Soil Carbon Stocks Under Fencelines and Adjacent Paddocks to Test the Importance of Dung Returns

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ABSTRACT

Soils are the largest terrestrial store of carbon (C), but agriculture has depleted around 133 Pg C from the upper 2 m of soil, contributing to increases in atmospheric CO_2. Soil C sequestration can help offset these atmospheric increases and is determined by the balance between C inputs and C outputs.

New Zealand's temperate climate supports year-round grazing on approximately one-third of the country's land area. The conversion of New Zealand's native forests to pastures increased soil C stocks, yet the mechanisms behind this increase remain unclear. Grazing animals influence the C cycle through the consumption of C embodied within the feed they eat, with excreta returning C to the soil. Although C balances of New Zealand pastures suggest excreta is an important return of C to the soil, this has been poorly quantified.

The objectives of this thesis were to determine if soil C stocks (0–0.6m) differed between paddock and fenceline areas, assuming the paddock received more dung input. To test this assumption, the spatial distribution of dung in relation to the fenceline was mapped, and dung loading was estimated. Stocks of particulate organic matter C (POM-C) and mineral-associated organic matter C (MAOM-C) were also determined in the top 0.1 m of soil to understand which forms of C contributed to any measured differences in total C stocks. Differences in Olsen P and pH were also determined.

Paddock and fenceline sites (38 pairs) distributed across six farms in the Waikato region were sampled to a depth of 0.6 m. On average, soil C and N stocks were 10.3 t C ha^{-1} ($P = .002$) and 0.96 t N ha^{-1} ($P = .002$) higher in paddock areas when compared to fenceline areas. When excluding one paired site with a very poor match of mineral surface area, the differences decreased to 9.3 t C ha^{-1} ($P = .004$) and 0.86 t N ha^{-1} ($P = .003$). The greatest differences were observed in the 0–0.1 m depth increment. At the 0–0.1 m depth increment, POM-C was significantly greater in paddock samples and largely accounted for the observed difference in total soil C. This suggested that the observed C stock increase was in a more degradable fraction, implying that decreases in dung returns could result in rapid soil C loss. There was no relationship between the age of the fenceline and C stock differences, indicating that differences may have occurred rapidly to a new steady state.

Mapping of 2000+ dug pats showed that paddocks received more dung, with only one pat being within the fenceline sampling zone. The average dung density was 0.2 pats m^{-2} and a dung-C loading rate of 1.1 t C ha^{-1} y^{-1} was calculated.

The detected differences in C stocks due to varying dung input aligned with other studies on cattle manure's influence on soil C, POM-C and MAOM-C stocks. Further research is needed to better understand the contribution of dung returns to soil C and its potential vulnerability to loss.

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CHAPTER ONE

Introduction

1.1. Background

Soils are a large global store of carbon (C), containing more C than terrestrial biomass and the atmosphere combined (Friedlingstein et al., 2023). Since the start of the Industrial Revolution in 1750, atmospheric carbon dioxide (CO_2) concentrations have risen by 50% (Lindsey, 2020; World Meteorological Association, 2023). This increase is primarily driven by the combustion of fossil fuels, which is responsible for approximately two-thirds of the increase, with the remainder attributed to soil C and biomass C losses resulting from land use alterations and cultivation practices (Arias et al., 2021). Various agricultural management practices have led to the depletion of approximately 133 Pg of C from the upper 2 m of soil (Sanderman et al., 2017), leading to a noticeable C loss.

Concerns about climate change and its impacts have increased the importance of finding strategies to mitigate greenhouse gas (GHG) emissions. Reducing fossil fuel usage remains one of the principal strategies for reducing emissions, while an equally significant component of climate mitigation is increasing C sequestration in soil (Amelung et al., 2020). An increase in the interest of land-based C storage as a climate solution has led to the development of the '4 per mille' initiative (4 per 1000, 2022). This initiative suggests that an annual soil organic C (SOC) sequestration rate of 0.4% of current soil C stocks could offset current annual CO_2 emissions from fossil fuel combustion. This initiative aligns with the objectives of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), specifically the goal of limiting the rise in average global temperature to 2°C (UNFCCC, 2016).

Soil C sequestration involves the storage of atmospheric CO_2 in soil through plants, plant residues and other organic materials (Olson et al., 2014). Changes in soil C stocks at the farm scale are influenced by the balance between C inputs (e.g., crop residues, root exudates, animal excreta, etc.) and outputs (e.g., mineralisation, respiration, harvests, leaching, etc.) (Martin et al., 2021). The '4 per mille' initiative has stimulated discussions on the potential of agricultural management practices to sequester significant C stocks globally (Dynarski et al., 2020). The response of soil C to a diverse range of farming practices has been studied in a New Zealand context, such as increased sward diversity, pasture renewal, irrigation and stocking type (Barnett et al., 2014; Kirschbaum et al., 2017; McNally et al., 2015; Mudge et al., 2017; Rutledge et al., 2017a; Wall et al., 2019).

New Zealand has a temperate climate which enables year-round grazing of pastures, primarily through rotational grazing systems. Occupying approximately one-third of New Zealand's total land area (Stats NZ, 2021a), grazing is a predominant land use. Historically, much of the grazing land was converted from indigenous forest or scrubland to accommodate agricultural needs (Taylor & Smith, 1997). The conversion of land to pastures, mainly consisting of ryegrass and white clover, has been driven by an increasing demand for agricultural products. Grazing by dairy cattle makes up about one-quarter (25%) of the grazing land area, while beef farms occupy 30% (Stats NZ, 2021a). The remaining 45% of grazing land is predominantly used for sheep farming (Stats NZ, 2021a). Despite beef farms covering a slightly larger land area, the population of dairy cattle is approximately 60% higher than that of beef (Stats NZ, 2021c). The higher population of dairy cattle, along with dairy farms being located on more productive land, has resulted in dairy farms being generally more intensively stocked compared to beef farms.

Research has demonstrated that grazing management practices impact soil C stocks in New Zealand. Mudge et al. (2017) found that irrigation led to significant losses of C to 0.3 m, with the magnitude of these losses driven by aridity; drier environments displayed no significant difference between irrigated and non-irrigated sites (Mudge et al., 2021). Schipper et al. (2010) observed that dairy pastures lost soil C at rates of 0.73 t C ha^{-1} y^{-1}, while drystock pastures remained stable. The loss of C in dairy farms led to the hypothesis that dairy farms had lower C stocks than drystock farms, which was tested in a study by Barnett et al. (2014) with differences observed in the A horizon. However, Barnett et al. (2014) detected no difference lower in the soil profile. Schipper et al. (2014b) extended the sampling of Schipper et al. (2010) to improve the distribution of major soil orders. From this, the changes in C stocks originally attributed to changes in land use were concluded to be due to soil order. It was found that losses in soil C were constrained to Allophanic and Gley soils, suggesting that these soil orders are more susceptible to C loss (Schipper et al., 2014b).

Grazing animals alter the cycling of C through the consumption of pasture, crops and imported supplemental feed. The ingested C then leaves the animal through aerobic respiration (CO_2), enteric fermentation (CH_4), excreta (dung + urine) and products (milk/meat) (Felber et al., 2016; Soussana et al., 2004). The C in excreta is not exported from the grazing system and is instead redeposited onto the soil surface. However, before this C can enter the soil, most of it is released into the atmosphere via microbial respiration. The remaining C is sequestered into the soil. Approximately 12% of the C in excreta is retained in the soil in the intermediate term (years to decades) (Maillard & Angers, 2014). Despite the influence of grazing animals on the cycling of C, some C cycling models do not account for grazing activity, focusing on the exchange of C between plants, microbes and the atmosphere (Rizzuto et al., 2024). Excluding grazing animals could lead to a misrepresentation of the transfer of C between the land and the atmosphere.

Measurements of net ecosystem C balances of New Zealand grazed pastures have suggested that grazing animals return about 1.75 t C ha^{-1} annually through the deposition of excreta (Wall et al., 2020; Wall et al., 2023; Wall et al., 2024). While this represents the total C deposited onto the soil surface, only a small fraction is sequestered into the soil. Despite studies on net ecosystem C balances in New Zealand highlighting the importance of excretal returns of C into pasture systems (Wall et al., 2019), the specific impact of excreta on soil C stocks remains largely unquantified.

The relative proportions of soil organic matter (SOM) fractions (e.g., particulate organic matter C, POM-C and mineral-associated organic matter C, MAOM-C) make up the total soil C stock. Particulate organic matter-C and MAOM-C have varying residence times in soil, with MAOM-C persisting for centuries to millennia, while POM-C is more vulnerable to loss (Haddix et al., 2020). Because SOM fractions have different residence times, understanding how management, climate and land use can alter the proportions of SOM fractions is important for predicting changes to total C stocks and C cycling dynamics. However, most studies focus on changes in total soil C stocks without considering the form in which this C is stored (Cotrufo et al., 2019). International studies have identified that different agricultural management practices alter the relative proportions of these SOM fractions. For example, Khatri-Chhetri et al. (2024) reported increases in MAOM-C in the top 0.15 m of pastures grazed using a rotational grazing system (rest to grazing ratio: 26.2) when compared to set stocking (rest to grazing ratio: 2.55), linking the differences to variations in the physical structure of the soil due to trampling. Other studies have found the application of organic amendments, cover crops, and N fertilisation to alter POM-C and MAOM-C. Kauer et al. (2021) reported that cover cropping, mineral N fertilisation, and composted cattle manure increased POM-C in the top 0.25 m of soil. Composted cattle manure also increased MAOM-C but to a lesser extent than POM-C. When cover cropping was combined with composted cattle manure, there was a greater increase in MAOM-C than cover cropping alone, which reduced the proportion of MAOM-C (Kauer et al., 2021).

Studies have shown that the application of cattle manure/effluent increases total soil C, POM-C and MAOM-C (Barkle et al., 2000; Bian et al., 2024; Gross & Glaser, 2021; Kauer et al., 2021; Li et al., 2020; Poulton et al., 2018). A study by Carran and Theobald (2000) measured C stocks (to 0.3 m) between fencelines and adjacent paddocks at six sites within a farm in the Manawatū region of New Zealand. Measurements showed greater total soil C in the paddock but only within the top 0.075 m. Using the assumption that little dung is deposited near the fenceline, they attributed the difference to direct dung deposition. However, no measurements of dung deposition were made to support this assumption. The findings of Carran and Theobald (2000) were limited to a shallow depth (0.3 m) and a small geographical area (one farm in Manawatū). Further research is needed to quantify the effect of dung deposition on total soil C, POM-C and MAOM-C stocks in New Zealand pastures.

This thesis will compare total soil C and N stocks, and POM-C and MAOM-C stocks between fenceline and paddock soils sampled from 38 paired sites on six farms in the Waikato region of New Zealand. To support the assumption of Carran and Theobald (2000) that little to no dung is deposited near the fenceline, the deposition of dung pats within 12 m from eight fencelines was measured.

1.2. Aims and objectives

The aim of this research was to compare soil C stocks between fencelines and paddocks to test the hypothesis that dung returns increase soil C stocks, using a soil coring and equivalent soil mass (ESM) approach. Soil samples (0–0.6 m) were collected from paddocks and adjacent fencelines with the assumption that there was little dung deposition under the fenceline. The hypothesis for this research was that C stocks would be lower under fencelines due to less dung deposition occurring here relative to the paddock.

The objectives were:

1. To measure and compare the soil C and N stocks in paddocks and under adjacent fencelines.
2. To determine the relative proportions of SOM fractions (POM-C and MAOM-C) within the top 0.1 m of fenceline and paddock samples.
3. To assess the spatial distribution of dung in relation to the fenceline and relate this to the results found in objective 1.
4. To measure and compare soil chemical properties (Olsen P and pH) between paddock and fenceline samples to 0.1 m.

1.3. Thesis layout

Chapter two reviews the literature on soil C cycling dynamics in grazed pastures, focusing on the importance of SOM fractions for understanding how management practices alter C cycling dynamics. This chapter also reviews the methods for measuring total soil C, POM-C and MAOM-C stocks.

Chapter three presents the results from a study on the importance of dung returns for building soil C. This chapter has been written in the form of a paper for subsequent submission to a peer-reviewed journal. Therefore, some content from the introduction and literature review is repeated here. The methods are outlined in this section. Additional details and supplementary material, including methods, raw data, and soil descriptions, can be found in the appendices.

Chapter four provides a conclusion that summarises the findings in relation to the above objectives and provides recommendations for future research.

CHAPTER TWO

Literature Review

2.1. Introduction

Greenhouse gas (GHG) emissions from agriculture, forestry and other land uses (AFOLU) account for 21% of total global net anthropogenic emissions (Nabuurs et al., 2023). Methane (CH_4) and nitrous oxide (N_2O) are the primary sources of these AFOLU GHG emissions (Smith et al., 2008). In agricultural systems, emissions of CH_4 mainly come from livestock digestive processes, particularly ruminant animals such as cattle and sheep, as well as anaerobic decomposition of organic matter in anoxic environments (Patra, 2012; Singh et al., 2018). On the other hand, N_2O emissions arise from the deposition of livestock urine patches (Singh et al., 2021) and soil management practices such as fertiliser application (Smith, 2017), irrigation (Sang et al., 2024), and tillage (Ostrom et al., 2021), which influence the microbial processes involved in nitrification (aerobic) and denitrification (anaerobic). In agricultural systems, soils act as both a source and sink for CO_2, leading to net CO_2 emissions being close to zero (Ministry for the Environment, 2024; Smith et al., 2008). Increasing the capture of CO_2 in soils could help reduce the concentration of CO_2 in the atmosphere, while losses of soil carbon (C) will contribute to increasing CO_2 concentrations in the atmosphere. Consequently, there is considerable research focused on understanding how agricultural management practices impact soil organic C (SOC) stocks (Whitehead et al., 2018).

Global SOC stocks currently amount to approximately 3,012 Pg C within the top two metres of soil (Sanderman et al., 2017). Present SOC stocks have decreased relative to historical levels, fluctuating over time due to changing climate, land use practices, and land management techniques. Agricultural management practices have led to the loss of approximately 133 Pg of C globally. Overgrazing is one of the causes of these losses, along with soil cultivation (Sanderman et al., 2017).

Over recent decades, increased attention has been directed towards understanding the dynamics of soil C pools and their responsiveness to various environmental drivers and land management practices. Photosynthesis and respiration control the land-atmosphere C flux, and changes to the balance between these processes dictate whether soil C stocks increase or decrease (Friedlingstein et al., 2023; Kirschbaum et al., 2017). It is becoming increasingly important to understand how grazing management practices affect soil C stocks to maintain or increase soil C levels (Whitehead et al., 2018). In addition, it is critical to understand how different management practices impact soil organic matter (SOM) fractions, as different fractions have varying decomposition rates and susceptibility to loss (Haddix et al., 2020).

This literature review examines the land-atmosphere C flux with a particular focus on the effect of grazing management. Firstly, it broadly discusses the biological C cycle (section 2.2), focusing on grazing management practices (section 2.2.1). Then, it outlines the proximal controls of C cycling (section 2.3), including temperature (section 2.3.1) and soil moisture (section 2.3.2). It addresses agricultural GHG emissions (section 2.4), and the effect of land conversion on soil C stocks (section 2.5). It then briefly explains SOM fractions, including particulate organic matter (POM) and mineral-associated organic matter (MAOM) (section 2.6). The influence of land management on soil C stocks is discussed in section 2.7. Finally, general methods for measuring changes in soil C are reviewed in section 2.8, including different methods for assessing soil C stocks by physical soil sampling, the importance of sampling depth and equivalent soil mass (ESM) corrections (section 2.8.1), and fractionation procedures (section 2.8.2), including physical, chemical, and dispersive methods.

2.2. Biological carbon cycle

Carbon undergoes continuous cycling between the Earth's spheres, including biological processes like photosynthesis and respiration, as well as anthropogenic processes such as fossil fuel combustion and land use activities (Lal, 2004a). Carbon pools are commonly categorised based on their position within the Earth’s spheres. Lal (2004a) identified five primary C pools: oceanic, geologic, pedologic (soil), atmospheric, and biotic. However, the soil and biotic pools are frequently combined into what is known as the terrestrial C pool (Reichle, 2020). This section of the review will explore the C cycling dynamics occurring amongst the soil, atmosphere, and biosphere, focusing on the interactions between these C pools.

In terrestrial ecosystems, atmospheric CO_2 is sequestered into biomass through photosynthesis (gross primary productivity, GPP) at a rate of 130 Pg C y^{-1} (Fig 2.1, Equation 2.1) (Friedlingstein et al., 2023). Roughly half of the CO_2 sequestered through photosynthesis is utilised in plant respiration (R_a) to synthesise and maintain living cells, releasing CO_2 into the atmosphere (Janzen, 2004; Waring & Running, 2007). The remaining CO_2 (GPP – R_a) is fixed into plants' vegetative tissue following conversion to organic C compounds via the metabolic activities of photoautotrophs (net primary productivity, NPP), as shown in equation 2.1 (Urry et al., 2018). In this reaction, water (H_2O) molecules are split during the light-dependent phase, releasing oxygen (O_2) and providing electrons and hydrogen ions for the conversion of CO_2 into carbohydrates ($C_6H_{12}O_6$) (Urry et al., 2018).

$$6CO_2 + 6H_2O \xrightarrow{Photons} C_6H_{12}O_6 + 6O_2 \tag{2.1}$$

This fixed C can enter the soil directly through decaying plant matter, residues, and root exudates or indirectly through plant-derived organic matter such as manure (Don et al., 2024; Zhalnina et al., 2018). Dead plants and microbial material are important for soil microorganisms, which decompose most of the NPP as an energy source (Horwath & Paul, 2015). Carbon stored in land can be released back into the atmosphere as CO_2 by heterotrophic respiration (microbial respiration, R_h) or additional disturbances (e.g., cultivation) (Ciais et al., 2013; Don et al., 2024).

The imbalance between GPP and ecosystem respiration (R_a + R_h) is known as the net ecosystem production (NEP). The difference between the flux of C into and out of the soil, including fluxes not directly related to photosynthesis and respiration (e.g., fire, leaching, harvesting crops, lateral transfer of organic C), is commonly termed the net ecosystem C balance (Chapin et al., 2006). Carbon sequestration occurs when the net ecosystem C balance is positive and atmospheric CO_2 is reduced (through photosynthetic pathways), increasing soil C and/or plant and animal biomass (Don et al., 2024). Carbon is sequestered into the land at an estimated rate of 3.3 Pg C y^{-1} (Friedlingstein et al., 2023).

Although biological processes largely control the C cycle, anthropogenic activity has and continues to have, a large effect on the cycling of C. Carbon is depleted from land by anthropogenic activities, including biomass burning, deforestation, land conversions, drainage of wetlands and accelerated soil erosion (land-use change) at a rate of 1.3 Pg C y^{-1} (Friedlingstein et al., 2023). The difference between the estimated land C uptake (3.3 Pg C y^{-1}) and the estimated emissions from land-use change (1.3 Pg C y^{-1}) leads to an atmosphere-to-land sink of approximately 2 Pg C y^{-1} (Friedlingstein et al., 2023; Lal, 2004a). The accelerated cycling of the lithospheric pool by fossil fuel burning for energy is the most influential activity, releasing 9.6 Pg C y^{-1} into the atmosphere, equivalent to almost three times the net annual land C uptake by the biosphere (3.3 Pg C y^{-1}) (Friedlingstein et al., 2023).

2.2.1. Role of grazing animals

In grazed pastures, animals alter the cycling of C through the consumption of pasture and supplemental feeds. The plant C ingested by animals is released through (i) aerobic respiration (CO_2), (ii) enteric fermentation (as CH_4), (iii) excreta (as dung and urine), and (iv) exported products (e.g., milk in dairy systems, meat and/or fibre) (Felber et al., 2016; Soussana et al., 2004). Carbon in excreta is recycled within the grazing system rather than exported. Soil microbes decompose much of the C in excreta as CO_2 via respiration or CH_4 via anaerobic digestive processes (Hanafiah et al., 2021). The remaining C is incorporated into the soil C pool. Previous research has shown approximately 12% of the C in animal manure is retained in the soil in the intermediate term (years/decades) (Maillard & Angers, 2014).

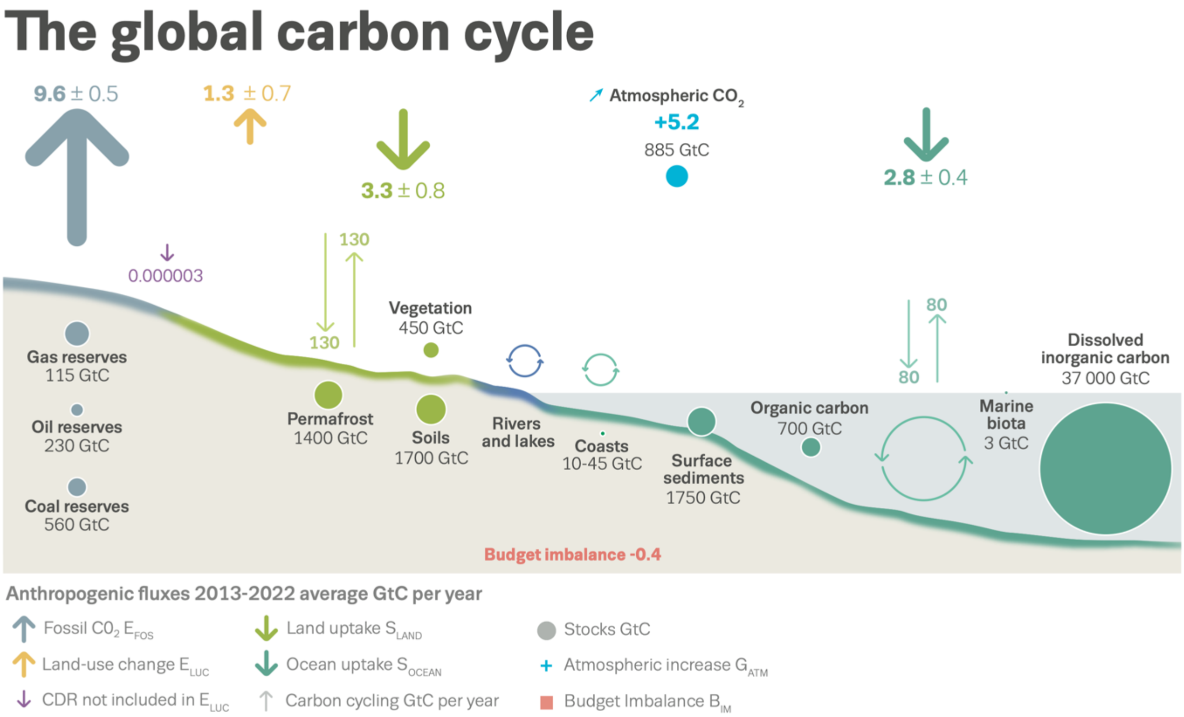

Fig 2.1: Diagram of the anthropogenic perturbations to the global carbon (C) cycle, averaged globally for the decade 2013 – 2022. All fluxes are given in Pg C y^{-1}, and uncertainties are ± 1σ. Source: (Friedlingstein et al., 2023), used under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

2.3. Proximal controls of carbon cycling

Variability in the land-atmosphere C flux is mainly driven by physiological processes (photosynthesis/respiration), which are subject to many environmental controls (e.g., temperature, soil moisture). Understanding how these controls regulate photosynthesis and respiration is important for understanding and managing C cycling in ecosystems.

2.3.1. Temperature

One of the main sources of CO_2 in the land-atmosphere C flux is respiration from microbial activity (heterotrophic, R_h) and the root component of R_a, which combine to give soil respiration (R_s). Soil respiration is influenced by several environmental factors. Like most biochemical reactions, R_s is temperature-dependent (Davidson & Janssens, 2006). Understanding the temperature response of R_s is essential for predicting variation in C cycling over different timescales (e.g., daily, seasonal, annual). Soil respiration rates generally increase with temperature due to increased microbial metabolic rates until a temperature optimum (T_{opt}, temperature at which the rate of respiration is highest) is reached, after which respiration decreases (Schipper et al., 2014a). Photosynthetic rates also increase with temperature, with studies showing a larger GPP with increasing temperature (Wang et al., 2019). However, photosynthetic rates also exhibit a T_{opt} (Duffy et al., 2021). Once the T_{opt} of photosynthesis is exceeded, photosynthetic rates will decline, while respiration rates will continue to rise with increasing temperature (i.e., the T_{opt} of photosynthesis is lower than the T_{opt} of respiration, Fig 2.2). This will result in a reduced capacity for land to uptake C (Duffy et al., 2021).

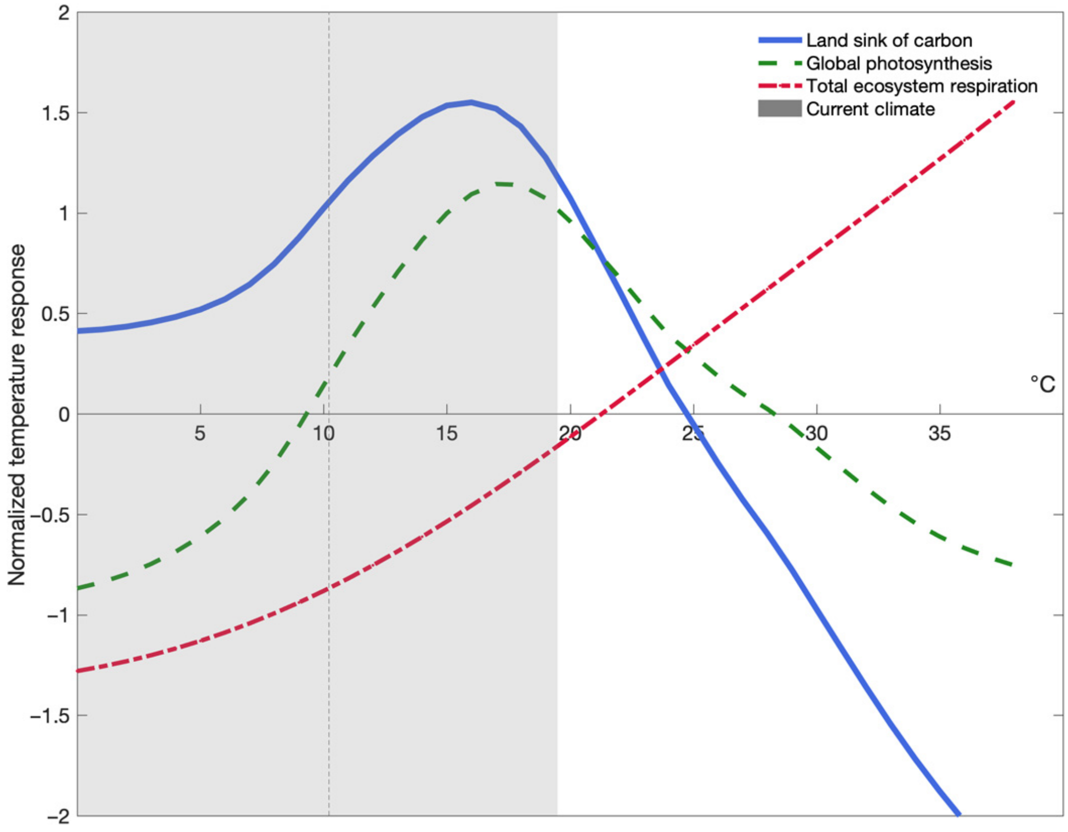

Fig 2.2: Temperature response curves for photosynthesis (C_3 and C_4 plants, green line) and respiration (red line). The blue line is the mass balance estimate of the land sink. The mean annual temperature between 1991 and 2015 is represented by the grey bar, and the vertical dashed line is the current annual mean temperature measured from the FLUXNET 2015 dataset. Source: (Duffy et al., 2021), used under CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/).

2.3.2. Moisture

Changes in soil moisture profoundly impact R_s and, therefore, the land-atmosphere C flux. Moisture significantly influences microbial activity and community composition, indirectly controlling the microbial mineralisation of SOM (Weixing et al., 2009). As soils dry out, microbial and enzymatic activities decrease, ceasing entirely at very low moisture levels (Manzoni et al., 2012). Soil moisture also influences the diffusion rate of gases and the availability and mobility of soluble SOM (Sun et al., 2023). During dry periods, the disconnection of water in soil pores slows down solute diffusion, limiting substrate supply to microbes and reducing respiration rates (Moyano et al., 2013). As water saturation increases, the diffusion rate of oxygen through water is significantly slower than through air, causing the metabolic activity of aerobic organisms to decrease (Neira et al., 2015). This balance between water and oxygen availability results in a curve where microbial activity is minimal at both low and high moisture extremes, peaking at optimal moisture levels (Moyano et al., 2013). Consequently, R_s follows a Gaussian (normal distribution) curve with changes in soil moisture. Changes in soil moisture can also alter the CO_2 flux by altering the balance between aerobic and anaerobic soil processes, with anaerobic processes dominating in saturated soils when oxygen is limited (Fairbairn et al., 2023). At low soil moisture contents, GPP is limited due to decreased photosynthetic rates from reduced stomatal conductivity and plant activity (Galmés et al., 2007). Soil respiration rates also decline due to moisture deficit limiting substrate supply and, therefore, microbial activity. When soil moisture is not limiting, GPP increases. Respiration rates also decrease as soils become more saturated, which can lead to a higher NPP (Lee et al., 2023). Soil respiration rates have been found to be highest at a soil moisture content of ~ 60% water holding capacity (WHC) (Robinson et al., 2020).

2.4. Agricultural GHG emissions

Twenty-one per cent of the global net anthropogenic GHG emissions are derived from AFOLU (Nabuurs et al., 2023). In agricultural ecosystems, emissions of CH_4 and N_2O mainly arise from ruminant processes and land use management (Patra, 2012; Singh et al., 2018; Smith et al., 2008). On the other hand, CO_2 is in flux between the land and the atmosphere (Smith et al., 2008). Soils are an important sink of C, containing approximately 3012 Pg C in the top 2 m of soil (Sanderman et al., 2017). However, compared to historical levels, soil C stocks have declined (Sanderman et al., 2017). Research related to the understanding of how land management alters soil C stocks has become recently important with the development of initiatives such as ‘4 per mille’ (4 per 1000, 2022) and the Food and Agriculture Organisation (FAO) of the United Nations Global Assessment of SOC sequestration Potential (GSOCseq) programme (FAO, 2019b) aimed at increasing global soil C stocks back to their initial level.

Grazed pastures are a dominant land use in New Zealand, occupying approximately one-third of the country's total land area (Stats NZ, 2021a). Fifty-three per cent of New Zealand's GHG emissions are from the agricultural sector (e.g., livestock rumen processes, fertilisers, agricultural soils, etc.) (Ministry for the Environment, 2024). Methane (49%) and N_2O (9%) make up over half of the gross emissions from New Zealand, with CO_2 making up most of the remaining emissions (40%). Land use, land-use change and forestry (e.g., afforestation, land biomass, etc.) offset 25% of the gross emissions in 2022 (Ministry for the Environment, 2024). Since 1990 emissions from the agricultural sector have increased by 12.4%. Agricultural soils contribute 35.4% to this increase, primarily from N_2O emissions due to the use of synthetic nitrogen fertilisers (Ministry for the Environment, 2024).

2.5. Land conversion and soil C stock

Land-use changes, or land conversions, are a significant driver of environmental change and GHG emissions. Over 80% of the global land surface area has been influenced by human activity, resulting in a loss of 133 Pg C in the top 2 m of the soil profile (Sanderman et al., 2017; Sanderson et al., 2002). Land-use change alters soil C stocks through changes in vegetation cover, soil disturbance, management practices, organic inputs, and microbial activity (Smith, 2008). Converting native soil to agricultural uses typically reduces SOC levels (Wei et al., 2014). However, certain agricultural practices, such as those used in New Zealand, can increase SOC by alleviating a previous constraint (e.g., nutrient deficiency, pH, etc.) (Lal, 2004b; Schipper et al., 2017).

The most significant losses of SOC per area occur where the C stocks are the largest (e.g., organic soils such as peatlands). Peatland drainage, oxidation, and subsidence emit 0.645 Pg C y^{-1} globally (Ma et al., 2022). Land conversions to croplands from various other land uses (grasslands, forests, and wetlands) result in a sharp decline in soil C stocks. Conversion from grasslands and forests to croplands decreased C stocks by 59% and 42%, respectively (Guo & Gifford, 2002). The impact of converting forests to agricultural land is not entirely clear, with studies finding decreases in soil C stocks (Wei et al., 2014), while other studies found an initial increase in C stocks (Schipper et al., 2017; Wang et al., 2022). Restoring soil C to its original or new equilibrium levels after conversion often requires a much longer timeframe, as the process occurs more slowly than the rapid pace of GHG emissions (Lal, 2004b). Soil C sequestration rates are site-dependent, with the existing C pool, soil properties and climate being large dictators of sequestration rates (Xu et al., 2020). As this literature review is New Zealand-orientated, the remainder of this section on land conversion and soil C stocks will be constrained to land conversions within New Zealand.

Before Polynesian and European settlers arrived, New Zealand was mostly covered in dense rainforests dominated by podocarp trees and *Nothofagus* species. The only areas with native grassland or shrubland were the dry eastern or alpine regions (Anderson & McGlone, 1992). Over 650 – 750 years, humans decreased the area of indigenous forests by 62% (Taylor & Smith, 1997). Land clearings by fire killed many native trees and shrubs due to their evolution under a low frequency of natural fires. Only a few plant genera show specific fire adaptations (Pawson & Brooking, 2013). Fire was beneficial to early Māori, who used it to encourage the growth of bracken fern, a staple part of their diet. Most of the destruction by Māori occurred between 1350 and 1550 as the population expanded, converting native forest to land dominated by bracken fern, tussock grass, and scrub (Taylor & Smith, 1997).

