ‘night’ grazing event. The total annual cow grazing hours for the DC treatment was 967 cow hrs with the SG treatment totalling 1181 cow hrs. On an annual basis, there was only a 18% difference in cow grazing hours between the DC and SG treatments. During the late-summer to early-winter period, the DC treatment had 214 hours and the SG treatment had 346 cow grazing hours, which resulted in the DC having 39% less grazing hours during this critical period. The biggest differences between DC and SG cow grazing hours occurred during the night grazing event (Grazing #3 Table 6.4), with 48 and 192 cow hours for the DC and SG treatment, respectively.

When comparing both treatments over the two experimental seasons, there was a noticeable difference in the percentage reduction in annual cow grazing hours, being 28% in 2014 compared to 18% in 2015. During both seasons, the DC treatments had similar cow grazing hours both annually and over the critical period. The number of annual cow grazing hours for the SG was also similar for both seasons. However, there was a 38% difference in the cow grazing hours for this treatment in the critical period, being 541 and 346 for the 2014 and 2015 seasons, respectively. The reason for the differences in cow grazing hours for the SG treatment between seasons can be explained by two factors: in 2014, two of the three grazing in the critical period were night grazings, and at the end of the critical period in 2014 there was a ‘dry cow’ grazing where the SG treatment was grazed for 24 hours.

Table 6.3 Grazing date, stocking intensity (cows/plot), grazing hours/cow and total grazing hours per plot (800 m^2) for DC and SG treatments during the 2014 season

Grazing #	Date	Cows/plot	Grazing type	DC (grazing. hrs/cow)	SG (grazing hrs/cow)	Total cow grazing hrs/plot (DC)	Total cow grazing hrs/plot (SG)	Difference in grazing hours
1	14/01	14	Night	13	13	182	182	0
2*	27/2	7	Day	4	7	28	49	21
3*	6/5	12	Night	4	13	48	156	108
4*	15/7	14	Day/Night**	8	24	112	336	224
5	16/9	15	Day	7	7	105	105	0
6	16/10	14	Night	13	13	182	182	0
7	5/11	12	Day	7	7	84	84	0
8	25/11	6	Night	13	13	78	78	0
9	17/12	12	Day	7	7	84	84	0
			Total			903	1256	353 (28%)

*** DC grazing period, ** Dry cow grazing.**

Table 6.4 Grazing date, average-stocking intensity (cows/plot), grazing hours/cow and total grazing hours for DC and SG treatments during the 2015 season

Grazing #	Date	Cows/plot	Grazing type	DC (grazing hrs/cow)	SG (grazing hrs/cow)	Total cow grazing hrs/plot (DC)	Total cow grazing hrs/plot (SG)	Difference in grazing hours
1	14/01	14	Night	13	13	182	182	0
2*	17/2	7	Day	4	8	28	56	28
3*	25/3	12	Night	4	16	48	192	144
4*	5/5	14	Day	4	7	56	98	42
5	18/6	15	Night	13	13	195	195	0
6	17/9	14	Day	7	7	98	98	0
7	15/10	12	Night	13.5	13.5	162	162	0
8	5/11	6	Day	7	7	42	42	0
9	3/12	12	Night	13	13	156	156	0
			Total			967	1181	214 (18%)

*** DC grazing period**

6.3.3 Nutrient return via slurry

Slurry was returned to the DC treatments twice in each experimental year at an average application depth of 5.9 mm/ha (Table 6.5). In 2014, there was a mid-winter application of slurry (end of July) to the DC treatments because of the unseasonably low rainfall and the SWD was sufficiently large enough for the tanker to apply slurry without causing noticeable wheel damage to soil or pasture. The final application in this year was applied in late November. Both the July and November applications had similar quantities of TN of 50 and 41 kg/ha, respectively, which provided an annual application of 91 kg TN/ha. Approximately half of this TN was inorganic, resulting in a mineral nitrogen (Min-N) application of 49.5 kg Min-N/ha.

In 2015, the first slurry application occurred at the start of April and the second application at the start of November. The combined annual TN applied was 169 kg/ha, which was almost double the quantity applied in 2014. However, at 56 kg Min-N/ha, the amount of Min-N applied in 2015 was similar to the previous year (2014). This resulted from the proportion of TN as Min-N being different between years, with Min-N being 33% of TN in 2015 and 54% in 2014 (Table 6.5). The difference in slurry Min-N % over the two seasons may be explained by the fact that in the 2014 season, the effluent pond was not completely emptied because the extraction hose, used to transfer the effluent into the slurry tanker, could not reach the bottom of the pond due to the pond's initial design. However, during the 2015 season, modifications were made to the effluent pond allowing the extraction hose to reach the bottom and, therefore, more solids were applied to the DC treatment, which contributed to the higher organic N content, and therefore a lower Mineral-N % of TN.

With regard to other nutrients applied in slurry to the DC treatments, 13.4 kg TP/ha was applied in 2014 and 31 kg TP/ha applied in 2015. There were no base cations (Ca^{2+}, Mg^{2+} and K^{+}) analysed for the second slurry application in 2014. The base cations applied in the first slurry application in 2014 to the DC treatments were 21.9 kg Ca/ha, 10.7 kg Mg/ha and 85.5 kg K/ha, compared with 94 kg Ca/ha, 40 kg Mg/ha and 245 kg K/ha in total for the two slurry applications in 2015.

Table 6.5 Slurry application depth(mm) and nutrient quantities applied in slurry applied to DC treatments.

Application date	Average application depth (mm)	Total N (kg N/ha)	Inorganic N (kg N/ha)		Inorganic N (% of total N)	Total P (kg P/ha)	Calcium (kg Ca/ha)	Magnesium (kg Mg/ha)	Potassium (kg K/ha)
			NO_3^-	NH_4^+					
31/07/2014	5.9	50	1.2	27.5	57	7.9	21.9	10.7	85.5
27/11/2014	5.9	41	1.2	19.6	51	5.5	n/a	n/a	n/a
Total		91	2.4	47.1	54	13.4	n/a	n/a	n/a
02/04/2015	5.9	105	1.2	31.2	31	20	62	26	160
1/11/2015	5.9	64	0.58	22.2	36	11	31	14	85
Total		169	1.78	54.4	33	31	94	40	245

6.3.4 Pasture accumulation and grazing treatments

Annual pasture accumulation in the 2014 season was not statistically different ($p > 0.05$) between the two grazing treatments. It appears neither of the slurry applications in 2014 caused any significant ($p > 0.05$) increase in pasture accumulation on the DC treatment compared to the SG treatment (Figure 6.3). During the first season (2014), the SG treatment accumulated an annual average of 10,929 kg DM/ha, which was similar to the value of 10,743 kg DM/ha which accumulated on the DC treatment (Figure 6.3).

In the 2015 season, annual pasture accumulation on both treatments was lower than in the previous year. Compared to the SG treatment with 9,233 kg DM/ha, annual pasture accumulation on the DC treatment of 9,983 kg DM/ha was significantly higher (8%; $p < 0.05$) by the end of the 2015 experimental year (Figure 6.3). The first application of slurry in April 2015 appeared to have caused an increase in pasture accumulation on the DC treatment in the subsequent measurement periods (until December 2015) (Figure 6.3). However, the second application in November did not further increase the difference between treatments (Figure 6.3). Annual average pasture accumulation across both experimental years was 10,081 kg DM/ha/yr. for the SG treatment, which was lower, but not significantly different ($p > 0.05$), to the 10,363 kg DM/ha/yr. on the DC treatment.

