Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Assessing Soil Organic Carbon Stocks and Sequestration Opportunities on a Taranaki Dairy Farm

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science
in
Agricultural Science

at Massey University, Manawatū,
New Zealand

Andrew Boot

2024

Abstract

Increasing soil organic carbon stocks (SOCS) on farms is widely accepted as a viable strategy to reduce agriculture's net carbon footprint. Despite this opportunity, unlike in other countries such as Australia, there are no government-led incentives for farmers to monitor or increase SOCS in New Zealand (NZ). This lack of incentives, combined with the high cost of SOCS benchmarking and monitoring systems, has hampered the monitoring of farm-scale SOCS in NZ. With the variety of climates and farming systems across the country, this lack of data has meant that the scope to increase SOCS has not been well characterised. Consequently, the strategies to enhance SOCS in soils which already have medium to high SOCS have not been explored thoroughly.

This study designed and implemented a practical, cost-effective farm-scale SOCS benchmarking and monitoring system based on a combination of international standards and the NZ Ministry for Primary Industries (MPI) soil carbon monitoring methods and applied this to the Dairy Trust Taranaki Kavanagh Farm in South Taranaki. The influence of soil drying and sample storage on possible changes in soil carbon respiration was also explored in this process and found some carbon respiration in both air-dried and imperfectly dried soil samples while in storage. The results of the benchmarking survey found that Kavanagh farm has 219.6 t C ha^{-1} to a depth of 60 cm and 162.14 t C ha^{-1} to a depth of 30 cm which is significantly above average for Allophanic pasture soils measured previously in NZ. The results also highlighted the importance of stratification of the farm as a way of reducing future survey cost. The final stratification of the farm reduced the number of samples required in the survey by 59% when compared to random sampling with no stratification.

Finally, the study reviewed NZ-based research to identify farm management practices which may increase SOCS on a dairy farm like the Kavanagh farm. Our review highlighted inversion tillage and biochar applications as practices with the most potential to increase SOCS in Kavanagh's high SOCS Allophanic soil by approximately 0.56 and 1.1 t C ha^{-1} $year^{-1}$ respectively over the next 20 – 30 years. If these sequestration rates could be achieved throughout the entire farm, then net greenhouse gas emissions from the farm could be offset by 46%. However, practical limitations and the financial viability of implementing these practices across the entire farm without financial incentives will likely result in a lower net rate of sequestration. Further research into the viability and efficacy of

these practices will be needed for more widespread adoption of carbon sequestration-enhancing practices in the NZ pastoral industry.

Acknowledgments

To begin, I would like to acknowledge the contributions from a wide range of people who made this thesis possible.

First and foremost, I would like to thank my supervisors for their direct input which helped shape this project and guide me through my journey into the world of academic research. Dr Lucy Burkitt has been a terrific primary supervisor helping me adapt to a self-driven work schedule and onboarding me into the day-to-day realities of post-graduate research. She has been of great help every step of the way and could always find time to assist in any way which was needed. My assistant supervisor Dr Paramsothy Jeyakumar has made numerous very helpful contributions at key decision-making points throughout this study and his input has been invaluable. I would also like to express deep gratitude for the input of Dr Paul Mudge who has played a significant advisory role for this study. This project could not have been done without his expertise in the field of soil carbon. Finally, I need to thank Paul Edwards from the DairyNZ academic committee for his assistance facilitating this project and for providing valuable feedback in the final few weeks of preparing this thesis

This research also would not have been possible without the financial support provided by Dairy Trust Taranaki and DairyNZ through the Colin Holmes Memorial Scholarship. Their funding allowed me to dedicate myself to this research full-time without needing to stress about personal finances. I must also give thanks to the team at DairyNZ. In particular, Susan Stokes from the DairyNZ academic committee who regularly checked in on my progress and provided support through the tougher parts of this project. Thanks to this funding and support, I was able to put my full effort into this research and for that I am deeply grateful.

I would also like to specifically thank the whole team at Dairy Trust Taranaki for all the help and assistance throughout this project from facilitating the sample taking process on their farm to providing extra data about the farm needed for the analysis. Another critical part of the data collection process was the soil mapping of the farm performed in rainy winter weather on short notice by Dr Alan Palmer. I am very thankful for his help in this regard.

A special thanks also goes to Kenneth and Rachel Short who very generously provided soil carbon data collected by Verdi from their farm, Shortland farm. These data provided the only existing data points I could find for SOCS on a Taranaki dairy farm. I also want to

thank the team at Taranaki Regen and Verdi for helping me to reach out to Kenneth and Rachel and in helping me to analyse and interpret the data they had collected.

To finish, I want to give thanks to everyone who has helped me in various ways on my journey to get to where I am today. Without them, I would not have been in this position writing this thesis. To my parents who have supported me every step of the way for as long as I can remember. They have unequivocally been the driving force which has enabled me to achieve everything I have done to date. Also, to everyone who has helped inspire and assist me down this path. First, to Eve Kawana-Brown who has repeatedly guided me and connected me with many key opportunities which led me here after finishing my bachelor's degree. To Fiona Young whose Taranaki regenerative farming events piqued my interest in regenerative agriculture and pastoral soil science, motivating me to return to study in this field. Finally, to my high school horticulture teacher, the late John Sims, to whom I would like to dedicate this thesis. His teaching inspired me to make a last-minute change to study agricultural science at university. While at the time I was unsure if it was going to be the right decision, I can now confidently say it was the best one I could have made.

Table of contents

Abstract ..... *ii*
Acknowledgments ..... *iv*
Table of contents ..... *vi*
List of figures ..... *ix*
Table of tables ..... *x*
Chapter 1 – Introduction *1*
Chapter 2 – Literature review *4*
2.1 Introduction to soil organic carbon 4
Potential to build soil carbon in NZ agricultural soils 5
2.2 Factors affecting soil organic carbon 7
2.2.1 Soil and landscape factors 7
Soil type 7
Aspect 8
Slope 8
2.2.2 Climatic factors 8
Rainfall 8
Temperature 9
2.2.3 Management factors affecting SOCS 9
Land use 9
Irrigation 10
Tillage 11
Grazing management 12
Supplementary feeds 13
Fertiliser 13
Pasture varieties and diverse pastures 14
Biochar 14
2.3 Sampling and measurement methodology 17
2.3.1 Survey accuracy 17
2.3.2 Stratified single random sampling 17
2.3.3 Number of samples 17
2.3.4 Strata 18
2.3.5 Stratification methods 18
2.3.6 Sample bulking 19
2.3.7 Sampling depth 19
2.3.8 Calculating SOCS 20
2.4 Research gaps and future research 20
Chapter 3 – Methods *22*
3.1 Study site 22
3.2 Carbon estimation area (CEA) 24
3.3 Stratification 26
3.3.1 Ancillary variables 26
3.3.2 Strata 29
3.3.3 Determination of sampling locations 31
3.4 Soil carbon sampling 33
3.4.1 Sampling method 33
Alternative sampling methods 34
Stony soils 34
Crumbly soils 34
3.4.2 Soil sampling equipment 34
3.4.3 Sample storage 35

3.5 Sample processing and analysis **35**
3.5.1 Sample processing 35
3.5.2 Statistical analysis 36
Chapter 4 – Results and discussion ***38***
4.1 Soil organic carbon stocks benchmarking survey **38**
4.1.1 Spatial distribution of SOCS 38
4.1.2 Comparison of SOC for each stratum for 0 – 30 cm depth 41
4.1.3 Comparison of SOC for each stratum for the 0 – 60 cm depth 42
4.1.4 SOCS in the bund 45
4.2 Effectiveness of strata **45**
Chapter 5 – Soil respiration experiment results and discussion ***46***
5.1 Data reliability 46
5.2 Sample Storage Respiration Experiment Results 46
Chapter 6 – General discussion ***49***
6.1 Rationale for revised strata **49**
6.2 Method for revising strata **49**
6.3 Proposed revised strata **50**
6.4 Survey accuracy **55**
6.5 Building the optimal ongoing SOCS monitoring system **57**
6.5.1 Variables to be kept consistent 58
Stratified random sampling and static synchronous sampling 58
Stratification 58
Sampling depth 59
Time of sampling 59
6.5.2 Variables to be changed 59
Total number of samples 59
Frequency of ongoing monitoring surveys 59
Sample bulking 60
6.5.3 Baseline strategy: regular stratified sampling 60
6.5.4 Optimisation strategy #1: less frequent, higher precision sampling surveys 60
6.5.5 Optimisation strategy #2: sample bulking 61
6.5.6 Number of samples 62
Deciding on a budget 62
Deciding on a minimum detectable difference 63
6.5.7 Finalising the new plan 64
6.6 Outlook and implications for the Kavanagh farm greenhouse gas budget **65**
6.6.1 Outlook for future SOCS changes 65
6.6.2 Recommended management practice changes 66
6.6.3 Management practices to increase soil carbon stocks 68
Inversion tillage 68
Biochar 70
6.6.4 Additional recommendations 70
Pasture varieties and diverse pasture 70
Importing feed 71
Deferred grazing 71
Reduced tillage and pasture renewal 71
Summertime irrigation 72
6.7 Full farm carbon budget **72**
References ***76***
Appendices ***92***
Appendix 1 – Calculations for pooled mean, pooled standard deviation, margin of error and 95% confidence interval **92**

Appendix 2 – ArcGIS and Kriging 97
Appendix 3 – Sampling equipment list 98
Appendix 4 – Soil sample respiration experiment methods 99
Appendix 5 – Data tables 103
Appendix 6 – Preliminary SOCS data 104
Appendix 7 – Calculations to make future SOCS change estimates and CO_2 to C conversion 107
Appendix 8 – Raw survey data 110

List of figures

Figure 1: A Violin plot showing the distribution of SOCS to a depth of 30 cm for grassland soils for 13 different NZ soil orders. Source: Mudge et al. (2020) with data from the National Soils Database (NSD). Permission granted by MPI August 2024. 7
Figure 2: A soil map of the Kavanagh farm. Source: Soil map produced by Dr Alan Palmer (Massey University) in June 2023. 23
Figure 3: The Carbon Estimation Area (CEA) on the Kavanagh Farm. Paddock C8 is not included in the CEA due to its anthropic soil. Paddock C8 is outlined in blue. 25
Figure 4: A map of the Kavanagh farm showing slope on the farm. The figure on the left displays slope categories as a raster with numerous slope categories while the figure on the right highlights the land which is flatter than and steeper than 7 degrees. 26
Figure 5: A map of the Kavanagh farm indicating which blocks receive effluent (effluent blocks marked in blue). 27
Figure 6: A map of the Kavanagh farm with annotated SOC concentrations (%C) in 15 cm soil cores taken in January 2022 for a separate project. 28
Figure 7: A map of the four initial soil strata. 30
Figure 8: A map of all sample locations including the randomly generated location and the actual location according to the RTK GPS. 32
Figure 9: A process flow-chart based on the SOCS sample processing and analysis protocol outlined by Mudge et al., (2020). 36
Figure 10: A stacked bar chart of the SOCS in each stratum broken down by depth. 38
Figure 11: A heat map showing the distribution of SOCS to a depth of 60 cm throughout the farm. 40
Figure 12: A box plot of SOCs sampled to a depth of 0 – 30 cm depth measured in each stratum. 41
Figure 13: A box plot comparing the SOCS by strata (combined 0 – 60 cm depth). 42
Figure 14: A boxplot comparing the SOCS by strata at different sample depths. a: 0 – 15 cm sampling depth. b: 15 – 30 cm sampling depth. c: 30 – 45 cm sampling depth. d: 45 – 60 cm sampling depth. 44
Figure 15: A box plot comparing the amount of CO_2 respired by soil in different treatments in the sample storage respiration trial. 47
Figure 16: A map of the revised SOCS strata. The revised strata grouped areas of the farm into low SOCS (L), medium-low SOCS (ML), medium-high SOCS (MH) and high SOCS (H) based on the initial benchmarking survey and the farm soil map. 51
Figure 17: Box plot comparing the SOCS of the revised strata from 0 – 60 cm. H: High SOCS strata. MH: Medium-high SOCS strata. ML: Medium-low SOCS strata. L: Low SOCS strata. 53
Figure 18: A chart depicting the number of samples required to attain a desired margin of error for a sampling survey on the Kavanagh farm. This curve will vary from farm to farm due to a different standard deviation in the dataset. This curve was calculated using equation 5 in Appendix 1 using the value S_p and it should be updated after future surveys to use S once the value of S is known. 56
Figure 19: A flow chart outlining a decision-making framework to determine the optimal SOC survey approach for Kavanagh farm. 57

Table of tables

Table 1: A table displaying the statistical power for each pair of the initial strata to detect a significant difference. A post-hoc power of >80% indicates that the trial can detect a significant difference. 45

Table 2: A table comparing the means, confidence intervals and minimum detectable difference for both iterations of the stratification and the unstratified data. SOC stock values are cumulative to 60 cm. All values in this table were calculated using the method 54

Table 3: The number of sample cores required to attain a corresponding minimum detectable difference along with the optimal distributions of cores across the strata. 56

Table 4: The baseline, optimistic and highest range estimates for the number of t C ha^{-1} year $^{-1}$ which could be sequestered by various management practices. 66

Chapter 1 – Introduction

Agriculture is responsible for approximately 12% of greenhouse gas (GHG) emissions globally as of 2020 (Friedlingstein et al., 2023). In New Zealand (NZ), agriculture is the largest of the country's primary industries and subsequently, it is responsible for as much as 53% of the nation's GHG emissions. About 80% of these agricultural emissions in NZ are attributed to enteric methane emitted by ruminants and another 10% comes from nitrous oxide from nitrogen fertiliser and animal excreta (Ministry for the Environment, 2024). Despite high total emissions, it is worth noting that the emissions intensity of NZ's dairy industry per kilogram of milk solids produced is one of the lowest in the world (Mazzetto et al., 2021). Also noteworthy is that the metrics of NZ's total emissions are based on a global warming potential (GWP) of 100 years which emphasises the impact of short-lived gases such as methane over longer-lived gases like carbon dioxide (CO_2). Consequently, there is an ongoing debate around the most representative impact of agriculture (Reisinger et al., 2017). Despite this, the agriculture industry is still a key contributor to NZ's carbon footprint.