By the early 2000s, native forests only covered 26% of New Zealand's land area (Stats NZ, 2021b). Conversion to pastoral land drove much of the land-use change, with pastoral land increasing 20-fold from 70,000 ha in 1861 to 1.4 million ha in 1881, reaching 4.5 million ha by 1901 (Taylor & Smith, 1997). The conversion of native forests to grasslands increased soil C stocks by approximately 13.7 t C ha^{-1} (Schipper et al., 2017). Similar results have been found in other studies examining the change in C stocks after conversion to pasture from forests (Hedley et al., 2009; Sparling et al., 2014). Decreases in C stocks following the afforestation of pastures back to exotic forests support the increase in soil C when converting to pastures (Davis & Condron, 2002; Hewitt et al., 2012; Parfitt & Ross, 2011).

2.6. Soil organic matter, particulate organic matter and mineral-associated organic matter

Soil organic matter contains more C than the atmospheric and vegetation pools combined (Fig 2.1) (Ciais et al., 2013; Friedlingstein et al., 2023). The balance between the formation of SOM from plant matter decomposition and its mineralisation determines the size of the SOM pool (Cotrufo et al., 2015). The partial decomposition and transformation of dead plants, animals and microbes produce SOM, which can be classified into two distinct physical fractions: particulate organic matter (POM) and mineral-associated organic matter (MAOM) (Cotrufo et al., 2015; Horwath & Paul, 2015). Other classifications have also been proposed (e.g., labile organic matter and recalcitrant organic matter (Rovira & Vallejo, 2002)).

To better understand the dynamics of SOM cycling, it is helpful to conceptualise total SOM into POM and MAOM (Lavallee et al., 2020). Particulate organic matter and MAOM differ in terms of their formation, persistence, and functioning, resulting in consistent differences in their turnover times (Haddix et al., 2020). Particulate organic matter predominantly comprises lightweight particles that are relatively unaltered parts of dead biomass, whereas MAOM consists of individual molecules or tiny fragments of organic matter tightly bound to mineral surfaces (Cotrufo et al., 2013; Lavallee et al., 2020). Two mechanisms contribute to the formation of these SOM fractions: (i) a physical pathway in which litter particles are transferred into mineral soil (physical transfer path, Fig 2.3) leading to the formation of POM, and (ii) a dissolved pathway that involves the vertical transportation of soluble and suspended C compounds through water movement (DOM–microbial path, Fig 2.3), leading to the formation of MAOM upon interaction with mineral surfaces (Cotrufo et al., 2015). The degradation of POM can also contribute to the formation of MAOM.

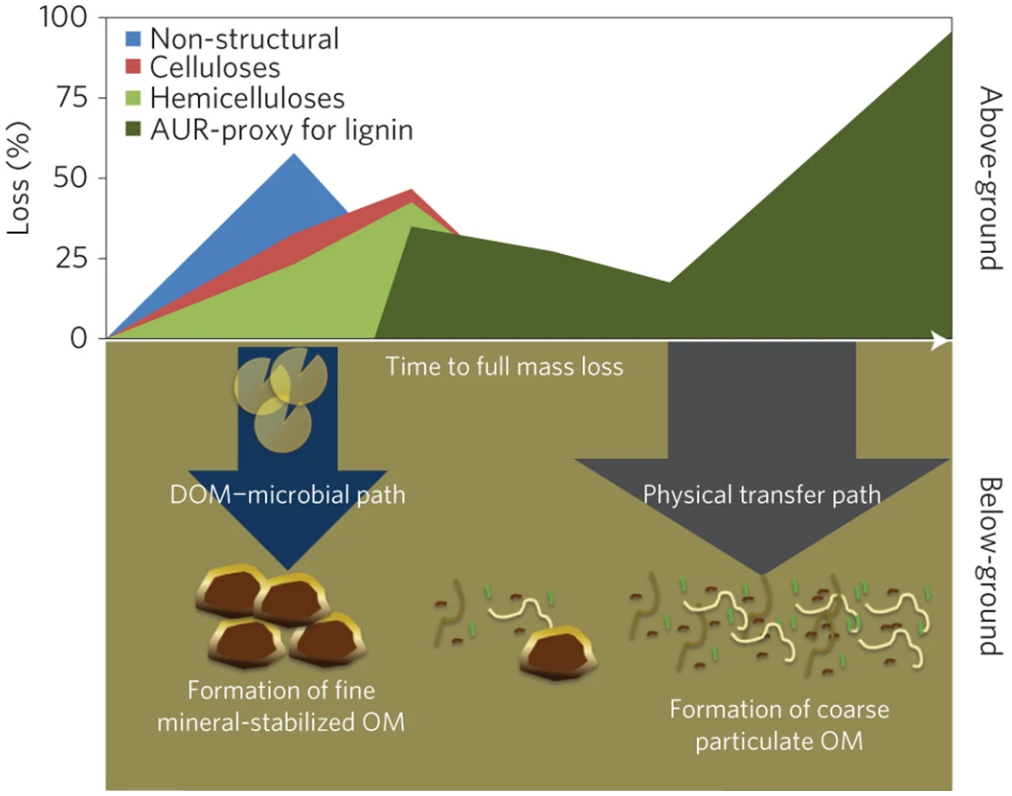

Fig 2.3: The progressive loss of litter chemical components and the two pathways to SOM formation. The top panel shows the decomposition of plant residues as a per cent loss over time. During the early stages of decomposition, the loss of non-structural, celluloses and hemicelluloses plant residues results in the formation of MAOM through the DOM-microbial pathway. The fibrous plant residues (acid unhydrolysable fraction, AUR) enter the soil by the physical transfer pathway. Source: (Cotrufo et al., 2015), Reproduced with permission from Springer Nature.

The adoption of physically defined SOM fractions (components of SOM distinguished by physical characteristics, e.g., POM and MAOM) is gaining support from the modelling community. Previously, ecosystem models such as RothC (Coleman & Jenkinson, 1996) and CENTURY (Parton et al., 1987) used conceptually defined C fractions instead of physically defined ones. The recent shift towards using measurable fractions has the potential to enable better alignment with empirical data, enhancing the opportunity to produce models with greater accuracy (Campbell & Paustian, 2015). Many methods to separate SOM into different fractions currently exist (Mikutta & Kaiser, 2011; Poeplau et al., 2018; Six et al., 2002; Six et al., 2001; von Lützow et al., 2007). However, using simple physical separations could lead to more extensive measurements of POM and MAOM and a better understanding of how land management may affect these SOM fractions (Lavallee et al., 2020; Zhang et al., 2021). Section 8.2 of this review addresses different fractionation techniques in more detail.

Initial soil biogeochemical models (e.g., RothC (Coleman & Jenkinson, 1996), CENTURY (Parton et al., 1987)) focus on the traditional SOM stabilisation theory of humification. However, recent research has challenged this theory, recognising organo-mineral interactions and aggregate formation as mechanisms of SOM stabilisation (Lehmann & Kleber, 2015). The Microbial Efficiency-Matrix Stabilisation (MEMS) framework initially proposed by Cotrufo et al. (2013) provides insight into the mechanisms controlling soil C dynamics and the formation of SOM fractions. The framework considers the proportion of substrate C assimilated into microbial biomass (microbial efficiency) and the physical and chemical protection of organic matter within soil aggregates (matrix stabilisation) (Cotrufo et al., 2013). Integrating the MEMS framework into these models could improve predictions by recognising the relationships between microbial processes and soil properties. This could lead to more accurate simulations of SOM dynamics under different environmental conditions and management practices (Robertson et al., 2019).

2.7. Influence of management on C stock of grazed pastures

Agricultural management activities, usually implemented to increase soil fertility and production (e.g., fertiliser application, irrigation, and stocking rate), can influence soil C dynamics and CO_2 emissions by altering rates of photosynthesis and respiration. This section of the review explores how various management practices could alter soil C stocks, focusing on grazed pastures.

2.7.1. Fertiliser

Applying fertiliser to grazed pastures is a common management practice to increase pasture production (Smith et al., 2012). The increase in pasture production could create a sink of C in the soil through increased C inputs from surface litter, root turnover, exudates, and excreta. However, increased respiration and grazing intensity may lead to higher exportation of C as a result of greater pasture production (Kirschbaum et al., 2017; MacLeod & Moller, 2006). Based on these assumptions, the impact of fertiliser application on soil C stocks is uncertain. The impact of mineral fertilisers on soil C can be assessed by analysing long-term trends in soil C from field experiments. Two global meta-analyses found that areas receiving mineral N fertiliser applications had noticeably higher SOC than those not (Geisseler & Scow, 2014; Ladha et al., 2011). Very little work has been done on the influence of N fertiliser on soil C in New Zealand. However, a series of long-term superphosphate trials observed no response in soil C stocks to increased phosphorus fertiliser inputs (Lambert et al., 2000; Schipper et al., 2011; Schipper et al., 2013). These results are somewhat different from other international studies on phosphorus fertilisation, which found that phosphorus and potassium fertiliser could deplete soil C stocks when N was limited (Poeplau et al., 2016). It was postulated that phosphorus fertilisation led to greater rates of heterotrophic respiration, reduced the abundance of mycorrhizal fungi and decreased root-to-shoot ratio, resulting in the observed decrease in soil C. At the same time, NPP had a much more pronounced response to N fertiliser (Poeplau et al., 2016). While fertiliser application to grazed pastures can enhance pasture production and potentially increase soil C stocks through enhanced C inputs, the overall impact on soil C remains uncertain and varies based on nutrient type and management practices, emphasising the need for further research and long-term monitoring.

2.7.2. Irrigation

Due to the increasing frequency of droughts, irrigation has increased in many areas of the world's agricultural land (Wang et al., 2014). Where irrigation increases productivity, C inputs to the soil would be expected to increase due to greater additions of organic matter from biomass and root growth, resulting in increased soil C (Núñez & Schipanski, 2023). However, irrigation can stimulate microbial activity, accelerating organic matter decomposition and C loss (Kelliher et al., 2012; Schipper et al., 2013). A meta-analysis on the effect of irrigation on soil C found that irrigation was positively correlated to NPP, microbial C biomass, and soil respiration. At the same time, drought increased root: shoot ratio and decreased heterotrophic respiration and soil C turnover (Zhou et al., 2016). Drought induced a more significant inhibition of the decomposition rate than soil C input, resulting in a minor increase in soil C. A similar increase was observed under irrigation. However, this was attributed to newly fixed C inputs (Zhou et al., 2016). The contrasting effects of drought and irrigation on plant C pools and ecosystem C fluxes observed in this study, highlight the complex interactions between water availability, plant production, decomposition rates and soil C storage in soil.

In New Zealand, irrigation decreased soil C in pastures when compared to adjacent non-irrigated pastures (Mudge et al., 2017; Schipper et al., 2019). These losses were dependent on soil aridity and irrigation duration, with moister soils displaying greater C loss (Mudge et al., 2021). While irrigation increases NPP, a more significant increase in aboveground biomass would likely result in higher pasture utilisation and stocking rate, thereby reducing the amount of aboveground C entering the soil (Schipper et al., 2013). Kelliher et al. (2012) estimated that irrigation led to a 36% increase in soil C inputs. However, they also found that irrigation caused a 97% increase in R_S. As a result, the net effect was a C loss of 61% (97% increase in respiration minus the 36% increase in C inputs) (Kelliher et al., 2012).

2.7.3. Cultivation for pasture renewal

Re-sowing pastures, often with a fodder crop (e.g., maize, kale, turnips, fodder beet, etc.) in between, has become an increasingly common management practice in grazed pastures. Pasture renewal is often used to improve underperforming paddocks by replacing them with new pasture to maintain pasture quality (Smith & Brazendale, 2011; Tozer et al., 2011). Pastures can deteriorate when they are invaded by weeds and low-quality grasses, exposed to extremely dry or wet conditions, suffer from poor fertility and drainage, are affected by diseases or insects, experience pugging or soil compaction, face overgrazing, or are subject to poor management practices (Smith & Brazendale, 2011; Tozer et al., 2011). Pasture renewal requires spraying existing pastures with herbicide, followed by either direct drilling of seeds or soil cultivation before sowing. While long-term cropping can lead to a decline in soil C, the effect of periodically re-sowing pastures needs to be better understood. Between spraying and seedling emergence, measurements of the gas flux from land during pasture renewal by roller drilling found a net loss in C (Rutledge et al., 2014). The loss is likely a result of reduced photosynthetic C input during cultivation, while soil respiratory losses remained constant (Rutledge et al., 2014). Losses from pasture renewal were directly related to the duration of the fallow period, with lower net CO_2 losses during shorter fallow periods (Rutledge et al., 2017b). While pasture renewal can result in a negative C balance during the year of renewal, incorporating lime and effluent as part of pasture renewal can offset C loss resulting from an absence of plant growth, and importing more supplemental feed can compensate for temporarily lower pasture production. Both of these may contribute to a positive net ecosystem C balance (Rutledge et al., 2015). Renewal to a high diversity sward could reduce the loss of C by increasing root biomass and production (McNally et al., 2015; Rutledge et al., 2017a), but experimental evidence in New Zealand is lacking (Wall et al., 2024).

2.7.4. Stocking rate and stock class

Determining the effect of stocking rate or stock class/type on soil properties is problematic because these are generally confounded with changes in other management practices (e.g., fertiliser use, feed imports, irrigation). However, a few studies have explored the relationship between C and stocking type and rate. A New Zealand-based study demonstrated that C stocks were notably higher in the A horizon of drystock farms (average stocking rate of 14 stock units (SU) ha^{-1}) in comparison to adjacent dairy farms (average stocking rate of 24 SU ha^{-1}). However, this disparity was not consistent throughout the entire sampled profile (to 0.6 m) (Barnett et al., 2014). Barnett et al. (2014) speculated that this could be attributed to differences in stocking rates between the two farm types. The theory suggests that dairy cows, due to their higher stocking rate, exert more pressure on the soil, consume more above-ground biomass, and deposit more intense urine patches, potentially leading to the observed differences (Barnett et al., 2014). Another study looked at the effect of grazing management on SOM fractions and observed that grazing cattle at high stocking densities with long periods between grazing events (e.g., rotational grazing, rest to grazing ratio: 26.2) increased SOC concentrations and stocks of MAOM (<53 µm) when compared to conventional grazing (set stocking, rest to grazing ratio: 2.55) (Khatri-Chhetri et al., 2024). The study reported that the increase in MAOM-C was linked to variations in the soil's physical structure caused by the heavy trampling from high stock density and higher fungal-to-bacteria ratios. This implies that biological mechanisms contributed to the observed increase (Khatri-Chhetri et al., 2024).

2.7.5. Organic amendments and soil C stocks

Organic amendments (e.g., composts, green manures, animal manures, farm effluent, etc.) are applied to soil as a supply of nutrients for plant growth. The application of farm effluent (liquid waste) to soil has become an increasingly popular practice for the disposal of waste from farmyards/milking sheds. This is the preferred mechanism by regulatory authorities as it protects water quality from contamination more effectively than traditional disposal methods (two-pond treatment system prior to discharge into freshwater streams) and allows the water and nutrients in the effluent to be used by the soil-plant system (Houlbrooke et al., 2004), offsetting the need for fertilisers. International studies have demonstrated considerable increases in soil C stocks following the application of various manure inputs, with the application of animal manure exhibiting the greatest increases in soil C, POM-C and MAOM-C (Bian et al., 2024; Gross & Glaser, 2021; Kauer et al., 2021; Li et al., 2020; Poulton et al., 2018). While some studies on the influence of farm effluent application on soil properties have exhibited decreases (Sparling et al., 2001) or no change (Schipper et al., 1996; Sparling et al., 2015) in total soil C, studies have also shown effluent increased organic matter and total soil C (Barkle et al., 2000; Manono et al., 2016). There is evidence that the application of cattle excreta, in the form of manure and effluent, may increase soil C stocks. Yet, there has been limited research on the influence of direct dung deposition on soil C stocks.

Measurements of C balances have suggested excreta (dung + urine) as an important return of C to pastures in New Zealand (Wall et al., 2019). A study looking at the influence of excreta on soil properties measured greater C and N stocks within the top 0.075 m (0.3 m full sampled profile) of areas receiving excreta from six transects within a farm in the Manawatū region of New Zealand (Carran & Theobald, 2000). Due to the small geographic range and relatively shallow sampling, more research is needed to understand the influence of excreta deposition on soil C stocks and the applicability of the findings of Carran and Theobald (2000) in New Zealand.

2.8. Methods for the determination of total soil C, POM-C and MAOM-C

It is essential to know how land use and land management impact soil C as part of national GHG inventories, as required under the Framework Convention on Climate Change (Smith et al., 2020). Soil C is variable over time and space, making it necessary to use reliable methods to detect differences resulting from land use and/or land management (Allen et al., 2010). Additionally, land use and management can affect POM and MAOM, which cycle differently over time (Haddix et al., 2020). Understanding how POM and MAOM are influenced by different land uses and/or management practices could provide valuable insights into changes in the C cycle. Methods for determining total C stocks by physical soil sampling are addressed in this section of the review. Different methods used to assess SOM fractions are also discussed.

2.8.1. Assessing total C stocks by soil sampling

Collection of soil samples and measurement of soil C content are required to accurately determine SOC stocks. This approach involves the quantification of (i) fine earth (<2mm) and coarse (>2mm) fractions of the soil, (ii) organic C concentration (%) of the fine earth fraction, and (iii) soil bulk density or fine earth mass (FAO, 2019a; Mudge et al., 2020). Management practices that impact the C content of the soil can also change the soil's bulk density so that the mass of soil sampled to a specific depth can also vary between sites or treatments. To allow comparisons to be made, these differences in bulk density between treatments or sites need to be accounted for, generally using an equivalent soil mass (ESM) correction (Ellert & Bettany, 1995). Section 8.1.5 of this review discusses the ESM correction in more detail.

Mudge et al. (2020) recommend three different soil sampling methods for determining SOC stocks: soil coring, pit and short cores, and quantitative pits. The method chosen is determined by site-specific conditions, with stony or friable soils requiring a pit sampling approach. Brief summaries of the methods for physical soil sampling are provided below, along with the methods for determining C concentration and the importance of sampling depth and bulking.

2.8.1.1. Soil physical sampling methods

The most economical and efficient sampling technique requires retrieving continuous, largely intact cores (≥0.3 m depth) from the soil and subsequently dividing them into distinct depth increments (Mudge et al., 2020). Larger corer diameters are recommended, as they provide more accurate estimates of bulk density and are less prone to compaction than corers with smaller diameters (Walter et al., 2016). To assess compaction post-extraction, the length of the core should be measured in relation to the depth of the hole from which it was extracted. Discrepancies in lengths would suggest either core compaction or soil loss during extraction (Mudge et al., 2020).

When continuous deep cores (≥0.3 m) cannot be taken, the preferred approach is to employ a pit method for collecting soil (Mudge et al., 2020). There are several circumstances where continuous intact cores cannot be taken. These include (i) stony soils where it is not possible to penetrate the ground, (ii) sandy soils where it is not feasible to keep the soil cores intact, or (iii) soils with a layer of friable soil that becomes compacted during extraction, leading to blockages of the coring equipment. The pit method involves excavating a pit and utilising shorter cores (e.g., 0.1 m) to collect samples continuously through the soil profile to the desired depth (Mudge et al., 2020).

In cases where the soil is significantly stony and pits with short coring are not possible, quantitative pits (where the soil is excavated from a pit and refilled to determine volume) are used. This provides direct measurements of total soil mass from a known volume (Vadeboncoeur et al., 2012). Quantitative pits require excavating a pit of specified surface area, removing and sieving all soil material and weighing fractions above and below 10 mm in the field to remove larger stones (Mudge et al., 2020). A representative subsample of the <10 mm material is collected for subsequent laboratory analysis (see section 2.8.1.2). To determine pit volume, the pit is lined with a thin layer of plastic and filled with a known amount of water, sand, or plastic beads. Then, the volume is calculated based on the volume-to-mass ratio of the infill material (Mudge et al., 2020). While this approach is considered less biased for stony soils than coring methods (Harrison et al., 2003), they are disruptive and often time, labour, and cost-restrictive (Rau et al., 2011).

2.8.1.2. Sample preparation and C analysis

Air-drying is employed to prepare and preserve many soil samples for elemental analysis, ensuring temperatures do not exceed 35°C. Drying at higher temperatures (e.g., 105°C) is not recommended as it can lead to organic matter oxidation and the loss of C (Nelson & Sommers, 1996). Once air-dried, samples are sieved to 2 mm to separate the fine earth fraction from larger particles (stones/gravels). The fraction retained in the sieve (>2 mm) is oven-dried at 105°C and weighed to provide a correction factor between the sieved and unsieved sample weights required for bulk density and C calculations. The fine earth fraction is subsampled to be ground for analysis or oven-dried to determine a moisture factor (used to calculate dry mass), with the remaining sample being stored for archiving (Palmer, 2003).

There are three broad laboratory procedures for the determination of C concentration in soil: (i) wet oxidation, (ii) dry combustion by ignition or (iii) dry combustion by evolved CO_2. Wet combustion for the determination of soil C concentration by chromic acid digestion involves oxidising organic matter to CO_2 in the presence of a strong oxidising agent (potassium dichromate, $K_2Cr_2O_7$) and catalyst (sulfuric acid, H_2SO_4) (Nelson & Sommers, 1996). The organic matter in the soil sample reacts with the potassium dichromate, generating temperatures sufficient to oxidise organic C (Chatterjee et al., 2009). The CO_2 produced from the reaction is generally measured by titration of the excess $Cr_2O_7^{2-}$ with ammonium iron (II) sulfate hexahydrate ($Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$). The amount of CO_2 produced is assumed to be proportional to the amount of SOC initially present in the soil sample (Chatterjee et al., 2009). This procedure produces results in agreement with dry combustion using common laboratory equipment. However, it is time-consuming (~25 min per sample) and generates toxic waste (Palmer, 2003).

Dry combustion methods are based on organic C oxidation and the thermal decomposition of inorganic carbonate minerals (Nelson & Sommers, 1996). Carbon dioxide produced is measured either by the mass loss on ignition or by collecting and determining the evolved CO_2 with automated instruments (Chatterjee et al., 2009). Both methods involve oxidising the SOC at high temperatures. The loss on ignition method assumes that the mass lost is only due to the combustion of SOM and that the C content of SOM is constant (Christensen & Malmros, 1982). An assumed SOC content (%) of SOM is used as a conversion factor to determine SOC. The loss on ignition method is relatively quick and inexpensive. However, the relationship between SOM and SOC must be determined for each soil, and measurements can often be influenced by the dehydroxylation (releasing of the hydroxyl group) of hydrated clay minerals or salts during heating (Palmer, 2003). Determination of C by automated C analysers measures evolved CO_2 by introducing a sample into a high-temperature oxidation zone where C converts to CO_2 (Chatterjee et al., 2009). The CO_2, carried by a carrier gas like helium, is separated from other gases using gas chromatography or selective traps. Carbon dioxide concentration is detected primarily using thermal conductivity, mass spectrometry, or infrared gas analysis methods (Chatterjee et al., 2009). This method is useful for the rapid determination of a large number of samples. However, analysis by dry combustion methods can be expensive, limiting access to these methods (Smith et al., 2020).

2.8.1.3. Bulking for spatial variability

Soil C stocks are highly variable over small spatial scales (Robertson et al., 1997), presenting a challenge for effective sampling design. There are two methods to estimate the mean SOC over an area: individual or composite (bulk) samples. The primary benefit of bulking soil samples is reducing the required analyses and lowering laboratory costs while accounting for spatial variability (de Gruijter et al., 2016). However, to accurately convey the certainty of the estimate, the variance of the estimated mean must be determined (Mudge et al., 2020). If all collected samples are combined into a single composite, only one measurement can be obtained from the stratum, making it impossible to determine the variance within the site from which the samples were collected. Therefore, multiple composite samples are necessary. These composites are formed by combining an equal number of samples within or across strata (Mudge et al., 2020). While bulking samples can be beneficial, it is important to note that reducing the number of measurements taken increases the contribution of measurement error to the overall estimation error of the mean and reduces the ability to determine whether differences at any specific site are statistically different (de Gruijter et al., 2016).

2.8.1.4. Importance of sampling depth

Soil organic C concentrations generally decline exponentially with depth (Don et al., 2007), because C inputs are concentrated at the soil surface. However, subsoil horizons can contribute to more than half of the total SOC stocks in some soils (Balesdent et al., 2018). Simo et al. (2019) found that 54% of the variation in total SOC stocks was accounted for by sampling to a depth of 0.3 m. However, sampling to 0.5 m was required to account for 90% of the variation (Simo et al., 2019). Despite this important limitation, about 90% of published papers only sample 0.3 m or less (Jandl et al., 2014). This statistic suggests that changes lower in the soil profile are poorly understood and not quantified.

The mechanisms regulating soil C stocks and turnover also differ with depth. At greater depths (>0.3 m), minerals (clays and silts) increasingly stabilise most of the organic matter and control its accessibility to microbes (Jackson et al., 2017). Temperature and soil moisture also become more stable with depth. As variability in environmental conditions becomes less pronounced with depth, the impact of soil mineral chemistry becomes more noticeable (Jobbágy & Jackson, 2000). Therefore, it is important to sample to at least 0.5 m to capture the full range of soil C dynamics and the influence of management practices on these dynamics (Chaplot & Smith, 2023).

2.8.1.5. ESM correction

Soil C concentrations are often extrapolated to an aerial basis using measurements of soil bulk density. However, soil bulk density can vary spatially and temporally (Kulmatiski & Beard, 2004). In New Zealand, soil bulk density in the top 0.1 m has been found to vary with land use and region (Hu et al., 2021). Quantifying and comparing soil C stocks between soils or sites to fixed sampling depths with unequal mass can lead to an over- or under-estimation in soil C solely due to differences in soil mass. The influence of differences in soil mass can be adjusted by applying an ESM correction, which allows for comparisons between soils, sites, or treatments using a consistent reference soil mass (Ellert & Bettany, 1995).

Without mass correction, land-use change can underestimate SOC stocks by up to 28% (Don, Schumacher, & Freibauer, 2011). To overcome this potential problem, Ellert and Bettany (1995) developed a straightforward method that allocates the heaviest soil layer as the equivalent mass for comparisons. The additional mass required to be added to the lighter soil to reach the selected ESM is then calculated as follows:

$$T_{add} = \frac{(M_{soil,\ equiv} - M_{soil,\ surf}) \times 0.0001\ ha.m^{-2}}{BD_{subsurf}} \tag{2.2}$$

Where:

T_{add} = additional depth needed to reach the ESM (m)

$M_{soil,\ equiv}$ = heaviest soil layer (ESM) (t ha^{-1})

$M_{soil,\ surf}$ = total soil mass in surface layers (t ha^{-1})

$BD_{subsurf}$ = bulk density of the subsurface (t m^{-3})

0.0001 converts between ha and m^2

When using an ESM approach, the C per unit area is calculated by adding the initial C in the topsoil layer with the C of the subsurface layers until the chosen ESM is reached (Ellert & Bettany, 1995). This is the earliest ESM method and requires sampling to be carried out by horizon (Gifford & Roderick, 2003). Zan et al. (2001) modified the approach of Ellert and Bettany (1995) by replacing genetic horizons with fixed depth increments taken from soil cores. Bulk density measurements are obtained by dividing the mass of oven-dry soil by the corer volume using the following equation:

$$M_{soil} = \frac{M_{sample}}{\pi\left(\frac{D}{2}\right)^2 \times n}\ 10{,}000 \tag{2.3}$$

Where:

M_{soil} = mass of soil (t ha^{-1})

M_{sample} = oven-dry mass (t)

$\pi(D/2)^2$ = cross-sectional area of core (m^2)

n = number of cores

10,000 converts between m^2 and ha

To adjust depth-based soil properties to the chosen ESM reference soil mass, a model fitting procedure is needed (Haden et al., 2020). The cumulative soil mass and cumulative C stocks throughout the soil profile (calculated by summing data from previous individual depth increments to the subsequent depth increment, e.g., 0–0.1 m + 0.1–0.2 m) are plotted against each other. A fitted line provides estimates of cumulative C stocks to any soil mass within the profile (Fig 2.4). Three different models are generally used for ESM adjustments (Gifford & Roderick, 2003; Rovira et al., 2015; Wendt & Hauser, 2013). These include (i) non-interpolating models, (ii) linear interpolation and (iii) cubic spline interpolation. Non-interpolating methods, such as exponential equations (Rovira et al., 2015), often fail to accurately predict data points because the model is unlikely to intersect the points of the original dataset (Haden et al., 2020). Furthermore, these models lack the flexibility of interpolating models, making them unsuitable for capturing relationships with abrupt changes in soil properties across the soil profile (Haden et al., 2020). Linear interpolation estimates unknown values by fitting a straight line to data points, assuming the change between the two known data points is linear. Linear interpolation has previously been used in ESM adjustments (Gifford & Roderick, 2003). However, because this model assumes soil properties are uniform within the depth increments, predictions may lack accuracy, depending on the number of data points available (Haden et al., 2020). When there is data for several depth increments, cubic spline functions can be used to determine unknown values (Haden et al., 2020). Using the cubic spline function, a smooth curve is fitted to a series of points with a piecewise series of cubic polynomial curves (Wendt & Hauser, 2013). Like linear interpolation, C stocks for the chosen ESM reference soil mass are determined by interpolation of the fitted line. Using the cubic spline function, the value at any point within the range of the data can be estimated. Unlike linear interpolation, which connects data points with straight lines, cubic splines produce a continuous curve, providing a more accurate estimation of values (Haden et al., 2020).

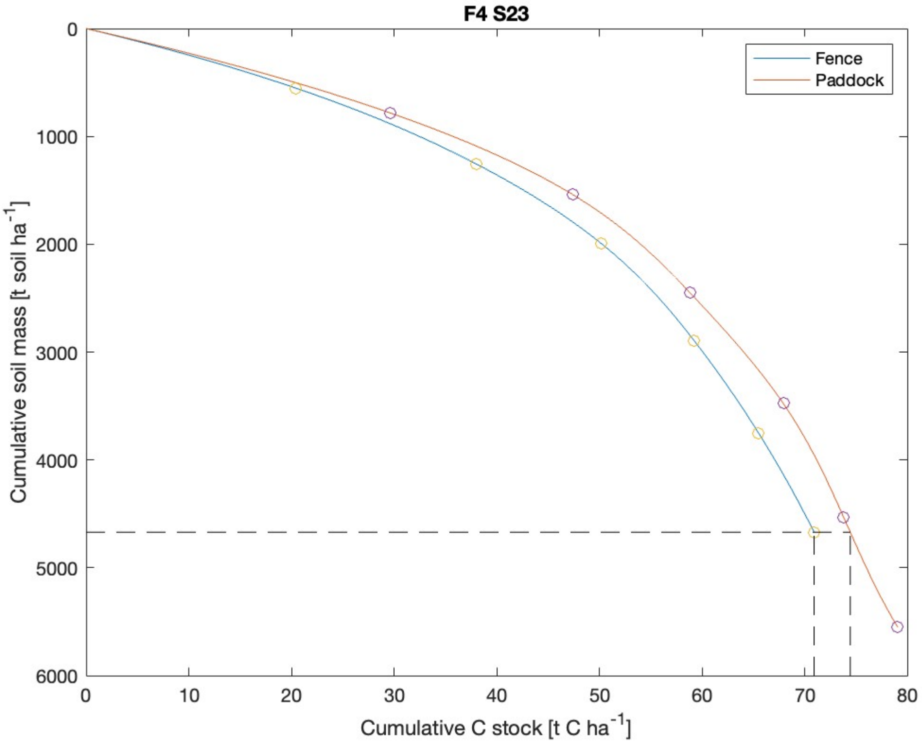

Fig 2.4: An example of a cubic spline interpolation used in the study of this thesis. Cumulative soil mass (t soil ha^{-1}) is plotted against the cumulative carbon (C) stocks (t C ha^{-1}). The horizontal dotted line is the lightest mass at 0.6 m (in this case, 4670 t soil ha^{-1}) in the paired site. The vertical dotted line interpolates the C stocks at this mass.

The reference soil mass used to calculate C stocks using ESM correction is important as it serves as a baseline for stock comparisons. Consistent use of the reference soil mass ensures valid comparisons between different treatments or time points, preventing inaccurate conclusions about changes in soil C stocks. Ellert and Bettany (1995) suggest using the heaviest layer as the reference soil mass to account for the entire soil profile, minimising the risk of underestimating C stocks. In contrast, other studies have used the lightest layer to minimise the potential of overestimating C stocks when comparing soils with different densities (Lee et al., 2009). However, Wendt and Hauser (2013) note that the reference soil mass must fall within the depth layers sampled. This ensures that the ESM method accurately reflects changes in soil C stocks over time. Thus, while the choice of reference soil mass may not be critically important if used consistently, it must accurately reflect the soil profile to ensure precise soil C stock estimates.

2.8.2. Soil C fractionation methods

Numerous methods have been developed to fractionate SOM based on specific objectives. Soils are most frequently fractionated to understand the fate of SOM under different conditions (von Lützow et al., 2007). Common fractionation methods include (i) physical segregation of SOM based on physical properties (e.g., particle size, density, cohesive strength of aggregates) (Leuthold et al., 2022), (ii) wet chemical techniques (e.g., extraction, hydrolysis, oxidation) (Helfrich et al., 2007), or (iii) a combination of the two.