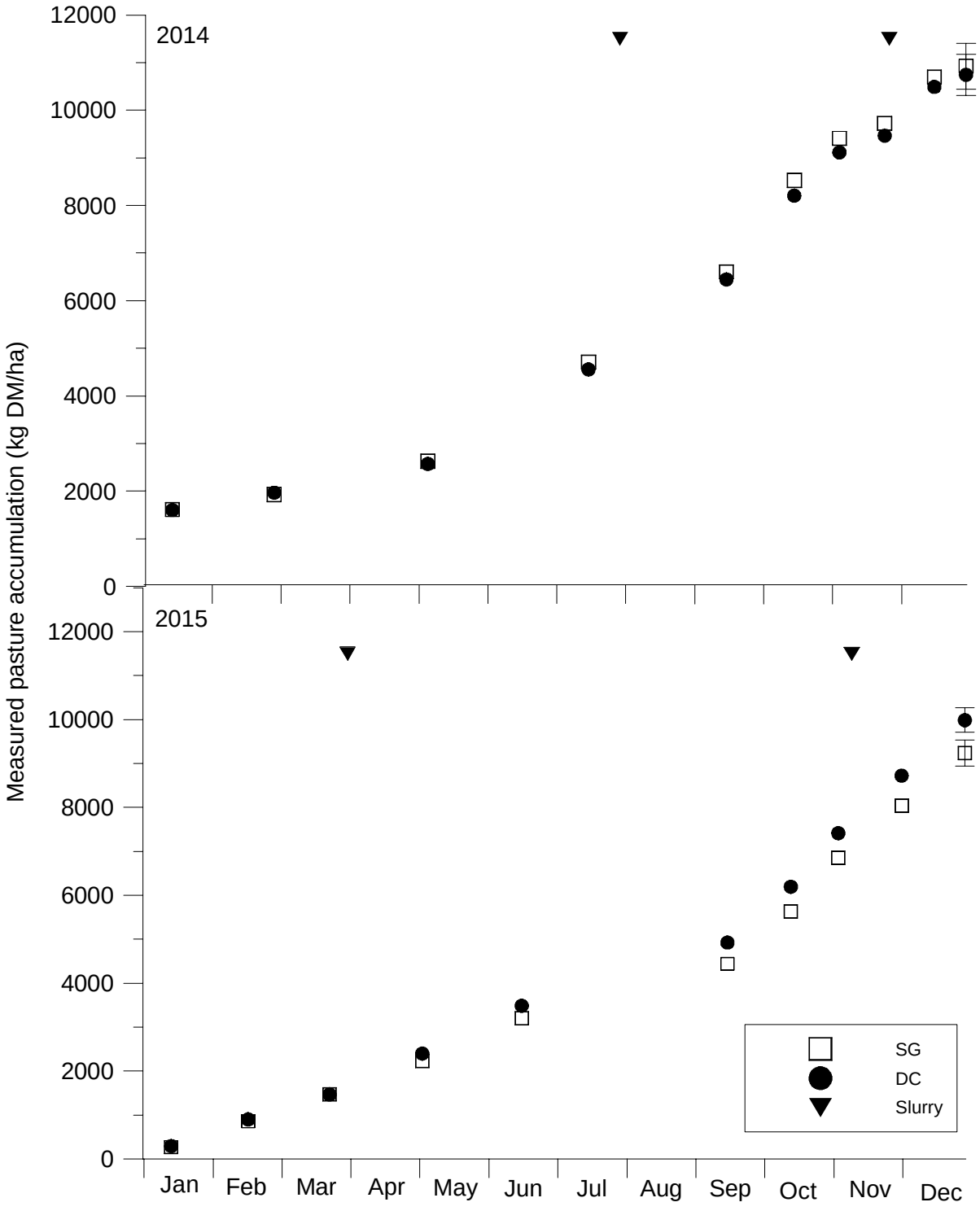

Figure 6.3 Measured pasture accumulation (kg DM/ha) for each experimental year, also showing slurry return to the DC treatment. Error bars represent standard error of mean for the total pasture accumulation.

Over four grazing seasons (2 years from the current trial and 2 from Christensen et al. (2018a), (Table 6.6), the effect on pasture accumulation of returning slurry to the DC treatment was compared. In the current trial, in one season there was no reduction in the DC treatment pasture accumulation, compared to that of SG treatment, and only a small significant advantage ($p < 0.05$) to the DC treatment in the second season. In the two years that slurry was applied in the Christensen et al. (2018a) study, there was no significant difference between treatments in pasture accumulation. However, Christensen et al. (2018a) also compared pasture growth in another year when no slurry was applied to the DC treatment, which resulted in a significant ($p < 0.05$) reduction in pasture accumulation compared to the SG treatment (Table 6.6). The results from Table 6.6 seem to be quite clear that when using DC grazing, slurry needs to be returned to grazing areas to ensure pasture accumulation is maintained. However, the benefits of slurry return to increasing pasture accumulation do not appear to be as clear and during four experimental years where slurry was applied, there was only one year when the DC treatment significantly ($p < 0.05$) out-performed the SG treatment.

Table 6.6 Average pasture accumulation and nutrient returned in slurry for SG and DC treatments for four experimental seasons.

Trial	Season	Pasture accumulation (kg DM/ha/yr)		Significantly different ($p < 0.05$)	Slurry applications to DC treatment	Nutrient applied to DC treatment from slurry return (kg/ha/yr)		
		SG Treatment	DC Treatment			N	P	K
Christensen et al. (2018a)	2008/09	15,213	14,616	No	1	212	48	61
Christensen et al. (2018a)	2010/11	14,990	13,619	No	4	115	26	111
Current trial	2014	10,929	10,743	No	2	91	134	n/a
Current trial	2015	9,233	9,983	Yes	2	169	31	245

6.3.5 Inorganic nitrogen losses in drainage water

In both years of this study, and for both treatments, there was a general trend of high NO_3^- concentrations at the start of the drainage season, which steadily declined over subsequent drainage events (Figure 6.4). This trend was also observed by Christensen et al. (2018b), Houlbrooke et al. (2003) and Monaghan et al. (2002) in similar trials.

Irrespective of drainage season and grazing treatment, the highest concentrations occurred in the first seven to eight drainage events, which equated to the initial 50 to 100 mm of drainage (Figure 6.4). The concentrations of NO_3^- in these initial drainage events from both treatments varied between years (Figure 6.4). The peak concentrations of NO_3^- from the SG treatment in 2014 and 2015 were 14.8 and 6.1 mg N/L, respectively, which were higher than the peak NO_3^- concentrations from the DC treatment of 10.2 and 4.8 mg N/L, respectively.

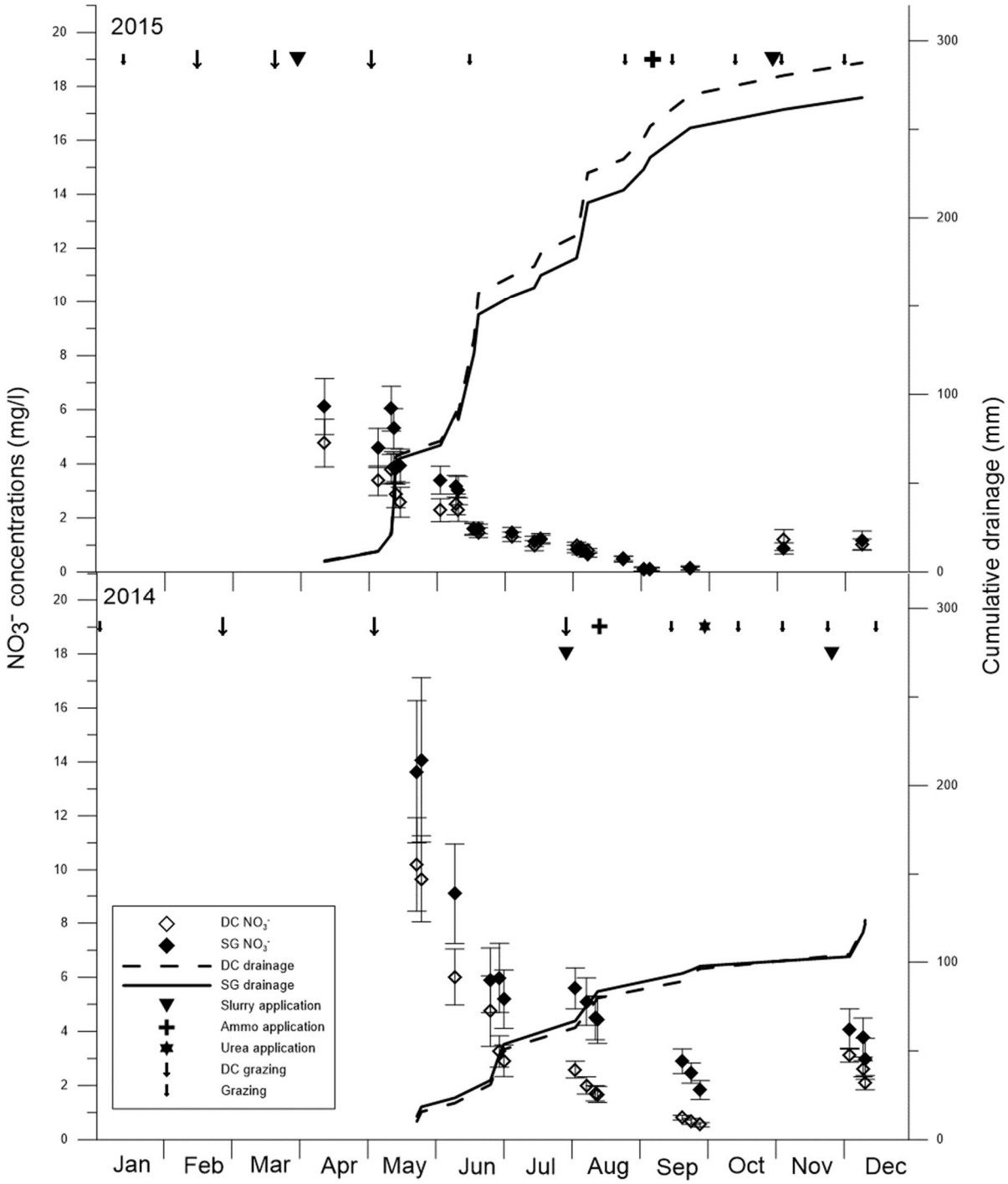

Figure 6.4 Concentrations of Nitrate-N$^-$ in drainage water for 2014 and 2015 with cumulative depth of drainage (mm) for DC and SG grazing treatments, error bars show standard error of the mean.