Due to these large quantities of GHG emitted by NZ's agricultural sector, there is increasing government and public pressure on the industry to reduce emissions. This is particularly important as reducing agricultural emissions will be critical to achieving NZ's climate goals. Of particular relevance is NZ's target to reduce methane emissions by 10% by 2030 and by 24% – 47% by 2050 (New Zealand Government, 2021). Failing to meet these targets could put significant economic and diplomatic pressure on the country from other trading nations and large organisations who purchase agricultural goods from NZ.

Beyond GHG emissions, there are also concerns about the long-term sustainability of the modern agricultural systems used by most farmers throughout NZ, particularly the high input systems. Concerns include negative impacts on water quality, erosion and topsoil loss, biodiversity loss and unsustainable use of phosphorus (P) fertiliser mined from exhaustible sources (Heckenmüller et al., 2014; Hoogendoorn et al., 2008; McDowell et al., 2006; Roach & Morton, 2005). These concerns are well founded with an estimated 74% of NZ freshwater fish at risk of extinction and 28% of all rivers in the country being deemed unsafe to swim in (Goodman et al., 2014; Ministry for the Environment, 2017).

While there are other industries also impacting these issues, intensive agriculture affects all of them and on-farm management practice changes can significantly reduce impacts.

One strategy which can help to remove the GHG (CO_2) from the earth's atmosphere without sacrificing production is to optimise farm management practices to increase soil organic carbon stocks (SOCS). SOCS consists of all forms of carbon containing molecules which are constantly cycling in the soil. This includes organic matter as well as smaller carbon-based molecules which can be labile or more stable and bound to soil particles (Naylor et al., 2020).

Increasing SOCS can substantially offset GHG emissions from the farm. This is achieved by using management practices which encourage carbon captured by pasture to be transferred into the soil and subsequently converted into more stable forms where it can remain in the soil for extended periods of time. Once in the soil, it also plays an important role in improving soil structure, facilitating microbial activity and increasing nutrient retention (Batjes, 2014; Stockmann et al., 2013; Whitehead et al., 2018).

Carbon sequestered in soil is already being introduced into some government run carbon credit schemes such as the Australian government's carbon credit system (Australian Government, 2021). Such schemes offer a financial incentive for farmers who increase the SOCS on their farm, thus offering an extra pathway for the agricultural industry to productively work towards achieving the country's climate goals. Currently, there is no soil carbon credits program in NZ, nor is agriculture included in the government's Emissions Trading Scheme (ETS) (Leining et al., 2020). However, NZ specific standards have been proposed by a report commissioned by the Ministry for Primary Industries which is a body of the NZ government (Mudge et al. 2020).

This potential to offset carbon emissions is the key factor which led to Dairy Trust Taranaki (DTT) launching this project. DTT in partnership with Nestlé have launched a project which aims to achieve net zero GHG emissions by 2032 on one of their dairy farms, Kavanagh farm. Because emissions from some farm operations are inevitable, DTT will need to find ways to sequester carbon as well as ways to reduce other GHG emissions if they are to

achieve this goal. Increasing SOCS is one way of achieving this goal without having to convert existing land into non-dairy enterprises to sequester carbon or offset emissions.

This study explores this opportunity through the following components:

- Designing a SOCS benchmarking and monitoring system for the Kavanagh farm
- Performing a benchmarking survey to assess current SOCS on the farm
- Assessing the opportunity for the farm to increase SOCS in the future
- Making recommendations to increase SOCS

Chapter 2 – Literature review

2.1 Introduction to soil organic carbon

There is increasing evidence that soil organic carbon (SOC) plays an important role in soil health and can mitigate climate change by sequestering atmospheric carbon underground. On the other hand, loss of soil carbon can exacerbate climate change. This is because soil organic carbon stocks (SOCS) constitute twice as much of the earth's carbon as atmospheric carbon (Batjes, 2014). However, soil carbon is in constant flux and SOCS can be lost quickly as land management practices change (Schipper et al., 2014). Consequently, there is a need for standardised systems of SOCS testing and monitoring as well as education around the importance of SOCS targeted to farmers and the wider industry. This review introduces current scientific understanding of soil carbon; the management factors which affect it and examines a range of existing soil testing standards and methodologies. More specifically, the review will primarily focus on factors affecting NZ agricultural land and pasture systems, but where local research is lacking, broader sources will be reviewed. Except for benchmarking standards, international soil carbon research is outside the scope of this review unless no NZ based research exists.

SOC can be in the form of organic matter, smaller labile carbon molecules and non-labile carbon which is bound to reactive surface sites on soil particles (Naylor et al., 2020). SOCS refers to the numerous forms of carbon containing molecules which are constantly cycling in the soil. It is quantified in terms of the mass of carbon in a given area of soil down to a certain sampling depth which is typically expressed as tonnes of carbon per hectare ($t\ C\ ha^{-1}$).

The presence of plants in soil is critical to building SOC. Soil organic carbon can enter the soil through two primary pathways, plant root exudates in the form of simple metabolisable organic compounds and through organic matter such as decaying roots, leaf litter or animal excreta (Naylor et al., 2020). These compounds make up the labile SOC which has a high turnover rate. This pool of labile SOC is then utilised by the soil microbiome and can subsequently go down two different pathways. The primary pathway is microbial respiration in which the organic compounds are metabolised and CO_2 is released into the atmosphere. The other pathway occurs under certain environmental conditions where the carbon can be decomposed into simpler compounds, which are then able to react with

mineral surfaces on soil particles to form organo-mineral complexes. These complexes are much more stable and inhibit further microbial decomposition (Kleber et al., 2015). It is through this non-labile form where carbon can be most effectively stored or sequestered.

Much of NZ's prime dairying soil has a large capacity for storing carbon due to high quantities of organo-mineral complexes in the soil that make it less labile and available to microorganisms (Beare et al., 2014). The formation of these organo-mineral complexes occurs after partial degradation of organic matter into smaller biopolymers and monomers. These smaller molecules react more readily with soil particles that have large surface areas and a high number of reactive surface sites (Dwivedi et al., 2019; Kleber et al., 2015). These are typical traits of soils which developed more recently from volcanic material like the Allophanic Soils found predominantly in NZ's Taranaki and Waikato regions.

Carbon becoming locked in stable organo-mineral complexes is only one part of the SOCS sequestration pathway. The formation of these organo-mineral complexes happens on a relatively short time span and unlike labile forms of soil carbon, in this form it is not readily metabolised and lost from the soil (Anderson & Paul, 1984). This allows the carbon to be incorporated into the formation of soil aggregates which is a much slower process. These soil aggregates physically prevent micro-organisms from accessing this carbon, resulting in highly stable SOCS which are both physically and chemically locked to soil particles and aggregates. (Jastrow, 1996).

A key contributing factor towards the formation of these stable soil aggregates is the creation of glomalin. Glomalin is a protein created by arbuscular mycorrhizal fungi which enhances soil aggregate stability and also protects labile forms of carbon (Hossain, 2021). However, many conventional agricultural systems are not optimised for the production of glomalin due to frequent tillage, high soil P fertility and use of biocides, all of which suppress mycorrhizal fungi activity, thus there could be an opportunity to increase SOCS through this pathway (Rillig, 2004).

Potential to build soil carbon in NZ agricultural soils

There are numerous benefits to increasing SOCS. The most prominent of which is the potential to offset global carbon emissions through soil carbon sequestration. It is estimated by the "4 per mille Soils for Food Security and Climate" project established at

the United Nations climate change conference COP21, that the implementation of SOCS promoting management practices in agriculture globally could increase SOCS by 0.4% per year over the course of the next 20 – 50 years. If this sequestration could be achieved on all global agricultural land, it would amount to as much as 30 – 60 Pg of carbon sequestered. This is enough to offset 20 – 35% of global carbon emissions over that 20 – 50 year period (Minasny et al., 2017).

In NZ, while SOCS potential is high, so too are existing SOCS levels. Currently the estimated nationwide average is 98.7 t C ha^{-1} to a depth of 30cm (Minasny et al., 2017). To achieve the 0.4% increase in SOCS per year target set under the 4 per mille project, 0.4 t C ha^{-1} would need to be sequestered nationwide over the next 20 years of the initiative. This is theoretically an attainable goal with SOCS sequestration potential to a depth of 30cm estimated to be 0.105 – 1 t C ha^{-1} $year^{-1}$ on a global scale and 0.32 – 0.57 t C ha^{-1} $year^{-1}$ for NZ (Conant et al., 2017; Minasny et al., 2017).

Other benefits to high SOCS aside from carbon sequestration, primarily relate to soil structure and fertility. Increases in SOC improve soil structure by promoting the mechanisms of aggregate formation (Stockmann et al., 2013). In turn this has positive effects in terms of increased water holding capacity (Lal, 2004). This makes soils and farm systems more resilient to the increased volatility of weather patterns brought by climate change. Additionally, with 90% of soil N stored in organic matter, a larger SOC pool increases the overall soil's N storage potential as well as other nutrients such as P and Sulphur (Batjes, 2014). Furthermore, other benefits such as an increased cation exchange capacity and the important role of organic matter as a nutrient pool and for microbial health are not to be understated. Overall, these benefits make increasing SOCS one of the best drivers of supporting the fertility and soil health of degraded and lower quality soil types (Whitehead et al., 2018). With the wide range of benefits of increased SOCS established, the remaining challenge for NZ farmers is how they can increase their SOCS.

2.2 Factors affecting soil organic carbon

2.2.1 Soil and landscape factors

Soil type

One of the primary defining factors influencing SOCS is the soil type. Across New Zealand's 13 soil orders, SOCS varies greatly. Allophanic soils generally have the highest SOCS, typically containing 100 – 200 t C ha^{-1} in the surface 30 cm, whereas other soil orders are primarily in the 50 – 150 t C ha^{-1} range (Mudge et al., 2020). The higher SOCS found in Allophanic soils is attributed to two things. First, the high allophane content in these soils allows for a large content of carbon containing organic matter to be adsorbed to soil particles through the formation of Al and Fe organic carbon complexes (Rodríguez-Rodríguez et al., 2006). The second mechanism through which Allophanic soils maintain high SOCS is through the sorption of organic compounds to mesopores and micropores (Parfitt, 2009). This mechanism is particularly significant for Allophanic soils due to the very large surface area found on Allophanic soil particles (Chevallier et al., 2010).