2.8.2.1. Physical fractionation

Physical fractionation methods are established on the principle that soil particles and their spatial configuration significantly influence SOM dynamics since the accessibility of organic matter to biological processes is essential for decomposition (von Lützow et al., 2007). Physical fractionation procedures can be divided into aggregate size fractionation, particle size fractionation and density fractionation. The main distinction between aggregate size fractionation and particle size fractionation is that particle size fractionation involves the dispersion of soil aggregates, while aggregate size fractionation methods intend to keep aggregates intact (Six et al., 2001). Keeping aggregates intact is useful for research that addresses soil structure as it gives an idea about the current distribution of aggregates in the soil. It is proposed that micro-aggregates (<53 µm) serve as a physical barrier between decomposers and substrate, thereby protecting SOM from rapid mineralisation (Six et al., 2002). However, the hierarchical arrangement of aggregates suggests that a single fractionation of SOM fractions based on aggregates with distinct turnover times is likely inadequate, as larger aggregates contain smaller aggregates. Fractionation based on particle size following dispersion by various methods (dispersive methods include ultrasonication, glass beads, and hexametaphosphate (HMP)) has demonstrated greater efficacy in isolating fractions with diverse turnover rates

(Poeplau et al., 2018). The primary organo-mineral complexes are extracted after complete dispersion. Consequently, the efficiency of dispersion procedures is crucial (von Lützow et al., 2007). Dispersion procedures are addressed in more detail in section 8.2.3 of this review.

Density fractionations are used to separate active, intermediate and passive organic matter pools (von Lützow et al., 2007). Separation is usually achieved by flotation and sedimentation in dense solution (e.g., sodium polytungstate). A single density cut-off (generally between 1.6 and 2 g cm^{-3}) separates the light fraction SOM, assumed to be recent and loosely integrated into the soil matrix, from material attached to the heavier mineral component (von Lützow et al., 2007). Solution densities of >2.8 g cm^{-3} are used to differentiate various minerals, recognised for their varied contributions to SOM stabilisation. Organic matter fractions separated with a density >2.8 g cm^{-3} predominantly bind to sesquioxides and exhibit extremely slow turnover rates (Poeplau et al., 2018).

2.8.2.2. Chemical fractionation

Chemical fractionation procedures typically involve using hot water, alkali, acid, or organic solvents. They can be broadly categorised into extraction and hydrolysis, chemical dissolution of the mineral phase, and oxidative degradation of organic matter (von Lützow et al., 2007). Extraction serves to isolate particular compounds with differing chemical resistance, a concept established on the idea of chemical recalcitrance for maintaining organic matter stability (Mikutta et al., 2006). The chemical dissolution of the mineral phase is intended to release and subsequently analyse, or measure complexed organic matter, which generally exhibits significantly longer turnover times than uncomplexed organic matter (Poeplau et al., 2018). Chemical oxidation is used to stimulate the enzymatic decay of organic matter. The resulting fraction, which is resistant to oxidation, is then linked to soil characteristics potentially impacting the stability of SOM (Mikutta & Kaiser, 2011).

2.8.2.3. Dispersion method

A significant challenge in particle size fractionation lies in effectively dispersing aggregates prior to separation, as numerous studies have struggled to achieve complete soil dispersion (Christensen, 1992). Commonly used dispersal methods include (i) shaking with water, (ii) shaking with water and glass beads, (iii) ultrasonication and (iv) sodium hexametaphosphate (Na-HMP) (Poeplau et al., 2018). While it is important to apply enough dispersive energy to break up soil aggregates, it is equally important that the dispersive energy does not break up the POM fraction, contaminating the MAOM (Six et al., 2024). When dispersing soil by ultrasonication, 3 kJ for every 10 g of soil is optimal, with ≥ 5 kJ causing contamination of MAOM with POM (Amelung & Zech, 1999). To minimise the risk of POM contamination while ensuring full dispersal of aggregates, careful consideration of the dispersal method and energy applied is required.

2.9. Summary and knowledge gaps

Twenty-one per cent of global anthropogenic GHG emissions are derived from AFOLU (Nabuurs et al., 2023), and agriculture is a major contributor to CH_4 and N_2O emissions through livestock ruminant processes and land management practices (Patra, 2012; Smith, 2017; Smith et al., 2008). The land and atmosphere C flux is mainly driven by photosynthesis and respiration, and the balance between these two processes dictates whether soil C stocks increase, decrease, or remain constant (Friedlingstein et al., 2023; Kirschbaum et al., 2017). Anthropogenic activity can influence these processes, and recent research has focused on understanding how soil C stocks can be increased or maintained. While changes to management practices (e.g., irrigation) could reduce the mineralisation rates of C (Mudge et al., 2017), the most effective way to increase soil C stocks is through increased C inputs (Virto et al., 2012).

Due to the high spatial variability of soil C, accurately quantifying soil C stocks and changes can be challenging. To account for spatial variability through physical soil sampling, it is necessary to collect a sufficient number of soil cores across the sampled area. To reduce laboratory costs while still accounting for spatial variability, soil cores are often bulked to produce a composite sample (Mudge et al., 2020). While bulking can be beneficial, it is important to recognise that reducing the number of individual measurements limits the ability to determine whether differences at any specific site are statistically different.

Soil C concentration (e.g., %C) is often converted to aerial estimates using bulk density measurements (Ellert & Bettany, 1995). However, soil bulk density varies spatially and temporally, so these variations need to be considered when comparing soil C stocks across space and time. An ESM correction can be used to adjust soil C stocks based on a selected reference soil mass when making comparisons (Ellert & Bettany, 1995). Typically, a cubic spline interpolation is employed to estimate soil C stock at this reference mass, ensuring more accurate comparisons by accounting for variations in bulk density (Wendt & Hauser, 2013).

Measuring SOM fractions is important for the understanding of long-term C sequestration and storage. Different SOM fractions, like POM and MAOM, have varying residency times in soil, influencing their roles in soil C dynamics and their permanence in soil (Haddix et al., 2020). Understanding the impact of management practices, climate and land use on SOM fractions is important for predicting how soil C stocks and C cycling dynamics will respond to environmental change. Incorporating the formation mechanisms of SOM fractions into biogeochemical models could lead to more accurate predictions of soil C cycling and inform more effective strategies for C sequestration and soil management (Cotrufo et al., 2013; Robertson et al., 2019).

The conversion of New Zealand's native forests to pastures increased New Zealand's soil C stocks (Schipper et al., 2017). However, the mechanisms driving the observed increase remain relatively unknown. In grazed pastures, grazing animals alter the cycling of C by digestion of pasture and supplemental feeds. The C they ingest is lost from the animal as CO_2 (aerobic respiration) and CH_4 (enteric fermentation), exported as product (e.g., milk) and recycled as excreta (dung + urine). Of all these pathways, excreta is the only form in which C is not directly exported from the system. With a 12% C retention rate, excreta could potentially increase C stocks (Maillard & Angers, 2014; Wall et al., 2019). Despite many net ecosystem C balance measurements demonstrating the importance of excreta returns for SOC sequestration (Wall et al., 2019), the influence of direct dung deposition on soil C stocks remains unquantified in New Zealand. A study by Carran and Theobald (2000) found that dung inputs increased soil C in the top 0.075 m. However, the findings of this study are limited by a small number of sample sites (6 sites, 1 farm), shallow sampling depth (0.3 m) and the absence of an ESM correction for bulk density. Further research is needed to quantify the influence of direct dung deposition on soil C stocks.

CHAPTER THREE

The Importance of Dung Returns for Building Soil Carbon

3.1. Abstract

Measurements of carbon (C) balances of New Zealand pastures have shown that excreta (dung + urine) return about 1.75 t C ha^{-1} y^{-1} to the pasture. While a proportion of this C is converted to methane and carbon dioxide, a proportion is also sequestered into soil C at an estimated rate of 0.21 t C ha^{-1} y^{-1}. Despite some measurements of net ecosystem C balances suggesting the potential for soil organic carbon sequestration from excreta deposition, the impact of dung inputs on soil carbon stocks remains largely unquantified in New Zealand pastures.

To quantify the influence of dung returns on soil C stocks, 38 adjacent paddock and fenceline sites (paired) were sampled from six farms (five dairy, one drystock) in the Waikato region. The assumption was that there were little dung returns under fencelines. Stocking rates ranged from 15 to 29 LSU ha^{-1} between farms. Soil samples to a depth of 0.6 m were analysed in 0.1 m depth increments for C and N. Six soil cores were taken along a 10 m fenceline transect, and another six cores were taken along a parallel 10 m transect, 10 m into the adjacent paddock. For the whole sampled profile (0–0.6 m), equivalent soil mass corrected soil C and N stocks were, on average, 10.3 t C ha^{-1} ($P = .002$) and 0.96 t N ha^{-1} (P = .002) higher in the paddock than fenceline sites. A large difference in mineral surface area was observed in one of the paired sites, indicating a mismatching of soil types between the paddock and fenceline, which was not apparent during sampling. When this site was excluded, the average difference in C and N stocks decreased to 9.3 t C ha^{-1} ($P = .004$) and 0.86 t N ha^{-1}($P = .003$), respectively. The 0–0.1 m depth increment had the greatest contribution to these differences. There was no relationship between the age of the fenceline and the differences in C stocks, suggesting that any difference observed accumulated early on (<10 years).

Soil samples of the 0–0.1 m depth increment were also fractionated into particulate organic matter carbon (POM-C, >53 µm) and mineral-associated organic matter carbon (MAOM-C, <53 µm). The increase in total C stocks observed could be attributed to increases in POM-C, which was significantly greater in paddock samples (*P* = .001). These results suggest that the increase in C stocks observed is in the fraction that is more degradable compared to the residence time of the MAOM-C fraction, suggesting that a decrease in dung returns to the paddock would potentially result in a rapid loss of soil C.

Dung pats within 12 m of eight fencelines were mapped to ensure the paddock and fenceline received different dung loadings. Over 2000 dung pats were recorded, with only one pat recorded within the fenceline sampling zone, verifying that the input of dung within the paddock differed from the fenceline. The average density of dung pats was 0.21 pats m^{-2} and 0.19 pats m^{-2} in the dairy and drystock farms, respectively. The average surface area of dung pats recorded for one dairy herd was 0.05 m^2. From this, it was calculated that 1% of the paddock is covered in dung after each grazing event. Using estimates of daily dung production and the C content of dung, a dung-C loading rate of 1.1 t C ha^{-1} y^{-1} was calculated.

The differences detected in C stocks of varying dung input are consistent with other studies looking at the influence of cattle manure on soil C, POM-C and MAOM-C stocks. Further work is needed to understand the contribution of dung returns to soil C and its susceptibility to loss.

3.2. Introduction

Soils contain approximately 48% of the total terrestrial carbon (C) store (Friedlingstein et al., 2023). Alteration of the global C cycle by anthropogenic activity has increased the atmospheric concentration of carbon dioxide (CO_2) (World Meteorological Association, 2023). The combustion of fossil fuels and soil C losses from land use change and management practices contribute to increased CO_2 concentration within the atmosphere (Intergovernmental Panel on Climate Change, 2015). Over the past 12,000 years, approximately 133 Pg of C has been lost from the top 2 m of the soil profile due to agricultural land use (Sanderman et al., 2017). The '4 per mille' initiative, which aims to increase soil C by 0.4% annually, has led to extensive research on the influence of land management practices on soil C sequestration rates (4 per 1000, 2022). Understanding the fate of sequestered C into soil organic matter (SOM) fractions (e.g., particulate organic matter (POM-C) and mineral-associated organic matter (MAOM-C)) has become increasingly important in understanding C cycling dynamics (Cotrufo et al., 2015; Cotrufo et al., 2013; Haddix et al., 2020). Recent research has highlighted the importance of conceptualising total soil C into fractions like POM-C and MAOM-C (Lavallee et al., 2020).

New Zealand's temperate climate allows pastures to be grazed year-round, mainly through rotational grazing systems. Cattle graze one-third of New Zealand's land area (Stats NZ, 2021a). Most of the land used for grazing was initially converted from indigenous forest or scrubland over the past 160 years (Taylor & Smith, 1997). Dairy farms occupy around one-quarter (25%) of the grazing land area, with beef farms making up approximately 30% (Stats NZ, 2021a). The remaining 45% is mainly grazed by sheep (Stats NZ, 2021a). An increase in the demand for agricultural products drove the conversion of native land to pastures mainly comprised of ryegrass and white clover, increasing the proportion of land area that is intensively managed (Taylor & Smith, 1997). Despite beef farms covering a slightly larger land area, the dairy cattle population is 60% higher than beef, making dairy farms generally more intensively stocked than beef farms.

Research has demonstrated that grazing management practices impact soil C stocks in New Zealand. Mudge et al. (2017) found that irrigation led to significant losses of C to 0.3 m, with the magnitude of these losses driven by aridity; drier environments displayed no significant difference between irrigated and non-irrigated sites (Mudge et al., 2021). Schipper et al. (2010) observed that dairy pastures lost soil C at rates of 0.73 t C ha^{-1} y^{-1}, while drystock pastures remained stable. The loss of C in dairy farms led to the hypothesis that dairy farms had lower C stocks than drystock farms, which was tested in a study by Barnett et al. (2014) with differences observed in the A horizon. However, Barnett et al. (2014) detected no difference lower in the soil profile. Schipper et al. (2014b) extended the sampling of Schipper et al. (2010) to improve the distribution of major soil orders. They concluded that soil order played a significant role in C losses, with Allophanic and Gley soils being more susceptible to C loss (Schipper et al., 2014b).

The conversion of New Zealand's native forests to pastures increased the nation's soil C stocks by approximately 13.7 t C ha^{-1} to a new steady state (Schipper et al., 2017). While the effect of various grazing management practices on soil C has been studied in New Zealand, the mechanisms driving the increased C stocks in pastures are still largely unknown. Grazing animals alter the cycling of C through the consumption of feed. The ingested C then leaves the animal through aerobic respiration (CO_2), enteric fermentation (CH_4), excreta (dung + urine) and products (milk/meat) (Felber et al., 2016; Soussana et al., 2004). Much of the C in excreta is not exported from the grazing system but is redeposited onto the soil surface. However, before excreta enters the soil, most of the C returns to the atmosphere following microbial respiration. The remaining C is sequestered into the soil, with approximately 12% of the C in excreta retained in the soil in the intermediate term (years to decades) (Maillard & Angers, 2014).

Measurements of net ecosystem C balances have suggested that excreta return about 1.75 t C ha^{-1} annually to New Zealand pasture systems (Wall et al., 2020; Wall et al., 2023; Wall et al., 2024). While this represents the total C deposited onto the soil surface, only a small fraction is sequestered into the soil. Despite studies of net ecosystem C balances of New Zealand pastures highlighting the importance of excretal returns of C into pasture systems (Wall et al., 2019), the specific impact of excreta on soil C stocks remains largely unquantified in New Zealand. Previous research by Carran and Theobald (2000) suggested that paddocks had higher C stocks than fencelines at six sites within a farm in the Manawatū region of New Zealand. Measurements showed greater soil C stocks in the paddock within the top 0.075 m. They assumed little dung was deposited near the fenceline and attributed the difference in soil C to greater dung deposition in the paddock. While this is a reasonable assumption, no measurements of dung deposition were made to prove this assumption. The sampling of Carran and Theobald (2000) was limited to a shallow depth (0.3 m) and a small sample area (six sites, one farm). Further research is needed to quantify the effect of direct dung deposition on soil C stocks in New Zealand pastures.

To address these gaps, this study aimed to compare C stocks in paddocks and adjacent fencelines to test the hypothesis that direct dung deposition affected soil C stocks. The objectives were to assess differences in C and N stocks between paddocks and fencelines, determine the influence of SOM fractions on these differences, and estimate the difference in dung loading rate between the paddock and fenceline. To address these objectives, a soil coring approach was used to collect samples from six farms in the Waikato region of New Zealand.

3.3. Methods

3.3.1. Study area

Six farms (with multiple sampling locations, see Table 3.1) in the Waikato region of New Zealand with varying stocking rates and feed inputs were sampled between November 2022 and December 2023. The Waikato region receives, on average, 1205 mm of rainfall annually (Stats NZ, 2023a), with rainfall patterns driven primarily by elevation and predominant wind direction. Areas in flatter terrain typically receive around 1100 mm of rainfall, while those at higher elevations can receive upward of 2000 mm (Chappell, 2014). Over the decade between 2012 and 2022, the mean annual temperature for the Waikato region was 14.2°C (Stats NZ, 2023b). The main mineral soil orders found in Central Waikato as classified by the New Zealand Soil Classification (NZSC) are Allophanic, Gley, Brown, Granular and Ultic (Landcare Research, 2023).

3.3.2. Farm and sampling site selection

The sample site selection process considered historical records of specific paddock management practices, such as recent cropping or pasture renewal, as these could significantly impact soil C stocks (Wall et al., 2021). Consequently, to isolate the effects of dung, the study was designed to exclude paddocks that had undergone recent cropping or pasture renewal (e.g., within the last five years). The age of the fencelines was a crucial factor in the selection process. Retrolens (https://retrolens.co.nz), a historical satellite imagery resource, was used to estimate the age of sampled fencelines along with discussions with farmers. While potential sampling locations had a variety of fenceline ages (see Appendix D), preference was given to older fencelines (50+ years) under the theory that these areas had been devoid of dung inputs for a longer duration.

3.3.3. Farm management

Five of the six farms were grazed by dairy cattle using rotational grazing on pastures mainly comprised of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). The remaining farm was drystock, grazed by beef cattle using a similar rotational grazing system. The dairy farms typically grazed the paddock for 24 hr or less with a grazing interval of approximately three to five weeks (varies seasonally). In contrast, the drystock farm had a grazing duration of four to seven days per paddock, followed by longer rest periods (~three to eight weeks). Two farms were located in Pokuru, with the remaining four in Cambridge, Waharoa, Ōtorohanga and Ōhaupō (Fig 3.1, Table 3.1). Farm size varied from 45 to 230 ha, with stocking rates at the time of sampling between 15 to 29 livestock units (LSU) per hectare (stock unit equivalents used to calculate LSU can be found in Appendix A). For comparison, the average stocking rate for drystock and dairy farms in New Zealand between 2007 and 2019 was 10 and 25 LSU ha^{-1}, respectively (Stats NZ, 2021d). Application of N fertiliser ranged from 0 to 164 kg N ha^{-1} y^{-1} across all farms.

The five dairy farms imported C through externally sourced supplemental feed, while the drystock farm harvested and exported C through feed (maize, hay and grass silage). Crops were grown on all farms either for export or on-farm feed. Cropping areas were not included within the grazing area used to calculate LSU (see Appendix A). Supplements and crops being fed included palm kernel extract (PKE), grass silage, maize silage, hay, cheese whey, turnips, and kale. Most grass silage, maize silage, turnips, and kale were grown on-farm. All PKE, hay, and cheese whey supplements were imported. Most farms utilised/fed out supplements on a feed pad for at least part of the year to maximise feed usage and minimise pugging, generally in the wetter months (March to October). Excreta C deposited on the feed pad is eventually applied to paddocks as effluent rather than direct dung deposition. Seven of the 38 paddocks received effluent at rates between 24 and 60 mm y^{-1} in the year of sampling. Supplements were fed in paddocks when the feed pad was not in use. For additional farm information, see Appendix A.

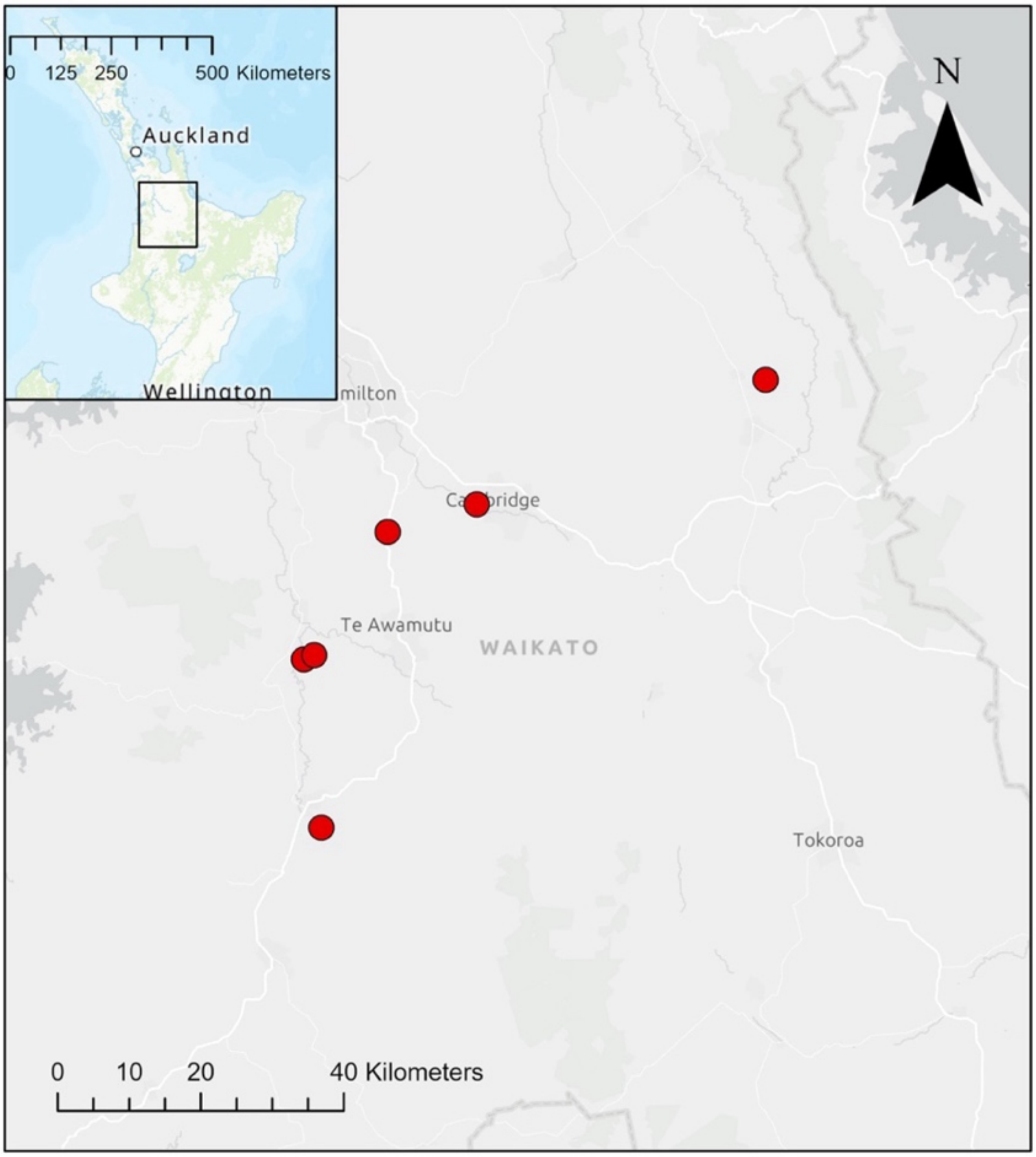

Fig 3.1: Location of the six farm sites sampled within the Waikato region, New Zealand.

Table 3.1: Site information for the six farms sampled. A detailed description of each site sampled within the farms can be found in Appendix D

Farm ID	Location	Farm type	Soil Orders (NZSC)	Stocking rate (LSU ha^{-1})	Number of paired sample sites
1	Cambridge	Dairy	Allophanic, Gley, Brown	22	8
2	Waharoa	Dairy	Allophanic, Gley	25	7
3	Ōtorohanga	Drystock	Allophanic, Brown	15	6
4	Ōhaupō	Dairy	Allophanic, Brown, Granular	27	5
5	Pokuru	Dairy	Allophanic, Brown	29	6
6	Pokuru	Dairy	Allophanic, Brown	21	6

3.3.4. Soil sampling

Between November 2022 and December 2023, five to eight paired sites were sampled at each of the six farms, totalling 38 paired sites (Table 3.1). At Farm 1, fencelines had been recently removed, facilitating easier access to the sampling sites. The removal was part of the farm's adoption of Halter® technology, which uses collars with sound and vibration cues to virtually fence cattle in paddocks (https://www.halterhq.com/how-halter-works). Sampling was undertaken within a year after the removal of fencelines. The locations of the old fencelines were identified using old farm maps, minor elevation changes due to compaction in adjacent paddocks (Fig 3.2) and filled postholes. For the remaining farms, samples were taken as close to the existing fenceline as possible (within 0.1 m of the fenceline).

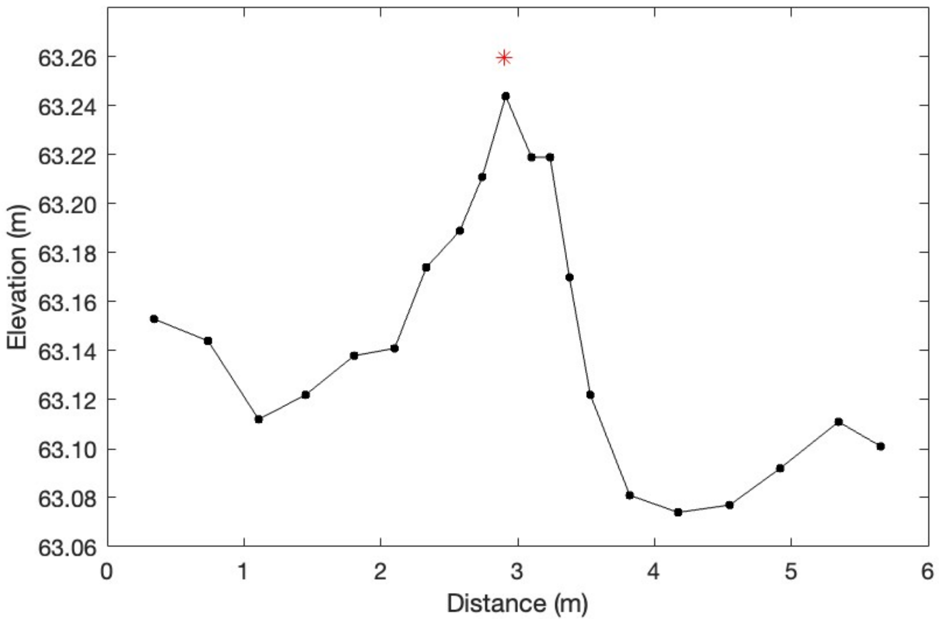

Fig 3.2: An example elevation profile perpendicular to the fenceline where a fenceline had been removed at Farm 1. The asterisk indicates the putative fenceline.

A 10 x 10 m plot was set up next to the fenceline and, where feasible, approximately 20 m from any other paddock boundary fencelines or high animal traffic areas (Fig 3.3). Within the 10 x 10 m plot was a 10 m transect along the fenceline, and another 10 m transect was 10 m into the adjacent paddock. Both ends of the plot were positioned on similar aspects, slope and topography, and a Dutch auger was used to visually confirm consistent soil type between the two transects. Soil corers with an average tip diameter of 38.2 mm were driven to a depth of 0.65 m using a post driver (Christie Engineering, Horsley Park, NSW, Australia). Six soil cores were taken, one every 2 m, along each transect. The six cores were bulked and divided by depth into six depth increments of 0.1 m (0–0.1 m, 0.1–0.2 m, 0.2–0.3 m, 0.3–0.4 m, 0.4–0.5 m, and 0.5–0.6 m). Each 0.1 m depth increment sample was bagged, labelled, and stored at 4°C until further analysis.

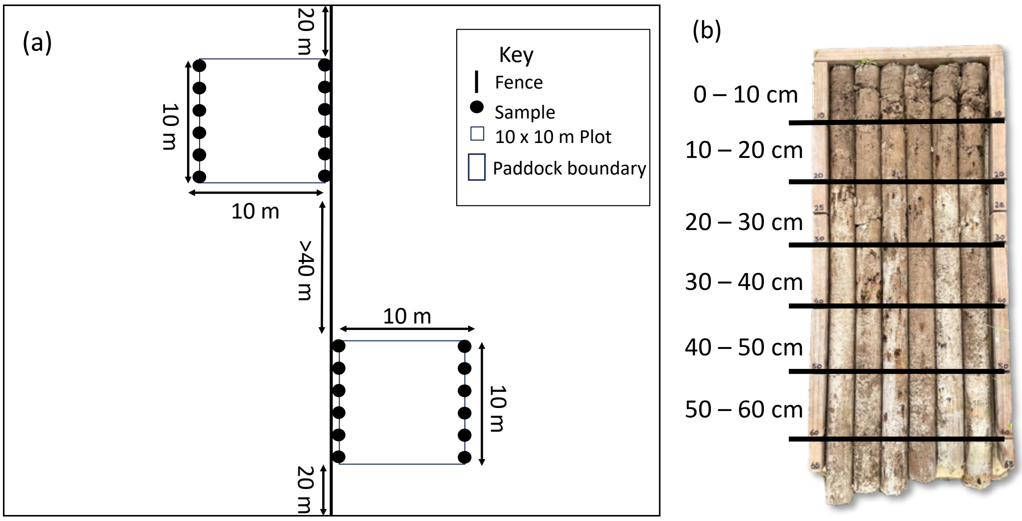

Fig 3.3: (a) The approach used to sample the paired sites. A 10 x 10 m plot was positioned next to the fenceline and ~20 m from the paddock boundary. Soil samples were collected along a 10 m transect in the paddock and along the fenceline. On occasion, the same fenceline was sampled for two adjacent pastures, but the fenceline sampling locations were generally more than ~40 m apart. (b) Six soil cores bulked by depth in 0.1 m increments to 0.6 m from each transect.

3.3.5. Soil analysis

To prepare soils for analysis, field moist samples were air-dried to a constant weight and passed through a 2 mm sieve to remove coarse material and large roots and homogenise the sample. A representative sub-sample was ground using a ball mill grinder (MM 400, Retsch GmbH, Haan, Germany). The total C and N concentration for all samples was determined by Dumas combustion using an Elementar (vario EL cube) combustion analyser (Elementar Analysensysteme GmbH, Elementar-Straße 1, 63505 Langenselbold, Germany). The concentration (%) of total C and N was multiplied by the soil mass within a specified volume (bulk density) and used to report the mass of C and N per unit area for each depth increment.

3.3.5.1. Calculation of C and N stocks

A moisture factor for each sample was determined by oven drying a subsample of the 2 mm sieved and ground soil at 105°C to a constant weight. The moisture factor was calculated by dividing the ground air-dry soil mass by the ground oven-dry soil mass. The C content of the oven-dry soil was calculated as follows:

$$\%C_{OD} = \%C_{AD} * MF/100 \tag{3.1}$$

Where: $\%C_{OD}$ is the C content of the oven-dry soil, $\%C_{AD}$ is the C content measured in the air-dry soil, and MF is the moisture factor.

The mass of oven-dry soil per unit area (t ha^{-1}) for each depth increment was calculated as follows:

$$M_{soil} = \left(\frac{M_{soil(OD)}}{\pi\left(\frac{D}{2}\right)^2 \times n}\right) \times\ 10{,}000/1{,}000{,}000 \tag{3.2}$$

Where: M_{soil} is the mass of soil per unit area (t ha^{-1}), $M_{soil(OD)}$ is the total mass of <2 mm oven-dry soil (g), D is the diameter of the core (m^2), n is the number of cores taken, 10,000 converts m^2 to ha, and dividing by 1,000,000 converts grams to tons.

For each depth increment, the total C stock (C_{stock}, t C ha^{-1}) was calculated using the mass of soil per unit area and the C content in oven-dry soil as follows:

$$C_{stock} = M_{soil} \times \%C_{OD} \tag{3.3}$$

Carbon and N stocks to each specified depth and the whole profile (0.6 m) were adjusted to an equivalent soil mass (ESM) correction using MATLAB's (R2023a version 9.14) fitted cubic spline function by interpolating a series of points to a smooth curve, using a piecewise series of cubic polynomial curves (Wendt & Hauser, 2013). The lightest mass of soil for each specified depth and the whole soil profile (0.6 m) from each paired site was considered the ESM reference soil mass. For comparison, the results also include C stocks calculated using a uniform reference soil mass (2500 t ha^{-1}) for all paired sites rather than a different reference soil mass for each paired site. Carbon stocks were also calculated to a fixed depth of 0.6 m. See Appendix A for a complete description of the ESM calculations used in this study.

3.3.5.2. Soil organic matter fractionation

The 0–0.1 m depth increment of each site was separated into >53 µm and <53µm fractions to determine the stocks of POM-C (>53 µm) and MAOM-C (<53 µm). For operational reasons, only 35 of the 38 pairs could be analysed for fractionation.

The fractional procedure used a 2:1 solution (liquid to soil, v/v basis) containing approximately 15 g of air-dried soil which was dispersed using ultrasonication (60s–120s; mean power output = 35.5 J s^{-1}; Q700, Qsonica Llc, Newtown, Connecticut, USA). A solution of 0.5% sodium hexametaphosphate was used instead of water to aid in soil dispersion. After dispersion, the soil was washed through a 53 µm sieve, with the >53 µm fraction defined as that remaining on the sieve (Poeplau et al., 2018). The >53 µm fraction was collected and dried at 60°C for at least 48 hr before being ground using a ball mill grinder. Total C and N concentration analysis was as described above (see section 3.3.5.1). The >53 µm fraction was converted to POM-C using the concentration of C in the > 53 µm fraction and mass of soil >53 µm as follows:

$$POM\text{-}C = M_{Soil>53\mu m} \times \%C_{Soil>53\mu m} \tag{3.4}$$

Where: POM-C is the amount of C in the >53µm subsample (g), $M_{Soil>53\mu m}$ is the mass of soil >53 µm in the subsample (g), and $\%C_{Soil>53\mu m}$ is the C concentration of the >53 µm soil fraction.

All soil masses and C contents used in SOM fraction calculations were corrected to a reference temperature of 60°C. The mass of total C in the fractionated subsample was calculated by multiplying the mass of the oven-dry subsample by $\%C_{AD}$. To account for the soil >53 µm fraction being dried at 60°C, an additional sub-sample of the air-dried soil was dried at 60°C, and the moisture factor (MF_{60}) was used to convert the subsample mass to a 60°C basis. The $\%C_{AD}$ was also converted to a 60°C basis ($\%C_{60}$) using the same formula as equation 3.1.