In both years, there was a prolonged period of soil water deficit during mid to late spring and both treatments showed slightly elevated NO_3^- concentrations in November and December drainage (Figure 6.4). There was also slurry applied to the DC treatment in November in both years, but it appears that this did not cause the increase in NO_3^-

concentrations for the DC treatment relative to the SG treatment, given that the SG treatment was also elevated even though no slurry was applied to this treatment. However, during this period (both years), there were two grazings (on both treatments) where NO_3^- may have accumulated in the dry soil, and this probably contributed to the increase in NO_3^- concentrations observed in drainage during November and December for both treatments (Figure 6.4).

The cumulative leaching load of NO_3^- in drainage from the DC treatment was lower than that of the SG treatment at the end of each drainage season (Table 6.7). However, the effect of the DC treatment was significantly different ($p < 0.05$) from the SG treatment only in the 2014 season. Average NO_3^- leaching loads from the SG treatment were 7.2 and 5.7 kg NO_3^--N/ha/yr for 2014 and 2015, respectively, and the loads from the DC treatment were 4.4 and 4.8 kg NO_3^--N/ha, respectively. Therefore, the DC treatment resulted in a 40% reduction in 2014 and a 17 % (non-significant) reduction in 2015, compared to the SG treatment. The average reduction in cumulative leaching load of NO_3^- for the two seasons combined was 28%. The respective percentage difference in NO_3^- leaching loads (between treatments) between the two seasons may be best explained by the difference between SG cow grazing hours (40% higher in 2014 compared to 2015 during the critical period) over the two experimental seasons.

The majority of the cumulative leaching of NO_3^- occurred relatively early in the season. In the 2014 season, 90% of the total NO_3^- load was leached in the first 100 mm of drainage, but this did not occur until November due to the small amount of drainage in that year. The 2015 season had 66% of the total NO_3^- leached in the first 100 mm (mid-June) of drainage, but 95% by the time 200 mm of accumulated drainage had occurred (mid-August). These results are similar to those reported by Christensen et al. (2018b).

The amount of NH_4^+ that leached in drainage was very small, with less than 0.1 kg of NH_4^+-N being leached from any treatment in any year. Given that these levels are so low and contribute only a very small proportion to the TN losses, data has not been presented here.

Table 6.7 Total amount of NO_3^- and TN leached in drainage water from 2014-2015 for DC and SG grazing treatments, and the proportions of N in the first 100 mm of drainage, 100-200 mm drainage and > 200 mm of drainage for each year, numbers with different superscripts are significantly different ($p < 0.05$)

					Annual N load and % of N leached					
					First 100 mm of drainage		100-200 mm of drainage		> 200 mm of drainage	
			Annual N leached (kg N/ha)	% reduction in N leaching from DC grazing	N leached (kg/ha)	% of annual N loss	N leached (kg /ha)	% of annual N loss	N leached (kg /ha)	% of annual N loss
2014	NO_3^-	DC	4.42 [a]	40	3.95	90	0.47	10	-	-
		SG	7.24 [b]		6.58	89	0.66	11	-	-
	TN	DC	5.81[a]	33	4.98	86	0.83	14	-	-
		SG	8.64[b]		7.66	89	0.98	11	-	-
2015	NO_3^-	DC	4.77 [a]	17	3.08	65	1.14	24	0.55	11
		SG	5.72 [a]		3.88	68	1.45	25	0.39	7
	TN	DC	8.96 [b]	8	4.56	51	2.66	30	1.74	19
		SG	9.78 [b]		5.40	55	2.99	31	1.39	14

6.3.6 Total nitrogen in drainage

Total N in drainage water consists of all mineral and organic forms of N. Concentrations of TN in drainage water and the cumulative leaching loads showed a similar trend to those observed for NO_3^-, with the TN concentrations for both treatments decreasing as the drainage season progressed (Figure 6.5). Similar trends to NO_3^- are not unexpected, as a large proportion of TN was comprised of NO_3^- (Table 6.6). As for NO_3^- concentrations, there was a significant difference ($p < 0.05$) between the TN concentration in drainage from SG and DC grazing treatments during the 2014 season, but not in 2015. Peak concentrations of TN for the SG treatment were 14.85 and 8.77 mg N/L in 2014 and 2015, respectively. In 2014 and 2015 the peak TN concentrations for the DC treatment were 10.35 and 6.97 mg/L, respectively. In both seasons and for both treatments, TN concentrations stabilised after a period of initial drainage. In 2014, TN concentrations were consistently between 3–6 mg N/L from the end of June, after approximately 75 mm of accumulated drainage, and between 2–3 mg/L after approximately 150 mm of accumulated drainage in 2015. In both seasons, these levels were maintained until approximately the start of December, when a slight increase in concentrations was observed.

The annual average TN loads in drainage for the SG treatment were 8.64 and 9.78 kg N/ha for 2014 and 2015, and for the DC treatment were 5.81 and 8.96 kg N/ha, respectively (Table 6.6). Losses from the DC treatment were 33% lower ($p < 0.05$) than the SG treatment in the 2014 season. However, in 2015 the TN losses in drainage were only 8% lower for the DC treatment compared to the SG treatment, and this difference was not statistically significant. There was an experimental period average TN loss reduction of 21% for the DC treatment. This reduction was slightly smaller than the corresponding experimental period average reduction in NO_3^- leaching.

The NO_3^- concentrations in 2015 were minimal from late August and, therefore, the majority of TN losses following this date are presumed to be total organic nitrogen (TON) (Figure 6.4 and Figure 6.5). However, the ratio of NO_3^- to TN over the same period for 2014 was higher, with less TN as TON. This pattern can be seen (Figure 6.6), with 2014 having a higher percentage of TN (kg/ha/yr.) as NO_3^-, compared to the 2015 season. This result differs to that of Christensen et al. (2018b) who reported the majority of TN losses as TON from August onwards, across a similar three year trial. However, Christensen et al. (2018b) had very similar drainage volumes over the three seasons of their experiment, while in the current study drainage depths varied between years, which is likely to have contributed to differences in the proportion of TON in drainage TN losses (van Kessel et al. 2009).