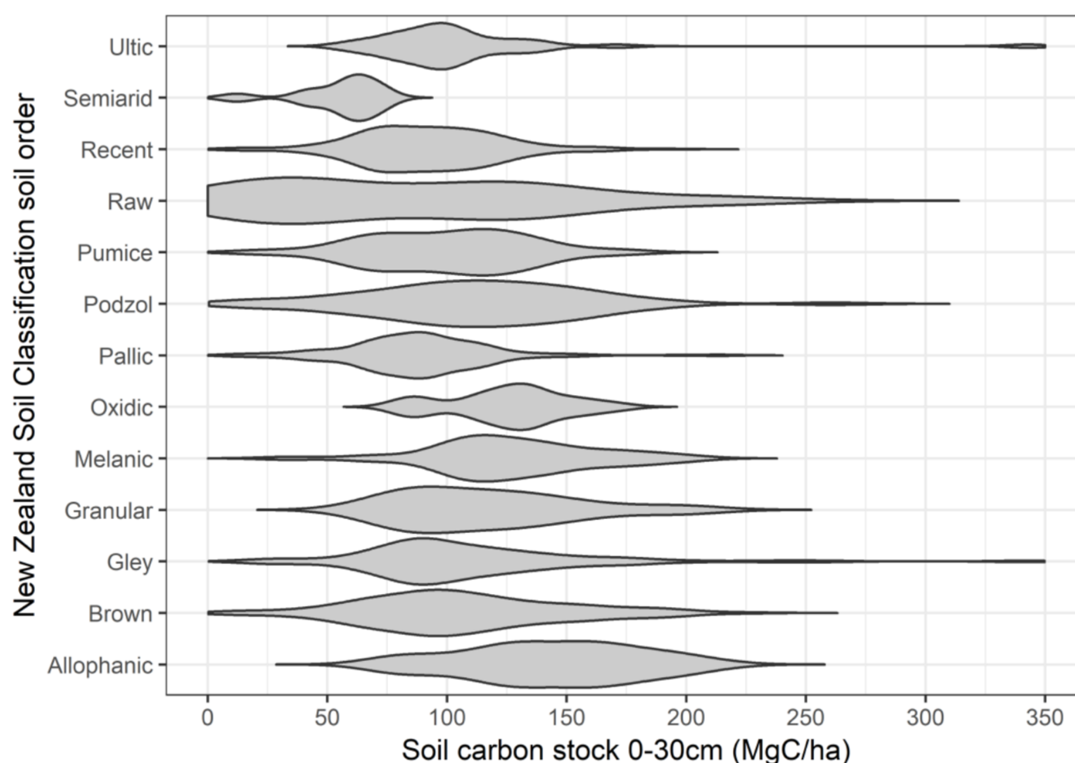


Figure 1: A Violin plot showing the distribution of SOCS to a depth of 30 cm for grassland soils for 13 different NZ soil orders. Source: Mudge et al. (2020) with data from the National Soils Database (NSD). Permission granted by MPI August 2024.

Aspect

The aspect of slopes, particularly in hill country landscapes, influence SOCS. Northern facing slopes in NZ receive more sunlight than south facing slopes, which influences the sunlight received by plants, the temperature and moisture content of the soil. Globally, literature on the impact of aspect on SOCS consistently shows increased SOCS on slopes facing away from the sun across all types of land use. This same literature has found 15 – 40% higher levels of SOCS on these less sunny-facing slopes (Bangroo et al., 2017; Egli et al., 2009; Jakšić et al., 2021). In NZ there is limited research into the impact of aspect, but it has been established that in most cases, other factors are more consequential than aspect for influencing the soil's carbon stocks (Hedley et al., 2015). A recent study by Mackay et al., (2021) found that on southern Hawkes Bay hill country, only 12 – 25° slopes were affected by aspect while slopes of less than 1 – 12° and greater than 25° showed no significant difference between different aspects. However, it is worth noting that this study did have a limited sample size and a broad focus beyond just slope and aspect.

Slope

Along with aspect, slope is one of the primary influences on SOCS. It is generally accepted that as slope increases, SOCS decreases (Tate et al., 2005). Data collected by Mackay et al. (2021) found that steep NZ hill country slopes greater than 25° had lower SOCS at all depths, despite having higher bulk density. This is attributed to a combination of factors including pasture production, different erosional and depositional soil processes compared to flatter topographies and differing animal behaviour on slopes (Hedley et al., 2015). It has also been shown that SOCS tend to be higher in more stable areas such as downslope near flatter areas, hilltops or boundaries such as hedgerows or riparian areas (Ford et al., 2019; Hedley et al., 2015).

2.2.2 Climatic factors

Rainfall

The most influential environmental factor affecting SOCS is rainfall (Jenny, 1980). The amount of rainfall and consequently, the availability of water in the soil affects multiple key parts of the SOC cycle. At the low end of the rainfall scale, there isn't sufficient soil moisture to facilitate optimal plant growth or microbial respiration. This low rate of plant growth reduces the flow of carbon into the soil via root growth and root exudate production

(Hunt et al., 2004; Kirschbaum et al., 2017). While models have been made for predicting SOCS based on rainfall (McNeill et al., 2014), there has also been a lot of focus on the impact of irrigation. The impact of irrigation on SOCS has been studied comprehensively due to the prevalence of irrigation in some regions and the complexity of its relationship with SOCS (Condron et al., 2014; Kirschbaum et al., 2017; Mudge et al., 2021; Schipper et al., 2019).

Temperature

The other environmental factor affecting SOCS is temperature. The exponential relationship between temperature and soil microbial activity has long been established (Bunt & Rovira, 1955; Chase & Gray, 1957). However, soil respiration only increases until another factor such as moisture, oxygen or mineralisable carbon limits it (Curtin et al., 2012). Furthermore, since soil temperature also impacts evapotranspiration, the relationship between soil temperature and SOCS is closely related to water availability and irrigation. This means that while increased temperature paired with water availability will increase soil respiration and subsequent loss of SOCS at an increasing rate up to ~55°C, as the SOCS decline, so too does microbial activity (Schipper et al., 2019).

2.2.3 Management factors affecting SOCS

Land use

The most influential management factor affecting SOCS is land use. In NZ, SOCS to a depth of 30 cm typically range from as low as 80 t C ha^{-1} to as high as 136 t C ha^{-1} across different land uses, though some Recent Soils or very stony soils can approach 0 t C ha^{-1} (Campbell et al., 2015; Hewitt et al., 2012). Wetlands with peaty soils provide the most conducive conditions for the formation and storage of high levels of SOCS (Blodau, 2002). Consequently, avoiding the disruption of wetlands or reinstating historical wetlands is one of the most effective ways of increasing or maintaining SOCS. For productive agricultural land use, long-term pasture on dairy farms tends to have the highest levels of SOCS, though it is not clear if this is due to a causal relationship between pastoral systems and the soil or simply due to pastoral systems being located on the soils which are most conducive to having high SOCS. Despite this, SOCS losses have been documented on flat dairy pastures (Schipper et al., 2010). Also worth mentioning is a study by Barnett et al. (2014) which found no significant difference in SOCS between dairy and dry stock farms to

a depth of 60 cm but did find higher SOCS in the soil A horizons on dry stock farms compared to dairy.

While there are still knowledge gaps in our understanding of the mechanisms behind high SOCS under grazed grasslands, it is generally accepted that the continued grazing of pasture leads to increased root biomass relative to above ground biomass, thus increasing carbon entering the soil in the form of roots and root exudates (Wilson et al., 2018). On the other hand, cropping soils generally see more disruption through forms of vehicle compaction, tillage and fallow periods, leading to lower SOCS than pasture-based land use (McNally et al., 2017). Finally, forested land, both commercial and native has the lowest SOCS of any land use with stocks being around 16.4% lower on average compared to pasture which amounts to around 13.7 – 17.4 t C ha^{-1} less SOC (Hewitt et al., 2012; Schipper et al., 2017).

Irrigation

While irrigation has been shown to increase SOCS by up to 500% in arid regions (Whitehead et al., 2018), in temperate regions where water stress is seasonal, irrigation has been repeatedly shown to decrease SOCS (Kirschbaum et al., 2017; Mudge et al., 2017, 2021). This is due to a balance between the positive effect of water on plant growth and therefore carbon sequestration through root exudate production and the increased loss of carbon with excessive irrigation through microbial respiration. In one NZ example, despite as much as 74% more pasture growth being achieved by irrigating from 750mm to 1,500mm equivalent rainfall, SOCS were reduced by as much as 26% in the surface 1 m of soil depth over a period of 62 years (Condron et al., 2014). It is also worth noting that this study found no significant loss of SOCS when irrigating to maintain 10% soil moisture content which resulted in a 44% pasture growth increase, indicating that there is an optimal rate of irrigation where pasture growth can be achieved without significant SOC loss.

This phenomenon has been attributed to numerous factors associated with the change in year-round water availability. With irrigation keeping the soil moist all summer, the water stress induced decrease in microbial activity is no longer a limiting factor to carbon loss. Consequently, under irrigation, microbial respiration continues to convert SOCS into CO_2 gas at an increased rate in the warm summer weather (Schipper et al., 2019). Furthermore, plants respond to the more consistent water availability by directing less

carbon to root growth (Kirschbaum et al., 2017). Finally, there is also evidence to support the theories that the changes in soil water availability change the types of root exudates and microbial functions which result in increased carbon losses (Mudge et al., 2021).

Tillage

Another significant management factor affecting SOCS is tillage. Due to the wide variety of different methods of tillage, there is significant variation in the impacts of different practices on SOCS. Some key attributes of different tillage practices have been identified for optimising SOCS. The most significant of which are the duration which the soil is left fallow, the amount of disruption to the soil with more disruptive tillage leading to greater carbon loss and the moisture content of the soil when it is cultivated (Whitehead et al., 2018). This is due to tillage breaking apart soil aggregates and exposing organic matter that was previously physically protected from biodegradation (Balesdent et al., 2000). If the soil remains moist after being cultivated, it creates suitable conditions for microbes to mineralise previously inaccessible carbon which has been exposed by the breaking up of large soil aggregates. This loss of carbon from tillage is primarily carbon from the top 8cm of the soil with no observed effect on soil carbon beneath 15cm for conventional tilling methods (Kern & Johnson, 1993).

Tillage practices contribute significantly to the difference in SOCS between pasture and cropping. The regular disturbance of most cropping soils with frequent planting and harvesting increases the time that soil is fallow and vulnerable to SOC losses (Six et al., 2000). Consequently, NZ cropping soils have a deficit relative to the soil's capacity of SOC which is 1.14 – 1.89 times greater than the carbon deficit of pasture soils (McNally et al., 2017). However, most pasture soils are not without disruption. The practice of pasture replacement is widespread and during this process, the soil may be tilled before new seeds are planted. This process can lead to a loss in SOCS between 0.8 and 4.1 t C ha^{-1}, though this is usually only performed on a subset of the total paddocks on the farm at any one time (Schipper et al., 2017).

An emerging tillage technique which is showing potential to increase SOCS is through the use of inversion tillage. Inversion tillage is the practice of inverting the topsoil, typically to a depth of approximately 30 cm before renewing pasture on the now inverted soil (Law-rence-Smith et al., 2021). The result of this is the carbon rich soil previously found in the top 15cm of the soil is relocated deeper underground where less carbon rich soil was

previously, and the new topsoil has lower soil carbon. In theory, this allows for a greater rate of carbon sequestration in the new topsoil in the years following the inversion while the former topsoil buried 30 cm deep can maintain a higher carbon content over time compared to the original deep soil's baseline carbon levels.

In practice, this strategy seems very promising. While currently there is a shortage of local studies investigating SOCS after inversion tillage over a decades long timescale, both international, and the few longer term local studies have shown positive results. In a 4-year study on Tokomaru Silt Loam, Calvelo-Pereira et al. (2018) found there was an 18% increase in SOCS in the inversion tillage treatment over the control treatment. However, it is worth noting that they expressed uncertainty about the longevity of the SOC gains. On the West Coast of the South Island, the deep inversion of a podzol soil down to 1 – 3 m saw an average increase of SOCS of 1.2 – 1.8 t C ha^{-1} per year in the new top 15 cm of the soil over 20 years (Schiedung et al., 2019). Regarding NZ's Allophanic soils specifically, a study by Lawrence-Smith et al. (2021) used existing data to model SOC sequestration following inversion tillage and predicted SOCS increases of 9.6 – 12.7 t C ha^{-1} on Allophanic soils after 20 years. Alongside the potential SOC benefits, there are also short-term benefits to inversion tillage via reduced carbon and N leaching and even the potential to increase summer crop yields (Calvelo-Pereira et al., 2022).