The total mass of C in the subsample was calculated as:

$$C_{Subsample} = \%C_{60} \times \left(\frac{M_{Subsample}}{MF_{60}}\right) \tag{3.5}$$

Where: $C_{Subsample}$ is the mass of C in the subsample (g), and $M_{subsample}$ is the total mass of the subsample (g, i.e., the >53 µm and <53 µm fractions).

MAOM-C was then determined by subtracting the POM-C content from the total C mass in the subsample.

$$MAOM\text{-}C = C_{Subsample} - POM\text{-}C. \tag{3.6}$$

Where: MAOM-C is the amount of C in the <53 µm subsample (g).

POM-C and MAOM-C stocks were calculated using the relative proportions of POM-C and MAOM-C in the subsample, and the ESM corrected total soil C stocks for the 0–0.1 m depth.

$$POM\text{-}C_{Stock} = \frac{POM\text{-}C}{C_{Subsample}} \times C_{Stock} \tag{3.7}$$

Where: $POM\text{-}C_{Stock}$ is the C stock of the >53 µm fraction (t C ha^{-1}).

$$MAOM\text{-}C_{Stock} = \frac{MAOM\text{-}C}{C_{Subsample}} \times C_{Stock} \tag{3.8}$$

Where: $MAOM\text{-}C_{Stock}$ is the C stock in the <53 µm fraction (t C ha^{-1}).

3.3.5.3. Surface area

Specific surface area (A_s, m^2 g^{-1}) was measured in the 0–0.1 m increment using the water adsorption of air-dried soil as described by Hedley et al. (2000) and Parfitt et al. (2001).

Briefly, soils were air-dried for a minimum of 48 hr in a controlled temperature and humidity cabinet (30°C and 30% relative humidity, RH). The water content of the air-dried soil was determined by further drying the soil samples in a 105°C oven for at least 16 hr. The water content of the air-dried soil (WC, g g^{-1}) was converted to specific surface area using the relationship between water area and WC (Parfitt et al., 2001):

$$A_s = 2 \times WC \tag{3.9}$$

Specific surface area was converted to mineral surface area (A_m, m^2 g^{-1}) by removing the contribution of soil organic C (SOC) on water adsorption using the factor described by Kirschbaum et al. (2020) as:

$$A_m = A_s - f_c \times \%C_{OD} \tag{3.10}$$

Where: f_c (0.43) is the factor that relates soil C to its water adsorption property.

Although the primary purpose of measuring A_m was to calculate the C loading of mineral surfaces (see section 3.3.5.4), it also served as an additional check of the mineralogy within paired site samples to ensure that the soils being compared had similar mineralogy.

3.3.5.4. Carbon loading of mineral surfaces

Carbon loading (mg C m^{-2}), a measure of MAOM saturation, was calculated as described by McNally et al. (2017). Briefly, the proportion of MAOM-C was divided by the mineral surface area (A_m, m^2 g^{-1}).

$$MAOM_{loading} = \frac{\left(\frac{MAOM\text{-}C}{C_{Subsample}}\right)}{A_m} \tag{3.11}$$

Where: $MAOM_{loading}$ is the C loading of the mineral surfaces.

3.3.5.5. Olsen P and pH

Wet chemical analysis (available phosphorus (Olsen P) and pH) was determined on the 0–0.1 m depth increment. The same 35 pairs used for fractionation were used for Olsen P and pH. For pH, 25 mL of distilled water was added to 10 g of soil and mixed using a high-speed stirrer for 15 seconds. Samples were left to stand for at least 12 hours before measuring pH using a pH meter (C700 Benchtop Meter, Oakton Instruments, Nijkerk, Gelderland, Netherlands).

For Olsen P, 40 mL 0.5 mol L^{-1} sodium bicarbonate ($NaHCO_3$) at a pH of 8.5 was added to 2 g of soil and shaken for 30 minutes in an end-over-end shaker. Samples were filtered through 110 mm filter paper (Advantec 5A), and 3 mL of 0.5 mol L^{-1} sulphuric acid (H_2SO_4) was added to 10 mL of the filtered extract. The amount of phosphorus extracted in each sample was measured using the Murphy and Riley (1962) method. Eight mL of the colour development reagent (ascorbic acid in 2.5 mol L^{-1} H_2SO_4 with 1.2% ammonium molybdate and 0.1 mg L^{-1} antimony) was added to the filtered extract. The solution was diluted with distilled water to 100 mL before being left for the colour to develop for 15–20 minutes. The absorbance for each sample was determined at 880 nm using a spectrometer (Halo VIS-20 Spectrophotometer, Dynamica Scientific Ltd., Livingston, UK). The absorbance recorded was converted to a concentration of phosphorus using a calibration curve (see Appendix A).

3.3.6. Dung distribution and area

3.3.6.1. Dung density

To check the assumption that the fenceline and the paddock sampling sites differed in their loadings of manure inputs, the frequency and distribution of dung deposits within approximately 12 m of fencelines was determined. Dung pats of varying stocking rates and types were mapped across four farms to understand how different grazing management practices impact dung distribution. Dung deposits in the 12 m range were mapped across eight paddocks by recording the coordinates of each deposit at the nearest point to the fenceline using a global navigation satellite system (GNSS, GS18 GNSS RTK Rover, Lecia Geosystems, St. Gallen, Switzerland). The distance of each dung deposit from the fenceline was then calculated using a geographic information system (GIS, ArcGIS Pro, "Near" tool).

3.3.6.2. Dung area

The surface area covered by a dung pat was estimated using 50 photographic images of dung pats within a 0.45 x 0.45 m quadrat. Using GIS software (ArcGIS Pro), the images were georeferenced to the landscape, and polygons were delineated around the dung pats to calculate their areas. The average dung pat area and dung density were used to estimate the proportion of the paddock covered in dung per grazing event.

3.3.7. Statistical analysis

Data were analysed using a paired t-test to test for statistically significant differences in ESM-corrected C and N stocks (MATLAB R2023a version 9.14). A *P*-value of ≤.05 was considered statistically significant. Analysis was conducted for individual soil depths (0.1 m increments) and the total soil profile (0–0.6 m). *P*-values related to correlations are calculated using a linear regression model (MATLAB's fitlm function https://au.mathworks.com/help/stats/fitlm.html). All differences are calculated as paddock minus fenceline unless stated otherwise. Data are presented as raw means, and error bars represent the standard error unless specified otherwise. Summary data are provided in the results section. All data from individual sites are given in Appendix B. Raw data can be found in Appendix C.

3.4. Results

3.4.1. Dung distribution and area

A total of 2068 dung pats were observed within 12 m from the fenceline (Fig 3.4), distributed over a sampled area of 10,406 m^2. These observations were made across eight fencelines – four fencelines at one drystock farm and four fencelines in total across three dairy farms. The average dung pat density was similar for drystock and dairy farms, with values of 0.19 ± 0.02 pats per m^2 and 0.21 ± 0.03 pats per m^2, respectively. The overall mean for both farm types was 0.2 pats per m^2. Only ten pats were recorded within 0.5 m from the fenceline, with nine being at least 0.3 m away. In other words, of the 2068 dung pats recorded, we observed one dung pat within the sampling zone under the fencelines. The surface area covered by individual dung pats measured ranged from 0.02 m^2 to 0.09 m^2, with an average of 0.05 ± 0.003 m^2. However, the surface area of dung was only measured for one herd of dairy cows. While measuring the dung distribution of drystock pats, it was visually observed that the area covered by a dung pat was related to the size and age of the grazing animal. When measuring drystock dung distribution, the distribution from two different-aged herds was measured, and the dung density was similar between herds, but the size of the dung pats was visually larger with older animals.

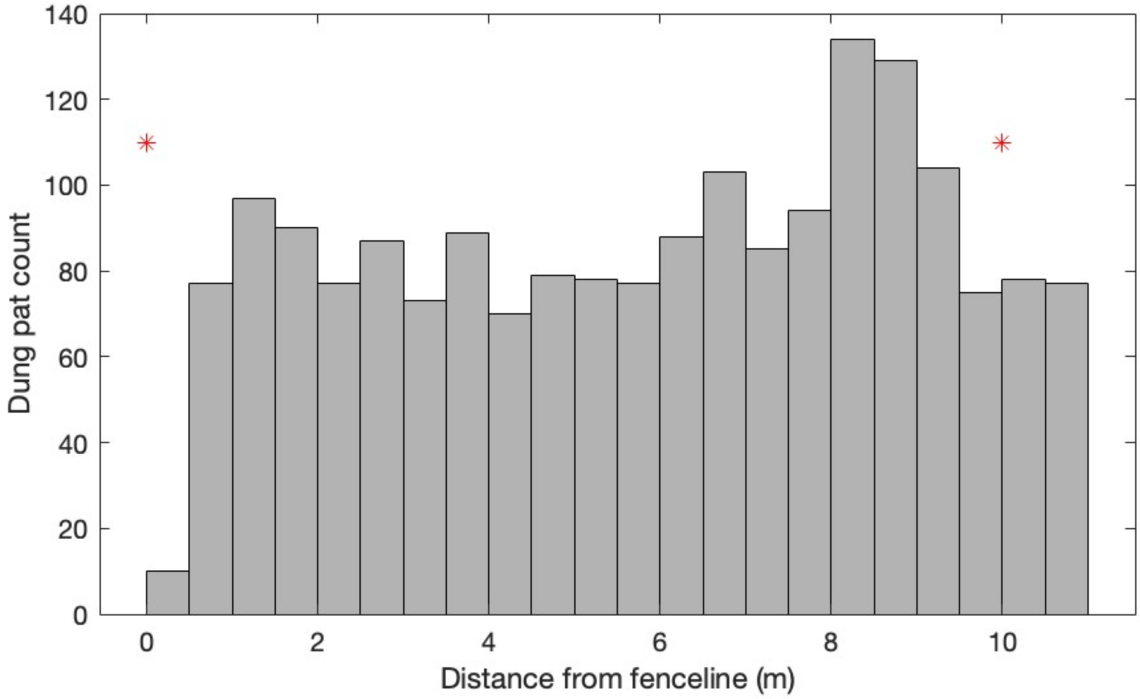

Fig 3.4: Dung pats observed within 12 m of the fenceline. The asterisks indicate the approximate location where samples were taken. Bars are in 0.5 m increments. Only one dung pat was observed within 0.3 m of the fenceline.

3.4.2. Soil properties

3.4.2.1. Soil pH and Olsen P

On average, soil pH and Olsen P in the 0–0.1 m depth increment were higher in paddocks than under fencelines (Table 3.2, Fig 3.5 & Fig 3.6). Soil pH was, on average, 0.39 ± 0.06 units ($P < .001$) higher in the paddock than under the fenceline (range of 1.0 increase to a decrease of 0.3). Similarly, average Olsen P values were 11.7 ± 2.8 µg g^{-1} ($P < .001$) higher in paddocks than under fencelines (range of 40 µg g^{-1} increase to a decrease of 57 µg g^{-1}).

Table 3.2: Mean pH and Olsen P in the 0–0.1 m depth increment for adjacent paddock and fenceline sites.

	pH	**Olsen P (µg g^{-1})**
Paddock	6.16 (0.05)[a]	25.7 (2.4)[a]
Fenceline	5.76 (0.05)[a]	14.1 (2.2)[a]
Difference[c]	0.39 (0.06)[b]	11.7 (2.8)[b]

[a] SEM, standard error of the mean in parenthesis (n = 35).
[b] SED, standard error of the difference between means in parenthesis (n = 35).
[c] Difference in pH and Olsen P (paddock – fenceline).

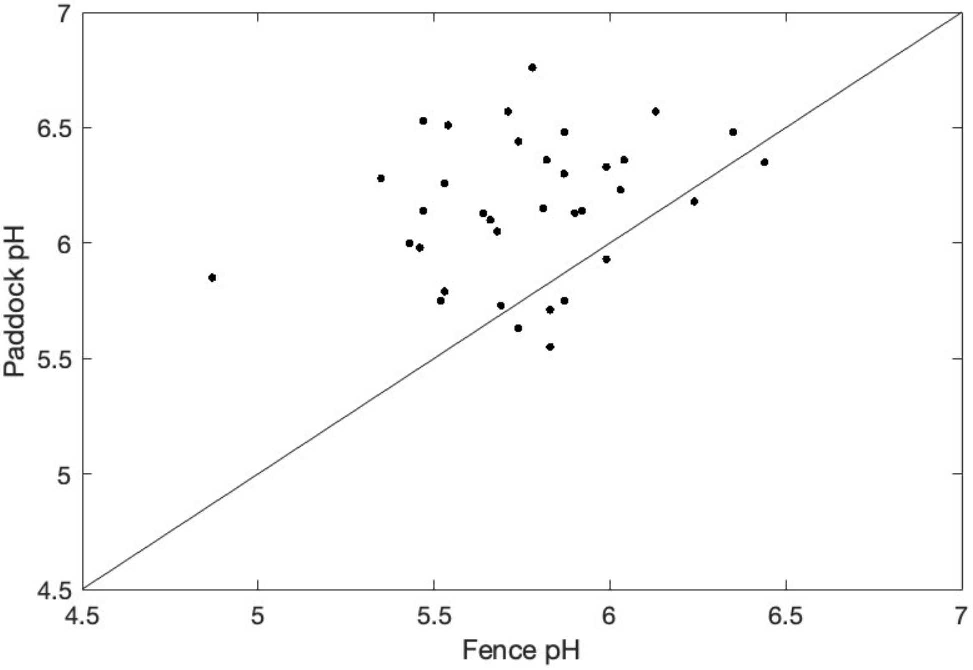

Fig 3.5: Relationship between pH of the paddock and fenceline for the 0–0.1 m depth increment. The line represents a 1:1 relationship.

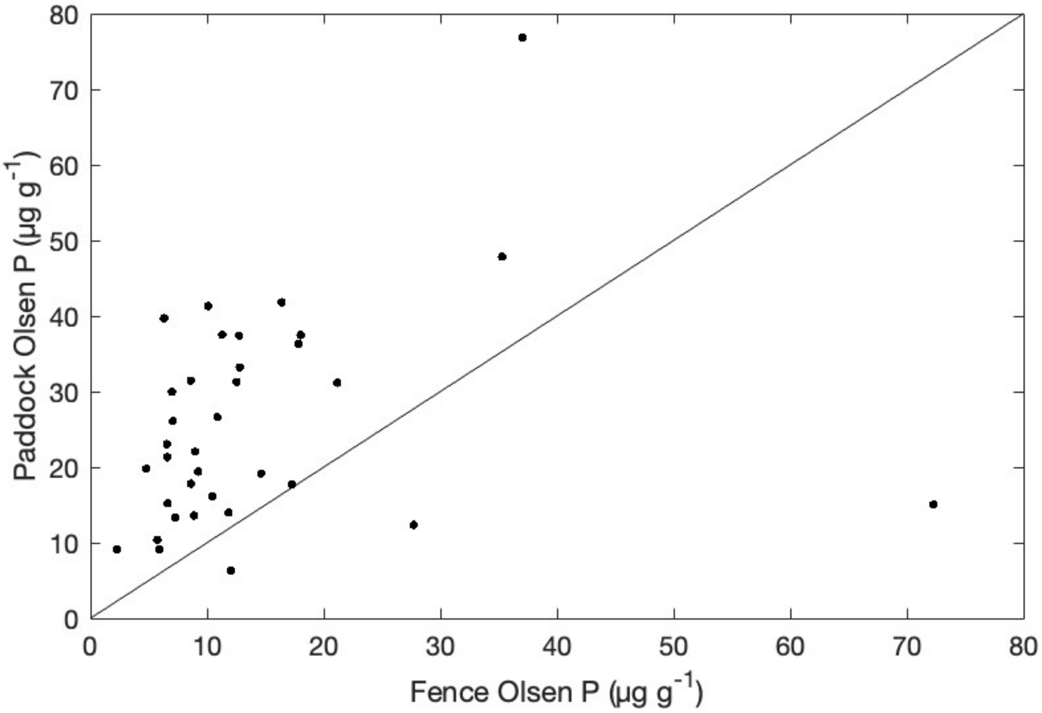

Fig 3.6: Relationship between Olsen P of the paddock and fenceline for the 0–0.1 m depth increment. The line represents a 1:1 relationship.

3.4.2.2. Mineral surface area

The mineral surface area (A_m) of the 0–0.1 m depth increment was used as an additional check that the soil types were comparable between the paddock and fenceline (Table 3.3). The average A_m for the paddock and fenceline was not significantly different (*P* = .779), with means of 88.9 ± 5.6 m^2 g^{-1} and 88.2 ± 5.9, respectively, indicating similar mineralogy within paired sites. However, differences in A_m were variable, with a range of a 31.1 m^2 g^{-1} increase to a decrease of 51.2 m^2 g^{-1}. The largest difference within a paired site was 51.2 m^2 $g^{-1,}$ or a difference of 58% (Fig 3.7). While there was little difference in most sites, the large difference of this site was considered when analysing stock changes between the two groups, with the statistical analysis performed both with and without this site.

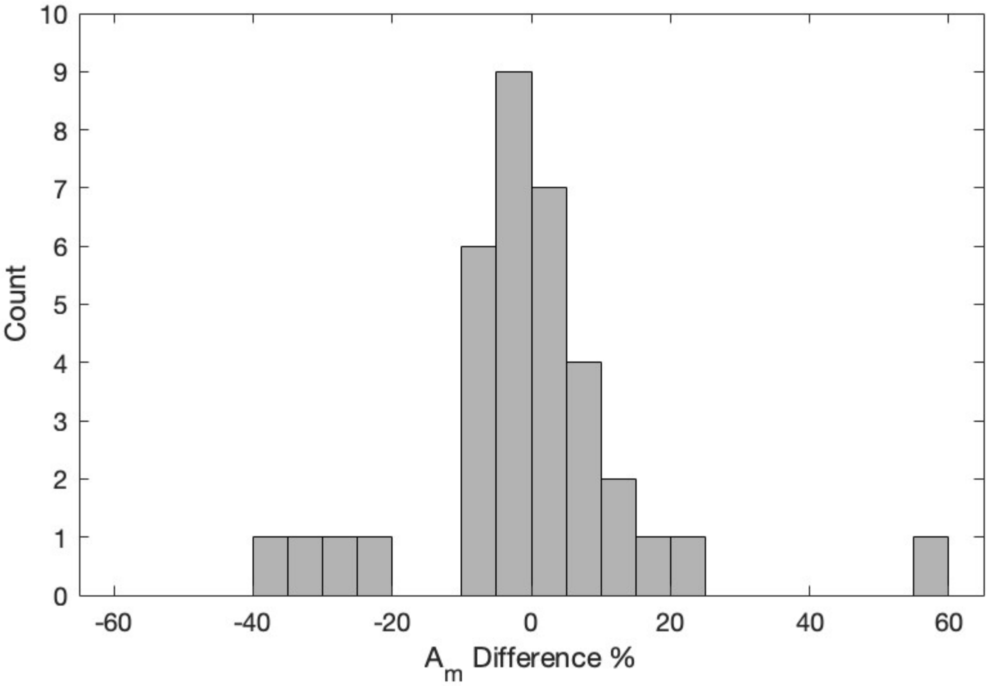

Fig 3.7: Percentage difference in mineral surface area (A_m) between corresponding pairs (paddock minus fenceline). Note the apparent outlier at 58% difference.

Table 3.3: Mean mineral surface area (A_m) for adjacent paddock and fenceline sites.

	A_m ($m^2\ g^{-1}$)	SE
Fenceline	88.9	5.6[a]
Paddock	88.2	5.9[a]
Difference[c]	−0.7	2.4[b]
P-value	0.78	

[a] SEM, standard error of the mean (n = 35).
[b] SED, standard error of the difference between means
[c] Difference in A_m (paddock – fenceline).

3.4.3. Soil C stocks

3.4.3.1. Soil mass

Average soil mass (t ha^{-1}) across all individually sampled depths (0.1 m depth increments) was greater in paddocks than under fencelines (Table 3.4). However, the difference in soil mass across individual depths was only significantly different to 0.4 m depth ($P \leq 0.05$). A significant difference was also seen in the cumulative mass to 0.6 m ($P <.001$). The average cumulative mass to 0.6 m was 4535 ± 206 t ha^{-1} for cores collected from paddocks and 4307 ± 205 t ha^{-1} for cores collected under fencelines. The greatest difference between paddock and fenceline was observed in the top 0.1 m, where 33.8% (77 t ha^{-1}) of the cumulative difference to 0.6 m (228 ± 53 t ha^{-1}) occurred. These differences reinforce the importance of calculating comparisons of C and N stocks on an ESM basis (see section 3.4.3.4).

Table 3.4: Average soil mass (t ha^{-1}) for adjacent paddock and fenceline sites for the respective soil layers. Bold *P*-values are considered significant. Standard error of the mean in parenthesis (n =38).

Soil Depth (m)	Paddock (t ha^{-1})	Fenceline (t ha^{-1})	Difference[a] (t ha^{-1})	SED[b]	*P*-value
0-0.1	669 (24.8)	592 (26.9)	77	12	**<.001**
0.1-0.2	726 (28.8)	667 (27.0)	59	9	**<.001**
0.2-0.3	757 (35.9)	723 (33.2)	34	13	**.014**
0.3-0.4	780 (38.7)	750 (41.6)	30	13	**.031**
0.4-0.5	792 (39.5)	770 (40.9)	21	17	.217
0.5-0.6	812 (41.7)	804 (42.0)	8	12	.517
0-0.6	4535 (206)	4307 (205)	228	53	**<.001**

[a] Difference in soil mass (paddock – fenceline).
[b] SED, Standard error of the difference between means (n = 38).

3.4.3.2. Soil C and N stocks

When calculating stocks on an ESM basis, the total average cumulative C stocks (to 0.6 m) of the paddock and fenceline were 152.9 ± 8.2 t C ha^{-1} (range: 62.0 t C ha^{-1} to 279.1 t C ha^{-1}) and 142.6 ± 7.3 t C ha^{-1} (range: 67.8 t C ha^{-1} to 254.5 t C ha^{-1}), respectively (Fig 3.8, Table 3.5). For N, the total average cumulative stocks (to 0.6 m) of the paddock and fenceline were 14.7 ± 0.6 t N ha^{-1} (range: 6.6 t N ha^{-1} to 25.4 t N ha^{-1}) and 13.7 ± 0.5 t N ha^{-1} (range: 6.9 t N ha^{-1} to 20.1 t N ha^{-1}), respectively (Fig 3.9, Table 3.6). On average, paddocks had 10.3 ± 3.1 t C ha^{-1} (P = .002) greater soil C than fencelines (range of 74.9 t C ha^{-1} increase to a decrease of 35.5 t C ha^{-1}). As shown in Fig 3.7, one site had an unusually large difference in A_m between paddock and fenceline soils of 58%, with the paddock having a much greater A_m than the fenceline. This disparity likely indicated a poor match of soil type between the paddock and fenceline at this location, which was not apparent during sampling. When this site was omitted from the dataset, the average C change remained well above zero (9.3 ± 3.0 t C ha^{-1}, P = .004). Similarly, average total N stocks were 0.96 ± 0.56 t N ha^{-1} (P = .002) greater in the paddock than under the fenceline. When the site with the unusual difference in A_m was omitted, the average change decreased to 0.86 ± 0.53 t N ha^{-1} (P = .003). The change in N was highly correlated to the change in C (Fig 3.10, Adjusted R^2 = 0.871, P <.001). The nominal age of the fenceline (range: 13 to >70 years, mean: ~42 years) and the difference in total C (P = .193), POM-C (P = .118) and MAOM-C (P = .599) stocks were not correlated (Fig 3.11).

Table 3.5: Average equivalent soil mass (ESM) adjusted total carbon (C) stocks for adjacent paddock and fenceline sites for the respective soil depths. Bold *P*-values are considered significant. Standard error of the mean in parenthesis (n = 38).

Soil Depth (m)	**Paddock (t C ha^{-1})**	**Fenceline (t C ha^{-1})**	**Difference[a] (t C ha^{-1})**	**Difference (%)**	**SED[b] (t C ha^{-1})**	***P*-value**
0-0.1	46.9 (1.94)	44.3 (2.06)	2.6	5.8	0.95	**.011**
0.1-0.2	37.3 (1.85)	35.9 (1.86)	1.3	3.8	0.81	.105
0.2-0.3	24.8 (1.63)	23.3 (1.36)	1.5	6.4	0.84	.084
0.3-0.4	17.5 (1.42)	15.8 (0.94)	1.7	10.6	0.81	**.046**
0.4-0.5	14.2 (1.23)	12.5 (0.92)	1.7	13.2	0.58	**.007**
0.5-0.6	12.1 (1.13)	10.6 (0.93)	1.5	14.4	0.51	**.005**
0-0.6	152.9 (8.20)	142.6 (7.31)	10.3	7.2	3.07	**.002**

[a] Difference in total C stocks (paddock – fenceline) calculated using an ESM for each paired site.

[b] SED, Standard error of the difference between means (n = 38).

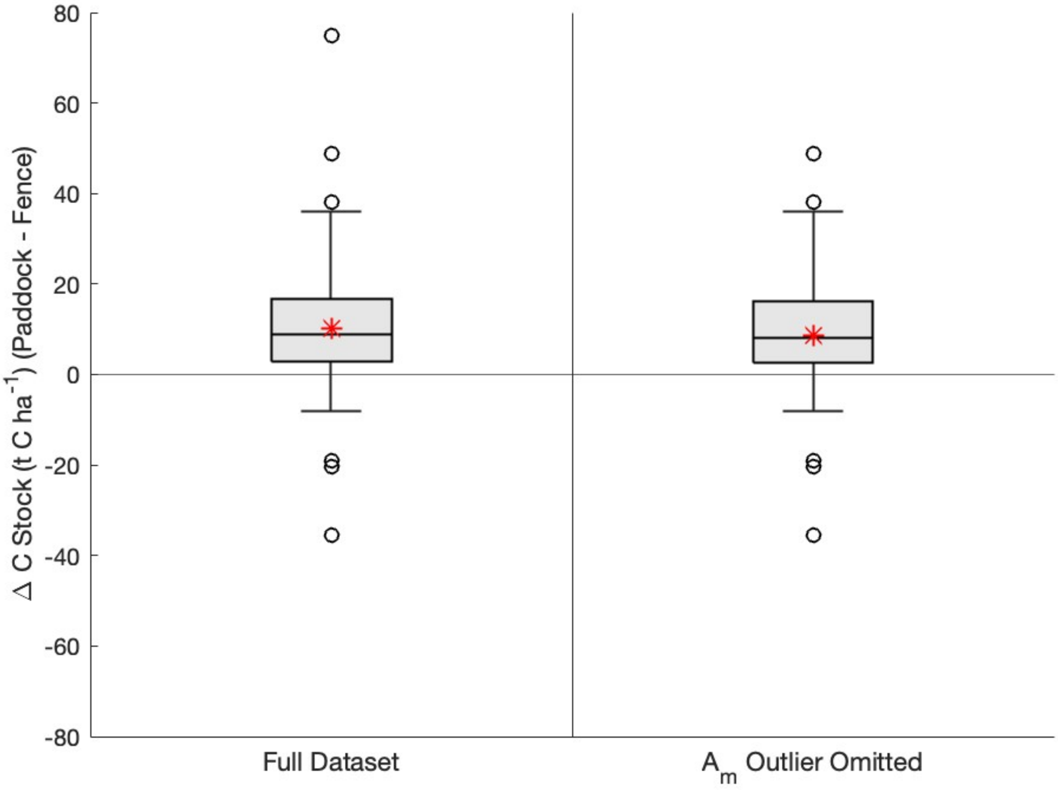

Fig 3.8: Difference in carbon (C) stocks (t C ha^{-1}) between paddock and fenceline samples to 0.6 m. Values above zero indicate higher C stocks in the paddock. While values below zero indicate higher C stocks in the fenceline. The boxplot on the left presents the overall results, including all data points (n = 38). The boxplot on the right excludes one site with a large discrepancy in mineral surface area (A$_m$, see text for further explanation). The asterisks indicate the mean, and the line indicates the median.

Table 3.6: Average equivalent soil mass (ESM) total nitrogen (N) stocks for adjacent paddock and fenceline sites for the respective soil layers. Bold *P*-values are considered significant. Standard error of the mean in parenthesis (n = 38).

Soil Depth (m)	**Paddock ($t\ N\ ha^{-1}$)**	**Fenceline ($t\ N\ ha^{-1}$)**	**Difference[a] ($t\ N\ ha^{-1}$)**	**Difference (%)**	**SED[b] ($t\ N\ ha^{-1}$)**	***P*-value**
0-0.1	4.85 (0.20)	4.40 (0.20)	0.45	10.2	0.10	**<.001**
0.1-0.2	3.63 (0.14)	3.49 (0.14)	0.15	4.2	0.09	.100
0.2-0.3	2.30 (0.11)	2.20 (0.10)	0.10	4.3	0.08	.228
0.3-0.4	1.58 (0.09)	1.51 (0.07)	0.07	4.5	0.06	.277
0.4-0.5	1.27 (0.09)	1.16 (0.07)	0.10	9.0	0.04	**.023**
0.5-0.6	1.06 (0.08)	0.96 (0.05)	0.10	10.3	0.04	**.028**
0-0.6	14.69 (0.61)	13.73 (0.54)	0.96	7.0	0.28	**.002**

[a] Difference in total N stocks (paddock – fenceline) calculated using an ESM for each paired site.

[b] SED, Standard error of the difference between means (n = 38).

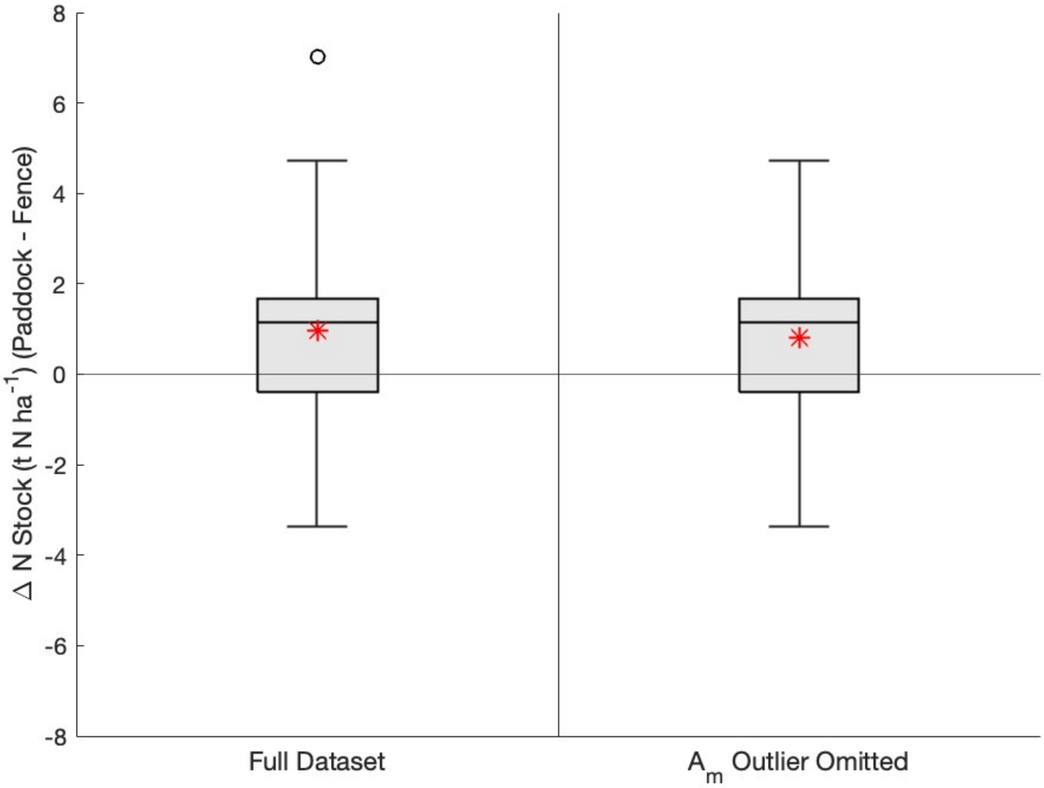

Fig 3.9: Difference in nitrogen (N) stocks ($t\ N\ ha^{-1}$) between paddock and fenceline samples to 0.6 m. Values above zero indicate higher N stocks in the paddock. While values below zero indicate higher N stocks in the fenceline. The boxplot on the left presents the overall results, including all data points (n = 38). The boxplot on the right excludes one site with a large discrepancy in mineral surface area (A_m, see text for further explanation). The asterisks indicate the mean, and the line indicates the median.

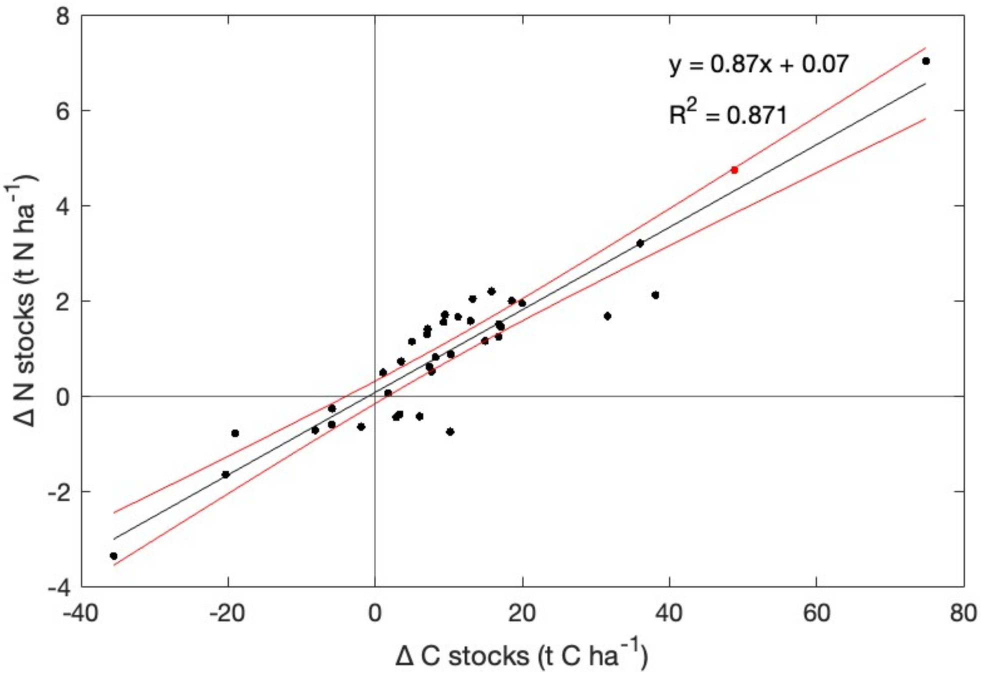

Fig 3.10: Relationship between the difference in carbon (C) stock (t C ha^{-1}) and the difference in nitrogen (N) stock (t N ha^{-1}) between the paddock and fenceline sites. The red dot indicates the mineral surface area (A_m) disparity. The black line is the linear regression, and the red lines on either side are the 95% confidence intervals of the regression line.