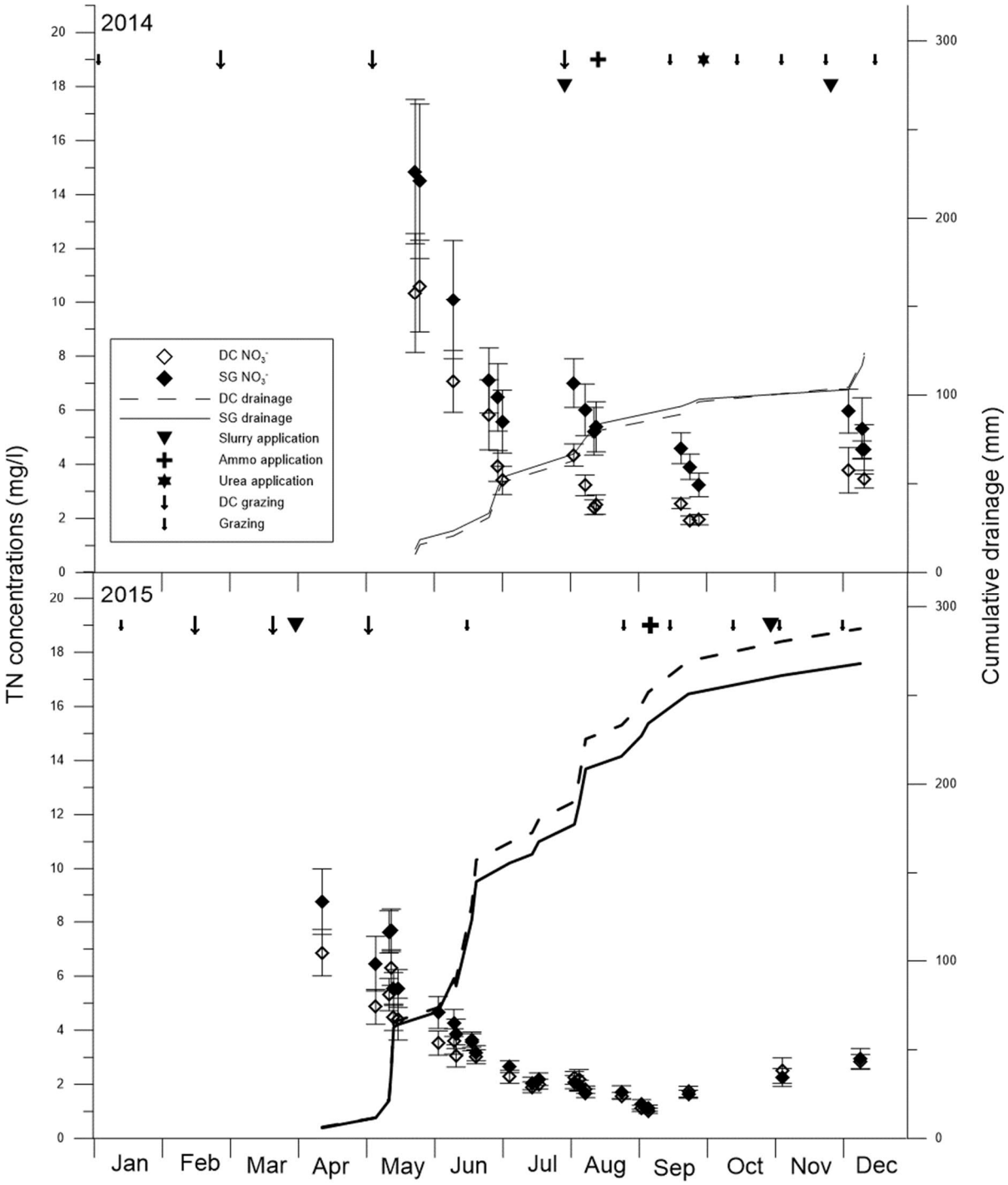

Figure 6.5 Concentrations of TN in drainage water for 2014 and 2015 with cumulative depth of drainage (mm) for DC and SG grazing treatments, error bars show standard error of the mean.

The 2014 season, with under half of the drainage depth of 2015, has a greater proportion of TN as NO_3^- (Figure 6.6). This is due to the first 100 mm of drainage (2014) taking nearly the entire drainage season to occur, and thus the NO_3^- was not flushed out of the soil as quickly as that of the 2015 season when the first 100 mm of drainage occurred by the start of June. However, while the proportion of TN lost as NO_3^- varied between years, the range (83-90% in 2014 and 69-76% in 2015) is very similar to the ranges reported by Hanly (2012) (55-82%) and Christensen et al. (2018b) (60-80%) in similar trials, and reported by van Kessel et al. (2009) (71-95%) when reviewing 11 pasture trials with various N inputs and precipitation.

While there were varying differences in the amount of TN leached as NO_3^- between the seasons (due to varying seasonal drainage), the amount of TON leached/mm drainage was relatively uniform (Figure 6.7). between treatments and experimental seasons, providing a more or less constant background concentration of TON in drainage that does not appear to be greatly influenced by grazing treatment. This is seen in Figure 6.7, where the percentage of TN as TON is very similar for each treatment for both 2014 and 2015. This relatively constant background TON would be expected given that the main sources of TON in agricultural soils are crop/pasture residues and soil organic matter (van Kessel et al. 2009), with TON being formed as part of the decomposition process. Thus, TON in soils is a stable pool (Quan et al. 2018) (long turnover or residence time) mainly composed of natively derived inert components, less affected by N addition from urine deposition (van Kessel et al. 2009). In addition, high mineralisation and sorption rates can buffer TON in soils (Ros et al. 2009), thus keeping levels relatively consistent. In both years (Figure 6.7), there is very little observable difference between treatments, with an average for the DC and SG treatments in 2014 of 11.9 and 11.3 g N/mm of drainage respectively, and 13.7 and 14.4 g N/mm of drainage

in 2015 respectively. The two year average for both treatments combined was approximately 13 g N/mm of drainage.

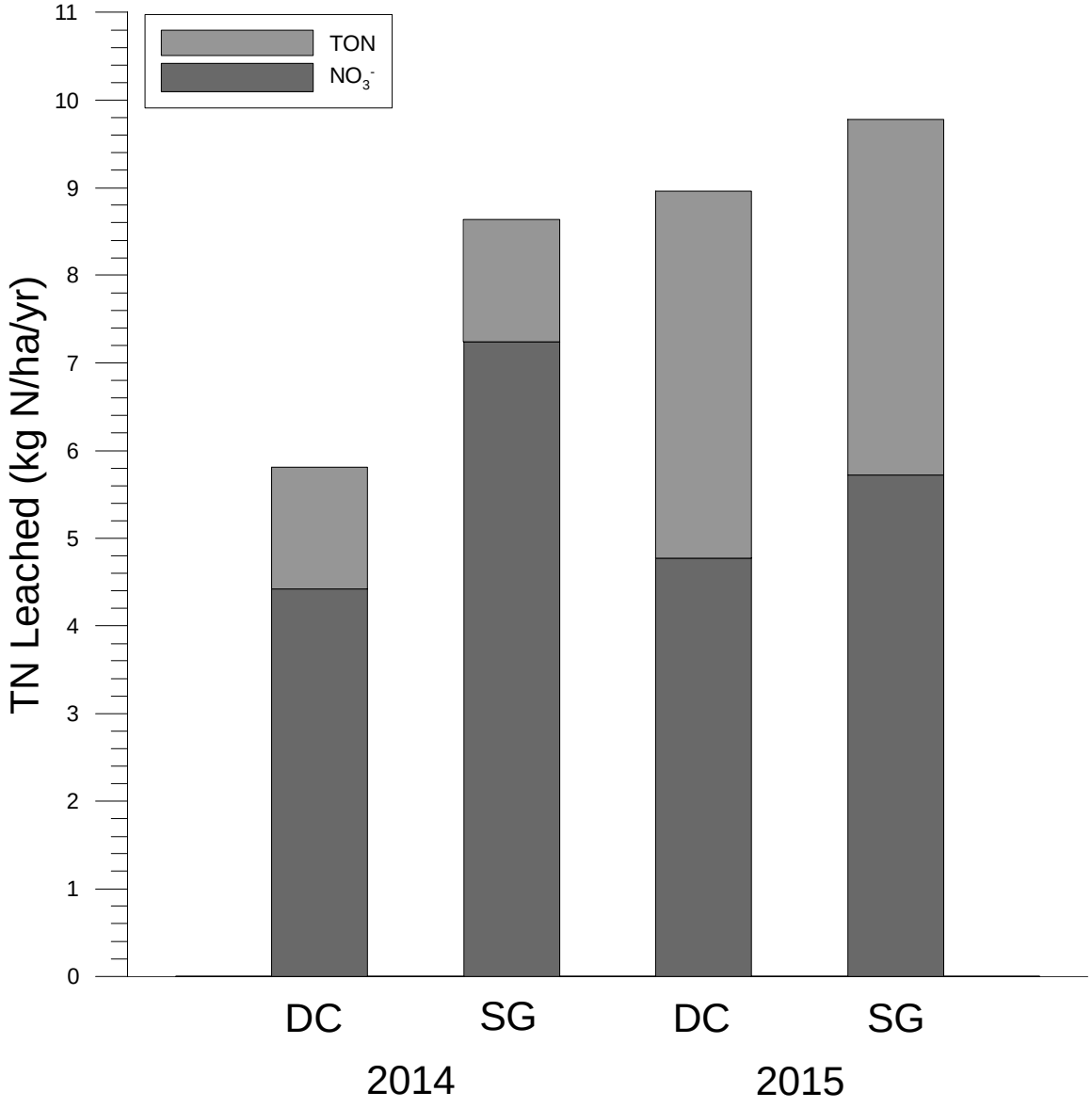

Figure 6.6 Total organic nitrogen (TON) and measured NO_3^- leached from DC and SG treatments in 2014 and 2015.