Grazing management

The management of animals grazing on pasture can also impact SOCS. One such grazing management strategy is the deferred grazing of pasture for longer periods of 50 – 120 days (DairyNZ, 2023). While modelling has shown deferred grazing can increase SOCS, it requires a significant change in management for a modelled marginal benefit in terms of soil carbon which has not been demonstrated in field trials. This modelling suggests a change in the grazing threshold from 2,000 to 3,000 kg DM/ha could increase SOCS by a mere 0.1 t C ha^{-1} $year^{-1}$ (Kirschbaum et al., 2015). Furthermore, paddocks with deferred grazing tend to only make up a small subset of the farm, typically around 10% each year, so any SOCS gains may be limited.

Regarding stocking rates, there is limited NZ based research (Schipper et al., 2017). However, a recent study by Mackay et al. (2021) concluded that increased fertility that led to higher pasture production and thus higher stocking rate had little to no impact on SOCS and that other management factors are much more consequential.

Supplementary feeds

One potential method of increasing SOCS under pasture is through the introduction of supplementary feed into the farm system. This provides a net flow of nutrients needed for carbon uptake and in the case of supplementary feed, a direct carbon input. However, the potential for a farm to benefit from this strategy may be limited depending on their existing levels of inputs. Many dairy farms in NZ already utilise significant inputs of supplementary feed (Parfitt et al., 2012).

Due to supplementary feed being one of the only ways to directly introduce carbon into the farm, it can be a useful tool to increase SOCS. Of the carbon contained in the feed, approximately 27% of it is returned to the soil through animal excreta while the rest is lost through respiration, milk production and enteric fermentation respectively (Kirschbaum et al., 2017). However, the benefit of supplementary feed is somewhat negated by the fact that this carbon has been removed from soil located elsewhere as nutrients and carbon are removed from soil by the harvested feed crop. To minimise SOCS losses at the harvest location, the planting of perennial grasses or winter wheat as the feed crop is advisable over maize (Wang et al., 2015).

Fertiliser

The impact of fertiliser on SOCS is disputed. Some research suggests that more fertiliser increases sequestration by increasing growth and carbon uptake by the pasture, some of which subsequently enters the soil through root exudates (Kirschbaum et al., 2017). Another study by McIntosh et al. (1999) found increased SOCS with P and sulphur fertiliser alongside over-sowing of pasture, though the impact of the over-sowing and increased fertiliser couldn't be separated. On the other hand, there is also evidence indicating that increased fertiliser use doesn't increase SOCS. A study by Schipper et al. (2013) found that varying rates of phosphorus fertiliser had no impact on SOCS to a depth of 7.5 cm over a 60 year period in a dry South Island grassland farm. These mixed results may be indicative of a more complicated relationship between different types of fertiliser and SOCS.

The carbon to nitrogen ratio (C:N) can also be a factor in increasing or preventing the breakdown of SOCS. It has been established that in soils with a high C:N ratio of 20 or

above, mineralisation of organic carbon and N into more plant available forms decreases (Haney et al., 2012). Consequently, the application of N fertiliser could increase the mineralisation of soil organic N and SOC. Despite this, there is currently no evidence that N fertiliser applications on NZ pasture increases carbon mineralisation and therefore SOCS losses.

Pasture varieties and diverse pastures

A novel method of potentially increasing SOCS is to utilise a variety of species in pasture with different rooting density and depths. While there is conflicting evidence for the efficacy of this strategy internationally, long-term studies and local data suggests that with a focus on planting species with high fine root density and deeper roots, SOCS can be increased (Steinbeiss et al., 2008; Whitehead et al., 2018). However, there is no clear consensus on this. On one hand, McNally et al. (2015) found diverse pastures increased soil carbon inputs into the soil by 1.2 t C ha^{-1} over the year long trial, though not all of this carbon ended up in stable SOCS. On the other hand, a study by Rutledge et al. (2017) investigated the impact of a diverse pasture with eight species over three years and found no significant difference compared to a ryegrass-clover control treatment. There seems to be some evidence supporting diverse pasture mixtures being able to increase SOCS where deeper rooting species can be maintained long after planting; or in situations where there is more climatic variability. In a more variable climate, diverse pastures can be more resilient, thus maintaining higher production in less favourable conditions which then removes the need for carbon depleting management practices to mitigate the poor conditions (Wall et al., 2021). However, more recent evidence has failed to demonstrate this in practice (Wall et al., 2024). Consequently, more research is needed to determine which factors influence SOCS changes under diverse pastures.

Biochar

A more promising management practice which can reliably increase SOCS is the application of biochar to the soil. Biochar refers to pyrogenic carbon, a source of black carbon which is produced by the incomplete combustion of fuels, usually organic matter. Biochar is significant because of it being a major source for black carbon which is one of only a few long-term persistent soil components acting as a pool for soil organic matter and therefore SOC (Marschner et al., 2008). This makes biochar particularly useful for soils with a low capacity for the storage of carbon in mineral associated compounds.

Furthermore, it provides an opportunity for less productive soils to improve the long-term storage capacity of organic forms of nutrients (Lorenz & Lal, 2014).

Another characteristic of biochar is its tendency to increase soil carbon stocks deeper in the soil. Black carbon makes up a greater proportion of soil carbon below the top 10 cm of soil (Dai et al., 2005). This is due to its propensity to leach down the soil profile with rainfall (Rumpel et al., 2009). However, if soil particle sizes are large enough, there could be significant SOC losses through leachate, diminishing the effectiveness of biochar as an additive to increase soil carbon sequestration (Yang et al., 2019).

The opportunity for soil carbon sequestration globally through the addition of biochar was reviewed by Gross et al. (2021) in a meta-analysis covering 64 studies in which they found an average increase in SOCS of over 13 t C ha^{-1} which corresponded to a 29% increase in carbon in field studies with biochar applications at varying rates over different durations. In the longer duration studies they reviewed, they found that over 10 years, up to 25.5 t C ha^{-1} could be sequestered which corresponds to an annual rate of 2.55 t C ha^{-1} $year^{-1}$. Finally, it is also worth noting that they found organic fertiliser co-applications alongside biochar to further boost sequestration. In particular, plant matter based fertilisers boosted sequestration more than faecal matter fertilisers due to a higher C:N ratio.

The annual rate of sequestration over a 10-year period found by Gross et al. (2021) matches the rate observed by an unrelated study in Canada by Gross et al. (2022) which compared biochar from manure compost to the application of raw manure compost and a control treatment over a three-year period. This study found lower GHG emissions and a 2.5 t C ha^{-1} $year^{-1}$ increase in SOCS under the biochar treatment. This increase in SOCS is due to improved retention of carbon inputs to the soil from pasture as this study excludes the carbon introduced directly by the biochar application. Even higher SOCS increases have been observed when including the mass of carbon in the biochar. A study performed by Blanco-Canqui et al. (2020) in the Midwest USA saw 11.58 t C ha^{-1} sequestered over 6 years which is equivalent to 1.94 t C ha^{-1} $year^{-1}$ or an approximately 2% annual increase in SOCS after a single application of 7.25 t C ha^{-1} of biochar. This indicates that even higher rates of sequestration may be possible due to much of the carbon in the applied biochar remaining in the soil in addition to better retention of carbon inputs to soil from pasture.

Unfortunately, none of these studies investigated the long-term impacts of biochar applications beyond 10 years, so the long-term prospects of carbon sequestration through biochar remain unclear. Whether these rates of sequestration can continue for many decades or if an equilibrium is reached after ~20 years as with other management practices is not yet established and further research is needed.

Another key consideration to large applications of biochar is the full life cycle assessment of the biochar. Depending on the source, production and transportation of the biochar, there could be other significant impacts on the net carbon emissions through reducing emissions from other sources like non-CO_2 GHG emissions or renewable energy generated by the combustion of the source material (Patel & Panwar, 2023). Depending on the proximity of the biochar production site and the farm where it is applied, there could be emissions from the transportation of the biochar as well (Roberts et al., 2010).

Another benefit of biochar is its ability to reduce nitrous oxide emissions. A study by Cayuela et al. (2013) demonstrated a 10-90% reduction in nitrous oxide emissions from denitrification in 14 different soils. Another study in South Korea by Lee et al. (2022) demonstrated that applications of some types of biochar such as barley straw biochar at 20 t ha^{-1} reduced nitrous oxide emissions by 33 – 75%. However, not all types of biochar decreased nitrous oxide emissions across all soil types, with poultry manure biochar increasing emissions in one soil type while decreasing them in others. Unfortunately, neither study identified the mechanism behind the observed reduction in emissions.

Despite the many benefits of biochar, it remains a nascent industry. Significant barriers to its adoption exist including a lack of infrastructure limiting its availability, leading to increased costs around production and transportation (Whitehead et al., 2018). More significantly, there is a lack of financial incentives for its application on farms. Some of the soil health benefits take years to appear after the application of biochar and most problematic of all, carbon sequestered from biochar is not priced under the NZ government’s ETS. This means that farmers face an upfront cost to apply biochar but get no tangible financial benefit aside from a potential increase in fertility which is hard to quantify (Arbestain et al., 2016).

2.3 Sampling and measurement methodology

SOCS can be assessed using two different methods. The current standard approach is repeated soil surveys which involves direct on-farm sampling using deep soil cores. This provides the highest degree of precision but is very labour intensive and expensive. Alternatively, a model-based approach can be used involving carbon budget accounting and chamber measurements. This is substantially cheaper, but also lacks the accuracy of repeated soil surveys (Smith et al., 2020).

2.3.1 Survey accuracy

The degree of accuracy required is a critical metric to determine before designing a repeating SOCS monitoring system. In a review outlining a standard approach for on-farm SOCS benchmarking and monitoring in NZ, Mudge et al. (2020) recommended a minimum degree of accuracy of 2 – 5%. With a nationwide average SOCS of 98.7 t C ha^{-1} to a depth of 30 cm, this equates to a precision of about 2 – 5 t C ha^{-1} (Minasny et al., 2017).

2.3.2 Stratified single random sampling

There are various existing methods of sampling for a SOCS survey with a variety of different trade-offs. Generally, the aim is to reduce the number of samples taken without compromising on the accuracy with which the samples represent the entire farm. The most widely accepted way to achieve this is through the use of stratified sampling (Mackay et al., 2021).

Stratified sampling involves separating the farm into different zones known as strata. These strata are created based on their unique combinations of factors such as soil type, climate, topography, and management practices which combine to create zones of similar SOCS. By grouping areas with similar levels of SOCS together, the variance amongst samples within each stratum is lower than the variance of samples taken across the entire farm. Consequently, the samples provide more precise estimates of SOCS within each stratum. This means that in total, less samples need to be taken to attain a desired degree of accuracy (de Gruijter et al., 2018).

2.3.3 Number of samples

Information collected from a pilot study is used to calculate the number of samples required for ongoing SOCS monitoring. This is calculated using a power analysis based on the mean and standard deviation of the samples collected in the pilot study, combined with

expectations of SOCS variability and the required level of precision (Bain & Engelhardt, 1992; Cohen, 2013; de Gruijter et al., 2018). This can then be balanced against the cost of taking samples to find an optimal number of samples for the farm in question.

2.3.4 Strata

The purpose of stratification is to reduce the standard deviation across sample groups so that it is lower than the standard deviation of all random samples across the entire CEA. Therefore, the number of strata should be dependent on the decrease in average standard deviation achieved by adding the marginal stratum. This applies up until the point where the number of sampling sites using stratified sampling surpasses the number of sites with non-stratified random sampling due to the minimum number of sites per strata (Mudge et al., 2020). At this point, stratified sampling is still more favourable due to the greater precision provided, but adding more strata beyond the marginal stratum will likely require more samples than is financially viable.

One issue is that it isn't always clear how significant the reduction in the standard deviation between samples is by adding the marginal stratum. This is because stratification occurs before the samples are taken. Consequently, the only way to assess this is based on the known geographical and farm management data which is known to impact SOCS. There are however multiple ways to stratify the farm based on the amount and quality of data available.

2.3.5 Stratification methods

The optimal method of stratification largely depends on the farm data (also known as ancillary variables) available. When there little to no data on the farm available, compact geographical stratification is the most appropriate method. In short, this simply involves dividing the farm into a grid with the assumption that SOCS is spatially correlated so the variation within each sub-region is smaller than the whole farm variation. Conversely, with a range of ancillary variables, strata can be drawn either directly based on the farm data (referred to as "stratification by ancillary variables"), or by predicting the expected SOCS levels using the ancillary variables and known relationships between these variables and SOCS in a process known as "stratification by a map of predictions" (de Gruijter et al., 2018).