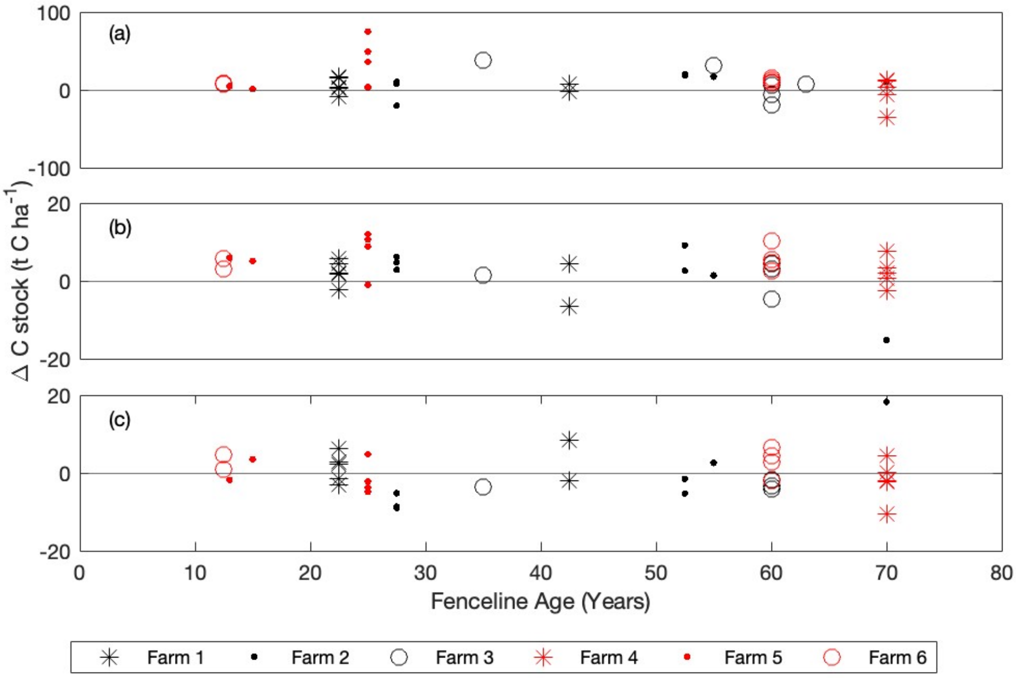

Fig 3.11: Relationship between the difference in (a) total carbon (C), (b) particulate organic matter C (POM-C) and (c) mineral-associated organic matter C (MAOM-C) stocks (t C ha^{-1}) between the paddock and fenceline sites and the nominal age of the fenceline (years).

3.4.3.3. Soil organic matter fractions

While soil C and N stocks were determined for the top 0.6m, POM-C and MAOM-C stocks were only measured for the upper layer (0-0.1m). For this upper layer, the average ESM adjusted total C stocks for the 35 soils fractionated were 46.6 ± 2.1 t C ha^{-1} for the paddock and 43.6 ± 2.2 t C ha^{-1} for the fenceline (Table 3.7), with a difference of 2.97 ± 1.0 t C ha^{-1} (*P* = .005). Total POM-C stocks in the paddock were 3.13 ± 0.9 t C ha^{-1} greater than under the fenceline (*P* = .001) with means of 15.2 ± 1.0 t C ha^{-1} and 12.1 ± 1.0 t C ha^{-1}, respectively. Total MAOM-C stocks in the paddock and fenceline were very similar, with means of 31.3 ± 1.7 t C ha^{-1} and 31.5 ± 1.8 t C ha^{-1}, respectively (*P* = .863). Carbon loading (a measure of MAOM saturation) was not significantly different (*P* = .926), with means of 0.662 ± 0.35 and 0.659 ± 0.34 in the paddock and fenceline, respectively. Due to calculations of C loading requiring A_m, the site with the large variation in A_m was excluded.

Table 3.7: Average equivalent soil mass (ESM) adjusted total particulate organic matter carbon (POM-C) and mineral-associated organic matter carbon (MAOM-C) stock (t C ha^{-1}) in the top 0.1 m. Bold *P*-values are considered significant. Standard error of the mean in parenthesis (n = 35).

Fraction	Paddock C stock (t C ha^{-1})	Fenceline C stock (t C ha^{-1})	Difference[a] (t C ha^{-1})	SED[b]	P-value
POM-C	15.24 (0.98)	12.11 (1.04)	3.13	0.87	**.001**
MAOM-C	31.33 (1.98)	31.50 (1.76)	−0.164	0.941	.863
Total	46.57 (2.09)	43.60 (2.16)	2.97	0.992	**.005**

[a] Difference in total SOM fraction stocks (paddock – fenceline) was calculated using an ESM for each paired site.

[b] SED, Standard error of the difference between means (n = 35).

3.4.3.4. Different approaches for estimating C and N stocks

Different stock calculation approaches were compared by calculating soil C stocks using fixed depth and two ESM approaches (a single reference mass and a site-specific reference mass). The average change in C stock was highest when stocks were calculated to a fixed depth (0.6 m) (14.6 ± 3.1 t C ha^{-1}) (Table 3.8, Fig 3.12). Applying a single ESM reference mass (2500 t ha^{-1}) across all sites resulted in the lowest difference in C stocks (8.3 ± 2.5 t C ha^{-1}). At one site, this soil mass was equivalent to a depth of 0.22 m. When applying a site-specific ESM mass at this site, the mass was equivalent to 0.57 m (see Appendix B). Using a site-specific ESM correction resulted in a change in C stocks of 10.3 ± 3.1 t C ha^{-1}.

Table 3.8: Mean change in soil carbon (C) stocks (t C ha^{-1}) calculated using three different methods. Fixed depth is the C stocks calculated to a fixed depth of 0.6 m. Common equivalent soil mass (ESM) is a single reference soil mass used to calculate stocks across all sites. Site-specific ESM is a site-specific reference soil mass used for each site.

ESM Method	Mean C stock (t C ha^{-1})	SEM[a]
Fixed Depth	14.6	3.1
Common ESM	8.3	2.5
Site-specific ESM	10.3	3.1

[a] SEM, Standard error of the mean (n = 38).

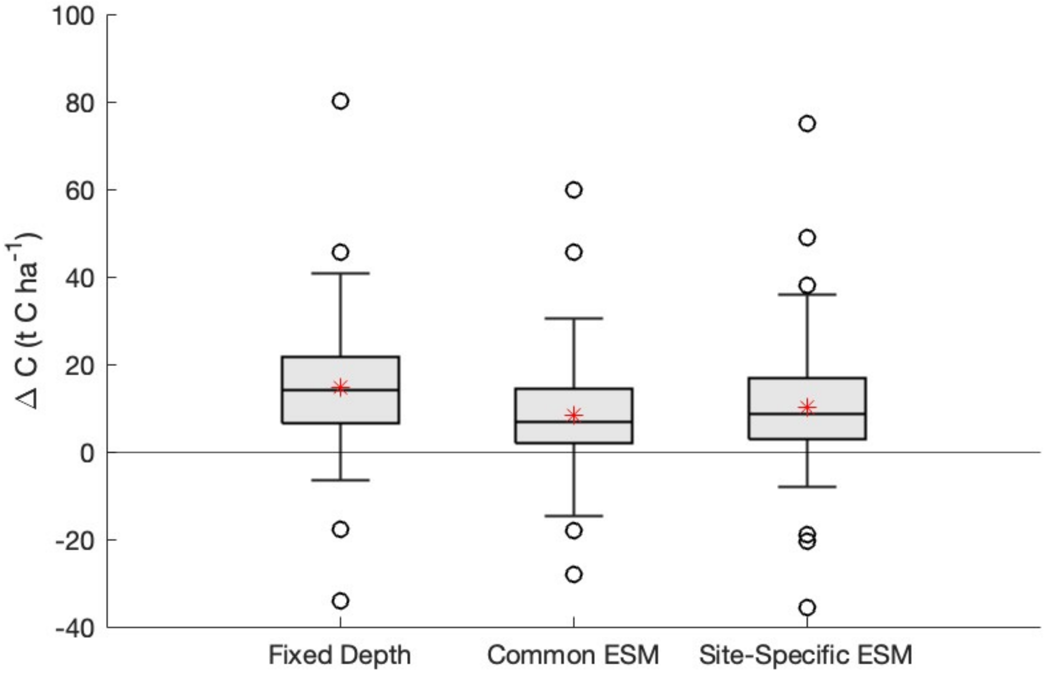

Fig 3.12: Mean change in soil carbon (C) stocks (t C ha^{-1}) calculated using three different methods. No equivalent soil mass (ESM) is the C stocks calculated to a fixed depth (0.6 m). Common ESM is a single mass used to calculate stocks across all sites. Site ESM is a site-specific mass used for each site. Asterisks indicate the mean.

3.4.3.5. Predicting profile change in soil C using shallower depths

The possibility of predicting the change in soil C stocks for the entire sampled profile using shallower sampling depth was tested. The relationship between the change in C stocks to 0.6 m and the change in C stocks to 0.4 m was considerably stronger than using shallower depths (0.1, 0.2, and 0.3 m) (Fig 3.13). While the relationship was stronger with depth, the change in C stocks was still underestimated at 0.4 and 0.5 m compared to the change seen at 0.6 m.

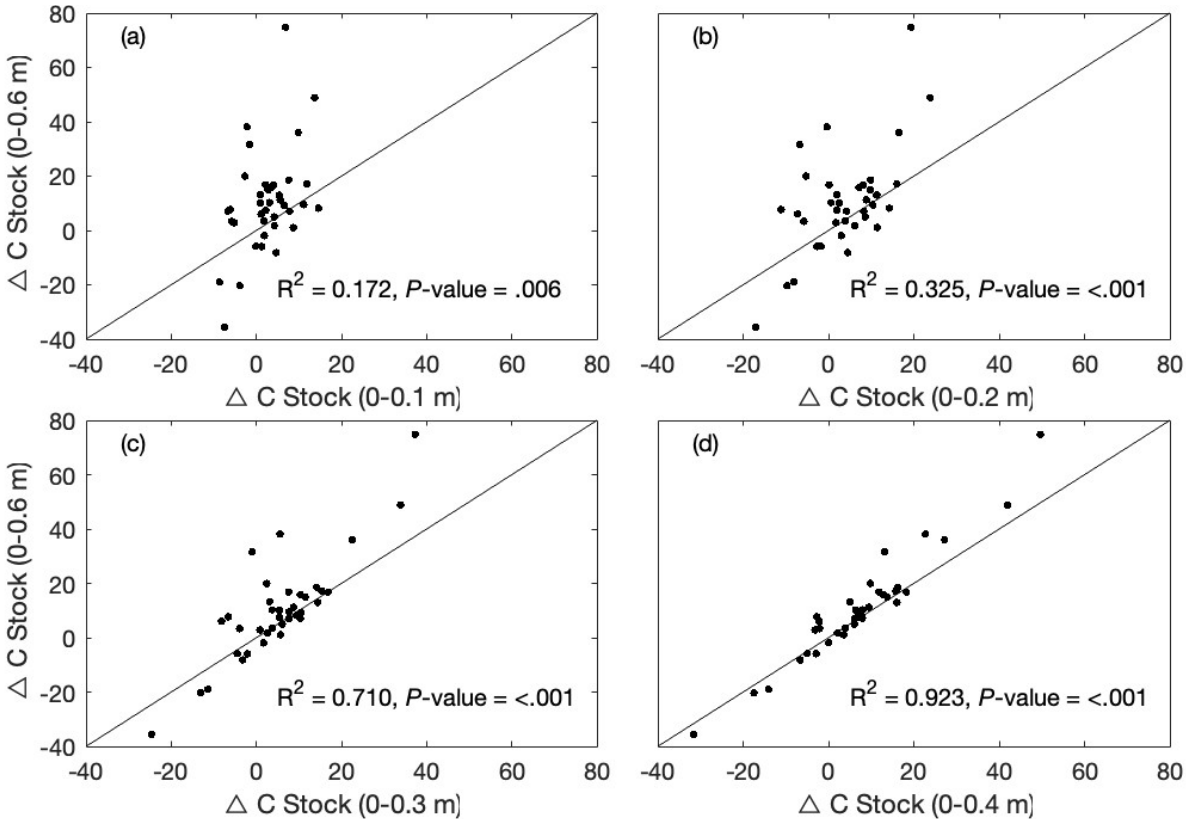

Fig 3.13: Relationship between the change in carbon (C) stocks (t C ha^{-1}) between the paddock and fenceline calculated to different depth increments, (a) 0-0.1 m, (b) 0-0.2 m, (c) 0-0.3 m, (d) 0-0.4 m, and the cumulative C stocks to 0.6 m. The line represents a 1:1 relationship.

3.5. Discussion

3.5.1. Comparison of paddock and fenceline C and N stocks

Paddocks had 10.3 t C ha^{-1} more C throughout the sampled profile (0.6 m) than fencelines. For one site, there was a very clear difference in A_m, suggesting a potential mismatch of soils within the pair. When this pair was excluded from the analysis, mean C stocks were 9.3 t C ha^{-1} higher in the paddock than under the fenceline. The largest contribution to this difference was in the topsoil (0–0.1 m, 2.6 t C ha^{-1}). The response of N followed soil C, with higher N stocks (0.96 t N ha^{-1}) throughout the soil profile (0.6 m) of paddocks than under the fenceline. When the A_m pair was excluded, the difference in N stocks decreased to 0.86 t N ha^{-1}. Like soil C, most of this difference in N stocks was observed in the 0–0.1 m depth increment (0.45 t N ha^{-1}).

No relationship was found between the age of the fenceline and the difference in C stocks, suggesting that any differences in C stocks induced by dung input may have occurred early (<10 years) before reaching a new steady state.

These results were generally consistent with Carran and Theobald (2000), who also reported greater C and N stocks in the paddock compared to the fenceline. However, their study was limited to a depth of 0.3 m, with only six sampling sites across a single farm, and did not apply an ESM correction. In contrast, this study extends these observations to greater depths (0.6 m) with increased site replication (38 sites) and incorporates an ESM correction, providing a more accurate understanding of the differences in soil C and N stocks throughout the soil profile of paddocks and fencelines.

The initial hypothesis was that any difference in C stocks depended on greater dung returns to paddocks than under fencelines (see section 3.5.4). While the study by Carran and Theobald (2000) is the only other New Zealand-based study comparing paddock and fenceline soil C and N stocks that we are aware of, there are other New Zealand-based studies where dung inputs differ due to differences in land management. Barnett et al. (2014) measured lower C stocks in dairy farms than in adjacent drystock farms by taking samples by horizon from a soil pit. However, these results were only significant within the A horizon due to the greater variability lower in the soil profile. Similar to our study on paddocks and fencelines, dairy farms receive higher excreta loadings than drystock farms due to higher stocking rates. Barnett et al. (2014) reported nearly double the stocking rate in dairy (24 SU ha^{-1}) than in drystock (14 SU ha^{-1}) farms. While irrigation is assumed to increase C and N stocks due to higher plant productivity and dung inputs, Mudge et al. (2017) reported irrigation reduced soil C stocks in the top 0.3 m of New Zealand pastures by 7.0 t C ha^{-1}. These reductions are likely due to increased decomposition rates with increasing organic matter inputs, leading to a faster turnover of plant-derived C inputs under irrigation (Carmona et al., 2020; Stoner et al., 2021).

International studies have also measured similar responses to the application of manure, which is stored excreta. A meta-analysis of the response of SOC stocks to a range of manure types and application rates found that the application of cattle manure increased C stocks by 32% or 15 t C ha^{-1} (Gross & Glaser, 2021). Additionally, Li et al. (2020) observed that increasing manure application rates led to higher concentrations of soil C. Their study found a significant linear relationship between the rate of SOC sequestration and C input, indicating that SOC was not saturated after nine years of manure application (Li et al., 2020). However, long-term trials (7–157 years) at Rothamsted Research in the United Kingdom showed that increases in C stocks declined with increasing trial duration, suggesting a trend towards equilibrium C content even in the presence of ongoing manure inputs (Poulton et al., 2018).

Differences in soil C were not limited to the surface soils where dung is deposited but also lower in the profile, suggesting that C is moving further down the profile. Lambie et al. (2012) demonstrated that urine deposition increased C leaching through soil cores. The fate of this leached C was not determined, but it may be stabilised lower in the profile, contributing to observed soil C stocks lower in the profile. Therefore, the C deposited by dung is possibly leached lower into the soil profile, resulting in the measured differences in C stock between the paddock and fenceline further down the soil profile.

3.5.2. POM-C and MAOM-C

The observed greater soil C stocks in the top 0.1 m of paddocks were primarily attributed to greater amounts of the fast-cycling POM fraction, with paddocks having approximately 3.1 t C ha^{-1} more POM-C than fencelines (*P* = .001). In contrast, we found no significant difference in the slow-cycling MAOM fraction (*P* = .863), suggesting that the MAOM pool in both the paddock and fenceline was at a steady state. Little work has been done in New Zealand on the impact of land management practices on SOM fractions. Shen et al. (2018) found that the relative contributions of POM and MAOM in New Zealand soils depended on soil order and land use. Mineral-associated organic matter was greatest in Allophanic soils due to higher amounts of short-range order constituents (i.e., Aluminium and iron oxy-hydroxides). In contrast, POM was greatest in ungrazed soils, while cropping decreased POM. Carbon contents were highest in permanently grazed grasslands and Allophanic soils. However, Allophanic soils also displayed the highest vulnerability to C loss (Shen et al., 2018). These findings support the findings of Schipper et al. (2014b), showing that the capacity of New Zealand soils to store C, as well as their susceptibility to C loss, is highly specific to each soil type (Schipper et al., 2014b; Shen et al., 2018).

While there seem to be limited New Zealand-based studies looking at dung or manure inputs and SOM fractions, other international studies have shown similar results. Kauer et al. (2021) found both POM-C and MAOM-C increased in the top 0.25 m of organically treated cropland soils (cover crops and manure application, inputs of 10–40 t ha^{-1}) in comparison to a control, which received no fertiliser or manure treatments. They showed that POM-C had a larger response to organic treatments (cover crops and manure application), with a larger increase than MAOM-C. However, when comparing the cover cropping treatment to the cover crop with cattle manure treatment, manure displayed no additional effect on POM-C stock but significantly increased the MAOM-C stock. The Kauer et al.

(2021) study considered MAOM <63 µm compared to our research, which considered MAOM <53 µm.

Additionally, Bian et al. (2024) found that applying inorganic NPK (inputs of 69 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1}, and 67.5 kg K_2O ha^{-1}) and green manure (inputs of 22.5 t ha^{-1}) with pig manure (inputs of 22.5 t ha^{-1}) increased the proportion of POM (>53 µm) in the top 0.2 m of soil, leading to gains in POM-C. However, no difference was found in MAOM-C. Like our study, the proportion of MAOM comprised most of the total SOC, making up 65–84% of the total SOC (Bian et al., 2024). The results of these studies suggest that manure inputs increase POM-C significantly and also have the potential to increase MAOM-C. However, this study found a difference only in POM-C, with no significant change observed in MAOM-C. Although the concept of manure application and dung deposition to increase soil C is largely the same, manure application is much more controlled regarding the timing, rate and spread. In contrast, dung is directly deposited by the grazing animal, leading to a more variable distribution and localised nutrient hotspots. So, while the principle behind these studies is similar to ours, the methods of manure and dung application differ considerably.

3.5.3. Olsen P and pH

Soil pH and available phosphorus (Olsen P) were, on average, significantly higher in areas receiving dung inputs. These differences were likely attributed to management impacts in the paddock differing from those in fenced areas, including but not limited to the influence of excretal inputs. In the paddock, the use of N fertiliser and the deposition of urine from livestock can result in the acidification of soil (Black, 1992). Regular lime application is commonly practised to counteract decreases in soil pH (Wheeler, 1997). Lime application is intentionally concentrated within the paddock boundary to increase soil pH for optimal plant growth for cattle feed (Morton, 2020). It is likely that soil under fencelines receives lower loads of lime, although some drift is inevitable. The differences in application rate between the paddock and fenceline likely contribute to the differences observed in soil pH. The pH of New Zealand's soil is naturally acidic (During, 1984), and conversion to grazed pastures led to ongoing decreases in soil pH (De Klein et al., 1997). The higher pH measured in agricultural soils reflects the widespread use of lime (Sparling & Schipper, 2004). The pH levels of other grazed pasture studies in New Zealand are slightly more acidic than in this study (Parfitt et al., 2014; Sparling & Schipper, 2004).

Phosphorus is a vital nutrient for plant growth, and its application to the field helps maintain optimal soil conditions for grass production (Malhotra et al., 2018). Phosphorus fertilisers are frequently applied to paddocks to improve soil fertility. Additionally, applying lime (and therefore increasing soil pH) can increase the amount of plant-available phosphorus at specific pH levels, decreasing the need for phosphate fertilisation (During, 1984; Mansell et al., 1984). A wide range of studies have demonstrated that phosphate fertiliser increases Olsen P values. The Olsen P value reflected the application rate, with higher application rates resulting in greater changes in Olsen P values. For example, Olsen P values in the study of Schipper et al. (2011) range between 10 $\mu g\ g^{-1}$ to 100 $\mu g\ g^{-1}$ increasing with increasing phosphate fertiliser applications of 0 to 100 kg $ha^{-1}\ y^{-1}$ over a 20 year period. Olsen P values measured in this thesis were slightly lower, ranging between 2 $\mu g\ g^{-1}$ and 77 $\mu g\ g^{-1}$, with the lower values observed at sites that did not receive fertiliser inputs. Like lime, fertiliser application is targeted within the paddock to increase grass production and minimise feed import costs for the farmer. Consequently, fertilisers are rarely applied intentionally to the fenceline, which likely explains the observed higher Olsen P within the paddock, along with greater returns of phosphorus in dung deposition. It is also likely that phosphorus in pasture biomass growing under the fenceline is continuously transferred to the paddock following grazing under fences and deposition of excreta on the paddock.

3.5.4. Dung distribution

As expected, dung distribution was nearly entirely in the paddock, with only one dung pat observed under the fenceline out of more than 2000 measured. The average density of dung pats was similar between the dairy farms (0.21 pats m^{-2})

and the drystock farm (0.19 pats per m^{-2}). This study's surface area of individual dung pats (0.05 m^2) aligned with those in other studies, with the average dung surface area ranging between 0.05 m^2 and 0.09 m^2 (Haynes & Williams, 1993).

Data from the current study were used to estimate dung loading based on the density and surface area of dung pats. It was calculated that 1% of the paddock was covered in dung after a single grazing. Two of our sampled farms had grazing rotations, resulting in paddocks being grazed between 11.5 and 13.5 times annually. By multiplying the 1% coverage per grazing event by the number of grazing's, we can estimate that between 11.5% and 13.5% of the paddock was covered in dung annually. Therefore, assuming an even distribution of dung, it would take between 7.4 and 8.7 years to fully cover a paddock with dung and longer if cow pats overlapped. Other New Zealand studies on the distribution of dung returns have reported higher return rates of dung, with 23% of the paddock being covered in dung annually when grazed with a stocking rate of 3 cows ha^{-1} (between 16.5 and 22.5 LSU ha^{-1}) (Williams, 1988, as cited in Haynes and Williams, 1993). Williams (1988) used a negative binomial distribution, which was found to closely match measurements of dung pats distribution (Petersen et al., 1956) and accounts for the possibility of an area being covered multiple times. A constant (k) is applied as a measure of the excretal patch aggregation. A mean k for higher stocking rates that resemble New Zealand dairy farms of 7 had been derived, suggesting a more uniform distribution of excreta throughout the paddock at higher stocking rates. Using the negative binomial distribution, our measured density of 0.2 pats m^{-2} and the k of 7, the calculated area covered in dung annually would be 18%. At this coverage rate, it would take 5.5 years to cover a paddock fully.

Assuming the typical dry weight of a dairy cow dung patch is 0.17 kg (Aarons et al., 2004; Haynes & Williams, 1993) and the average number of defecations per day is 14 pats day^{-1} (Haynes & Williams, 1993; Hirata et al., 2011), it can be estimated that the daily dung production per cow is 2.4 kg of dry weight per day. This, combined with the typical stocking rate for a New Zealand farm of 2.7 cows ha^{-1} (DairyNZ, 2023), results in a yearly dung production of 2365 kg DM ha^{-1} y^{-1}.

Using the C content of dung reported by Rutledge et al. (2017a) of 46.6%, it can be estimated that the yearly C loading from dung of 1102 kg C ha^{-1} y^{-1} or 1.1 t C ha^{-1} y^{-1}. While this is the estimated total amount of C applied to the soil surface via dung, it is thought that only 12% enters the soil (Maillard & Angers, 2014) which is equal to a dung C sequestration rate of 0.13 t C ha^{-1} y^{-1} in the short-to-medium term. This accumulation is likely balanced by ongoing decomposition of soil organic matter as most grazed soils are considered at steady state in New Zealand (Schipper et al., 2017; Wall et al., 2024).

Net ecosystem C balances have suggested that C is returned to New Zealand pasture systems through excreta (dung + urine) at a rate of 1.75 t C ha^{-1} y^{-1} (Wall et al., 2020; Wall et al., 2023; Wall et al., 2024), similar to the calculated estimates above. Although this represents the total amount of excreta C applied to the paddock, as mentioned above only 12% enters the soil, equal to a sequestration rate of 0.21 t C ha^{-1} y^{-1}. Assuming that the C in dung accumulates consistently over time, at the sequestration rate of 0.21 t C ha y^{-1}, it would take approximately 49 years to reach the observed stock differences measured at our sites. This accumulation rate in paddocks is possible as the sampled farms had been operating for at least 50 years, and fencelines had been present for, on average, 42 years. Yet we found no relationship between the differences in C stocks and the fenceline age, suggesting that the C derived from dung may accumulate more quickly than previous calculations suggest (Poulton et al., 2018). However, this calculation assumes that the change in C is due solely to excreta and does not include contributions from other sources such as effluent, supplemental feed residue (when fed in the paddock), fertiliser application, and plant contributions or the turnover rate of dung-derived soil C.

3.5.5. Implications for grazing management and soil C sequestration

These findings have implications for grazing management and soil C sequestration. Recycling grazed pasture through dung returns likely contributes to increased POM-C and total C stocks in paddocks. In contrast, the lack of dung returns beneath fencelines likely resulted in the lower POM-C and total C stocks.

It is difficult to determine whether dung returns have actively increased soil C in paddocks or just maintained C stocks relative to historical levels. Studies have suggested that New Zealand pastures typically display higher C stocks compared to their original forested state (Schipper et al., 2017). Additionally, C balances have suggested harvesting pasture results in a net source of GHGs compared to grazed pastures, which are a net sink (Koncz et al., 2017; Senapati et al., 2014). These results indicate that the insufficient return of dung in continuous pasture harvesting systems for feeding animals housed indoors may lead to a decline in soil C stocks compared to grazed pastures. The distinction between whether the paddock is gaining C or the fenceline is losing C is crucial for understanding the long-term impacts of grazing management on soil C sequestration.

3.5.6. Methodology and sampling depth

Soil bulk density was significantly higher in paddocks than fencelines at each depth increment to 0.4 m and at a cumulative depth of 0.6 m (Table 3.4). The largest difference was observed in the top 0.1 m and likely reflects the impact of regular cattle treading on soil compaction (Drewry et al., 2008). These differences were considered when calculating soil C and N stocks between treatments by employing a site-specific ESM correction, as recommended by Ellert and Bettany (1995). Equivalent soil mass is a concept used to standardise stock comparison by adjusting for variations in bulk density. Many studies recognise calculating stocks on an ESM basis as a best practice (Gifford & Roderick, 2003; Rovira et al., 2015; Wendt & Hauser, 2013). However, the specific choice of reference soil mass when implementing ESM corrections can lead to important differences in the calculated stocks. For instance, calculating C stocks to a fixed depth of 0.6 m for comparison and not applying any ESM correction led to an overestimation of C stock differences between the paddock and fenceline in this study of 4.3 t C ha^{-1}, as variations in bulk density were not accounted for. Conversely, calculating stocks based on a single reference mass across all sites led to the difference being underestimated by 2.0 t C ha^{-1} as site-specific variation was not accounted for. These results highlight the importance of using an ESM reference soil mass that reflects the soil profile to ensure more accurate estimates of soil C stocks (Wendt & Hauser, 2013).

The IPCC guidelines require stocks to be reported to a depth of at least 0.3 m (Intergovernmental Panel on Climate Change, 2003). However, numerous studies have highlighted that significant stock changes can occur at greater depths (Chaplot & Smith, 2023; Gross & Harrison, 2019; Simo et al., 2019; Skadell et al., 2023). Our research supports these findings, showing that C stock changes were detectable down to 0.6 m, suggesting that current guidelines may underestimate contributions at deeper levels. Our findings highlight the importance of considering soil sampling depth in soil stock comparisons.

The results of this study show that C stocks under the fencelines had very little influence from dung addition, with little to no dung deposited within the vicinity of the fenceline samples. Comparing samples taken beneath fencelines with those taken in adjacent paddocks proved to be an effective way of analysing the impact of grazing animals on soil properties. The inability of cattle to position themselves directly beneath the fenceline created an area of approximately 0.3 m on either side of the fence, where there were minimal dung returns or trampling. Although grazing management along fencelines likely differs from that within paddocks, the simultaneous removal of pasture beneath the fenceline and within the paddock through grazing allowed for a targeted comparison of the effect of cattle activity, such as dung returns or cattle treading, on soil properties.

3.5.7. Limitations

The findings of this study have potential limitations that need to be recognised. Firstly, the number of farms sampled was relatively small. Restricting the findings to a small range of climatic conditions and soil types limits the applicability of these findings to other regions (e.g., outside of the Waikato) with varying climates, agricultural practices or soil types. To ensure applicability, future research should involve a diverse selection of farms across different climatic zones.

Another consideration is the possibility of response bias since the study relied on farmers' self-reported information about their farming practices. This could lead to inaccuracies or selective reporting by participants (Dillman et al., 2014). Despite efforts like interviews and cross-referencing to mitigate bias, many studies still face challenges due to the nature of self-reported data (Floress et al., 2018).

Practical constraints such as time and funding prevented an evaluation of factors that might influence the findings. Potential variations between the paddock and fenceline, other than dung returns, such as pasture composition, were unable to be assessed. Future studies should include these variables and their impact on C stocks.

Although estimated through calculations in this study, the results are further confounded by the unmeasured rate of dung input. Accurately quantifying dung input is needed to determine the contribution of dung to soil C sequestration. Future studies should aim to measure dung input rates more accurately to better understand how dung inputs relate to soil C stock changes.

3.6. Conclusion

The significant difference in soil C stocks between paddocks and fencelines throughout the soil profile (0.6 m) supported net ecosystem C balance measurements, which suggested inputs of excreta result in higher C stocks (Wall et al., 2019). Paddocks contained, on average, 10.3 t C ha^{-1} more soil C than fencelines, with the topsoil (0–0.1 m) contributing the most to this difference. This pattern was consistent with N stocks, where paddocks exhibited 0.96 t N ha^{-1} more than fencelines, particularly in the top 0.1 m. The difference in C stocks was primarily accounted for by greater POM-C stocks in the topsoil of paddocks. Stocks of MAOM-C were relatively similar between paddocks and fencelines. The faster-cycling nature of POM-C suggests that the higher C stocks in pastures may be relatively short-lived, continuously being formed and degraded. At the same time, the lack of relationship between fenceline age and C stock differences suggests that dung input may increase C stocks to a new steady state relatively quickly (<10 years). Further research is needed to understand how quickly C from dung returns depletes to levels found beneath the fenceline.

Measurements suggest that an area of approximately 0.3 m on either side of the fenceline receives little to no dung input, while the paddock receives dung at an estimated rate of 1.1 t C ha^{-1} y^{-1}. Similar returns were estimated at a rate of 1.75 t ha^{-1} y^{-1} (Wall et al., 2020; Wall et al., 2023; Wall et al., 2024), leading to a potential C sequestration rate of 0.21 t C ha y^{-1}. At this rate, it would take around 49 years to accumulate the observed C stock differences between the paddock and fenceline, which aligns with the operational history of the sampled farms. However, no relationship between C stock differences and fenceline age, suggesting that C from dung may accumulate faster than estimated. The estimated calculation assumes that the change in C is solely due to excreta, not accounting for other sources or the turnover rate of dung-derived soil C. Clarifying whether paddocks are gaining C or fencelines are losing it is important for understanding the C dynamics of New Zealand’s grazed pastures.

CHAPTER FOUR

Summary and Conclusions

4.1. Introduction

Soil represents a substantial proportion of global terrestrial carbon (C), making it an important store of atmospheric carbon dioxide (CO_2). Carbon is in a continuous exchange between the land and atmosphere, and land management practices have influenced this land-atmosphere flux, leading to increased atmospheric CO_2 concentrations and decreased soil C stocks. Increasing soil C stocks will sequester and store CO_2 from the atmosphere.