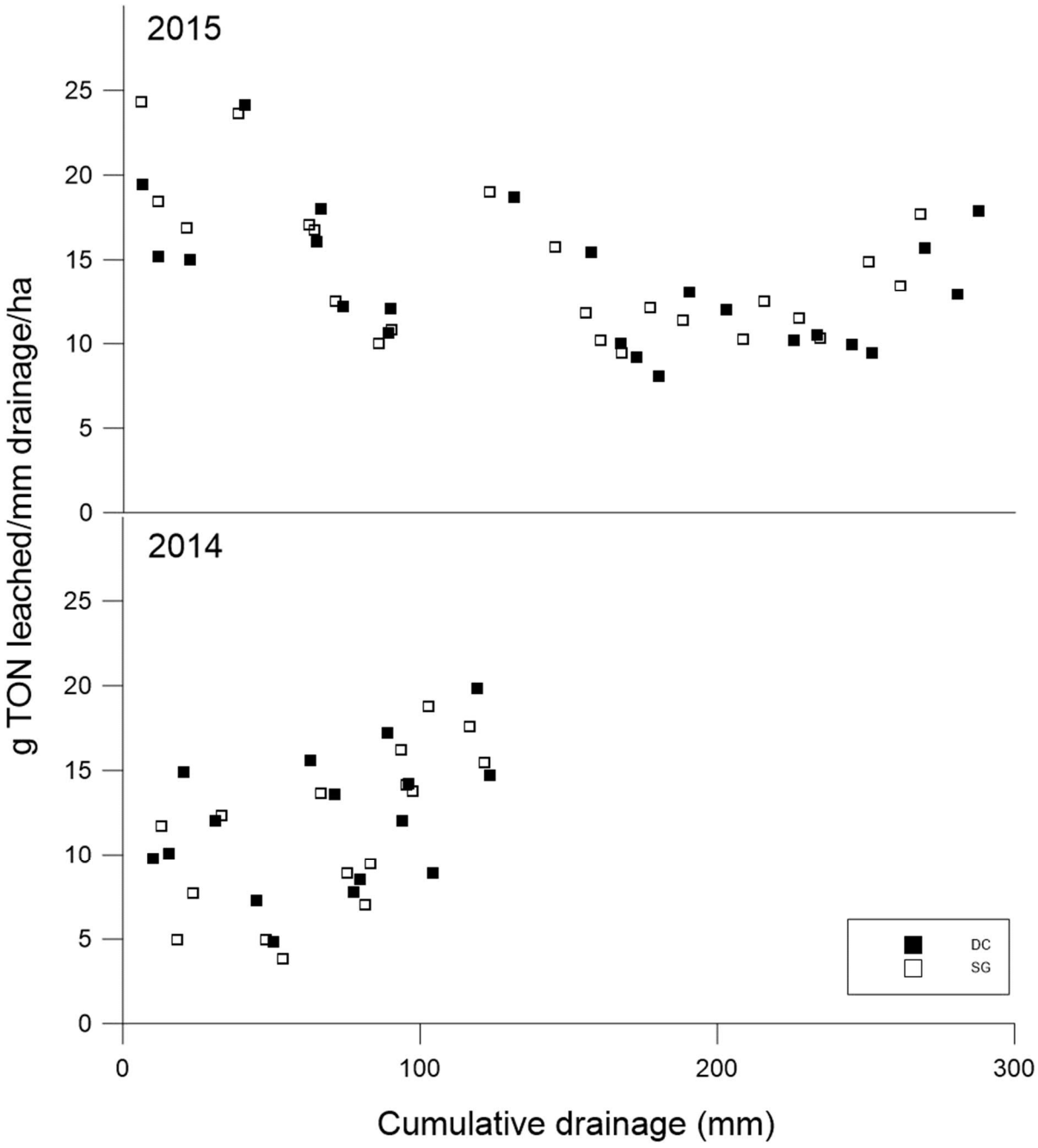

Figure 6.7 Total organic nitrogen (TON) leached with cumulative drainage from DC and SG treatments.

6.4 Discussion

Duration controlled grazing was targeted to a period that has previously been alluded to as a critical period (i.e. late summer to early winter) for the accumulation of NO_3^- in the soil that will subsequently be at risk of leaching (Cuttle & Bourne 1993; Decau et al. 2004; Shepherd et al. 2010; Vogeler et al. 2010; Shepherd et al. 2011; Christensen et al. 2018b). Previous work by Christensen et al. (2018b) on year-round DC grazing has shown that NO_3^- and TN losses to water can be reduced by 52% and 42% respectively, by reducing cow grazing hours by ca. 60% year-round.

6.4.1 Effect of targeted duration controlled grazing on NO_3^- leaching

In both experimental seasons and for both treatments, there was a general trend of high NO_3^- concentrations at the start of the drainage season, which rapidly declined over subsequent drainage events. What was interesting about the decrease in concentrations of NO_3^- in drainage, is that neither spring grazing events nor the N fertiliser applications appeared to increase concentrations of NO_3^- in drainage. This could be due to a number of factors, including the spring being an active period for pasture growth and increased NO_3^- uptake by pasture (Christensen et al. 2018b), as well as the potential for denitrification in warm wet soils (Saggar et al. 2004; Luo et al. 2008). However, drainage events in December did show small elevations in NO_3^- concentrations. These late drainage events followed periods of relatively high soil moisture deficits, and therefore only a small accumulation of NO_3^- in the drainage was observed. This could be due to the actively growing pasture being able to take up the NO_3^- more effectively than pasture under water stress during the critical period. This slight increase in NO_3^- concentration in early summer drainage has previously been reported by other studies conducted at this experimental site (Houlbrooke et al. 2008; Hanly 2012; Christensen et

al. 2018b). This indicates that the critical period could potentially include December onwards, particularly in seasons when drainage extends into early summer, or when the drainage season commences early in late summer or early autumn, due to atypically high summer rainfall, such as occurred at this site in 2009 (Christensen et al. 2018b).

The lower concentrations of NO_3^- observed in drainage for DC grazing treatments is a reflection of the reduced urine patches being deposited on pasture (Christensen et al. 2018a), due to the reduction in cow grazing hours on this treatment compared to the SG treatment. The period of high concentrations of NO_3^- at the beginning of each drainage season was the main contributor to annual NO_3^- leaching losses from both treatments. Compared with SG grazing, targeted DC grazing resulted in an average reduction in NO_3^- leached to water of 28%. This was achieved with an average reduction in annual grazing time of 21% compared to the SG treatment.

In this experiment there were lower drainage NO_3^- concentrations from both treatments compared to that reported by Christensen et al. (2018b). The reason for this difference may be explained as follows: the average pasture production in the Christensen et al. (2018b) study was 13,570 kg DM/ha, whereas the current experiment averaged only 10,222 kg DM/ha. This would have resulted in the potential for less N to be cycling during the different experiments, compared to Christensen et al. (2018b) and, therefore, less leachable N in the system potentially. Owing to less pasture grown, there was a lower stocking rate and reduced cow grazing hours that in turn would decrease the amount of N leached from both treatments. For example, in the current study the grazing intensity ranged from 70 to 180 cows/ha/grazing, whereas in the Christensen et al. (2018a) study, there were reported intensities ranging from 235-353 cows/ha/grazing.

The lower NO_3^- losses for the DC treatment in the present study represented annual reductions of 40% and 17%, respectively, providing a two-year average reduction of 28%. This compares to NO_3^- leaching reductions of 53% reported by Christensen et al. (2018b), as a result of year-round DC grazing that had an approximately 60% reduction in grazing time (Christensen 2013). In comparison the current trial using modified DC grazing resulted in only a 21% annual reduction in grazing time while still achieving an average reduction in NO_3^- of 28%. This reduction in NO_3^- leaching, while smaller than Christensen et al. (2018b), is still a substantial reduction, given the shorter amount of time the cows are off pasture during the grazing season. It is this shortened period of standoff which makes targeted DC grazing more appealing than year-round DC grazing (even though year-round DC grazing delivers a bigger reduction in NO_3^- leaching). The reason for this is the implementation of year round DC grazing requires the inclusion of cow housing or suitable standoff facilities to the farm system (Christensen 2013). These structures are costly and can pose a financial risk to the farmer (Christensen 2013), even though they can provide valuable reductions in NO_3^- leaching. The shorter period of standoff could possibly allow farmers to use current standoff facilities (i.e. feed pads) or to build cheaper alternative options (rather than a free stall barn) that would only need to house cows over the critical period (a significantly shorter time than year-round DC grazing), but still gain substantial reductions in NO_3^- leaching for a much lower financial investment (Hanly et al. 2014). The management and financial performance of such a system was not investigated in this study. However, it does give rise to an interesting question as to whether NO_3^- leaching could be adequately mitigated following relatively low cost modifications to an existing feed pad (of which is common on modern dairy farms), thus allowing greater standoff of cows later in the lactation season (Hanly et al. 2014), without as big a financial risk to the farmer.