Further, building on all of these methods, (De Gruijter et al., 2015) created a method called "Ospats" which has been shown to more accurately stratify an area based on the target variable. Ospats achieves this by optimising the strata locations by considering uncertainties in the predictions of a map of a more basic predictions-based model. This makes it a superior model for stratification with numerous ancillary variables. Caution was however given to the use of this method by Mudge et al. (2020) in scenarios where the accuracy of the ancillary variables is lacking.

2.3.6 Sample bulking

Sample bulking or sample compositing is a common way of reducing the cost of soil sampling by grouping and mixing samples of the same sampling depth together thoroughly before laboratory analysis. The bulked sample should be representative of the mean SOC value of all of the individual samples, whereas only one sample needs to be analysed for total C. This reduces the number of laboratory sample analyses required by anywhere from 3 – 10x depending on the size of the bulked group.

While the potential labour and cost savings are significant, there are numerous downsides to sample bulking. Firstly, it makes optimising the number of samples harder since the total number of samples has to be a multiple of the number of samples per bulked group. Furthermore, it reduces the accuracy of the data through multiple mechanisms such as magnifying laboratory testing variability as well as introducing potential mixing error. More importantly, it removes the ability to analyse the spatial distribution of SOCS any more precisely than across a full stratum. Finally, it also removes the viability of further refining or redrawing the soil strata for subsequent sampling rounds which can be an important step in making the ongoing monitoring surveys more accurate and cost effective. This is because knowing the location and SOCS content of each sample is a critical part of quantifying SOCS variability across the farm and then redistributing samples accordingly to increase survey accuracy (de Gruijter et al., 2018). Despite the drawbacks, sample bulking has been used successfully in other trials and is notably a feature of the Australian government's measurement of soil carbon sequestration in agricultural systems methodology (Australian Government, 2021; Chappell & Viscarra Rossel, 2013).

2.3.7 Sampling depth

Sampling depth is an important question determining the accuracy and cost of a benchmarking system. It also varies significantly between different countries SOCS

standard methodologies. As a bare minimum, sampling should be done to a depth of 30 cm. This minimum is widely recommended, most notably by the Intergovernmental Panel on Climate Change (IPCC), Food and Agriculture Organization (FAO) and by the Australian government's soil carbon methodology determination (FAO, 2020; Australian Government, 2021; Eggleston et al., 2006). Alternatively, depths of up to 75 cm can be important for tracking all changes occurring in the soil depending on the rooting depth of the crop or pasture being grown (Olson & Al-Kaisi, 2015). Furthermore, it is good practice to separate the cores into different sections according to their depths. This is important because there is a substantial difference between SOC content at different depths, with the surface root zone often containing the highest soil carbon levels and so it is useful to track the distribution of carbon content throughout the soil profile (Olson & Al-Kaisi, 2015). When choosing depth intervals, it is important to align the intervals with standard sampling depths such as the top 15 cm and top 30 cm for easy comparison to other studies and to minimise the number of samples required per core since more depth intervals increases laboratory analysis costs.

2.3.8 Calculating SOCS

Common practice when measuring SOCS is to sample to a certain depth. However, simply measuring the SOC in that sample is not a reliable method of assessing SOCS due to variation in soil bulk density. This is problematic because when using a volume-based measurement, a more compacted soil will result in overestimated SOC readings relative to a soil with a lower bulk density (Wendt & Hauser, 2013). Consequently, best practice is to assess SOCS based on an equivalent soil mass. This requires the calculation of soil bulk density by knowing the mass and volume of the core sampled and measuring moisture content on a subsample. However, for soils which are stony or have poor aggregate formation, short cores, or quantitative pits can be used to ensure that the soil volume and therefore bulk density is accurately measured.

2.4 Research gaps and future research

Despite SOCS being an increasingly relevant field of agricultural research in NZ, we are still a long way away from having a comprehensive understanding of the factors affecting SOCS across the wide range of farming environments in NZ. Current research both local and international has provided a strong foundation of understanding around the core mechanisms behind SOCS formation and loss. However, there remains a substantial

knowledge gap around the impacts of many on-farm management practices on SOCS in NZ. Consequently, in some cases international research must be relied on to make predictions for NZ farms. This can be problematic due to the wide variety of environments and climate types which NZ farms are located in and each influencing SOCS dynamics differently. Additionally, there is a distinct lack of long-term research tracking the potential for SOCS sequestration over a period of decades and longer. To remedy these shortcomings, more data and more research is needed on SOCS on NZ farms.

With foundational work from Mudge et al. (2020) laying the framework for farm scale SOCS benchmarking and monitoring systems for NZ farms, the lack of a clear standard for SOCS benchmarking and monitoring is no longer the primary factor preventing widespread adoption of SOCS monitoring. Instead, the key limitation preventing more widespread adoption of monitoring SOCS is now cost. To resolve this issue, there needs to be significant progress in reducing the on-farm sampling costs through research and development into more effective benchmarking and monitoring systems. Alternatively, financial incentives for farmers to monitor and increase their SOCS like the Australian soil carbon credits protocol could also alleviate the cost barriers preventing more widespread SOCS monitoring.

Chapter 3 – Methods

3.1 Study site

The Kavanagh farm is a 213 ha effective dairy farm located adjacent to Fonterra's Whareroa processing facility on the outskirts of Hawera, South Taranaki (-39.611265°, 174.307060°). The farm has a total of 550 Friesian cross cows, 95 R1 replacement heifers and a smaller number of dry stock which graze on the less productive areas of the farm.

The farm itself is largely situated on flat to rolling terrain inside the Taranaki ring plain. Consequently, the farm has highly productive Allophanic Soils covering most of the farm with a smaller proportion of steeper terrain and hill soils located around small streams and wetlands. The farm was soil mapped by Dr Alan Palmer (Massey University) in June 2023 and the distribution of different soil types across the farm is displayed in the image below (Figure 2). The vast majority of the farm is Egmont black loam with some limited sections of Egmont hill soil and reworked black sand soils.

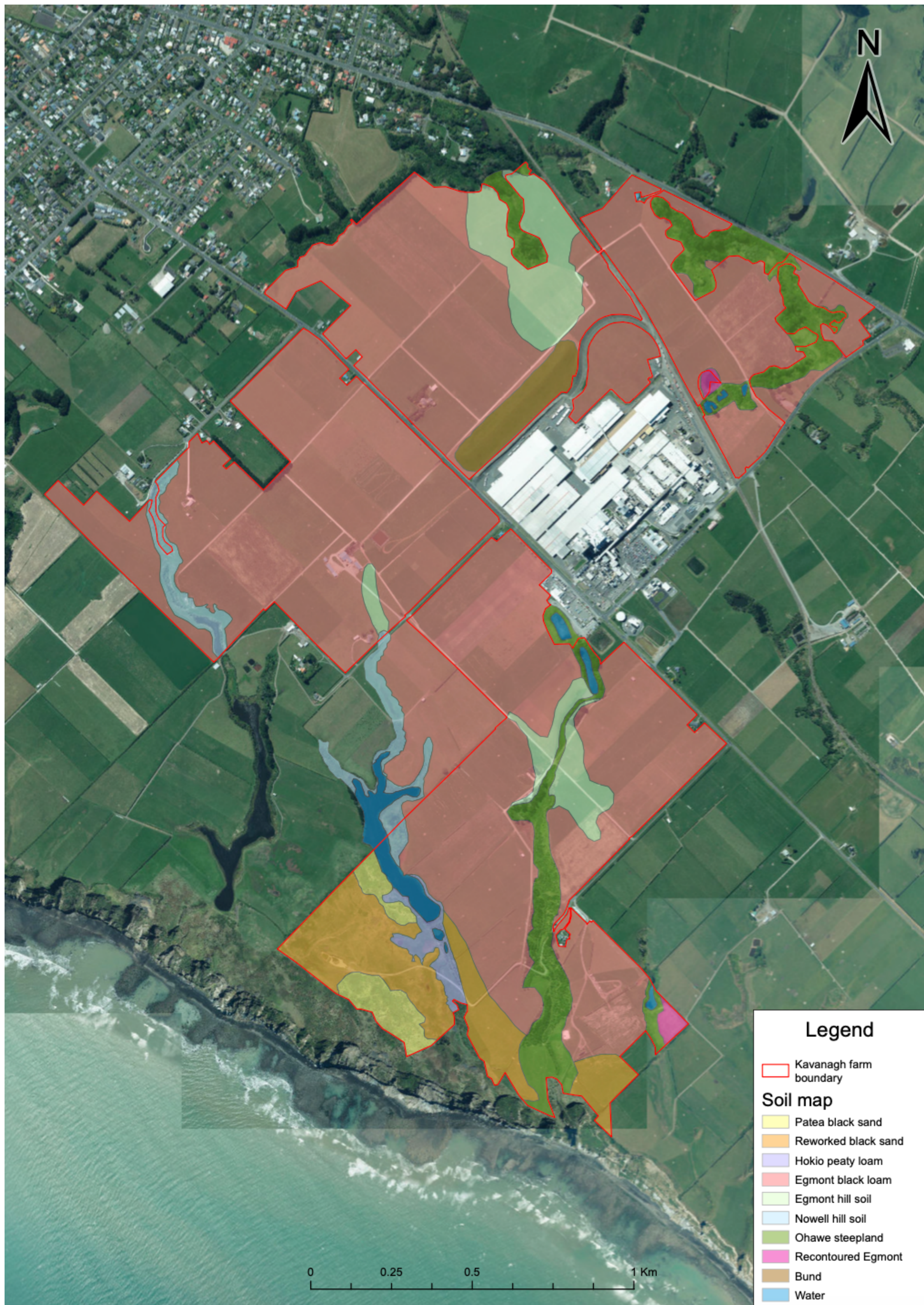


Figure 2: A soil map of the Kavanagh farm. Source: Soil map produced by Dr Alan Palmer (Massey University) in June 2023.

3.2 Carbon estimation area (CEA)

The CEA is the entire effective area of the Kavanagh farm with the exception of paddock C8 which is also referred to as the bund (Figure 3). This is because C8 has an anthropic soil which was created when the neighbouring Whareroa dairy factory was built. Because of this, the anthropogenic nature of the soil might make its SOCS less predictable, likely resulting in data reliability issues for any strata it might be a part of. Instead, paddock C8 had 4 sample cores to determine its SOCS for reference and full farm calculations but it remains distinct from the four strata used in the SOCS mapping. The CEA covers a total of 231.5 ha and C8 is also shown as outlined in blue (Figure 3).

Figure 3: The Carbon Estimation Area (CEA) on the Kavanagh Farm. Paddock C8 is not included in the CEA due to its anthropic soil. Paddock C8 is outlined in blue.