A review by Schipper et al. (2017) demonstrated that the conversion from native forests to pastures led to a gain in New Zealand's soil C stocks. Soils gained approximately 13.7 t C ha^{-1} until a new steady state was reached. While many studies have explored the impact of pastoral land management practices on soil C stocks in New Zealand (Barnett et al., 2014; McNally et al., 2015; Mudge et al., 2017; Schipper et al., 2011; Whitehead et al., 2018), the mechanisms behind the measured increase are still largely unknown. Measurements of net ecosystem C balances in New Zealand pastures have demonstrated that animal excreta (urine + dung) is an important return of C to pastoral soils (Wall et al., 2019). Despite net ecosystem C balance measurements suggesting excreta may sequester soil C at a rate of approximately 0.21 t C ha^{-1} y^{-1} (Wall et al., 2020; Wall et al., 2023; Wall et al., 2024), the influence of direct dung deposition on soil C stocks in New Zealand remains unquantified.

The primary aim of this thesis was to investigate whether there were significant differences in the C and N stocks of soil beneath fencelines and paddocks with the assumption that these areas receive different loadings of dung C. To achieve this, 38 paired adjacent paddock and fenceline sites were sampled from six farms within the Waikato region using a soil coring approach. Carbon and N stocks were calculated using an ESM correction to account for potential differences in soil mass between paddock and fenceline sample sites.

The following sections will summarise the main findings of the research presented in Chapter 3 in relation to the objectives of this study, which are outlined in Chapter 1.2. Recommendations for future research are presented in section 4.5.

4.2. Differences in paired paddock and fenceline C and N stocks

Across the sampled soil profiles (0–0.6 m), paddocks had 10.3 t ha^{-1} more C than fenceline sites (*P* = .002) to approximately 0.6 m. These findings agreed with Carran and Theobald (2000) who demonstrated that the concentration of C was higher within paddocks than fencelines at one site in the Manawatū region to 0.15 m. A possible explanation for the higher C stocks in paddocks was related to higher dung input in these areas. To support the assumption that paddocks and fencelines had different dung loadings, the dung pats within 12 m of eight fencelines were mapped. One dung pat was observed within an area of approximately 0.3 m on either side of the fenceline. The application rate of dung-C to the soil surface in the paddock was calculated in this study using an estimate of daily dung production. A dung application rate of 1.1 t C ha^{-1} y^{-1} was estimated. Measurements of net ecosystem C balances have estimated a similar deposition of excreta (dung + urine) at 1.75 t C ha^{-1} y^{-1} (Wall et al., 2020; Wall et al., 2023; Wall et al., 2024). Using Maillard and Angers (2014) manure-C retention coefficient of 12%, an input rate of 1.75 t C ha^{-1} y^{-1} is equal to an excreta sequestration rate of approximately 0.21 t C ha^{-1} y^{-1}. At this rate, assuming changes in C are solely from dung deposition, it would take approximately 49 years to accumulate the C stock changes (to 0.6 m) seen in this study. Although the average fenceline age in this study (42 years) matches this accumulation rate, no relationship was found between the fenceline age (range: 13 years to >70 years) and C stock differences. This suggests that the differences observed may have accumulated relatively quickly (<10 years) before a new steady state was reached, implying a retention rate higher than the 12% reported by Maillard and Angers (2014). Alternatively, the measured differences might not be solely due to changes in the paddock C stocks. It is possible that while paddock C stocks increased, fenceline C stocks decreased, resulting in the difference measured at a faster rate than predicted. The estimate of 49 years assumes that the differences observed were attributed to dung deposition alone. Other inputs of C to the paddock (e.g., supplemental feed residue, effluent, etc.) should be considered along with the turnover rate of dung-derived soil C. Few studies have examined the influence of direct dung deposition on soil C stocks. However, research has found a strong relationship between cattle/farmyard manure or effluent application and increasing soil C (Barkle et al., 2000; Gross & Glaser, 2021; Li et al., 2020; Poulton et al., 2018), with studies also indicating a move towards equilibrium C content despite ongoing manure inputs (Poulton et al., 2018).

4.3. Differences in MAOM-C and POM-C between paired paddock and fenceline sites

The second objective of this thesis was to determine if there were significant differences in the C stocks of the soil organic matter (SOM) fractions between the paddock and fenceline and how these might contribute to measured differences in total C stocks.

The difference observed in total C stocks to 0.1 m could be attributed to the particulate organic matter C (POM-C) fraction, with significantly higher stocks of POM-C in the 0–0.1 m depth increment of the paddock than the fenceline (P = .001). No significant difference was found in the mineral-associated organic matter C (MAOM-C) stocks (P = .863). International studies have reported similar responses in SOM fractions to organic amendments, including pig and cattle manure, to a depth of 0.2 to 0.25 m (Bian et al., 2024; Kauer et al., 2021). If dung returns to the soil ceased, there would likely be a rapid loss of POM-C, causing the paddock C stocks to reflect C stocks beneath fencelines. The increase in POM-C suggests that the return of dung to the paddock initially enters the soil as POM-

C, which is then quickly lost as CO_2 before it can be converted to MAOM-C. The frequent addition of dung to pastures results in the new equilibrium C stocks observed in the paddock.

4.4. The importance of dung return for building soil carbon

The importance of dung returns for building soil C indicated in this study suggests that including livestock into other agricultural systems (e.g., cropping) where C is typically removed but not returned could improve the sequestration rate of C and increase soil C stocks. Higher C stocks in these systems would also have the potential to improve soil structure and increase soil fertility and crop yield (Hartmann & Six, 2023). However, the impact of integrative crop-livestock systems on soil C stocks remains ambiguous (Assmann et al., 2014; Brewer et al., 2023; Cecagno et al., 2018; da Silva et al., 2014; de Faccio Carvalho et al., 2010; Salton et al., 2014). While there is potential for integrated crop-livestock systems to sequester C, the sequestration rates in these systems are variable and dependent on factors such as grazing intensity, soil type, residue returns (amount and quality), and climate (Brewer & Gaudin, 2020).

Increasing the input of dung to soil likely has the potential to contribute towards initiatives like the 4 per mille initiative that aims to increase soil C stocks by 0.4% per year within the top 0.3 to 0.4 m of soil (4 per 1000, 2022). However, this potential is limited, as changes in C stocks from dung deposition and other organic matter additions eventually plateau, as demonstrated in this study by the lack of change with fenceline age and other studies (Smith, 2014). Thus, the potential for continuous increases in soil C stocks by dung deposition is unlikely. While new or increased dung inputs, either by increasing animal numbers or feed input, may increase soil C, the resulting increases in greenhouse gas (GHG) emissions through increased methane and nitrous oxide emissions would likely offset any sequestered CO_2. Therefore, while dung inputs may offer some potential to sequester atmospheric CO_2, a comprehensive assessment of all GHG emissions should be considered when considering dung returns as a climate change mitigation strategy.

4.5. Future work

Differences in C stocks between paddocks and fencelines were significant for the full sampled soil profile (0.6 m). It was hypothesised that the differences observed were driven by the large differences in dung loading between the paddock and fenceline, with the research in this thesis showing a significantly lower return of dung to the fenceline area. However, other management factors not explored that differ between the paddock and fenceline could also be contributing to the differences observed. While cattle have access to graze beneath the fenceline, less excretal returns and fertiliser application to the fenceline areas likely result in lower pasture growth within these areas and, therefore, lower organic matter return and C inputs to the soil. Additions of dung-derived C can be traced using stable isotope analysis, as demonstrated by Amelung et al. (1999). Using these techniques, the contribution of dung-derived C might be separated from the contributions of other sources (e.g., increased pasture growth). However, because SOM and dung-derived organic matter both predominately originate from plant-derived organic matter, this can be challenging as differences in isotopes may be small. Dungait et al. (2010) demonstrated that by feeding cattle a diet of C_4 plants (e.g., maize) and applying this dung to C_3-dominated grassland soils, the incorporation of dung-derived C could be traced using the natural abundance ^{13}C isotope labelling. Using similar techniques, the contribution of dung-derived C to the total C stocks of paddocks could be determined.

While we were able to detect a significant difference, the direction of change relative to historical levels is unknown. Determining whether the C stocks within the paddock have increased or been maintained relative to previous stock levels is important for understanding the impact of dung returns on the C cycling dynamics of grazed systems. Re-sampling of sites in this thesis after a period of time (e.g., 10 years) could indicate whether the change in C stocks found in the study of this thesis is due to changes in stocks in the fenceline or paddock.

While many studies on SOM fractions have been limited to the top 0.2 m (Cotrufo et al., 2019; Lugato et al., 2021), it is important to note that SOM fraction dynamics change with depth, extending beyond 0.2 m (Zani et al., 2022). In the study of this thesis, POM-C was found to be greater in paddocks compared to fencelines within the top 0.1 m. However, changes in total C stocks extended further down the soil profile. To gain a more comprehensive understanding of the C forms driving the change in total soil C, future research should extend the measurements of POM-C and MAOM-C stocks further down the soil profile. Extending measurements could be beneficial to determine if POM-C alone is driving the total change measured through the sampled profile (to 0.6 m).

Understanding the susceptibility of dung-derived C and SOM fraction C stocks to loss is important for understanding the long-term sequestration potential of dung additions, along with understanding how to better manage dung inputs for maximum soil C stocks. Excluding animals from a section of a paddock that previously received regular dung inputs and monitoring changes in total soil C and SOM fractions over time could give insight into how dung influences C cycling and sequestration. By comparing these results to a baseline (the rest of the paddock receiving regular dung inputs), the influence of dung on C stocks and its susceptibility to loss could be determined.

Schipper et al. (2014b) demonstrated that changes in soil C stocks could be attributed to soil order, with Allophanic and Gley Soils displaying more susceptibility to soil C loss than other soil orders (e.g., Brown Soils). Twenty-two of the 38 paired sites in the study of this thesis were Allophanic soils. Only four of the 15 main soil orders of New Zealand were sampled in this study. Extending the sampling of this study to cover a broader range of soil orders with a more even spread could help better understand whether the response of soil C stocks to dung inputs is different with differing soil orders.

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APPENDIX A

Additional Methods

Equivalent soil mass correction

To address the differences in soil mass at a fixed depth between paddock and fenceline samples, soil C and N stocks were adjusted to an equivalent soil mass (ESM) for each paired site. Soils were sampled to a depth of 0.65 m, and the initial total C and N stocks were calculated to a fixed depth of 0.6 m. The soil mass at 0.6 m was compared between the corresponding fenceline and paddock samples, with the lowest soil mass within the paired sites used as the ESM reference soil mass (see Table B.1). For example, at Farm 4 Site 23, the mass at 0.6 m in the paddock and fence sample was 5552 t ha^{-1} and 4670 t ha^{-1}, respectively. At this particular site, a mass of 4670 t ha^{-1} was considered the reference soil mass (Fig A.1).

For each site, cumulative C and N were plotted against cumulative soil mass, and a cubic spline was fitted using MATLAB's (R2023a version 9.14) spline function (https://www.mathworks.com/help/matlab/ref/spline.html). The soil C and N stock was adjusted to the chosen ESM. For example, in Fig A.1, the C stock at 4670 t ha^{-1} (horizontal dotted line) is determined by interpolation (vertical dotted lines). For comparison, stocks were also calculated to a single reference soil mass across all sites (determined using the lightest mass across all sites and rounding to the nearest hundred, 2500 t ha^{-1}). This was also done using the cubic spline function in MATLAB.

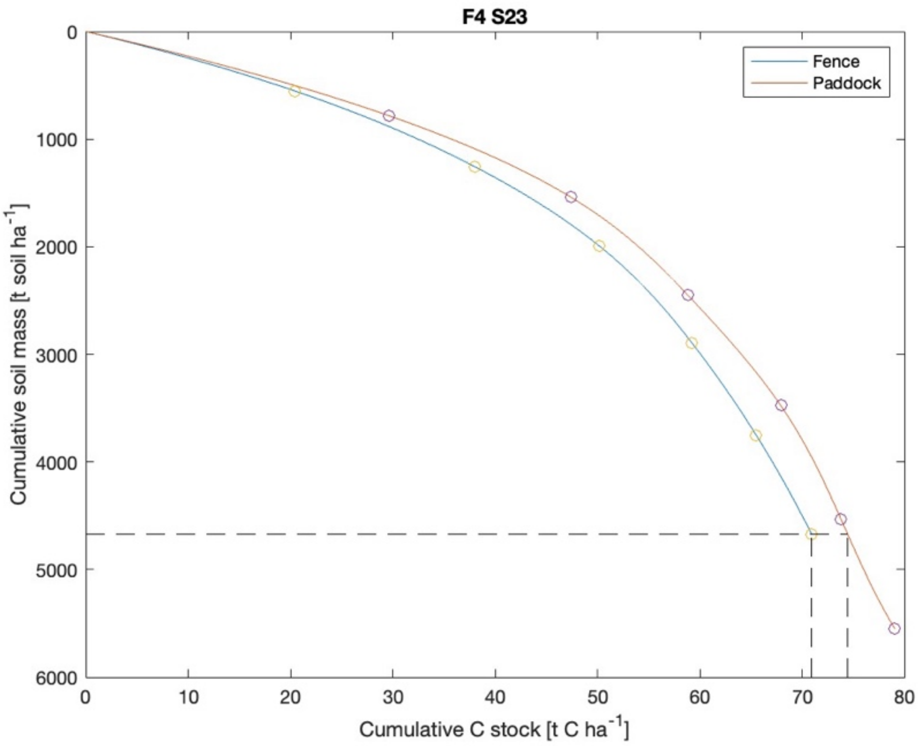

Fig A.1: An example of the cubic spline function used to fit the data and interpolate C stocks to an ESM reference soil mass. In this example, the C stocks at a reference soil mass of 4670 t ha^{-1} were determined by interpolation (dotted line).

Stock Unit Equivalents

Table A.1: The stock unit equivalents (SUE) used to calculate livestock units. Source: Stats NZ. (2021, 15 June). Modelling agricultural and horticultural land use area. https://www.stats.govt.nz/methods/modelling-agricultural-and-horticultural-land-use-area/ .

Land use	Description	SUE
Beef	Beef cow/heifers in calf 2 years and over	5.5
	Beef cow/heifers in calf over 1 year but under 2 years	4.4
	Beef cow/heifers in NOT calf 2 years and over	5.5
	Beef cow/heifers in NOT calf over 1 year but under 2 years	4.4
	Beef heifer and calves under 1 year old	3.5
	Steers 2 years and over	5.5
	Steers over 1 year but under 2 years	5
	Steers under 1 year old	4.5
	Breeding bulls (all ages)	5.5
	Non-breeding bulls 2 years and over	5.5
	Non-breeding bulls over 1 year but under 2 years	5.5
	Non-breeding bulls under 1 year old	4.5
	Calves born to beef heifers/cows	NA
Dairy	Dairy cows and heifers in milk/calf 2 yrs+	7.5
	Dairy cows and heifers in milk/calf 1-2 yrs	4.4
	Dairy cows and heifers NOT in milk/calf 2 yrs+	5.5
	Dairy cows and heifers NOT in milk/calf 1-2 yrs	4.4
	Rising 1 year old dairy heifer and heifer calves	3.5
	Dairy bulls to be used for dairy breeding	5
	Calves born to dairy heifers/cows	NA
	All other calves still on farm	2

Livestock Units (LSU) calculations

The area cropped at each farm was assumed to be returned to pasture and grazed from the beginning of May to the end of August (122 days). To account for this in LSU calculations, the area in permanent pasture was multiplied by 365, and the contribution of the cropped area was added by multiplying it by 122. The total was then divided by 365 to determine the total area grazed annually. This calculation allowed for the inclusion of the cropped area temporarily grazed when it was not under cultivation.

The number of calves on-farm for part of the year (September to May, 241 days) was accounted for by multiplying the LSU by the number of days these animals were on-farm. The LSU for animals on-farm year-round was multiplied by 365. The total was then divided by 365 to give the LSU on-farm annually. This allowed the LSU calculations to reflect the overall stocking rate annually.

Olsen P calculations

Olsen P was calculated by converting the mean absorbance to a concentration of phosphorus (P) using the equation of the straight line from Fig A.2. The concentration of P (µg P mL^{-1}) was then converted to Olsen P (µg P g^{-1}) by multiplying it by the volume of the extract used (40 mL) and dividing it by the mass of soil (~2 g). Raw data for Olsen P calculations can be found in Table C.3.

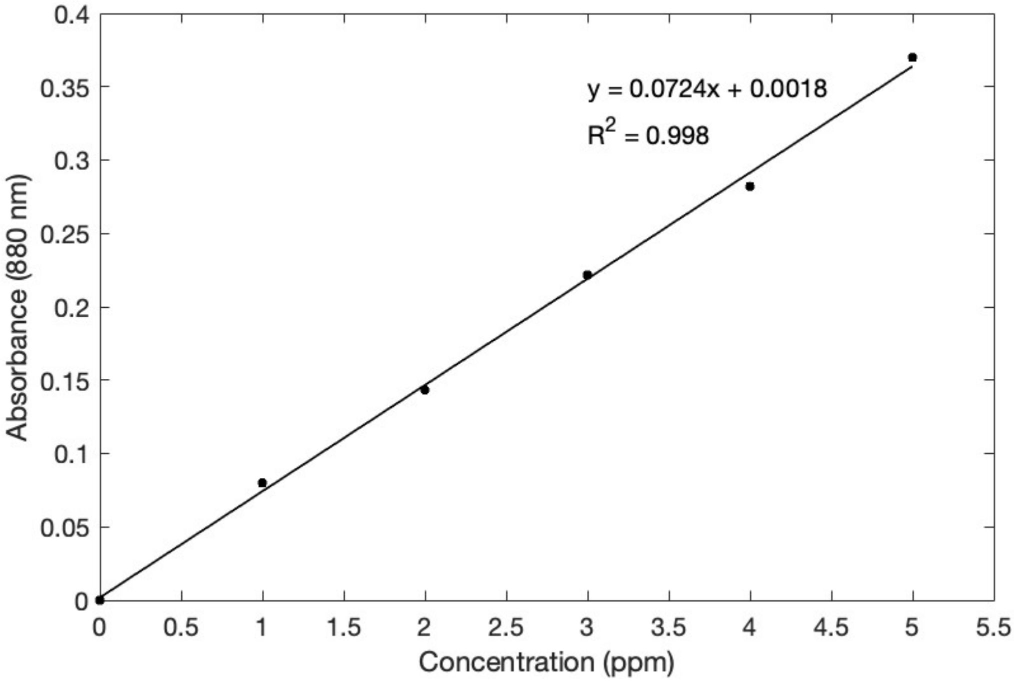

Fig A.2: Calibration curve used to calculate Olsen P values from the absorbance at 880 nm.

Farm management

Table A.2: Farm management information. The nitrogen (N) fertiliser application is averaged over the whole farm, or if data was given for the sampled paddocks, is the average application over the paddocks sampled. For the calculation of livestock unit equivalents, see Table A.1.

Farm	**Total Livestock Unit (LSU) Equivalents**	**Farm Size (ha)**	**Crop Area (ha)**	**Feed Import**	**Feed Export**	**N Fertiliser (kg N ha^{-1} y^{-1})**
1	2942	144	14	PKE, Silage	None	138
2	4719	199	15	Grass Silage, PKE, DDG	None	164
3	550	45	13	None	Maize, Hay, Silage	39
4	2767	104	2	Blend, Maize, Silage, Cheese Whey	None	0
5	5480	193	8	Maize, PKE, GDDG	None	108
6	4712	230	10	PKE	None	30

APPENDIX B

Additional Data

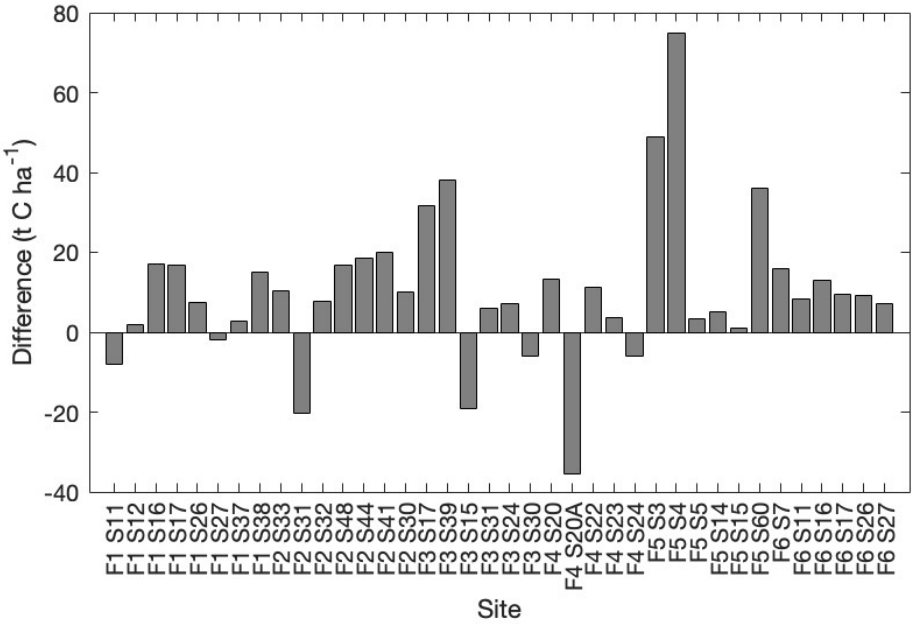

Fig B.1: Plot of individual site differences to 0.6 m (paddock – fence).

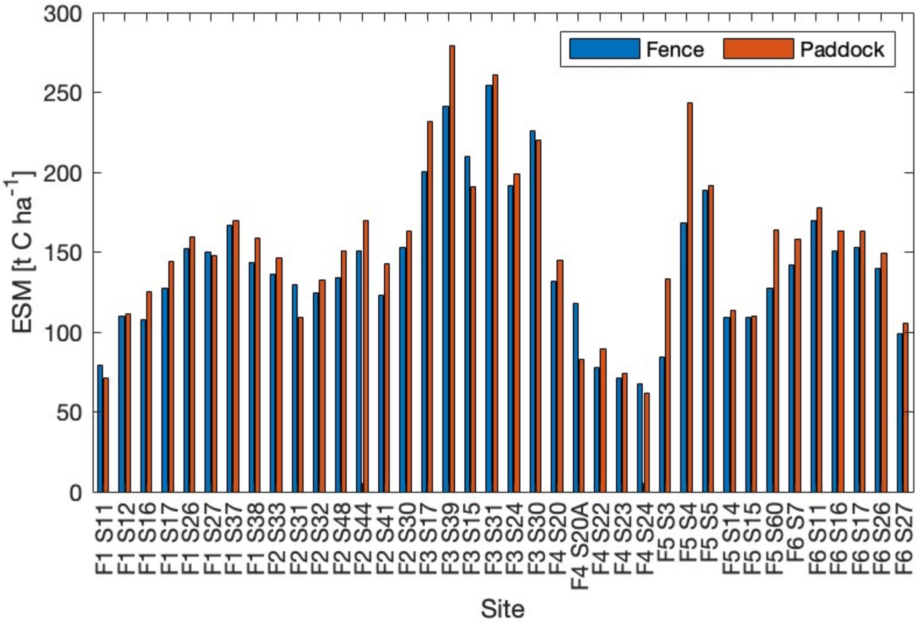

Fig B.2: Plot of individual total C stocks to 0.6 m.

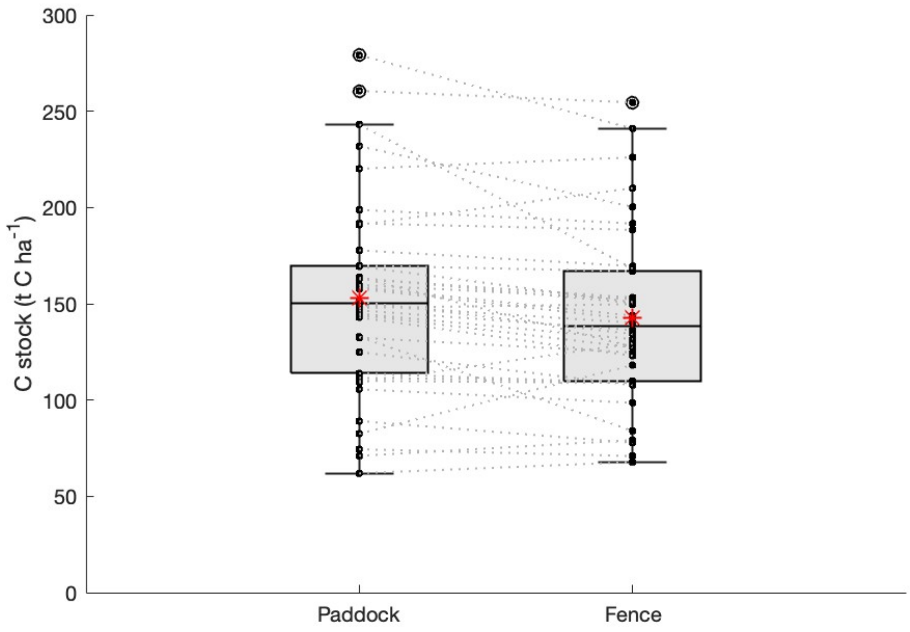

Fig B.3: Boxplot showing total C stocks (t C ha^{-1}) for paddock and fenceline sites. Dotted lines connect corresponding pairs. The middle line is the median, and the asterisks indicate the means.

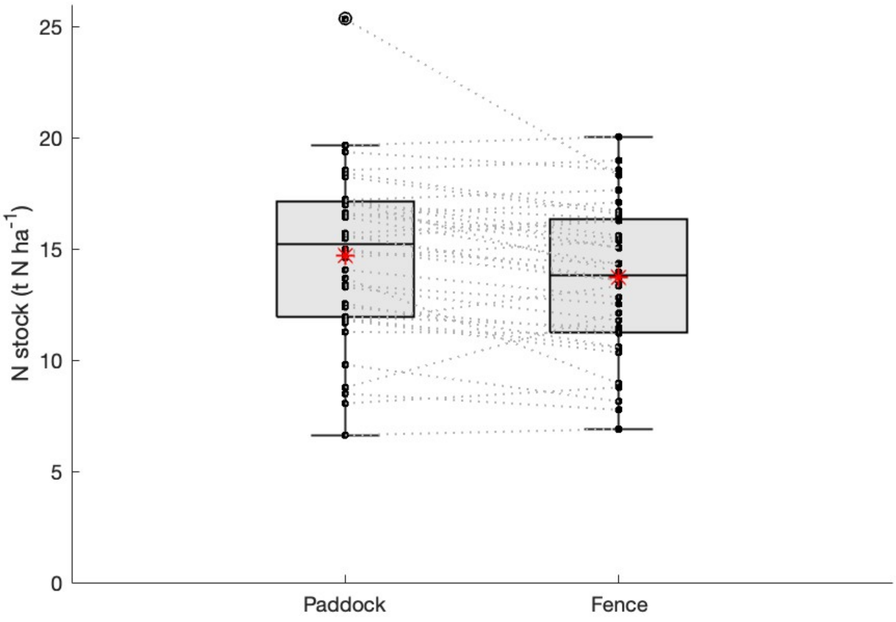

Fig B.4: Boxplot showing total N stocks (t N ha^{-1}) for paddock and fenceline sites. Dotted lines connect corresponding pairs. The middle line is the median, and the asterisks indicate the means.

Table B.1: Soil masses for the whole profile (0.6 m) for all sites. The equivalent soil mass (ESM) is the mass C stocks were adjusted to for each site. The equivalent depth is the soil depth to which the ESM corresponds. The equivalent depth to 2500 t ha^{-1} is the depth corresponding to the reference mass used for the uniform ESM calculations.

Farm Number	Treatment	Site Number	Mass of soil (t ha^{-1})	Equivalent Depth (m)	Reference soil mass (t ha^{-1})	Equivalent Depth to 2500 t ha^{-1} (m)
1	Fence	11	6631	0.600	6631	0.237
	Paddock		7095	0.565	6631	0.219
1	Fence	12	6019	0.600	6019	0.262
	Paddock		6206	0.582	6019	0.253
1	Fence	16	6016	0.576	5777	0.274
	Paddock		5777	0.600	5777	0.283
1	Fence	17	5488	0.600	5488	0.284
	Paddock		5675	0.582	5488	0.289
1	Fence	26	4964	0.600	4964	0.351
	Paddock		5150	0.587	4964	0.327
1	Fence	27	4920	0.573	4640	0.337
	Paddock		4640	0.600	4640	0.339
1	Fence	37	4774	0.600	4774	0.333
	Paddock		5103	0.562	4774	0.310
1	Fence	38	5139	0.592	5045	0.321
	Paddock		5045	0.600	5045	0.322
2	Fence	33	4755	0.600	4755	0.325
	Paddock		5171	0.551	4755	0.284
2	Fence	31	5219	0.600	5219	0.332
	Paddock		5887	0.539	5219	0.298
2	Fence	32	4023	0.600	4023	0.396
	Paddock		4917	0.493	4023	0.308
2	Fence	48	3877	0.600	3877	0.423
	Paddock		4900	0.491	3877	0.336

Farm Number	Treatment	Site Number	Mass of soil (t ha^{-1})	Equivalent Depth (m)	Reference soil mass (t ha^{-1})	Equivalent Depth to 2500 t ha^{-1} (m)
2	Fence	44	3806	0.600	3806	0.419
	Paddock		3990	0.573	3806	0.386
2	Fence	41	5226	0.552	4742	0.344
	Paddock		4742	0.600	4742	0.349
2	Fence	30	3746	0.600	3746	0.403
	Paddock		3787	0.594	3746	0.393
3	Fence	17	3023	0.600	3023	0.498
	Paddock		3067	0.591	3023	0.483
3	Fence	39	4421	0.600	4421	0.396
	Paddock		4627	0.586	4421	0.362
3	Fence	15	2577	0.600	2577	0.585
	Paddock		3049	0.502	2577	0.487
3	Fence	31	2616	0.600	2616	0.578
	Paddock		2868	0.548	2616	0.524
3	Fence	24	2712	0.600	2712	0.553
	Paddock		3476	0.478	2712	0.443
3	Fence	30	2541	0.600	2541	0.590
	Paddock		2923	0.516	2541	0.508
4	Fence	20	4425	0.593	4355	0.377
	Paddock		4355	0.600	4355	0.365
4	Fence	20A	4697	0.600	4697	0.343
	Paddock		5004	0.568	4697	0.332
4	Fence	22	4821	0.571	4520	0.349
	Paddock		4520	0.600	4520	0.362
4	Fence	23	4670	0.600	4670	0.357
	Paddock		5552	0.513	4670	0.305

Farm Number	Treatment	Site Number	Mass of soil (t ha^{-1})	Equivalent Depth (m)	Reference soil mass (t ha^{-1})	Equivalent Depth to 2500 t ha^{-1} (m)
4	Fence	24	5547	0.600	5547	0.293
	Paddock		6039	0.556	5547	0.267
5	Fence	3	3278	0.566	3104	0.442
	Paddock		3104	0.600	3104	0.473
5	Fence	4	3171	0.600	3171	0.481
	Paddock		3371	0.560	3171	0.441
5	Fence	5	3110	0.600	3110	0.497
	Paddock		3210	0.577	3110	0.460
5	Fence	14	6211	0.600	6211	0.287
	Paddock		6382	0.581	6211	0.256
5	Fence	15	6539	0.600	6539	0.267
	Paddock		6705	0.585	6539	0.253
5	Fence	60	3250	0.576	3125	0.474
	Paddock		3125	0.600	3125	0.484
6	Fence	7	2690	0.600	2690	0.559
	Paddock		2930	0.548	2690	0.511
6	Fence	11	3065	0.600	3065	0.503
	Paddock		3272	0.563	3065	0.462
6	Fence	16	3082	0.600	3082	0.474
	Paddock		3233	0.570	3082	0.457
6	Fence	17	3042	0.600	3042	0.494
	Paddock		3248	0.559	3042	0.454
6	Fence	26	3121	0.600	3121	0.490
	Paddock		3511	0.536	3121	0.430
6	Fence	27	6450	0.600	6450	0.273
	Paddock		6690	0.583	6450	0.254

APPENDIX C

Raw Data

Table C.1: Raw data for the calculation of carbon (C) and nitrogen (N) stocks at each depth increment. Carbon and N stocks reported are equivalent soil mass corrected.