In this study, there was relatively high variation (between experimental years) in the percentage reduction of NO_3^- leaching between the DC and SG treatments. It is important to recognise the cause of this variation, so that results from this field trial can be used to inform the parameterisation of software used to support decisions for farm management changes to reduce farm N loss (i.e. Overseer). One of the reasons for the inter-year difference in NO_3^- leaching concerns when the night grazings (during the critical period) were performed between each season. During the night grazings there will be a larger difference between DC and SG grazing hours (day grazing DC = 4 hr, SG = 7 hr, night grazing DC = 4 hrs, SG = 13 hrs) and, therefore, more urine will be deposited in this grazing period in the SG treatment. In the 2014 season (with the 40% difference in NO_3^- leaching) there were two night-grazings and both of these were late in the season (May onwards). During this period of the grazing season (prior to the main drainage season) it could be expected that a greater loss of NO_3^- would be observed (Cuttle & Bourne 1993; Shepherd et al. 2011). In comparison, during the 2015 season there was only one night-grazing (during the critical period) and this occurred in late March. However, the main reason for the percentage difference in NO_3^- leaching observed between seasons can become clearer when the cow grazing hours during the critical period for both seasons are investigated closer. For example, during the DC grazing period (2014) there were 188 and 541 cow grazing hours for the DC and SG treatments respectively; this is a 65% reduction in cow grazing hours between the DC and SG treatments, and the percentage reduction in NO_3^- was 40% for the season. This percentage reduction in cow grazing hours over the critical period is very similar to that of historical N leaching trials conducted on the same experimental area (J. Hanly pers comm) with the percentage reduction similar to that reported in the literature for similar experiments (where restricted grazing was only over the autumn period) by de Klein et

al. (2006) and Monaghan et al. (2016). During the critical period (2015) there were a total of 214 cow grazing hours for the DC treatments and 346 cow grazing hours recorded for the SG treatments. This difference gives only a 38% reduction in cow grazing hours between the DC and SG treatments (in the critical period), and the resulting percentage reduction in NO_3^- was only 17% for the season. There were minimal differences in cow grazing hours for the DC treatment, 188 (2014) vs. 214 (2015) (between experimental seasons) during the critical period and minimal differences (between DC grazing seasons) in annual NO_3^- leaching 4.42 kg N/ha (2014) vs. 4.77 kg N/ha (2015). This highlights the importance of cow grazing hours during the critical period. For example, in 2014 the SG cow grazing hours during the critical period were 541 with an annual total of 1256, giving 43% of the annual cow grazing hours occurring during the critical period with a reported NO_3^- leaching of 7.24 kg N/ha/yr. However, during 2015 there were only 346 cow grazing hours with an annual total of 1181, resulting in only 29% of the annual cow grazing hours and a lower reported NO_3^- leaching of 5.72 kg N/ha/yr. This, therefore, points to the reduction in SG cow grazing hours during the critical period of 2015 (and thus the urinary N load) being a major contributor to the lower NO_3^- leaching observed in 2015 than in 2014. Therefore, it could be assumed that if the SG cow grazing hours during 2015 had been similar to that of 2014, then the reported average percentage reduction in NO_3^- leaching between the DC and SG treatments (28%) may have in fact be closer to 40% (2014 season).

The average annual reduction in TN leaching load from the DC treatment (21%) was lower than the NO_3^- load (28%). This reflects the relatively constant amount of TON leached from both treatments, which appeared not to be influenced by grazing treatment or slurry return. The most likely source of background TON, observed in this trial, is the decomposition of plant litter and soil organic matter (van Kessel et al. 2009;

Christensen et al. 2018b). Given the average drainage recorded for each season (123 and 278 mm) and the average TON loss observed was 13 g TON/mm drainage, this would indicate that 1.6 kg and 3.6 kg TON ha/yr would be leached in 2014 and 2015 respectively, regardless of the intensity of grazing management (and consequent urine deposition).

This further reinforces the fact that the modelling of TN leaching losses needs to consider not only NO_3^- leached, based on urinary N return predominantly in late summer/autumn, but also needs to account for drainage depth to estimate potential TON leached (van Kessel et al. 2009).

The above discussion re-enforces the large contribution that urine spots deposited in the late summer-autumn period are having on annual NO_3^- leaching, and that restricting grazing duration during this critical period can have a significant effect on NO_3^- leaching. Given that the proportional reduction in cow grazing hours is considerably lower when compared to year-round DC grazing (and therefore may require less financial investment to implement), farmers could more easily change their grazing management to include late summer/autumn DC grazing to gain a reduction in NO_3^- leaching from their farm.

6.4.2 Effect of Slurry return on N leaching

Slurry was returned to the DC treatments twice each experimental year. The form of N in the slurry applied varied between years with 2014 and 2015 seasons being 54% and 33% inorganic N, respectively. The application of TN in slurry was 91 and 169 kg N/ha for 2014 and 2015, respectively, with the largest application being 105 kg N/ha in early April. Despite the high rates of slurry applied, NO_3^- concentrations in drainage on the DC treatment remained lower than the SG treatment. Over both years there was no

evidence that the applications of slurry increased N leaching. Slurry applications were carried out during dry soil moisture conditions, well in advance of any drainage period, in an even manner and with relatively low rates of min-N. Therefore, there was minimal risk of direct loss of slurry to water during application, which is when the predominate losses are expected from effluent application. Also, plant uptake of N and immobilisation of N from the slurry would have resulted in lower surplus N in the soil, compared with the highly concentrated return of N in urine spots. However, what is unclear from this current trial is that if slurry had been applied at a lower rate over a greater number of applications, could the difference in NO_3^- leaching have been greater between the two treatments?

6.4.3 Effect of Slurry return on pasture production

On average across the two years, the use of DC grazing during the critical period, when combined with slurry return, did not reduce pasture production compared to the SG treatment, with a small advantage (8%) in pasture production seen in the 2015 season. This percentage increase in pasture production is similar to that reported by de Klein (2001) when modelling DC grazing systems (2 - 8% increase in pasture production predicted from slurry return). The significant increase in pasture accumulation observed in the 2015 season could most likely be attributed to a high nutrient load in an April application of slurry.

The fact that the return of slurry to the DC treatments had little impact on increasing pasture production, when compared to the SG treatment, is not surprising given that Christensen et al. (2018a) reported no increased benefit to pasture production from slurry applied to DC treatments in a similar trial. However, it is clear that slurry needs to be applied back to areas that have been DC grazed to ensure pasture accumulation is

not compromised Christensen et al. (2018a). The results presented in this chapter suggest that the application of slurry to DC farming systems should be seen as a method of ensuring pasture production stays at the status quo, rather than being an economic tool to either replace fertiliser or grow extra pasture (to allow for greater animal production).

6.5 Conclusion

The use of DC grazing that targets just the critical period for NO_3^- accumulation (i.e. the late summer-early winter period), with the uniform return of slurry, showed that a significant reduction in NO_3^- leaching load can be achieved. By reducing annual cow grazing hours by an average of 21% (targeting the critical period) a reduction in NO_3^- and TN leaching losses of 28% and 20% (respectively) was achieved. The results presented in this chapter highlight the importance of limiting the duration of summer-early winter grazings, as well as re-enforcing the importance of the urine patches deposited during this period, and the effect they have on the concentration of NO_3^- in winter drainage water. The uniform return of slurry (during various times of the year) did not increase NO_3^- losses compared to the SG treatment, but the return of slurry had minimal effect in increasing pasture production. Therefore, the application of slurry to DC farming systems should be seen as a method of ensuring pasture production stays at the status quo, rather than being an economic tool to either replace fertiliser or grow extra pasture (to allow for greater animal production).

7 HYPOTHESES ADDRESSED, GENERAL DISCUSSION AND CONCLUSIONS

7.1 Introduction

At the time of writing, environmental regulations for New Zealand's primary industries are undergoing a paradigm shift. In early September 2019, the Government released the 'Action for Healthy Waterways' (AHW) (MfE 2019), which has the following objectives:

1. Stop further degradation of New Zealand's freshwater resources and start making immediate improvements so that water quality is materially improving within five years.
2. Reverse past damage to bring New Zealand's freshwater resources, waterways and ecosystems to a healthy state within a generation.
3. Address water allocation issues having regard to all interests including Māori and existing and potential new users.

Two of the key environmental issues identified in the AHW, namely the high levels of dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) in NZ waterways, are frequently linked to dairy farming, particularly in regions such as Southland, Canterbury and parts of Waikato. Dairying in these regions face major challenges as the AHW estimates that N loss from many of these farms must be reduced by at least 50%. Furthermore, the poor management of winter grazing (with dairy farms, again, under the spotlight) where cows are grazing severely pugged paddocks has come under increasing public scrutiny. The pastoral industries do not want to promote images of animals standing in mud. In summary, the AHW is a major development in regulatory changes, which seek to further protect soil and water resources from degradation, and that forms the context for the study reported here.

Duration controlled (DC) grazing is recognised as a mitigation measure for the twin problems of environmental and soil protection outlined above. Accordingly, the overall objective of this thesis was to explore the management of DC grazing and how it can be modified or improved, particularly as it relates to: 1) the interaction between DC grazing in the winter-spring period and treading damage, and 2) the N leaching that results from grazings in the 'critical' period of mid-summer to early-winter (Shepherd et al. 2010; Shepherd et al. 2011; Christensen et al. 2018b). Therefore, the subject of this thesis and its results are highly relevant to the current political/environmental situation, and the certainty of increased regulation regarding nutrient loss and winter grazing in the future. More than ever, farmers and industry professionals will be looking for effective and practical N leaching mitigation methods, as well as improved strategies to reduce winter grazing damage.

Duration controlled grazing has two purposes and associated management strategies. The first of these is to reduce N leaching by only allowing cows to graze for a limited period (e.g. 4 hours) at any grazing, with the rest of their day spent off-paddock in structures, such as a free stall barn. This has been proven to be very successful at reducing N leaching (Christensen et al. 2018b). The second reason that DC grazing is practised is to protect pasture and soils from pugging damage in wet conditions (i.e. typically in the winter/early spring period). Shorter grazing intervals have also been shown to reduce treading damage to pasture and soils (Drewry 2003; Zegwaard 2006). However, while there have been a number of studies of these larger benefits of DC grazing, there has not been any detailed research into the means to modify or improve the management of DC systems.