3.3 Stratification

3.3.1 Ancillary variables

The farm was stratified manually based on the following ancillary variables:

- Slope
- Soil type
- Management practices (primarily effluent application for the Kavanagh farm)
- Preliminary soil carbon data

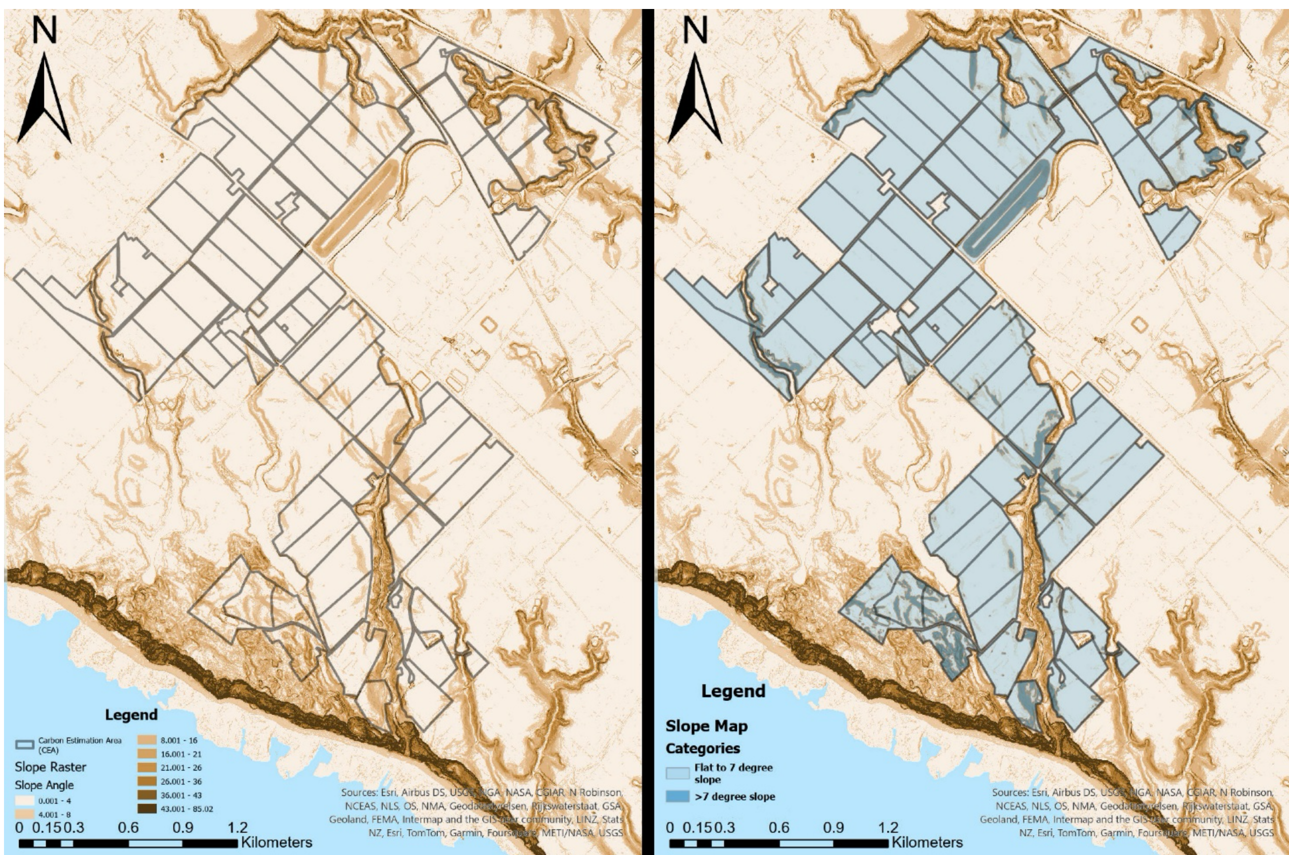


Figure 4: A map of the Kavanagh farm showing slope on the farm. The figure on the left displays slope categories as a raster with numerous slope categories while the figure on the right highlights the land which is flatter than and steeper than 7 degrees.

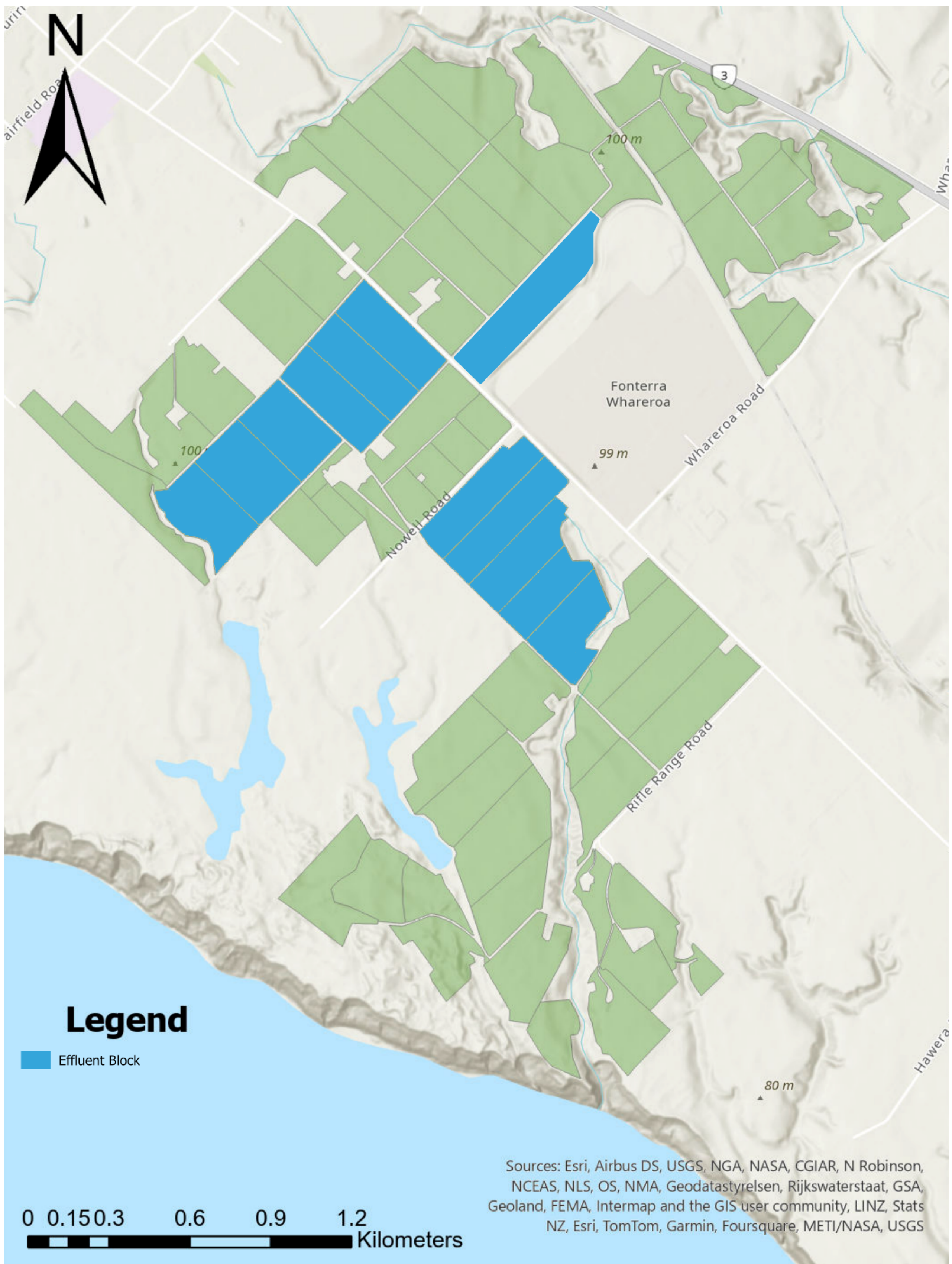


Figure 5: A map of the Kavanagh farm indicating which blocks receive effluent (effluent blocks marked in blue).

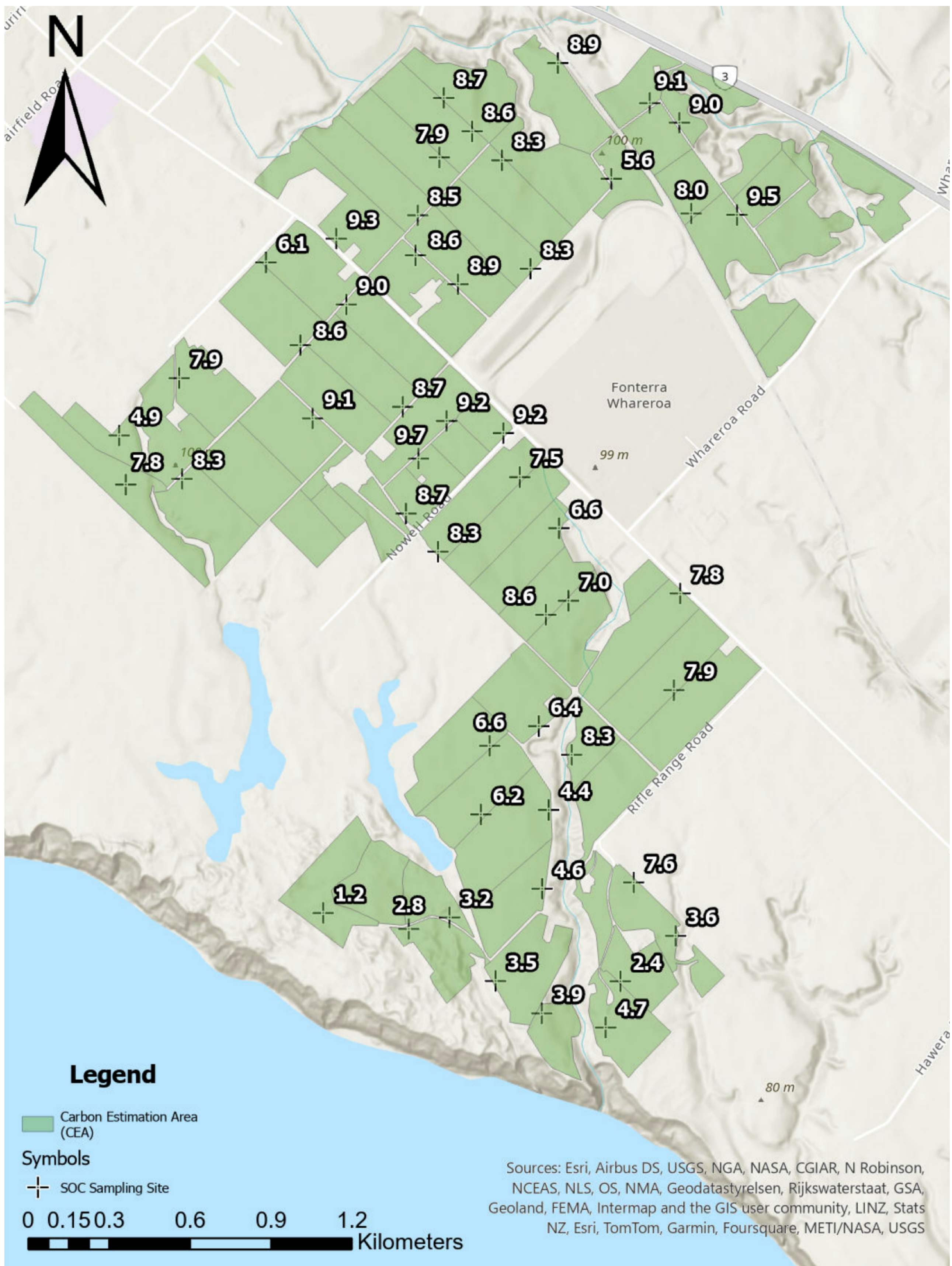


Figure 6: A map of the Kavanagh farm with annotated SOC concentrations (%C) in 15 cm soil cores taken in January 2022 for a separate project.

3.3.2 Strata

Based on the ancillary variables, the following four strata were created (Figure 7). Stratum A covers all of the flat Egmont black loam soil where we expect to see the highest SOCS. Stratum B is primarily Egmont black loam located on slightly more undulating land and due to the slope there may be slightly lower SOCS. Stratum C is closer to the coast where there are lower SOC concentrations in the preliminary SOC data. It also has some hill soils and rolling slopes throughout which we expect to lead to a lower SOCS content than strata A and B. Finally, stratum D consists of a combination of the Patea black sand soils and steeper Egmont black loam. Consequently, we expect stratum D to have the lowest SOCS values.