Farm Number	**Treatment**	**Site Number**	**Depth (m)**	**Mass of soil <2 mm[a] (t ha^{-1})**	**Bulk density of all material (kg m^{-3})**	**%C (OD)**	**%N (OD)**	**C stock (t C ha^{-1})**	**N stock (t N ha^{-1})**
1	Fence	11	0-0.1	1050	1053	2.40	0.24	25	2.5
1	Fence	11	0.1-0.2	1073	1098	1.65	0.18	18	1.9
1	Fence	11	0.2-0.3	1045	1055	1.51	0.17	16	1.8
1	Fence	11	0.3-0.4	1185	1217	0.80	0.10	10	1.1
1	Fence	11	0.4-0.5	1166	1183	0.51	0.06	6	0.8
1	Fence	11	0.5-0.6	1111	1115	0.45	0.06	5	0.6
1	Paddock	11	0-0.1	1082	1087	2.82	0.30	30	3.1
1	Paddock	11	0.1-0.2	1185	1186	1.56	0.17	18	1.9
1	Paddock	11	0.2-0.3	1244	1249	0.67	0.08	8	0.9
1	Paddock	11	0.3-0.4	1203	1219	0.50	0.06	6	0.8
1	Paddock	11	0.4-0.5	1145	1150	0.42	0.06	5	0.7
1	Paddock	11	0.5-0.6	1236	1236	0.37	0.05	4	0.6
1	Fence	12	0-0.1	979	980	3.86	0.37	37	3.6
1	Fence	12	0.1-0.2	928	942	2.77	0.29	26	2.8
1	Fence	12	0.2-0.3	985	986	2.25	0.23	22	2.3
1	Fence	12	0.3-0.4	1101	1102	0.95	0.10	10	1.1
1	Fence	12	0.4-0.5	1048	1049	0.69	0.07	7	0.8
1	Fence	12	0.5-0.6	977	977	0.65	0.07	6	0.7

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
1	Paddock	12	0-0.1	961	986	4.32	0.41	41	4.0
1	Paddock	12	0.1-0.2	969	976	2.98	0.31	28	3.0
1	Paddock	12	0.2-0.3	1103	1108	1.80	0.18	19	1.9
1	Paddock	12	0.3-0.4	1123	1123	0.82	0.09	10	1.1
1	Paddock	12	0.4-0.5	1030	1030	0.70	0.07	7	0.8
1	Paddock	12	0.5-0.6	1020	1021	0.56	0.06	6	0.6
1	Fence	16	0-0.1	920	922	5.02	0.47	42	3.9
1	Fence	16	0.1-0.2	839	859	3.21	0.30	29	2.8
1	Fence	16	0.2-0.3	1021	1037	1.59	0.16	17	1.6
1	Fence	16	0.3-0.4	1060	1106	0.77	0.08	8	0.8
1	Fence	16	0.4-0.5	1120	1152	0.55	0.06	6	0.6
1	Fence	16	0.5-0.6	1056	1061	0.50	0.06	5	0.6
1	Paddock	16	0-0.1	828	831	6.55	0.64	54	5.3
1	Paddock	16	0.1-0.2	870	880	3.84	0.35	33	3.1
1	Paddock	16	0.2-0.3	975	1057	1.63	0.14	16	1.4
1	Paddock	16	0.3-0.4	1034	1134	0.86	0.08	9	0.9
1	Paddock	16	0.4-0.5	1019	1193	0.65	0.06	7	0.6
1	Paddock	16	0.5-0.6	1052	1103	0.56	0.05	6	0.6
1	Fence	17	0-0.1	838	843	5.22	0.51	43	4.2
1	Fence	17	0.1-0.2	836	883	3.47	0.33	30	2.8
1	Fence	17	0.2-0.3	987	1032	1.91	0.17	18	1.6
1	Fence	17	0.3-0.4	990	1007	1.52	0.13	16	1.4
1	Fence	17	0.4-0.5	907	910	1.26	0.11	11	1.0
1	Fence	17	0.5-0.6	930	931	0.99	0.09	9	0.8

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
1	Paddock	17	0-0.1	821	846	5.50	0.52	45	4.3
1	Paddock	17	0.1-0.2	857	910	4.20	0.40	36	3.5
1	Paddock	17	0.2-0.3	934	991	2.85	0.26	27	2.4
1	Paddock	17	0.3-0.4	1038	1050	1.65	0.14	17	1.4
1	Paddock	17	0.4-0.5	1003	1004	1.23	0.11	11	1.0
1	Paddock	17	0.5-0.6	1023	1024	0.78	0.07	8	0.7
1	Fence	26	0-0.1	701	701	7.81	0.83	55	5.8
1	Fence	26	0.1-0.2	696	698	5.45	0.58	38	4.0
1	Fence	26	0.2-0.3	707	709	3.19	0.35	23	2.5
1	Fence	26	0.3-0.4	807	807	2.12	0.23	17	1.9
1	Fence	26	0.4-0.5	974	978	1.31	0.14	13	1.4
1	Fence	26	0.5-0.6	1080	1082	0.67	0.07	7	0.8
1	Paddock	26	0-0.1	705	707	8.12	0.87	57	6.1
1	Paddock	26	0.1-0.2	780	782	5.28	0.56	38	4.0
1	Paddock	26	0.2-0.3	795	795	3.42	0.36	26	2.7
1	Paddock	26	0.3-0.4	822	823	2.02	0.22	18	2.0
1	Paddock	26	0.4-0.5	892	892	1.21	0.13	13	1.4
1	Paddock	26	0.5-0.6	1155	1156	0.66	0.06	8	0.8
1	Fence	27	0-0.1	703	704	7.17	0.79	49	5.4
1	Fence	27	0.1-0.2	740	751	4.92	0.54	38	4.1
1	Fence	27	0.2-0.3	766	773	3.00	0.33	23	2.5
1	Fence	27	0.3-0.4	808	817	2.15	0.24	17	1.9
1	Fence	27	0.4-0.5	902	918	1.56	0.17	13	1.4
1	Fence	27	0.5-0.6	1001	1041	1.15	0.12	11	1.2

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
1	Paddock	27	0-0.1	682	685	7.48	0.82	51	5.6
1	Paddock	27	0.1-0.2	757	777	5.11	0.56	39	4.2
1	Paddock	27	0.2-0.3	760	768	2.84	0.29	22	2.2
1	Paddock	27	0.3-0.4	769	784	1.96	0.20	15	1.5
1	Paddock	27	0.4-0.5	779	809	1.53	0.16	12	1.2
1	Paddock	27	0.5-0.6	893	909	1.08	0.10	10	0.9
1	Fence	37	0-0.1	672	679	8.81	0.93	58	6.2
1	Fence	37	0.1-0.2	687	707	5.92	0.60	41	4.2
1	Fence	37	0.2-0.3	857	871	3.32	0.36	28	3.1
1	Fence	37	0.3-0.4	850	888	2.04	0.22	17	1.9
1	Fence	37	0.4-0.5	823	876	1.33	0.14	11	1.2
1	Fence	37	0.5-0.6	885	916	1.16	0.12	10	1.1
1	Paddock	37	0-0.1	662	670	8.04	0.81	53	5.3
1	Paddock	37	0.1-0.2	853	865	6.59	0.66	48	4.8
1	Paddock	37	0.2-0.3	892	909	2.56	0.27	28	2.9
1	Paddock	37	0.3-0.4	898	915	1.57	0.17	13	1.5
1	Paddock	37	0.4-0.5	916	939	1.61	0.16	13	1.3
1	Paddock	37	0.5-0.6	882	919	1.54	0.15	14	1.4
1	Fence	38	0-0.1	700	702	7.95	0.85	55	5.9
1	Fence	38	0.1-0.2	771	779	4.98	0.52	39	4.1
1	Fence	38	0.2-0.3	841	845	2.39	0.27	20	2.3
1	Fence	38	0.3-0.4	910	916	1.40	0.16	12	1.4
1	Fence	38	0.4-0.5	913	916	1.12	0.12	10	1.1
1	Fence	38	0.5-0.6	1005	1011	0.71	0.08	7	0.8

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
1	Paddock	38	0-0.1	693	698	8.36	0.88	58	6.1
1	Paddock	38	0.1-0.2	775	783	5.90	0.61	46	4.7
1	Paddock	38	0.2-0.3	837	846	2.61	0.29	22	2.4
1	Paddock	38	0.3-0.4	884	889	1.67	0.17	15	1.5
1	Paddock	38	0.4-0.5	882	890	1.17	0.12	10	1.1
1	Paddock	38	0.5-0.6	975	985	0.84	0.08	8	0.8
2	Fence	33	0-0.1	695	707	5.31	0.53	36	3.7
2	Fence	33	0.1-0.2	676	862	3.52	0.34	23	2.3
2	Fence	33	0.2-0.3	892	909	2.74	0.24	24	2.1
2	Fence	33	0.3-0.4	921	931	2.62	0.22	23	2.0
2	Fence	33	0.4-0.5	797	800	2.19	0.17	17	1.4
2	Fence	33	0.5-0.6	774	780	1.79	0.13	13	1.0
2	Paddock	33	0-0.1	812	834	5.46	0.56	39	4.1
2	Paddock	33	0.1-0.2	904	1042	2.88	0.28	21	2.1
2	Paddock	33	0.2-0.3	927	942	3.34	0.28	27	2.4
2	Paddock	33	0.3-0.4	877	880	2.72	0.21	28	2.2
2	Paddock	33	0.4-0.5	821	828	2.17	0.17	18	1.4
2	Paddock	33	0.5-0.6	830	835	1.56	0.12	14	1.1
2	Fence	31	0-0.1	660	661	7.29	0.76	47	5.0
2	Fence	31	0.1-0.2	741	747	4.95	0.51	36	3.8
2	Fence	31	0.2-0.3	829	831	2.51	0.24	20	2.0
2	Fence	31	0.3-0.4	863	867	1.60	0.15	13	1.3
2	Fence	31	0.4-0.5	944	956	0.81	0.08	8	0.7
2	Fence	31	0.5-0.6	1182	1191	0.39	0.04	5	0.5

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
2	Paddock	31	0-0.1	753	754	6.51	0.73	43	5.0
2	Paddock	31	0.1-0.2	854	859	3.71	0.36	30	3.1
2	Paddock	31	0.2-0.3	915	921	1.66	0.16	17	1.6
2	Paddock	31	0.3-0.4	1004	1014	0.88	0.09	9	0.9
2	Paddock	31	0.4-0.5	1210	1221	0.40	0.05	6	0.6
2	Paddock	31	0.5-0.6	1150	1154	0.34	0.04	4	0.4
2	Fence	32	0-0.1	567	567	8.21	0.93	45	5.3
2	Fence	32	0.1-0.2	676	677	5.48	0.61	36	4.1
2	Fence	32	0.2-0.3	630	630	2.56	0.28	16	1.8
2	Fence	32	0.3-0.4	655	656	1.87	0.21	12	1.3
2	Fence	32	0.4-0.5	700	701	1.38	0.15	9	1.1
2	Fence	32	0.5-0.6	794	795	0.94	0.10	7	0.8
2	Paddock	32	0-0.1	733	736	6.57	0.78	39	4.7
2	Paddock	32	0.1-0.2	836	838	4.03	0.45	31	3.6
2	Paddock	32	0.2-0.3	860	861	2.68	0.28	20	2.2
2	Paddock	32	0.3-0.4	838	839	1.92	0.19	16	1.7
2	Paddock	32	0.4-0.5	814	816	1.84	0.18	13	1.3
2	Paddock	32	0.5-0.6	836	836	1.28	0.14	14	1.4
2	Fence	48	0-0.1	458	458	10.05	0.94	44	4.3
2	Fence	48	0.1-0.2	555	556	7.64	0.73	41	4.0
2	Fence	48	0.2-0.3	658	658	2.71	0.24	17	1.6
2	Fence	48	0.3-0.4	675	675	1.75	0.15	12	1.0
2	Fence	48	0.4-0.5	703	703	1.59	0.14	11	1.0
2	Fence	48	0.5-0.6	828	828	1.20	0.11	10	0.9

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
2	Paddock	48	0-0.1	586	587	10.42	1.00	48	4.9
2	Paddock	48	0.1-0.2	756	761	5.58	0.51	37	3.6
2	Paddock	48	0.2-0.3	839	841	2.78	0.24	25	2.2
2	Paddock	48	0.3-0.4	899	900	2.02	0.17	16	1.4
2	Paddock	48	0.4-0.5	875	876	1.41	0.10	14	1.1
2	Paddock	48	0.5-0.6	944	946	0.84	0.08	12	0.9
2	Fence	44	0-0.1	537	537	10.91	0.92	50	4.9
2	Fence	44	0.1-0.2	609	609	6.66	0.60	40	3.7
2	Fence	44	0.2-0.3	599	599	3.61	0.29	21	1.7
2	Fence	44	0.3-0.4	632	632	2.49	0.20	15	1.2
2	Fence	44	0.4-0.5	685	685	2.02	0.15	13	1.1
2	Fence	44	0.5-0.6	746	746	1.79	0.13	13	1.0
2	Paddock	44	0-0.1	639	640	10.69	1.12	57	6.3
2	Paddock	44	0.1-0.2	679	680	6.39	0.53	42	3.8
2	Paddock	44	0.2-0.3	650	650	3.73	0.29	25	2.0
2	Paddock	44	0.3-0.4	621	621	2.52	0.19	17	1.4
2	Paddock	44	0.4-0.5	691	691	2.12	0.15	14	1.1
2	Paddock	44	0.5-0.6	709	709	1.89	0.13	14	1.0
2	Fence	41	0-0.1	576	576	7.42	0.68	43	3.9
2	Fence	41	0.1-0.2	662	663	5.33	0.47	35	3.1
2	Fence	41	0.2-0.3	858	858	2.84	0.24	24	2.0
2	Fence	41	0.3-0.4	939	939	1.12	0.08	10	0.7
2	Fence	41	0.4-0.5	1124	1124	0.62	0.05	6	0.4
2	Fence	41	0.5-0.6	1068	1068	0.54	0.04	5	0.4

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
2	Paddock	41	0-0.1	725	729	6.67	0.71	40	4.3
2	Paddock	41	0.1-0.2	705	706	4.60	0.44	33	3.3
2	Paddock	41	0.2-0.3	705	705	3.57	0.27	32	2.6
2	Paddock	41	0.3-0.4	769	769	2.05	0.14	17	1.1
2	Paddock	41	0.4-0.5	891	892	1.22	0.07	11	0.7
2	Paddock	41	0.5-0.6	947	948	1.10	0.07	10	0.6
2	Fence	30	0-0.1	585	585	9.50	0.98	56	5.7
2	Fence	30	0.1-0.2	633	633	6.57	0.67	42	4.2
2	Fence	30	0.2-0.3	631	631	3.30	0.34	21	2.1
2	Fence	30	0.3-0.4	633	633	2.23	0.22	14	1.4
2	Fence	30	0.4-0.5	622	622	1.87	0.18	12	1.1
2	Fence	30	0.5-0.6	641	641	1.43	0.12	9	0.8
2	Paddock	30	0-0.1	604	604	9.62	0.95	57	5.6
2	Paddock	30	0.1-0.2	661	661	6.64	0.60	43	3.9
2	Paddock	30	0.2-0.3	650	651	3.55	0.31	24	2.1
2	Paddock	30	0.3-0.4	631	631	2.32	0.18	15	1.2
2	Paddock	30	0.4-0.5	615	615	2.02	0.15	13	1.0
2	Paddock	30	0.5-0.6	626	626	1.86	0.15	12	0.9
3	Fence	17	0-0.1	423	423	13.38	1.22	57	5.2
3	Fence	17	0.1-0.2	533	533	10.31	0.87	55	4.6
3	Fence	17	0.2-0.3	512	512	6.78	0.54	35	2.8
3	Fence	17	0.3-0.4	483	483	4.01	0.32	19	1.5
3	Fence	17	0.4-0.5	559	559	3.43	0.25	19	1.4
3	Fence	17	0.5-0.6	514	514	3.01	0.21	15	1.1

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
3	Paddock	17	0-0.1	521	522	12.55	1.17	55	5.2
3	Paddock	17	0.1-0.2	541	543	8.88	0.71	50	4.1
3	Paddock	17	0.2-0.3	531	531	7.75	0.54	41	2.8
3	Paddock	17	0.3-0.4	502	502	6.58	0.50	33	2.5
3	Paddock	17	0.4-0.5	485	485	5.24	0.36	31	2.2
3	Paddock	17	0.5-0.6	488	488	4.22	0.28	22	1.5
3	Fence	39	0-0.1	437	437	13.90	0.98	61	4.3
3	Fence	39	0.1-0.2	543	544	11.82	0.76	64	4.1
3	Fence	39	0.2-0.3	670	670	7.73	0.37	52	2.5
3	Fence	39	0.3-0.4	886	886	3.14	0.17	28	1.5
3	Fence	39	0.4-0.5	870	870	2.30	0.12	20	1.1
3	Fence	39	0.5-0.6	1015	1015	1.62	0.09	16	0.9
3	Paddock	39	0-0.1	604	604	13.26	1.02	59	4.7
3	Paddock	39	0.1-0.2	630	630	11.12	0.66	66	4.2
3	Paddock	39	0.2-0.3	741	741	6.91	0.34	58	3.0
3	Paddock	39	0.3-0.4	839	839	4.36	0.20	45	2.1
3	Paddock	39	0.4-0.5	781	781	3.14	0.15	30	1.4
3	Paddock	39	0.5-0.6	1033	1033	1.87	0.09	22	1.1
3	Fence	15	0-0.1	354	354	16.68	1.42	59	5.0
3	Fence	15	0.1-0.2	427	455	12.35	0.98	53	4.2
3	Fence	15	0.2-0.3	483	483	8.30	0.60	40	2.9
3	Fence	15	0.3-0.4	441	442	5.27	0.39	23	1.7
3	Fence	15	0.4-0.5	411	411	4.17	0.29	17	1.2
3	Fence	15	0.5-0.6	462	462	3.85	0.26	18	1.2

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
3	Paddock	15	0-0.1	483	487	14.05	1.26	50	4.6
3	Paddock	15	0.1-0.2	530	531	10.78	0.89	53	4.5
3	Paddock	15	0.2-0.3	462	462	5.51	0.39	37	2.8
3	Paddock	15	0.3-0.4	529	529	4.43	0.31	21	1.4
3	Paddock	15	0.4-0.5	564	564	3.00	0.21	17	1.2
3	Paddock	15	0.5-0.6	481	481	3.09	0.21	13	0.9
3	Fence	31	0-0.1	395	395	15.29	1.34	60	5.3
3	Fence	31	0.1-0.2	495	495	12.75	1.10	63	5.4
3	Fence	31	0.2-0.3	426	426	8.92	0.63	38	2.7
3	Fence	31	0.3-0.4	475	475	7.04	0.45	33	2.1
3	Fence	31	0.4-0.5	390	390	6.99	0.45	27	1.8
3	Fence	31	0.5-0.6	435	435	7.45	0.40	32	1.7
3	Paddock	31	0-0.1	484	487	15.05	1.40	61	5.8
3	Paddock	31	0.1-0.2	526	526	10.33	0.78	55	4.3
3	Paddock	31	0.2-0.3	475	475	8.43	0.53	37	2.4
3	Paddock	31	0.3-0.4	437	438	8.33	0.49	39	2.4
3	Paddock	31	0.4-0.5	464	464	8.18	0.45	32	1.8
3	Paddock	31	0.5-0.6	482	482	8.38	0.39	36	1.8
3	Fence	24	0-0.1	379	379	15.71	1.29	60	4.9
3	Fence	24	0.1-0.2	485	485	8.71	0.64	42	3.1
3	Fence	24	0.2-0.3	480	480	5.69	0.37	27	1.8
3	Fence	24	0.3-0.4	413	413	5.04	0.33	21	1.4
3	Fence	24	0.4-0.5	482	482	4.52	0.28	22	1.3
3	Fence	24	0.5-0.6	472	472	4.21	0.24	20	1.1

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
3	Paddock	24	0-0.1	528	528	13.46	1.18	53	4.7
3	Paddock	24	0.1-0.2	591	592	9.34	0.74	53	4.4
3	Paddock	24	0.2-0.3	572	572	5.04	0.33	33	2.4
3	Paddock	24	0.3-0.4	562	562	4.33	0.25	18	1.1
3	Paddock	24	0.4-0.5	592	592	4.19	0.24	21	1.2
3	Paddock	24	0.5-0.6	632	632	3.56	0.20	20	1.2
3	Fence	30	0-0.1	422	422	15.81	1.39	67	5.9
3	Fence	30	0.1-0.2	478	478	11.06	0.93	53	4.4
3	Fence	30	0.2-0.3	426	426	7.59	0.52	32	2.2
3	Fence	30	0.3-0.4	394	394	6.53	0.41	26	1.6
3	Fence	30	0.4-0.5	413	414	6.23	0.36	26	1.5
3	Fence	30	0.5-0.6	408	408	5.57	0.36	23	1.5
3	Paddock	30	0-0.1	485	485	15.62	1.40	68	6.1
3	Paddock	30	0.1-0.2	534	534	9.68	0.74	49	3.9
3	Paddock	30	0.2-0.3	463	463	7.43	0.48	33	2.2
3	Paddock	30	0.3-0.4	466	466	5.95	0.38	25	1.6
3	Paddock	30	0.4-0.5	556	556	5.48	0.33	23	1.4
3	Paddock	30	0.5-0.6	468	468	5.92	0.32	22	1.3
4	Fence	20	0-0.1	538	538	7.81	0.74	40	4.0
4	Fence	20	0.1-0.2	619	619	5.40	0.51	32	3.2
4	Fence	20	0.2-0.3	738	738	3.38	0.34	24	2.5
4	Fence	20	0.3-0.4	786	786	2.22	0.24	17	1.9
4	Fence	20	0.4-0.5	837	837	1.32	0.14	11	1.2
4	Fence	20	0.5-0.6	908	908	1.00	0.10	8	0.8

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
4	Paddock	20	0-0.1	668	669	7.68	0.83	41	4.7
4	Paddock	20	0.1-0.2	683	683	5.01	0.50	33	3.5
4	Paddock	20	0.2-0.3	693	694	3.18	0.33	25	2.7
4	Paddock	20	0.3-0.4	715	715	2.41	0.23	19	1.9
4	Paddock	20	0.4-0.5	787	787	2.00	0.20	16	1.7
4	Paddock	20	0.5-0.6	809	809	1.30	0.15	11	1.2
4	Fence	20A	0-0.1	526	526	5.79	0.55	29	2.9
4	Fence	20A	0.1-0.2	750	751	4.34	0.41	31	3.1
4	Fence	20A	0.2-0.3	845	845	2.88	0.28	24	2.4
4	Fence	20A	0.3-0.4	862	862	2.11	0.23	18	2.0
4	Fence	20A	0.4-0.5	800	800	1.15	0.12	9	1.0
4	Fence	20A	0.5-0.6	914	914	0.83	0.08	7	0.8
4	Paddock	20A	0-0.1	659	670	4.20	0.42	22	2.3
4	Paddock	20A	0.1-0.2	774	774	2.77	0.28	22	2.3
4	Paddock	20A	0.2-0.3	798	798	1.84	0.18	16	1.7
4	Paddock	20A	0.3-0.4	884	884	1.20	0.13	11	1.1
4	Paddock	20A	0.4-0.5	934	934	0.81	0.09	7	0.7
4	Paddock	20A	0.5-0.6	954	954	0.55	0.06	5	0.6
4	Fence	22	0-0.1	607	607	4.23	0.41	24	2.5
4	Fence	22	0.1-0.2	671	671	3.00	0.29	19	2.0
4	Fence	22	0.2-0.3	784	784	1.82	0.18	13	1.3
4	Fence	22	0.3-0.4	902	902	1.16	0.12	9	1.0
4	Fence	22	0.4-0.5	895	895	0.82	0.08	7	0.7
4	Fence	22	0.5-0.6	963	963	0.61	0.06	6	0.6

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
4	Paddock	22	0-0.1	619	620	5.25	0.54	30	3.3
4	Paddock	22	0.1-0.2	660	660	3.54	0.35	22	2.4
4	Paddock	22	0.2-0.3	719	719	1.88	0.20	13	1.4
4	Paddock	22	0.3-0.4	819	820	1.32	0.14	10	1.1
4	Paddock	22	0.4-0.5	801	801	0.96	0.10	7	0.8
4	Paddock	22	0.5-0.6	902	902	0.79	0.08	7	0.7
4	Fence	23	0-0.1	553	554	3.90	0.37	20	2.1
4	Fence	23	0.1-0.2	703	710	2.63	0.27	18	1.9
4	Fence	23	0.2-0.3	739	740	1.76	0.18	12	1.3
4	Fence	23	0.3-0.4	898	899	1.08	0.12	9	1.1
4	Fence	23	0.4-0.5	857	857	0.78	0.09	6	0.8
4	Fence	23	0.5-0.6	919	919	0.62	0.07	5	0.7
4	Paddock	23	0-0.1	784	785	3.97	0.41	22	2.4
4	Paddock	23	0.1-0.2	757	757	2.44	0.27	20	2.2
4	Paddock	23	0.2-0.3	911	911	1.31	0.15	12	1.4
4	Paddock	23	0.3-0.4	1025	1025	0.92	0.11	9	1.1
4	Paddock	23	0.4-0.5	1055	1055	0.58	0.07	7	0.8
4	Paddock	23	0.5-0.6	1020	1021	0.54	0.06	5	0.6
4	Fence	24	0-0.1	657	657	3.17	0.30	20	2.0
4	Fence	24	0.1-0.2	927	928	1.99	0.19	18	1.8
4	Fence	24	0.2-0.3	981	981	1.33	0.12	12	1.2
4	Fence	24	0.3-0.4	934	934	0.81	0.09	7	0.8
4	Fence	24	0.4-0.5	1035	1035	0.56	0.06	6	0.7
4	Fence	24	0.5-0.6	1012	1012	0.49	0.05	5	0.5

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
4	Paddock	24	0-0.1	825	825	2.97	0.30	20	2.1
4	Paddock	24	0.1-0.2	1008	1008	1.57	0.16	16	1.7
4	Paddock	24	0.2-0.3	994	995	0.94	0.10	10	1.1
4	Paddock	24	0.3-0.4	1055	1055	0.69	0.07	7	0.7
4	Paddock	24	0.4-0.5	1060	1060	0.47	0.05	5	0.6
4	Paddock	24	0.5-0.6	1096	1096	0.45	0.05	4	0.5
5	Fence	3	0-0.1	584	621	4.21	0.43	20	2.1
5	Fence	3	0.1-0.2	563	790	3.33	0.34	20	2.2
5	Fence	3	0.2-0.3	560	692	2.36	0.24	11	1.1
5	Fence	3	0.3-0.4	577	594	2.69	0.27	15	1.6
5	Fence	3	0.4-0.5	500	507	2.22	0.21	10	1.1
5	Fence	3	0.5-0.6	494	496	2.01	0.19	9	0.9
5	Paddock	3	0-0.1	484	487	7.45	0.74	33	3.6
5	Paddock	3	0.1-0.2	596	596	5.45	0.53	30	3.1
5	Paddock	3	0.2-0.3	463	463	4.79	0.46	21	2.1
5	Paddock	3	0.3-0.4	611	612	4.01	0.37	23	2.3
5	Paddock	3	0.4-0.5	462	462	3.47	0.32	15	1.5
5	Paddock	3	0.5-0.6	487	488	2.51	0.23	11	1.1
5	Fence	4	0-0.1	451	452	11.24	1.13	47	5.1
5	Fence	4	0.1-0.2	518	518	7.86	0.76	37	3.9
5	Fence	4	0.2-0.3	593	593	5.34	0.54	29	3.2
5	Fence	4	0.3-0.4	488	488	4.32	0.44	20	2.1
5	Fence	4	0.4-0.5	562	562	3.98	0.40	21	2.3
5	Fence	4	0.5-0.6	560	560	2.84	0.30	15	1.7

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
5	Paddock	4	0-0.1	507	510	12.69	1.28	54	5.8
5	Paddock	4	0.1-0.2	581	584	10.10	0.97	50	5.2
5	Paddock	4	0.2-0.3	636	636	8.27	0.77	47	4.8
5	Paddock	4	0.3-0.4	546	546	6.61	0.63	32	3.2
5	Paddock	4	0.4-0.5	575	576	6.16	0.60	34	3.5
5	Paddock	4	0.5-0.6	527	527	3.91	0.38	27	2.8
5	Fence	5	0-0.1	484	484	12.70	1.22	58	5.9
5	Fence	5	0.1-0.2	516	516	8.46	0.80	40	4.1
5	Fence	5	0.2-0.3	488	488	6.32	0.65	29	3.2
5	Fence	5	0.3-0.4	494	494	5.25	0.56	24	2.7
5	Fence	5	0.4-0.5	532	532	4.29	0.45	22	2.4
5	Fence	5	0.5-0.6	596	596	2.87	0.28	16	1.7
5	Paddock	5	0-0.1	507	508	11.39	1.09	52	5.3
5	Paddock	5	0.1-0.2	492	492	8.36	0.79	40	4.1
5	Paddock	5	0.2-0.3	574	574	6.63	0.64	31	3.2
5	Paddock	5	0.3-0.4	580	580	5.38	0.51	26	2.7
5	Paddock	5	0.4-0.5	574	574	4.19	0.40	22	2.3
5	Paddock	5	0.5-0.6	485	485	3.62	0.34	21	2.1
5	Fence	14	0-0.1	692	693	4.59	0.42	31	2.9
5	Fence	14	0.1-0.2	936	936	3.16	0.31	29	2.9
5	Fence	14	0.2-0.3	1017	1017	2.14	0.21	21	2.2
5	Fence	14	0.3-0.4	1209	1209	0.95	0.10	11	1.3
5	Fence	14	0.4-0.5	1172	1172	0.80	0.09	9	1.1
5	Fence	14	0.5-0.6	1185	1185	0.66	0.08	8	1.0

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
5	Paddock	14	0-0.1	904	907	5.04	0.51	35	3.7
5	Paddock	14	0.1-0.2	986	986	3.20	0.32	33	3.5
5	Paddock	14	0.2-0.3	1114	1114	1.50	0.16	19	2.0
5	Paddock	14	0.3-0.4	1141	1141	0.86	0.10	11	1.3
5	Paddock	14	0.4-0.5	1216	1216	0.72	0.08	9	1.0
5	Paddock	14	0.5-0.6	1022	1022	0.58	0.07	7	0.9
5	Fence	15	0-0.1	789	790	3.81	0.36	29	2.9
5	Fence	15	0.1-0.2	972	972	2.86	0.28	27	2.7
5	Fence	15	0.2-0.3	1132	1132	2.05	0.20	23	2.3
5	Fence	15	0.3-0.4	1211	1211	1.06	0.12	13	1.4
5	Fence	15	0.4-0.5	1180	1180	0.76	0.09	9	1.1
5	Fence	15	0.5-0.6	1255	1255	0.69	0.09	8	1.1
5	Paddock	15	0-0.1	926	928	4.83	0.48	38	3.9
5	Paddock	15	0.1-0.2	982	982	2.91	0.29	30	3.1
5	Paddock	15	0.2-0.3	1149	1149	1.40	0.15	17	1.9
5	Paddock	15	0.3-0.4	1199	1199	0.84	0.10	10	1.3
5	Paddock	15	0.4-0.5	1263	1263	0.64	0.08	8	0.9
5	Paddock	15	0.5-0.6	1186	1186	0.58	0.07	7	0.9
5	Fence	60	0-0.1	456	456	10.07	1.00	42	4.6
5	Fence	60	0.1-0.2	478	479	7.16	0.74	32	3.5
5	Fence	60	0.2-0.3	586	586	3.81	0.40	21	2.3
5	Fence	60	0.3-0.4	531	531	2.68	0.28	13	1.5
5	Fence	60	0.4-0.5	619	619	2.13	0.21	10	1.1
5	Fence	60	0.5-0.6	580	580	1.65	0.16	9	0.9

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
5	Paddock	60	0-0.1	530	532	12.11	1.17	52	5.5
5	Paddock	60	0.1-0.2	571	571	7.79	0.76	39	4.1
5	Paddock	60	0.2-0.3	538	538	4.21	0.43	27	2.9
5	Paddock	60	0.3-0.4	486	486	3.61	0.35	18	1.9
5	Paddock	60	0.4-0.5	449	450	2.88	0.28	14	1.5
5	Paddock	60	0.5-0.6	551	552	2.72	0.25	14	1.4
6	Fence	7	0-0.1	401	401	14.01	1.35	51	5.4
6	Fence	7	0.1-0.2	475	475	8.67	0.81	38	3.9
6	Fence	7	0.2-0.3	472	472	4.57	0.46	20	2.1
6	Fence	7	0.3-0.4	445	445	3.47	0.34	14	1.5
6	Fence	7	0.4-0.5	440	440	2.79	0.27	11	1.2
6	Fence	7	0.5-0.6	458	458	2.00	0.20	8	0.9
6	Paddock	7	0-0.1	489	489	14.31	1.47	55	6.2
6	Paddock	7	0.1-0.2	480	480	8.55	0.82	41	4.3
6	Paddock	7	0.2-0.3	456	456	4.85	0.50	23	2.5
6	Paddock	7	0.3-0.4	493	493	3.92	0.39	16	1.8
6	Paddock	7	0.4-0.5	528	528	2.69	0.25	12	1.3
6	Paddock	7	0.5-0.6	485	485	2.86	0.27	10	1.1
6	Fence	11	0-0.1	438	438	12.39	1.18	50	5.2
6	Fence	11	0.1-0.2	512	512	8.96	0.87	42	4.5
6	Fence	11	0.2-0.3	538	538	6.15	0.64	30	3.4
6	Fence	11	0.3-0.4	461	461	4.24	0.46	18	2.1
6	Fence	11	0.4-0.5	532	532	3.17	0.33	16	1.8
6	Fence	11	0.5-0.6	585	585	2.65	0.27	14	1.6

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
6	Paddock	11	0-0.1	472	472	15.73	1.58	64	7.0
6	Paddock	11	0.1-0.2	539	539	8.35	0.82	42	4.4
6	Paddock	11	0.2-0.3	586	587	4.80	0.51	25	2.9
6	Paddock	11	0.3-0.4	557	557	3.63	0.37	16	1.8
6	Paddock	11	0.4-0.5	560	560	2.94	0.29	16	1.7
6	Paddock	11	0.5-0.6	559	559	2.61	0.25	15	1.5
6	Fence	16	0-0.1	533	533	10.27	0.97	50	5.2
6	Fence	16	0.1-0.2	613	613	6.80	0.64	39	3.9
6	Fence	16	0.2-0.3	541	541	4.24	0.39	21	2.1
6	Fence	16	0.3-0.4	459	459	3.63	0.31	15	1.4
6	Fence	16	0.4-0.5	480	480	3.29	0.29	14	1.4
6	Fence	16	0.5-0.6	457	457	2.51	0.22	11	1.0
6	Paddock	16	0-0.1	661	661	10.99	1.05	56	5.8
6	Paddock	16	0.1-0.2	583	583	7.29	0.67	45	4.5
6	Paddock	16	0.2-0.3	514	514	4.59	0.40	24	2.3
6	Paddock	16	0.3-0.4	462	462	3.93	0.37	17	1.7
6	Paddock	16	0.4-0.5	504	504	2.78	0.26	13	1.4
6	Paddock	16	0.5-0.6	510	510	2.02	0.18	9	0.9
6	Fence	17	0-0.1	500	508	9.38	0.95	44	4.8
6	Fence	17	0.1-0.2	527	527	8.53	0.85	41	4.5
6	Fence	17	0.2-0.3	523	523	5.95	0.59	28	3.1
6	Fence	17	0.3-0.4	464	464	3.74	0.39	16	1.8
6	Fence	17	0.4-0.5	515	515	2.79	0.28	13	1.4
6	Fence	17	0.5-0.6	512	512	2.21	0.22	10	1.1

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
6	Paddock	17	0-0.1	593	598	11.62	1.22	55	6.3
6	Paddock	17	0.1-0.2	542	543	7.75	0.80	40	4.5
6	Paddock	17	0.2-0.3	553	553	4.87	0.51	26	2.9
6	Paddock	17	0.3-0.4	527	527	3.41	0.36	16	1.8
6	Paddock	17	0.4-0.5	524	524	2.75	0.27	14	1.5
6	Paddock	17	0.5-0.6	509	509	2.41	0.24	12	1.3
6	Fence	26	0-0.1	490	491	10.50	1.09	47	5.3
6	Fence	26	0.1-0.2	526	526	7.06	0.73	34	3.9
6	Fence	26	0.2-0.3	550	550	4.12	0.42	21	2.3
6	Fence	26	0.3-0.4	466	466	3.50	0.35	15	1.6
6	Fence	26	0.4-0.5	523	523	2.57	0.25	12	1.3
6	Fence	26	0.5-0.6	566	566	1.97	0.20	10	1.1
6	Paddock	26	0-0.1	559	560	11.63	1.24	54	6.2
6	Paddock	26	0.1-0.2	592	592	7.11	0.74	38	4.3
6	Paddock	26	0.2-0.3	571	571	3.50	0.37	21	2.4
6	Paddock	26	0.3-0.4	601	601	2.76	0.30	12	1.4
6	Paddock	26	0.4-0.5	586	586	2.40	0.25	13	1.5
6	Paddock	26	0.5-0.6	602	602	2.03	0.21	12	1.3
6	Fence	27	0-0.1	742	744	4.75	0.48	34	3.6
6	Fence	27	0.1-0.2	973	974	2.88	0.29	27	2.8
6	Fence	27	0.2-0.3	1085	1085	1.32	0.14	14	1.6
6	Fence	27	0.3-0.4	1211	1211	0.90	0.10	11	1.2
6	Fence	27	0.4-0.5	1241	1241	0.61	0.06	7	0.8
6	Fence	27	0.5-0.6	1198	1198	0.48	0.05	6	0.6

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Farm Number	Treatment	Site Number	Depth (m)	Mass of soil <2 mm[a] (t ha^{-1})	Bulk density of all material (kg m^{-3})	%C (OD)	%N (OD)	C stock (t C ha^{-1})	N stock (t N ha^{-1})
6	Paddock	27	0-0.1	844	846	5.63	0.59	42	4.6
6	Paddock	27	0.1-0.2	1036	1036	2.62	0.26	28	2.9
6	Paddock	27	0.2-0.3	1156	1156	1.16	0.13	14	1.5
6	Paddock	27	0.3-0.4	1196	1196	0.74	0.09	9	1.1
6	Paddock	27	0.4-0.5	1179	1179	0.62	0.08	8	1.0
6	Paddock	27	0.5-0.6	1278	1278	0.51	0.06	6	0.8

[a] The mass of soil <2 mm is equal to the dry bulk density of the fine (<2mm) fraction.