7.2 Evaluation of Hypotheses One

Hypothesis 1: Even on farms with extensive standoff facilities, it will often be necessary to graze pasture in wet conditions (i.e. near saturation) in order to maintain pasture quality, but providing that these grazings are confined to relatively short periods (i.e. four hours) the associated treading damage will have a relatively small effect on pasture production and will not undermine the overall efficacy of DC grazing management.

This study revealed that on a fine textured soil, such as the Tokomaru silt loam, treading damage to the soil surface can be expected if cows graze when the SWD is less than a critical value of 2 mm, and that this damage will be more severe at longer grazing durations (i.e. 8 hours in this study). Modelling in this thesis suggests that under BMP (i.e. DC grazing) the need to control pasture covers will result in the frequent grazing of wet soils and the damage of relatively large areas of the farm. In a year of average rainfall, up to 60% of the farm area may be damaged. While there is a short-term small reduction in APP of approximately 500 kg DM/ha following a winter grazing of four hours duration when the SWD is < 2 mm, there is unlikely to be a long-term effect i.e. on the annual APP. The shorter grazing period of 4 hours resulted in less damage and better short term APP compared to the 8-hour grazing duration. Therefore, the need to graze in wet conditions (at or near saturation) for short durations (up to 4 hours) in order to protect pasture quality need not undermine the usefulness or overall success of DC practices.

7.2.1 General discussion

As noted above, the use of DC grazing has the benefit of protecting soils and pastures from treading damage during wet conditions. Treading damage is a perennial issue on dairy farms throughout New Zealand, but it is especially challenging on fine textured

soils, such as those found in the Manawatu and Southland regions (Drewry et al. 2000). On a fine textured soil, such as the Tokomaru silt loam, treading damage to the soil surface can be expected if cows graze when the SWD is less than some critical value and the degree of damage will be less severe at shorter grazing durations. The research on the adverse impacts of prolonged grazing of dairy cows on very wet soils is convincing: if cows graze an area of near-saturated soil for periods of 12 to 48 hours then severe damage will be inflicted on both soil and pasture. The consequences of this damage are widely appreciated by dairy farmers on fine-textured soils, many of whom have strategies in place to reduce the extent of treading damage. However, there is very little understanding of the relationship between soil moisture content, grazing duration and the severity of treading damage, to inform the day-to-day management of these strategies.

This study set out to identify the critical SWD criteria for a fine textured soil and to elucidate the relationship between treading damage, SWD and grazing duration. Firstly, however, there was a challenge that related to the available methods or techniques to measure treading damage. Treading damage on wet soils can be easy to observe, but it can be time consuming to actually measure and even more difficult to quantify in a spatially aware manner. As a result, there are no commonly agreed upon methods to assess the extent and severity of treading damage to soils or pasture. Therefore, two new methods of assessing treading damage, the *visual scoring method* and the *pugometer*, were designed as part of the research presented in this thesis (Chapter 3). The first technique, the *visual scoring* method was developed as a user friendly simple tool to help farmers assess the extent of treading damage so that they can gauge: when grazing should cease and/or recommence, anticipate and plan for a likely feed deficit if large areas of the farm are damaged, and identify paddocks to crop and use for

pasture renewal. The second method, the *pugometer* provides a more quantitative technique that is capable of measuring and mapping treading damage in a more detailed manner. Both of these new methods are considered to be appropriate at various scales, from small research areas to large plots and paddock-scale measurements. The two new methods correlated well against more established methods like the *depth of pug* and *roller chain* methods (R^2 0.75 to 0.87). Both of these new methods were easy to perform and infinitely quicker than more established measurement methods. However, the advantage of the *pugometer* is that it can capture spatial variability rapidly and automatically.

The methods that were developed to assess treading damage were employed to study the extent of treading damage over a range of SWDs (Chapter 4). Only minor treading damage was associated with grazing at SWD > 2 mm. Furthermore, grazing interval (i.e. four or eight hours) had no significant effect on damage at these slightly larger SWDs (> 2mm). Therefore, dairy farmers on fine textured soil, similar to the Tokomaru silt loam, could use this 2 mm SWD as a guide as to when soils are too wet to graze and, therefore, cows should be removed from paddocks. Conversely, following standoff, grazing can resume once a deficit of 2 mm is reached, which is close to the 3 mm SWD recommended by Laurenson and Houlbrooke (2016) on fine textured soils. It should be acknowledged that there is probably no unique critical SWD value for a soil, and that the value of 2 mm proposed here is for relatively short grazing durations (four to eight hours). If an area had to sustain grazing for 24 hours, then the critical SWD may well be greater i.e. the soil may need to be drier to adequately support animals for a longer grazing interval.

In theory, the most straightforward way to protect wet soils and pastures from treading damage would be to remove the grazing animals until soils can be safely grazed (i.e.

SWD > 2 mm). However, for some climate/soil combinations, this could involve weeks (in the middle of winter to early spring) of little to no grazing time. This prolonged standoff needs to be balanced against other concerns. For example, standing cows off during wet conditions may result in increases in average herbage mass and, consequently, reductions in pasture quality (Kemp et al. 1999) and depressed net pasture growth rates because of greater losses through senescence (Chapman & Lemaire 1993). This is more likely to be a major consideration in the North Island, where pasture growth rates in the wet winter period might be greater than 15 kg DM/ha/d (DairyNZ 2019a). In contrast, it could be argued that in Southland where winter pasture production is minimal (Smith 2012) that this wouldn't be a pressing problem. Therefore, even those farms with standoff facilities which enable year-round standoff will still have to graze wet soil (SWD < 2 mm) when the need to control winter/spring pasture covers overrides the necessity to protect them from the very real damage quantified in this study. This raised the interesting question as to the extent of damage on a dairy farm practising DC grazing on a fine textured soil (i.e. how frequent damage and what area of a farm is is damaged). A follow-up question is: will, paradoxically, the treading damage associated with the requirement to graze longer pasture in wet conditions undermine the utility and effectiveness of DC grazing as a means of preventing treading damage? In other words, on fine-textured soils, the system-level effects of DC grazing on pasture production are not well known.

The Dairy NZ Whole Farm Model (WFM) was used to identify the extent of treading damage under DC grazing on the Tokomaru silt loam soil (in the Manawatu) (Chapter 4). This simulation exercise suggests that under DC grazing in this situation, the need to control pasture covers in early lactation will result in the frequent grazing of wet soils when the SWD is less than the critical value of 2 mm and, therefore, damage to relatively

large areas of the farm appears to be unavoidable. In an average year, up to 60% of the farm area may be damaged. Furthermore, about half of this will be repeat damage (damaged at least twice). This is compared to a wet year (when DC grazing will be most needed) when 90% of the farm will be damaged, and half of this being at least a double damage. Interpreted in isolation, this modelling exercise would suggest that the requirement to graze in wet conditions in order to maintain pasture quality is going to markedly constrain the ability of DC grazing to protect soil and pastures.

This raises the obvious and important question as to what is the impact of grazing wet soil under the DC protocol on pasture production? The effect of relatively short grazing durations (four and eight hours) in wet conditions on pasture production was quantified in a field trial (Chapter 5). It was found that while the damage inflicted on pastures might look unsightly the effect on pasture production seems to be more short term and this damage may have very little influence on overall accumulated (annual) pasture production. A single grazing (damage event) in winter at SWD < 2 mm (the critical value) may result in reductions in APP of ca. 500 kg DM/ha (4hr and 8 hr durations). This penalty to short term pasture production for an eight hour grazing lasts for approx. 127 days (from grazing date), whereas the four hour grazing penalty is 21 days shorter. While 500 kg DM/ha may not seem like a large quantity of pasture, it must be remembered that this is valuable pasture as it is lost at a time when growth rates are slow and there is typically a feed deficit.

Winter is not the only time of year in which widespread treading damage can be expected: spring can also be a time of considerable damage. In addition, there is a good chance that this spring damage will be inflicted on paddocks (as shown by the WFM Chapter 4) that were damaged in winter (i.e. repeat damage). However, as long as the grazing interval is relatively short (four hours in this study), this repeat damage in spring

is unlikely to result in a further reduction in APP. However, a repeat grazing for 8 hours can result in a further short-term reduction of ca. 500 kg DM/ha. Again, this points to the advantages of a four hour grazing duration over an eight hour interval.

While the loss of this relatively small overall quantity of pasture discussed above may not be a major problem in dry or average winters, such a reduction may result in more of a challenge in wet years when, as noted above, upwards of 90% of the farm's pasture area may be damaged. However, it bears repeating that while the short-term reduction in pasture may be unavoidable and not ideal given that it coincides with peak lactation, it appears to have no long-term effect on APP i.e. annual pasture production is not likely to be significantly affected. The relative weighting or importance of the short-term impact versus long-term effect of treading damage will vary from farm to farm.