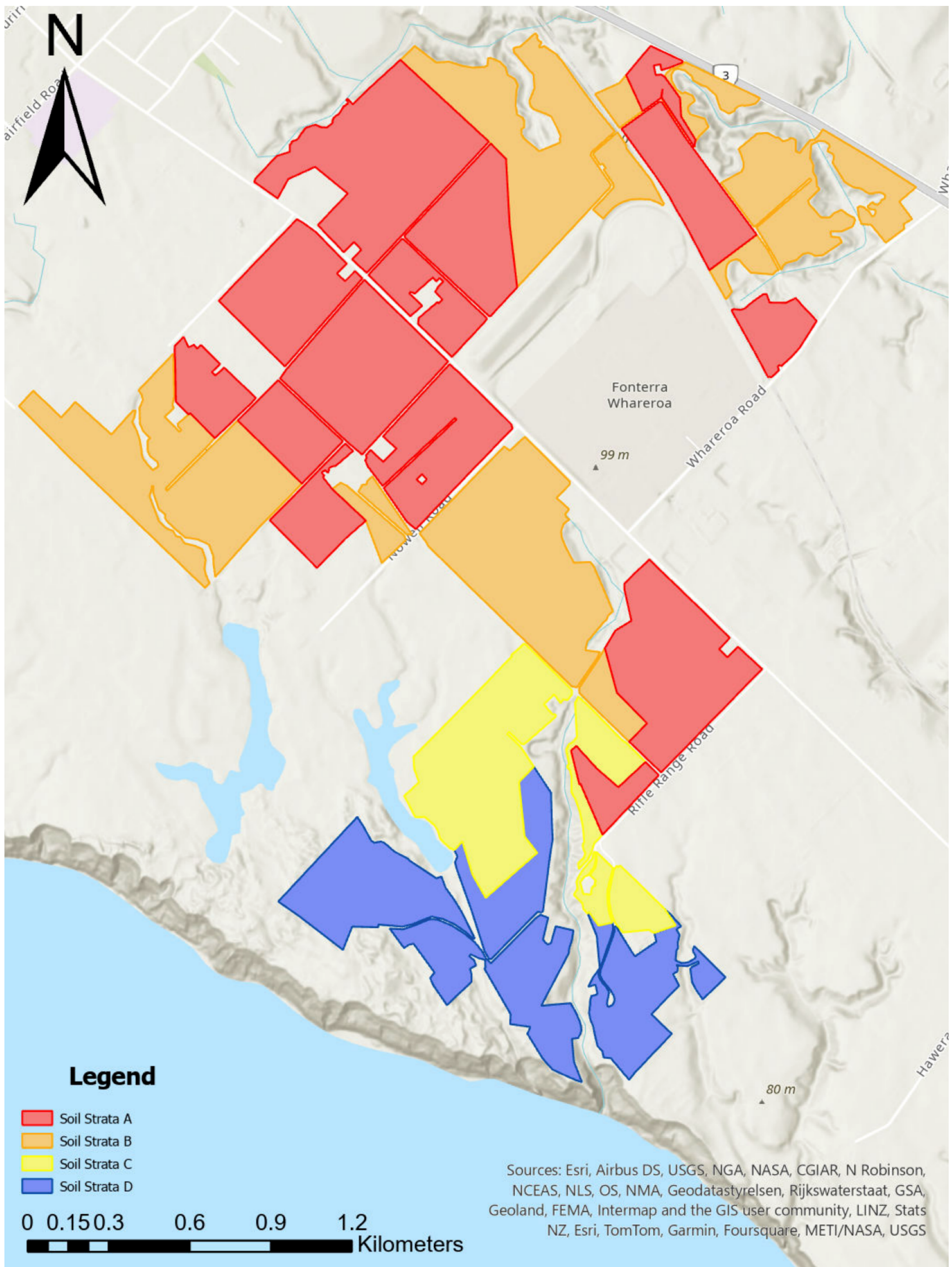


Figure 7: A map of the four initial soil strata.

3.3.3 Determination of sampling locations

The number of soil carbon cores required was estimated using preliminary data on the spatial variation of SOCS and the size of the CEA. While a dedicated preliminary survey of SOCS was not performed, a limited soil carbon survey to a depth of 15 cm along fence lines had previously been undertaken on the farm for other purposes (details in Appendix 6). However, the preliminary data was incomplete for the purpose of accurately representing SOCS due to being limited to a depth of 15 cm and having only a small number of bulk density measurements from which SOCS could be calculated. This meant that the standard practice of running a comprehensive power analysis to estimate the required number of soil carbon samples couldn't be performed in this case (Mudge et al., 2020). Instead, statisticians and a soil carbon expert were consulted to determine the total number of soil carbon cores required in this assessment.

A power analysis was undertaken to determine the number of samples needed to detect a statistically significant difference between strata. This resulted in 31 samples per strata, or a total of 120 samples with standard type 1 and type 2 error values of 0.05 and 80% respectively. A soil carbon expert was consulted and further statistical advice was sought before the number of samples was decreased to 30 samples per strata for rounding and cost reduction reasons.

The location of sampling positions within each strata was randomly generated in ArcGIS Pro 3.1.2 with the end result displayed in Figure 8. Any generated sample locations near obstructions such as water troughs or areas of excessive animal traffic were avoided and changed to a new location, as is standard practice (FAO, 2020). Any points located within 2 m of fence lines or paddock boundaries were also changed to a new location. New locations were generated using a random number generator to generate 2 numbers, one as a compass bearing for a direction to travel in away from the old location and the second number between 1 and 20 determining the distance to travel in metres. All new locations were marked and recorded by real time kinematic (RTK) GPS. Future samples taken after the benchmarking study are taken using static synchronous sampling design. This is where future samples are taken no more than 5 m away in a random direction from the original sample location. The direction is generated using a random number generator to generate a random compass bearing.

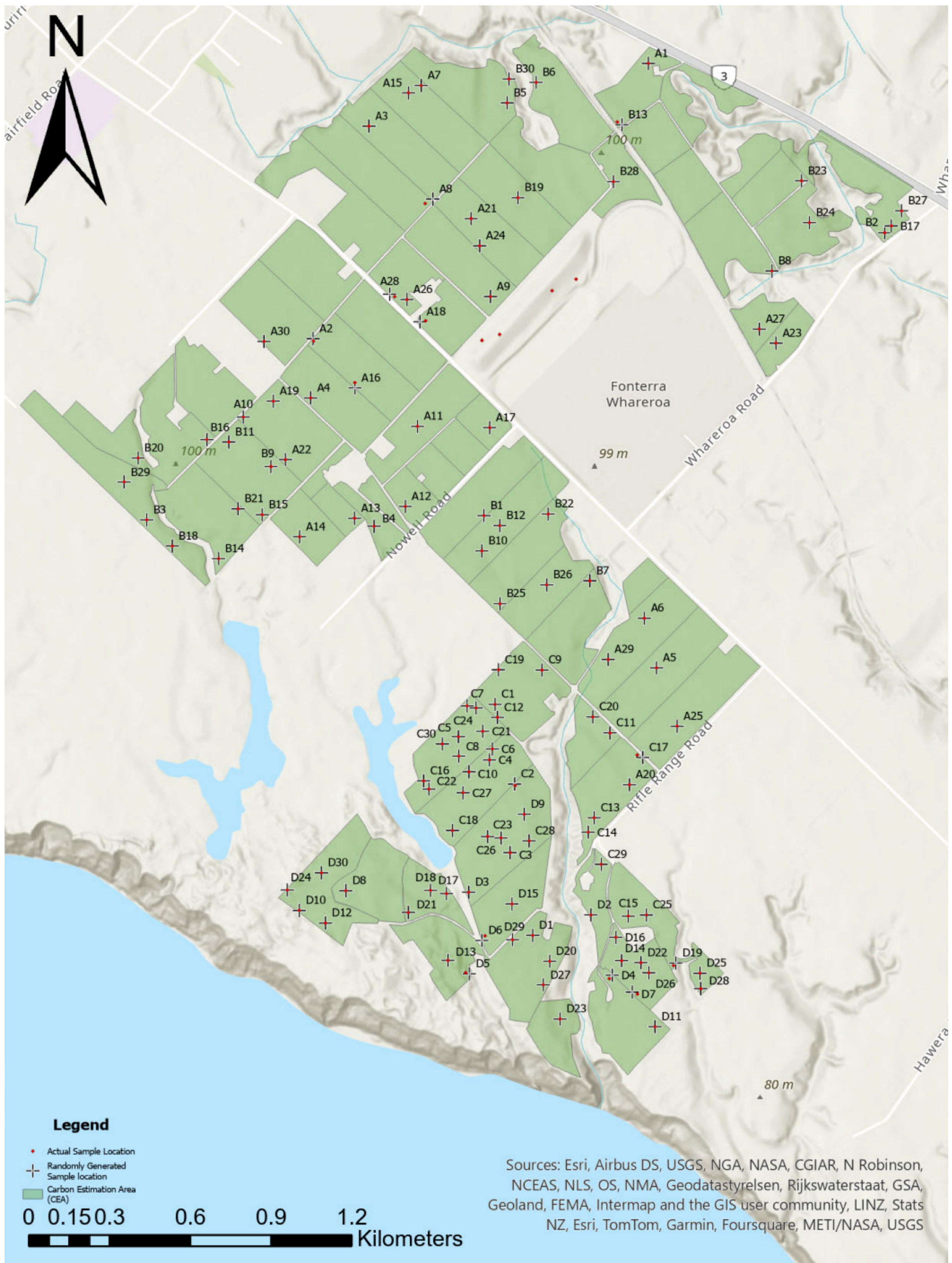


Figure 8: A map of all sample locations including the randomly generated location and the actual location according to the RTK GPS.

3.4 Soil carbon sampling

3.4.1 Sampling method

All cores were taken following the methods outlined in Australian Government (2021) and Mudge et al. (2020). This involved coring to a minimum depth of 30 cm using a corer with a cutting diameter of 4.2 cm to minimise any soil compaction. In this case, soils were cored to a depth of 60 cm by driving the corer in to the soil using a waratah rammer and then extracting using a jack. The core was then removed from the corer using a long pole, carefully pushing the core into a plastic half-pipe while minimising compaction of the sample. The corer was wiped out between samples using water, a cloth and a long pole. Once removed from the corer, cores were measured in their full length to check for any compaction during the removal process and then accurately cut into four 15 cm depths (0 – 15, 15 – 30, 30 – 45 and 45 – 60 cm) and placed into individually labelled bags and stored in a chilly bin and subsequently a chiller.

If issues were encountered during the sampling process, other tools were useful, including:

- A bung for the corer allowing for better suction to keep the core in the corer while removing it.
- A flat plank of wood to put beneath the jack, giving it a wider base of support on muddy or uneven ground.
- If soil was consistently getting stuck in the corer, the addition of more water to wash the inside of the corer was useful.

The depth increments were chosen to provide good insight into soil carbon dynamics deeper in the soil, particularly in the farms low carbon areas such as the coastal dunes. These depth increments also allowed for analysis to a depth of 30 cm which is standard in many soil carbon inventory frameworks (FAO, 2020; Australian Government, 2021; Mudge et al., 2020).

If the core was taken on a slope, it was sampled perpendicular to the soil surface and an inclinometer was used to record the angle of the core. When extracting the cores, it was very important to retain the full core volume in order to calculate bulk density. If the soil was stony, a different methodology such as quantitative pits or short cores must be used, but this wasn’t required in this case.

Alternative sampling methods

One limitation to the deep core method of sampling is that it isn't suitable for all soil types. Stony soils are problematic because the stones prevent the corer from being inserted into the soil. Soils which have poor aggregation properties are also problematic as they tend to fall apart and will crumble before the core can be cut to required depths. The result is that the volume of each section of the core cannot be ascertained with confidence, therefore bulk density and total SOCS cannot be accurately calculated. There are two alternative methods of sampling which mitigate these problems. They are however quite time consuming compared to the standard coring method. Specific details on the methodologies which are summarised below can be found in Hedley et al. (2012) and Davis et al. (2004).

Stony soils

For stony soils, the use of quantitative pits is employed. This involves excavating a pit of a known surface area and screening all soil material from the pit through a 10 mm sieve. This splits the soil material into particles >10 mm and particles <10 mm, each of which are weighed in the field. Following this, a homogenous sample of the <10 mm soil is collected to be analysed in the laboratory. Finally, the pit is lined with a plastic bag and then a known quantity a medium such as sand or water is poured into the pit, allowing the volume of the pit to be calculated.

Crumbly soils

Crumbly soils can be assessed using pits and short cores. This is where a pit is dug around a central area where a short core of ~10 cm is placed to extract a smaller sample which can be extracted in its entirety, ensuring that the volume of soil collected is accurate. The pit is continually dug deeper and short cores taken until soil is collected from the full depth.

3.4.2 Soil sampling equipment

A complete list of sampling equipment can be found in Appendix 3.

3.4.3 Sample storage

Samples were kept cool until they could be air dried. Air drying involved placing samples into a forced air oven at a temperature of up to a maximum of 40°C for four days. However, while it was expected that this would be sufficient drying time and samples appeared dry, a proportion of the soil samples did not fully dry, a situation which was discovered approximately 2 months later, prior to laboratory analysis. Given that it was possible that the incompletely dried soil samples may have measured some SOC loss due to microbial respiration during the storage period, a separate study was established to quantify any possible changes in SOC in the soil samples during this storage period. The method used in this study can be found in Appendix 4 and the results from this study are discussed in Chapter 5.