Table C.2: Raw data for the calculation of particulate organic matter carbon (POM-C) and mineral-associated organic matter carbon (MAOM-C). The proportion of POM-C and MAOM-C were converted to stocks by multiplying them by the total C stock in Table C.1.

Farm Number	Treatment	Site Number	Air-dry C content	MF60	Fractionation Sample Mass to 60°C (g)	>53 µm Mass (g)	<53 µm Mass (g)	>53 µm C%	Proportion POM-C (>53 µm)[a]	Proportion MAOM-C (<53 µm)[a]
1	Fence	11	2.31	1.03	14.42	5.32	9.10	1.36	0.21	0.79
	Paddock		2.71	1.03	14.80	5.29	9.51	1.86	0.24	0.76
1	Fence	12	3.6	1.05	14.27	5.87	8.41	1.76	0.19	0.81
	Paddock		4.05	1.05	14.55	5.74	8.81	2.37	0.22	0.78
1	Fence	16	4.78	1.03	14.54	3.05	11.50	2.24	0.09	0.91
	Paddock		6.21	1.04	14.86	4.00	10.86	4.28	0.18	0.82
1	Fence	26	7.15	1.06	14.27	4.75	9.52	5.27	0.23	0.77
	Paddock		6.96	1.12	13.50	6.13	7.37	5.09	0.3	0.7
1	Fence	27	6.53	1.10	13.72	6.82	6.90	7.80	0.54	0.46
	Paddock		6.97	1.09	13.85	7.81	6.04	5.26	0.39	0.61
1	Fence	37	8.26	1.05	14.37	7.82	6.56	6.84	0.43	0.57
	Paddock		7.44	1.04	14.35	9.34	5.01	5.13	0.43	0.57
1	Fence	38	7.49	1.06	14.22	7.95	6.27	3.87	0.27	0.73
	Paddock		7.89	1.06	14.27	7.98	6.29	5.02	0.33	0.67
2	Fence	33	5.16	1.03	14.51	6.08	8.43	7.21	0.57	0.43
	Paddock		5.33	1.03	14.91	6.98	7.93	1.58	0.14	0.86
2	Fence	31	7.14	1.12	13.51	6.05	7.46	3.07	0.17	0.83
	Paddock		6.37	1.10	13.65	6.74	6.90	4.23	0.3	0.7
2	Fence	32	7.9	1.11	13.44	5.66	7.78	4.66	0.22	0.78
	Paddock		6.48	1.14	13.32	6.70	6.62	4.89	0.33	0.67
2	Fence	48	9.61	1.07	14.03	5.96	8.07	5.75	0.24	0.76
	Paddock		9.96	1.04	14.41	5.82	8.60	6.36	0.25	0.75

[a] The proportion of the respective fraction. Calculated by dividing the mass of carbon (C) in the respective fraction by the total mass of C in the fractionated subsample.

Farm Number	Treatment	Site Number	Air-dry C content	MF60	Fractionation Sample Mass to 60°C (g)	>53 µm Mass (g)	<53 µm Mass (g)	>53 µm C%	Proportion POM-C (>53 µm)[a]	Proportion MAOM-C (<53 µm)[a]
2	Fence	44	9.26	1.13	13.28	5.75	7.53	5.64	0.23	0.77
	Paddock		10.31	1.18	12.74	7.11	5.64	7.89	0.36	0.64
2	Fence	41	7.22	1.12	13.38	3.94	9.45	3.18	0.12	0.88
	Paddock		6.5	1.15	13.04	5.25	7.79	3.50	0.19	0.81
2	Fence	30	9.11	1.08	14.04	5.92	8.12	4.21	0.18	0.82
	Paddock		9.21	1.05	14.46	6.53	7.93	6.10	0.29	0.71
3	Fence	39	13.35	1.04	14.44	3.95	10.49	11.17	0.22	0.78
	Paddock		12.79	1.04	14.49	4.05	10.44	12.09	0.25	0.75
3	Fence	15	15.63	1.07	14.14	6.34	7.80	16.35	0.44	0.56
	Paddock		13.23	1.07	14.05	6.77	7.28	12.36	0.42	0.58
3	Fence	31	14.48	1.05	14.25	3.73	10.52	10.21	0.18	0.82
	Paddock		14.29	1.06	14.27	4.85	9.42	10.87	0.24	0.76
3	Fence	30	14.33	1.10	13.70	5.06	8.64	12.74	0.3	0.7
	Paddock		14.35	1.08	13.87	5.47	8.40	13.34	0.34	0.66
4	Fence	20	7.48	1.04	15.20	4.26	10.94	5.93	0.21	0.79
	Paddock		7.37	1.05	15.20	3.72	11.48	7.16	0.23	0.77
4	Fence	20A	5.59	1.04	15.09	4.15	10.94	5.95	0.28	0.72
	Paddock		4.03	1.04	14.43	4.79	9.64	6.62	0.52	0.48
4	Fence	22	4.01	1.06	14.49	4.64	9.86	5.94	0.45	0.55
	Paddock		4.92	1.07	14.53	5.70	8.83	8.24	0.62	0.38
4	Fence	23	3.7	1.06	14.27	4.43	9.84	6.19	0.49	0.51
	Paddock		3.78	1.05	14.35	3.02	11.33	6.43	0.34	0.66
4	Fence	24	3.06	1.04	14.47	3.50	10.97	4.18	0.32	0.68
	Paddock		2.88	1.04	15.14	4.02	11.13	4.76	0.42	0.58

[a] The proportion of the respective fraction. Calculated by dividing the mass of carbon (C) in the respective fraction by the total mass of C in the fractionated subsample.

Farm Number	Treatment	Site Number	Air-dry C content	MF60	Fractionation Sample Mass to 60°C (g)	>53 µm Mass (g)	<53 µm Mass (g)	>53 µm C%	Proportion POM-C (>53 µm)[a]	Proportion MAOM-C (<53 µm)[a]
5	Fence	3	4.01	1.04	14.38	5.63	8.76	3.14	0.29	0.71
	Paddock		6.88	1.06	14.08	4.90	9.18	9.26	0.44	0.56
5	Fence	4	10.36	1.06	14.08	5.92	8.16	10.01	0.38	0.62
	Paddock		11.74	1.06	14.06	7.07	7.00	13.21	0.53	0.47
5	Fence	5	11.88	1.07	14.15	5.93	8.22	10.97	0.36	0.64
	Paddock		10.61	1.07	14.36	6.12	8.24	10.23	0.38	0.62
5	Fence	14	4.48	1.03	14.79	2.75	12.04	4.66	0.19	0.81
	Paddock		4.89	1.02	14.94	3.57	11.37	7.02	0.34	0.66
5	Fence	15	3.7	1.09	13.89	2.96	10.93	3.77	0.2	0.8
	Paddock		4.65	1.03	14.77	3.55	11.22	5.78	0.29	0.71
5	Fence	60	9.33	1.07	14.00	4.47	9.53	8.46	0.27	0.73
	Paddock		11.21	1.08	14.16	6.37	7.80	12.06	0.45	0.55
6	Fence	7	12.74	1.08	14.12	5.53	8.59	12.57	0.36	0.64
	Paddock		13.08	1.08	14.13	6.08	8.05	14.19	0.43	0.57
6	Fence	11	11.32	1.07	14.06	4.68	9.38	8.46	0.23	0.77
	Paddock		14.38	1.07	14.00	5.39	8.61	13.61	0.34	0.66
6	Fence	16	9.45	1.07	13.93	4.79	9.15	6.55	0.22	0.78
	Paddock		10.09	1.07	13.97	5.05	8.93	7.34	0.24	0.76
6	Fence	17	8.76	1.07	14.07	4.56	9.52	7.38	0.26	0.74
	Paddock		10.68	1.07	14.03	5.00	9.03	9.21	0.29	0.71
6	Fence	26	9.66	1.07	14.09	3.87	10.22	8.88	0.24	0.76
	Paddock		10.73	1.07	13.93	5.08	8.84	9.82	0.31	0.69
6	Fence	27	4.55	1.04	14.70	3.83	10.87	3.84	0.21	0.79
	Paddock		5.4	1.04	14.37	3.61	10.77	5.52	0.25	0.75

[a] The proportion of the respective fraction. Calculated by dividing the mass of carbon (C) in the respective fraction by the total mass of C in the fractionated subsample.

Table C.3: Raw data for specific surface area (A_s), mineral surface area (A_m), pH and Olsen P calculations. Calibration curve used to convert absorbance to a concentration of phosphorous (P) can be found in Fig A.2.

Farm Number	Treatment	Site Number	Air dry water content for A_s (mg g^{-1})	As (m^2 g^{-1})	Am (m^2 g^{-1})	pH	Soil mass for Olsen P (g)	Mean Absorbance (880 nm)	Concentration of P (ppm)	Olsen P (µg g^{-1})
1	Fence	11	24.32	48.64	38.71	5.71	1.95	0.047	0.624	12.80
	Paddock		26.06	52.12	40.47	6.57	2.00	0.122	1.660	33.20
1	Fence	12	35.53	71.06	55.58	6.03	2.00	0.045	0.592	11.85
	Paddock		34.73	69.46	52.02	6.23	2.02	0.053	0.707	14.00
1	Fence	16	38.19	76.39	55.83	5.74	2.03	0.068	0.914	18.03
	Paddock		45.38	90.75	64.05	6.44	2.00	0.138	1.877	37.48
1	Fence	26	66.20	132.40	101.66	5.99	2.00	0.102	1.384	27.72
	Paddock		63.34	126.67	96.74	6.33	2.04	0.047	0.629	12.35
1	Fence	27	63.04	126.07	98.01	6.04	2.02	0.040	0.528	10.47
	Paddock		63.72	127.45	97.49	6.36	2.02	0.061	0.813	16.13
1	Fence	37	57.83	115.66	80.16	6.44	2.04	0.269	3.686	72.27
	Paddock		54.47	108.95	76.95	6.35	1.98	0.056	0.744	15.04
1	Fence	38	56.24	112.48	80.25	6.35	2.00	0.066	0.891	17.83
	Paddock		59.68	119.35	85.41	6.48	1.96	0.131	1.780	36.31
2	Fence	33	33.34	66.67	44.49	5.87	1.97	0.027	0.348	7.07
	Paddock		31.62	63.24	40.33	6.48	1.98	0.095	1.292	26.09
2	Fence	31	40.99	81.98	51.29	5.43	1.97	0.028	0.357	7.25
	Paddock		39.33	78.67	51.26	6	1.99	0.050	0.666	13.35
2	Fence	32	58.00	116.01	82.03	5.68	1.96	0.034	0.440	8.98
	Paddock		39.13	78.26	50.39	6.05	1.99	0.081	1.094	22.04
2	Fence	48	66.62	133.24	91.90	5.87	2.00	0.033	0.431	8.61
	Paddock		51.84	103.67	60.83	6.3	1.97	0.114	1.545	31.45
2	Fence	44	54.29	108.58	68.76	5.52	2.03	0.026	0.334	6.59
	Paddock		51.77	103.54	59.22	5.75	2.03	0.080	1.080	21.34

Farm Number	Treatment	Site Number	Air dry water content for A_s (mg g^{-1})	As (m^2 g^{-1})	Am (m^2 g^{-1})	pH	Soil mass for Olsen P (g)	Mean Absorbance (880 nm)	Concentration of P (ppm)	Olsen P (μg g^{-1})
2	Fence	41	41.28	82.56	51.50	5.69	2.00	0.055	0.730	14.63
	Paddock		38.35	76.69	48.74	5.73	1.97	0.070	0.942	19.17
2	Fence	30	64.53	129.06	89.89	5.47	2.02	0.026	0.334	6.62
	Paddock		55.23	110.47	70.85	6.53	1.97	0.056	0.749	15.21
3	Fence	39	54.63	109.25	51.84	5.53	2.05	0.036	0.472	9.23
	Paddock		51.84	103.68	48.67	5.79	2.02	0.073	0.979	19.41
3	Fence	15	93.04	186.08	118.87	5.53	1.98	0.045	0.597	12.03
	Paddock		95.75	191.49	134.60	6.26	1.97	0.024	0.311	6.32
3	Fence	31	79.22	158.43	96.17	5.78	2.00	0.010	0.113	2.27
	Paddock		81.78	163.56	102.11	6.76	2.00	0.035	0.454	9.10
3	Fence	30	109.84	219.67	158.07	5.82	2.05	0.024	0.302	5.91
	Paddock		96.29	192.58	130.89	6.36	2.00	0.035	0.459	9.17
4	Fence	20	57.27	114.54	82.36	5.92	2.03	0.025	0.320	6.31
	Paddock		58.59	117.18	85.47	6.14	2.03	0.148	2.015	39.72
4	Fence	20A	47.61	95.23	71.19	5.83	2.02	0.033	0.436	8.62
	Paddock		53.65	107.29	89.97	5.55	2.02	0.067	0.901	17.80
4	Fence	22	63.61	127.23	109.97	5.9	2.00	0.034	0.445	8.88
	Paddock		72.30	144.61	123.45	6.13	2.00	0.051	0.680	13.59
4	Fence	23	58.86	117.71	101.81	5.47	2.04	0.048	0.638	12.54
	Paddock		55.36	110.71	94.44	6.14	2.00	0.115	1.564	31.27
4	Fence	24	41.63	83.27	70.13	5.74	2.20	0.025	0.316	5.74
	Paddock		42.27	84.54	72.17	5.63	1.99	0.039	0.518	10.40
5	Fence	3	54.14	108.27	91.04	6.24	2.00	0.136	1.849	37.07
	Paddock		86.68	173.35	143.76	6.18	2.02	0.282	3.870	76.83
5	Fence	4	88.94	177.87	133.31	4.87	2.02	0.131	1.780	35.30
	Paddock		88.83	177.67	127.20	5.85	2.03	0.177	2.424	47.84

Farm Number	Treatment	Site Number	Air dry water content for A_s (mg g^{-1})	As (m^2 g^{-1})	Am (m^2 g^{-1})	pH	Soil mass for Olsen P (g)	Mean Absorbance (880 nm)	Concentration of P (ppm)	Olsen P (µg g^{-1})
5	Fence	5	89.90	179.80	128.71	5.81	1.99	0.041	0.541	10.88
	Paddock		90.65	181.31	135.68	6.15	1.98	0.097	1.320	26.64
5	Fence	14	36.04	72.09	52.81	5.54	2.04	0.039	0.514	10.10
	Paddock		39.12	78.24	57.22	6.51	2.02	0.153	2.084	41.32
5	Fence	15	32.74	65.48	49.58	5.66	2.03	0.019	0.242	4.78
	Paddock		35.98	71.96	51.95	6.1	2.04	0.075	1.006	19.77
5	Fence	60	90.54	181.08	140.97	6.13	2.02	0.062	0.827	16.40
	Paddock		93.12	186.24	138.03	6.57	2.00	0.153	2.093	41.82
6	Fence	7	98.53	197.06	142.26	5.46	2.00	0.043	0.564	11.30
	Paddock		98.88	197.76	141.50	5.98	2.01	0.138	1.881	37.53
6	Fence	11	90.73	181.45	132.79	5.83	2.03	0.049	0.647	12.75
	Paddock		95.52	191.04	129.22	5.71	2.04	0.140	1.904	37.41
6	Fence	16	96.09	192.19	151.57	5.87	2.01	0.026	0.330	6.56
	Paddock		93.42	186.84	143.45	5.75	1.99	0.085	1.149	23.05
6	Fence	17	81.88	163.76	126.08	5.35	2.00	0.064	0.864	17.26
	Paddock		91.31	182.62	136.71	6.28	2.03	0.067	0.901	17.73
6	Fence	26	85.67	171.35	129.81	5.99	2.02	0.079	1.071	21.16
	Paddock		87.60	175.20	129.07	5.93	1.99	0.114	1.550	31.17
6	Fence	27	41.66	83.32	63.77	5.64	1.99	0.027	0.348	6.98
	Paddock		40.70	81.40	58.17	6.13	1.98	0.109	1.481	29.94

APPENDIX D

Site Descriptions

Farm 1

Site:	**11**
Date sampled:	16.11.2022
Reference data	
Soil name (Series, Family):	Te Kowhai silt loam, Pukehina
NZSC:	Typic Orthic Gley Soil
Site data	
Location:	Cambridge
GPS reference:	175.4291°E 37.8872°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	62 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	15 – 30 years

Soil Data

Fence

Paddock

Site:	**12**
Date sampled:	16.11.2022
Reference data	
Soil name (Series, Family):	Bruntwood silt loam, Silverdale
NZSC:	Mottled Orthic Brown Soil
Site data	
Location:	Cambridge
GPS reference:	175.4298°E 37.8866°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	63 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	15 – 30 years

Soil Data

Fence

Paddock

Site:	**16**
Date sampled:	16.11.2022

Reference data

Soil name:	Te Kowhai silt loam, Pukehina
NZSC:	Typic Orthic Gley Soil

Site data

Location:	Cambridge
GPS reference:	175.4242°E 37.8861°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	61 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	15 – 30 years

Soil Data

Fence

Paddock

Site:	**17**
Date sampled:	06.12.2022
Reference data	
Soil name (Series, Family):	Bruntwood silt loam, Silverdale
NZSC:	Mottled Orthic Brown Soil
Site data	
Location:	Cambridge
GPS reference:	175.4255°E 37.8852°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	62 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	15 – 30 years

Soil Data

Fence

Paddock

Site:	**26**
Date sampled:	06.12.2022
Reference data	
Soil name (Series, Family):	Horotiu, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Cambridge
GPS reference:	175.4238°E 37.8885°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	60 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	30 – 55 years

Soil Data

Fence

Paddock

Site:	**27**
Date sampled:	06.12.2022

Reference data

Soil name (Series, Family):	Horotiu, Otorohanga
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Cambridge
GPS reference:	175.4244°E 37.8892°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	61 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	30 – 55 years

Soil Data

Fence

Paddock

Site:	**37**
Date sampled:	24.01.2023
Reference data	
Soil name (Series, Family):	Horotiu, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Cambridge
GPS reference:	175.4204°E 37.8896 °S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	57 m (ASL)
Geomorphic position:	Flat to gently undulating
Livestock units:	22
Fenceline age:	15 – 30 year

Soil Data

Fence

Note: Sixth core taken but not pictured

Paddock

Site:	**38**
Date sampled:	06.12.2022
Reference data	
Soil name (Series, Family):	Horotiu, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Cambridge
GPS reference:	175.4237°E 37.8918°S
Annual rainfall:	1213 mm
Mean air temperature:	13.8 °C
Elevation:	57 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	22
Fenceline age:	15 – 30 years

Soil Data

Fence

Paddock

Farm 2

Site:	**33**
Date sampled:	28.07.2023
Reference data	
Soil name (Series, Family):	Piarere silt loam, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Waharoa
GPS reference:	175.8016°E 37.7650°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	56 m (ASL)
Geomorphic position:	Flat to undulating with a slope of 1-2°
Livestock units:	25
Fenceline age:	> 70 years

Soil Data

Fence

Paddock

Site:	**32**
Date sampled:	04.08.2023
Reference data	
Soil name:	Waihou, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Waharoa
GPS reference:	175.8031°E 37.7688°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	56 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	25
Fenceline age:	20 – 35 years
Soil Data	
Fence	Paddock

Site:	**31**
Date sampled:	04.08.2023
Reference data	
Soil name (Series, Family):	Te Puninga, Bruntwood
NZSC:	Typic Orthic Gley Soil
Site data	
Location:	Waharoa
GPS reference:	175.8013°E 37.7686°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	56 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	25
Fenceline age:	20 – 35 years

Soil Data

Fence

Paddock

Site:	**48**
Date sampled:	04.08.2023
Reference data	
Soil name (Series, Family):	Piarere silt loam, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Waharoa
GPS reference:	175.7949°E 37.7575°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	53 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope of 1-2°
Livestock units:	25
Fenceline age:	50 – 60 years

Soil Data

Fence

Paddock

Site:	**44**
Date sampled:	11.08.2023

Reference data

Soil name (Series, Family):	Piarere silt loam, Otorohanga
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Waharoa
GPS reference:	175.7945°E 37.7615°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	53 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	25
Fenceline age:	50 – 55 years

Soil Data

Fence

Paddock

Site:	**41**
Date sampled:	11.08.2023
Reference data	
Soil name (Series, Family):	Te Puninga, Bruntwood
NZSC:	Typic Orthic Gley Soil
Site data	
Location:	Waharoa
GPS reference:	175.7957°E 37.7612°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	52 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units	25
Fenceline age:	50 – 55 years

Soil Data

Fence

Paddock

Site:	**30**
Date sampled:	11.08.2023
Reference data	
Soil name (Series, Family):	Waihou, Otorohanga
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Waharoa
GPS reference:	175.8013°E 37.7676°S
Annual rainfall:	1291 mm
Mean air temperature:	13.5 °C
Elevation:	57 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	25
Fenceline age:	20 – 35 years

Soil Data

Fence

Paddock

Farm 3

Site:	**17**
Date sampled:	01.09.2023

Reference data

Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Otorohanga
GPS reference:	175.2297°E 38.2012°S
Annual rainfall:	1763 mm
Mean air temperature:	13.6 °C
Elevation:	41 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	15
Fenceline age:	45 – 65 years

Soil Photos

Fence

Paddock

Site:	**39**
Date sampled:	01.09.2023

Reference data

Soil name:	Whatawhata, Airfield
NZSC:	Mottled Orthic Brown Soil

Site data

Location:	Otorohanga
GPS reference:	175.2272°E 38.2122°S
Annual rainfall:	1763 mm
Mean air temperature:	13.6 °C
Elevation:	39 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope of 1-2°
Livestock units:	15
Fenceline age:	30 – 40 years

Soil Data

Fence

Paddock

Site:	**15**
Date sampled:	22.09.2023

Reference data

Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Otorohanga
GPS reference:	175.2313°E 38.2014°S
Annual rainfall:	1763 mm
Mean air temperature:	13.6 °C
Elevation:	41 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope of 1-2°
Livestock units:	15
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site:	**31**
Date sampled:	22.09.2023
Reference data	
Soil name (Series, Family):	Whatawhata, Airfield
NZSC:	Mottled Orthic Brown Soil
Site data	
Location:	Otorohanga
GPS reference:	175.2299°E 38.2090°S
Annual rainfall:	1763 mm
Mean air temperature:	13.6 °C
Elevation:	40 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope of 1-2°
Livestock units:	15
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site:	**24**
Date sampled:	13.10.2023
Reference data	
Soil name (Series, Family):	Whatawhata, Airfield
NZSC:	Mottled Orthic Brown Soil
Site data	
Location:	Otorohanga
GPS reference:	175.2335°E 38.2054°S
Annual rainfall:	1763 mm
Mean air temperature:	13.6 °C
Elevation:	43 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope of 1-2°
Livestock units:	15
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site: **30**

Date sampled: 13.10.2023

Reference data

Soil name (Series, Family): Whatawhata, Airfield
NZSC: Mottled Orthic Brown Soil

Site data

Location: Otorohanga
GPS reference: 175.2305°E 38.2097°S
Annual rainfall: 1763 mm
Mean air temperature: 13.6 °C
Elevation: 41 m (ASL)
Geomorphic position: Flat to gently undulating with a slope ≤ 1°
Livestock units: 15
Fenceline age: > 60 years

Soil Data

Fence

Paddock

Farm 4

Site:	**22**
Date sampled:	07.11.2023
Reference data	
Soil name (Series, Family):	Ohaupo, Mairoa
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Ohaupo
GPS reference:	175.3125°E 37.9120°S
Annual rainfall:	1212 mm
Mean air temperature:	13.8 °C
Elevation:	58 m (ASL)
Geomorphic position:	Undulating with a southeast facing slope of 5-6°
Livestock units:	27
Fenceline age:	> 70 years

Soil Data

Fence

Paddock

Site:	**23**
Date sampled:	07.11.2023
Reference data	
Soil name (Series, Family):	Hamilton, Morrinsville
NZSC:	Typic Orthic Granular Soil
Site data	
Location:	Ohaupo
GPS reference:	175.3125°E 37.9111°S
Annual rainfall:	1212 mm
Mean air temperature:	13.8 °C
Elevation:	64 m (ASL)
Geomorphic position:	Undulating with an east facing slope of 4-5°
Livestock units:	27
Fenceline age:	> 70 years

Soil Data

Fence

Paddock

Site:	**20**
Date sampled:	07.11.2023

Reference data

Soil name (Series, Family) :	Ohaupo, Te Rahu
NZSC:	Typic Orthic Brown Soil

Site data

Location:	Ohaupo
GPS reference:	175.3122°E 37.9127°S
Annual rainfall:	1212 mm
Mean air temperature:	13.8 °C
Elevation:	56 m (ASL)
Geomorphic position:	Toe of slope beneath site 20A. Flat to gently undulating with a slope ≤ 3°
Livestock units:	27
Fenceline age:	> 70 years

Soil Data

Fence

Paddock

Site:	**20A**
Date sampled:	07.11.2023

Reference data

Soil name (Series, Family):	Ohaupo, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Ohaupo
GPS reference:	175.3118°E 37.9125°S
Annual rainfall:	1212 mm
Mean air temperature:	13.8 °C
Elevation:	61 m (ASL)
Geomorphic position:	Rolling with a southeast facing slope of 11-12°
Livestock units:	27
Fenceline age:	> 70 years

Soil Data

Fence

Paddock

Site:	**24**
Date sampled:	08.11.2023
Reference data	
Soil name (Series, Family):	Ohaupo, Te Rahu
NZSC:	Typic Orthic Granular Soil
Site data	
Location:	Ohaupo
GPS reference:	175.3139°E 37.9103°S
Annual rainfall:	1212 mm
Mean air temperature:	13.8 °C
Elevation:	63 m (ASL)
Geomorphic position:	Rolling to strongly rolling with a southeast facing slope of 19-20°
Livestock units:	27
Fenceline age:	> 70 years

Soil Data

Fence

Paddock

Farm 5

Site:	**3**
Date sampled:	01.12.2023
Reference data	
Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Pokuru
GPS reference:	175.2124°E 38.0440°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	49 m (ASL)
Geomorphic position:	Undulating with a west facing slope of 3-4°
Livestock units:	29
Fenceline age:	20 – 30 years

Soil Data

Fence

Paddock

Site:	**4**
Date sampled:	01.12.2023
Reference data	
Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Pokuru
GPS reference:	175.2109°E 38.0446°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	51 m (ASL)
Geomorphic position:	Undulating with a south facing slope of 3-4°
Livestock units:	29
Fenceline age:	20–30 years

Soil Data

Fence

Paddock

Site:	**5**
Date sampled:	01.12.2023

Reference data

Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Pokuru
GPS reference:	175.2090°E 38.0442°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	63 m (ASL)
Geomorphic position:	Undulating with a northwest facing slope of 5-6°
Livestock units:	29
Fenceline age:	20–30 years

Soil Data

Fence

Paddock

Site:	**14**
Date sampled:	01.12.2023
Reference data	
Soil name (Series, Family):	Whatawhata, Airfield
NZSC:	Mottled Orthic Brown Soil
Site data	
Location:	Pokuru
GPS reference:	175.2001°E 38.0441°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	31 m (ASL)
Geomorphic position:	Flat to gently undulating with a southwest facing slope of 2-3°
Livestock units:	29
Fenceline age:	13–14 years

Soil Data

Fence

Paddock

Site:	**15**
Date sampled:	05.12.2023

Reference data

Soil name (Series, Family):	Whatawhata, Airfield
NZSC:	Mottled Orthic Brown Soil

Site data

Location:	Pokuru
GPS reference:	175.1996°E 38.0435°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	31 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	29
Fenceline age:	14–16 years

Soil Data

Fence

Paddock

Site:	**60**
Date sampled:	05.12.2023
Reference data	
Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Pokuru
GPS reference:	175.2145°E 38.0369°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	61 m (ASL)
Geomorphic position:	Rolling with a northwest facing slope of 10-11°
Livestock units:	29
Fenceline age:	20–30 years

Soil Data

Fence

Paddock

Farm 6

Site:	**7**
Date sampled:	05.12.2023

Reference data

Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Pokuru
GPS reference:	175.2216°E 38.0409°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	58 m (ASL)
Geomorphic position:	Rolling with a south facing slope of 11-12°
Livestock units:	21
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site:	**11**
Date sampled:	05.12.2023
Reference data	
Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Pokuru
GPS reference:	175.2241°E 38.0405°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	53 m (ASL)
Geomorphic position:	Undulating with a southwest facing slope of 3-4°
Livestock units:	21
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site:	**16**
Date sampled:	06.12.2023
Reference data	
Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil
Site data	
Location:	Pokuru
GPS reference:	175.2171°E 38.0142°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	38 m (ASL)
Geomorphic position:	Undulating with a southeast facing slope of 6-7°
Livestock units:	21
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site:	**17**
Date sampled:	06.12.2023

Reference data

Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Pokuru
GPS reference:	175.2146°E 38.0140°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	38 m (ASL)
Geomorphic position:	Flat to gently undulating with a slope ≤ 1°
Livestock units:	21
Fenceline age:	> 60 years

Soil Data

Fence

Paddock

Site:	**26**
Date sampled:	06.12.2023

Reference data

Soil name (Series, Family):	Otorohanga, Mairoa
NZSC:	Typic Orthic Allophanic Soil

Site data

Location:	Pokuru
GPS reference:	175.2093°E 38.0171°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	48 m (ASL)
Geomorphic position:	Undulating with a north facing slope of 3-4°
Livestock units:	21
Fenceline age:	10–15 years

Soil Data

Fence

Paddock

Site:	**27**
Date sampled:	06.12.2023
Reference data	
Soil name (Series, Family):	Whatawhata, Airfield
NZSC:	Mottled Orthic Brown Soil
Site data	
Location:	Pokuru
GPS reference:	175.2106°E 38.0162°S
Annual rainfall:	1501 mm
Mean air temperature:	13.8 °C
Elevation:	31 m (ASL)
Geomorphic position:	Toe of slope beneath site 26. Flat to gently undulating with a slope of 1-2°
Livestock units:	21
Fenceline age:	10–15 years

Soil Data

Fence

Paddock