7.3 Evaluation of Hypothesis Two

Hypothesis 2: While large reductions in N leaching have been achieved under year-round DC grazing, substantial reductions in N leaching can also be achieved when duration controlled grazing is only practised during the late-lactation period (i.e. critical period).

The use of DC grazing that targets just the critical period for NO_3^- accumulation in the soil profile (i.e. the late summer-early winter period), with the uniform return of slurry, showed that a significant reduction in NO_3^- leaching load can be achieved. By reducing annual cow grazing hours by an average of 21% (targeting the critical period) a reduction in NO_3^- and TN leaching losses of 28% and 20% (respectively) was achieved.

7.3.1 General discussion

The study by Christensen et al. (2018b) reports a large reduction in N leaching (ca. 50%) from practising year-round DC grazing. The infrastructure required to achieve this level

of standoff and N leaching reduction involves a large capital investment by the farmer. However, there is some evidence in the literature to suggest that there could be an opportunity to restrict DC grazing to the critical period of late-summer to early-winter, when relatively large amounts of NO_3^- accumulates in the soil profile (Shepherd et al. 2010; Shepherd et al. 2011; Christensen et al. 2018b). This NO_3^- is particularly vulnerable to leaching. Duration controlled grazing during this period will reduce the amount of NO_3^- in the soil at the commencement of the drainage season and so mitigate N leaching. Confining DC grazing to the critical period, rather than year round, may afford the farmer the opportunity to construct less costly standoff facilities, which could make DC grazing for environmental protection more financially viable. However, an economic analysis was beyond the scope of this study.

The results presented in this thesis reinforce our understanding of the connection between the concentration of NO_3^- in winter drainage and the urine patches deposited during the critical period and, therefore, highlights the importance of limiting the duration of late-summer to early-winter grazings. For example, in Chapter 6 it was shown that irrespective of drainage season and grazing treatment, the highest NO_3^- concentrations occurred in the first seven to eight drainage events, which equated to the initial 50 to 100 mm of drainage. Following this, NO_3^- concentrations in drainage were small, suggesting a reduced effect of urine patches deposited after this period.

The average reductions in NO_3^- and TN leaching over the two drainage seasons in this study were 28% and 20% (respectively). This was achieved by reducing yearly cow grazing hours by 21%, whereas year-round DC grazing (to reduce N leaching by 50%) requires ca. 60% yearly standoff time. As noted above, the reduction in cow grazing hours, and associated increase in standoff time, for summer-autumn DC grazing is considerably lower than year-round DC grazing, and so could be practised using a less

complex standoff facility (such as an uncovered feed pad) that may require less financial investment to implement. DC grazing which is confined to the critical period is likely to be well suited to free draining soils where DC grazing may not be required for protection of soil and pasture in winter and spring.

Given the increasing need for dairy farms to reduce N leaching due to the current and future environmental/political climate, DC grazing offers the ability for farmers to achieve substantial reductions. While implementing DC grazing during the late summer to early winter period was effective at reducing N leaching by 28% on average (this could possibly be up to 40% depending on season), it is conceivable that further reductions could be achieved by extending the practice to include early summer. This may make DC grazing an adjustable mitigation option – more standoff for greater reductions in N leaching - for farmers who may need to continue to demonstrate greater reductions in N leaching over time to enable them to continue farming under likely future regulations.

An important implication of DC grazing is the need to manage greater amounts of effluent. Even with the uniform return of slurry (during various times of the year) to the DC plots they still achieved lower NO_3^- leaching compared to the standard grazing treatment. It is often argued that a further advantage of standoff and the capture of excreta is that, unlike urine patches, effluent slurry can be returned more uniformly across paddocks, thereby potentially growing more pasture. However, while the uniform return of slurry contributed to the DC plots maintaining similar pasture production compared to the standard grazing treatment, it did not consistently result in increased pasture production. Therefore, the results presented here suggest that the application of slurry to DC farming systems may be seen as a method for maintaining pasture production rather than a means of growing extra pasture.

7.4 Conclusions

- Using DC grazing during only the critical period resulted in an average 28% reduction in NO_3^- leaching with only a 21% overall average reduction in yearly grazing time. This can be seen as a valid part of a wider mitigation toolbox to help farmers reduce N leaching to meet new environmental standards such as those proposed in the AHW.
- In terms of NO_3^- leaching, the effectiveness of DC grazing over the critical period is explained by reference to the large proportion of the annual NO_3^- flux that appears in the first 100 mm of drainage. This NO_3^- has accumulated over the preceding summer/early winter period and so the results of this study highlight the importance of limiting the urine input to pastoral systems over this time.
- The results of this study support other studies in showing that the critical time for NO_3^- accumulation in soils appears to be late summer/early winter.
- The application of slurry to DC farming systems should be seen as a method of ensuring pasture production stays at the status quo, rather than being a practice that either replaces fertiliser application or grows extra pasture.
- On a fine textured soil like the Tokomaru silt loam, waiting to graze until there is a SWD of > 2 mm should ensure minimal treading damage to soils and no reduction in pasture production for grazing durations up to 8 hours.
- If compelled to graze at SWD < 2mm then the results presented here suggest that grazing intervals should be kept as short as possible. In this study, there was less soil damage and a smaller reduction in pasture production when plots were grazed for four hours compared to an eight-hour grazing.

- Although substantial areas of a farm which is practising DC grazing on a fine textured soil may incur soil damage, this may not translate into large losses of annual pasture production and does not undermine the integrity of DC grazing as a BMP.
- The *pugometer* and *visual scoring* methods are useful and quick methods for measuring pugging damage in small or large areas. The *visual scoring* method was the quickest and simplest method to perform and so could be employed easily by a farmer. The *pugometer* provided a quantitative measure of the spatial variability of treading damage and so would be a useful research or regulatory tool.

7.5 Limitations of research

- This study only examined the effects of treading damage on a fine textured soil, and at only two grazing intervals. More severe forms of treading damage, from longer grazing intervals and at greater stocking rates, may result in greater and more persistent damage to soils and reductions in pasture growth. For example, 24 hours of grazing at a SWD of 4 mm may well result in substantial treading damage. However, as noted on numerous occasions in this thesis, this study was interested in understanding the interactions between SMD and treading damage under BMP to help refine and improve management on leading farms.
- Furthermore, this study did not look at the long-term accumulative effects of repeat damage over multiple years. Although repeat damage in spring did not appear to result in a compounding effect, little can be said about the effects of repeat damage to soils and pastures year upon year.
- Treading damage in this study was defined in a manner which bracketed soil compaction. Therefore, no connection can be drawn between the critical SWD

value of 2 mm identified here and the compaction caused by the hooves of grazing cows. If the intention was to avoid soil compaction then a drier SWD at grazing may be required.

7.6 Further suggested research

Some key research questions arising from this study are:

- Modelling conducted with Dairy NZ WFM only concentrated on one particular area of the country (central Manawatu). However, as highlighted in the discussion, the standoff requirements in areas of the country that experience low winter pasture growth rates might make the management of DC grazing to protect soils and pasture more straightforward and beneficial. Therefore, nationwide modelling should be undertaken, especially in areas of the country such as Southland (with low winter pasture growth rates) where there may not be the need to graze wet pastures in winter to maintain pasture quality.
- In this study, only one rate of slurry was applied in only two applications due to the ties between the trial and the operations of the general farm system. Therefore, the effects of slurry return at lower rates and more frequent applications may have resulted in a larger difference in NO_3^- leaching between the DC and SG treatments, and potential increases in pasture production. Thus, the rate and timing of effluent/slurry application should be studied further to explore the potential to grow extra pasture and further reduce NO_3^- leaching
- This study was conducted on a fine textured soil. The benefit of standing cows off pasture during the critical period, on free draining coarse textured soils needs to be verified, as the benefits could be greater on these soil types and, as noted,

this could be a very cost effective means of reducing N leaching on these soil types.

- There may be potential to further reduce N leaching using DC grazing that starts early summer (instead of late summer as in this study). A study that extends DC grazing into this period could be useful to see if further meaningful reductions can be made.

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Jay Howes
Name/title of Primary Supervisor:	Associate Professor David Horne
Name of Research Output and full reference:	
[redacted]	
In which Chapter is the Manuscript /Published work:	Chapter 3
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	75%
and	
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The candidate adapted or refined three of the four techniques presented here. He also designed and performed almost all of the field work in this publication. He conducted all of the statistical analysis. He also took the lead role in interpreting the	
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Candidate's Signature:	Jamal Howes Digitally signed by Jamal Howes Date: 2019.11.25 12:27:07 +13'00'
Date:	
Primary Supervisor's Signature:	David John Horne Digitally signed by David John Horne Date: 2019.11.25 12:23:07 +13'00'
Date:	25/11/2019

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