3.5 Sample processing and analysis

3.5.1 Sample processing

The protocol for sample processing and analysis is well documented and presented in Figure 9. First, the sample is crushed and sieved to separate out any stones and gravel which were greater than 2 mm in diameter. The mass of any gravel larger than 2 mm was weighed. Next, the sample was mixed thoroughly and then split into subsamples, one for soil carbon analysis and another as an archive sample. The soil carbon sample was then mixed thoroughly, and two more subsamples were created. One of these subsamples was further dried at 105°C until they were a constant mass, to calculate the water content while the other sample was finely ground and passed through a 0.5 mm sieve. This finely ground sample was analysed for total soil carbon using an Elementar Vario MACRO Cube CHNOS dry combustion analyser. Bulk density of the samples was calculated based on the sample mass, minus >2 mm gravel mass and then adjusting this sample mass by the moisture content of the sample. From here, the moisture adjusted sample mass was divided by the sample volume. The concentration of soil organic carbon in g C kg^{-1} soil and the bulk density in g soil cm^{-3} were then used to calculate the SOCS per hectare for each sampling depth required.

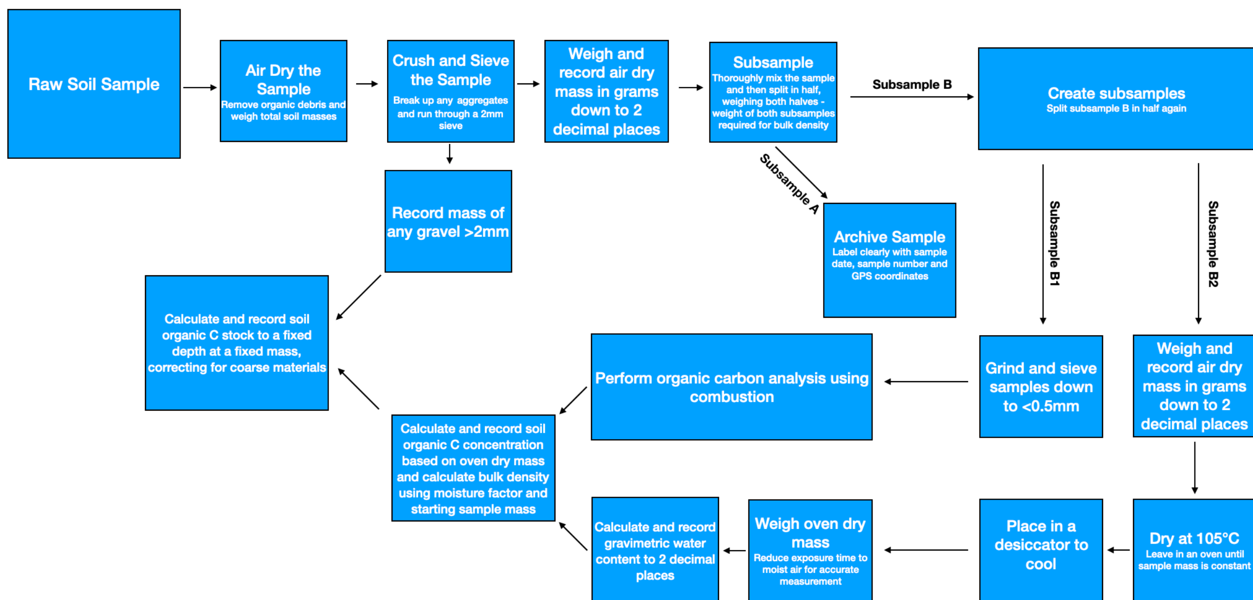


Figure 9: A process flow-chart based on the SOCS sample processing and analysis protocol outlined by Mudge et al., (2020).

3.5.2 Statistical analysis

RStudio version 2023.09.1+494 and R version 4.3.2 was used for the statistical analysis. A data summary was produced outlining the following values of the total SOCS values; minimum, 1st quartile, median, mean, 3rd quartile and maximum. Box and whisker plots were also created to express these values on a chart allowing easy comparison between the values for each soil strata. We performed a one-way F-test with ANOVA for all 4 strata to determine if there were any statistically significant differences between means. Following this, a Tukey test was performed to identify which strata pairs were significantly different. Finally, a post-hoc power analysis was performed to assess the statistical power of the differences between means. This was done using an online post-hoc power analysis tool (Kane, 2024).

The farm SOCS heat map was created using kriging through the geostatistical wizard in ArcGIS Pro version 3.1.2. The kriging method used was simple kriging with normal score transformation. An exact list of settings can be found in Appendix 2.

Determining the number of samples required for a SOCS benchmarking and monitoring survey is one of the key objectives of this study. A recommendation was made as part of this report, outlining the precise sampling methodology for the Kavanagh farm going forward. Since this study is effectively one large pilot study, more samples were taken than

were required. With the final data, a sensitivity analysis was performed to determine the degree of accuracy of the data collected. Since the existing soil strata were not satisfactory in their ability to reduce the number of samples, the strata were re-drawn to further optimise future sampling surveys as outlined in section 6.3.

Chapter 4 – Results and discussion

4.1 Soil organic carbon stocks benchmarking survey

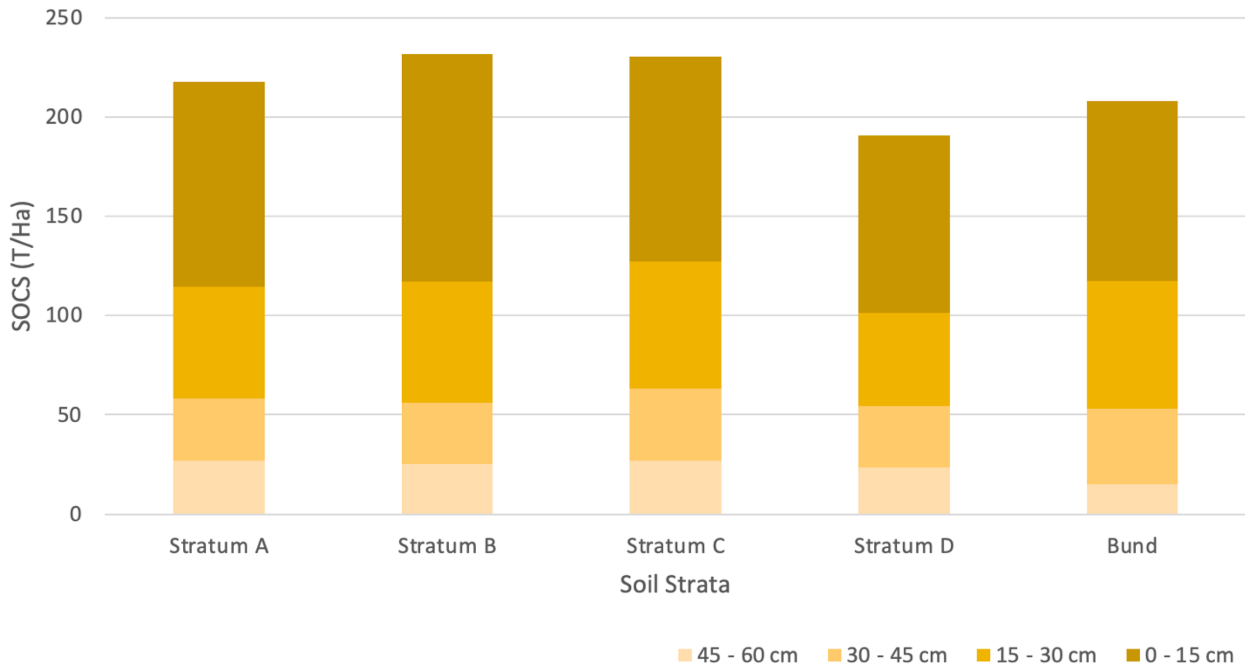


Figure 10: A stacked bar chart of the SOCS in each stratum broken down by depth.

Across all four strata, the Kavanagh farm had a weighted mean SOCS of 219.6 t C ha^{-1} down to a 60 cm depth. Strata A, B and C measured high SOCS, though stratum B was the highest at 231.8 t C ha^{-1}. Meanwhile, stratum D had the lowest average SOCS at 190.48 t C ha^{-1}. In terms of depth, unsurprisingly, the surface 15 cm of the soil made up the largest proportion of the total SOCS out of all of the depths, accounting for 47% of the total SOCS across all strata.

4.1.1 Spatial distribution of SOCS

A heat map displaying the distribution of the SOCS around the farm shows that the majority of the farm, which includes Egmont black loam soils and the hill soils, all have similar SOCS (Figure 11). Only the small pocket of black sand soil in the southwest of the farm has a substantially different SOCS from the rest of the farm.

A comparison of slope (Figure 4) and effluent (Figure 5) to the heap map (Figure 11), suggests that these variables do not explain the variation in SOCS across the farm. However, if we compare the heat map to the soil type and strata map, this suggests that

improvements can be made to the strata by redrawing their boundaries to better align them with the distribution of higher and lower areas of SOCS and with soil type.

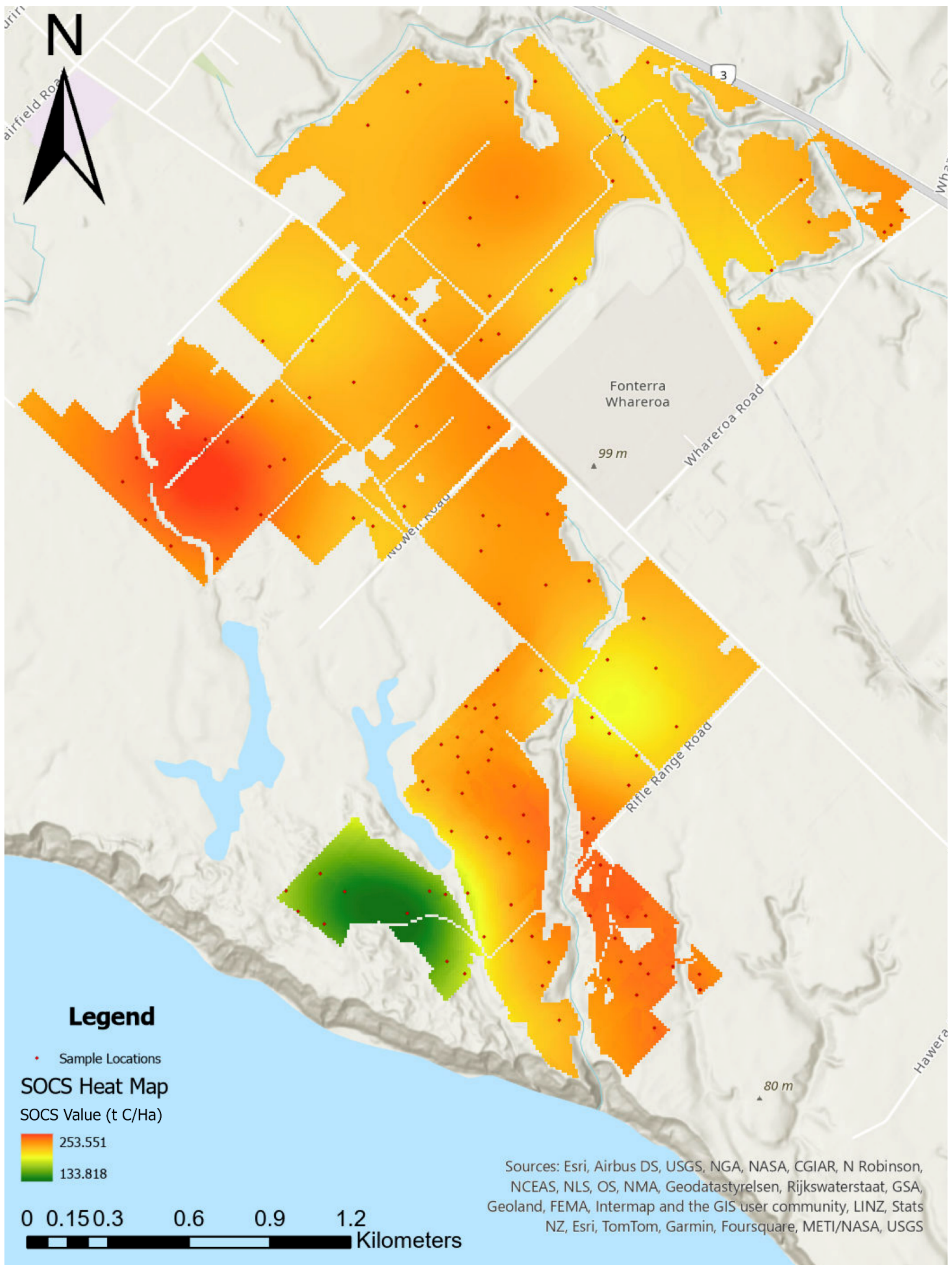


Figure 11: A heat map showing the distribution of SOCS to a depth of 60 cm throughout the farm.

4.1.2 Comparison of SOC for each stratum for 0 – 30 cm depth

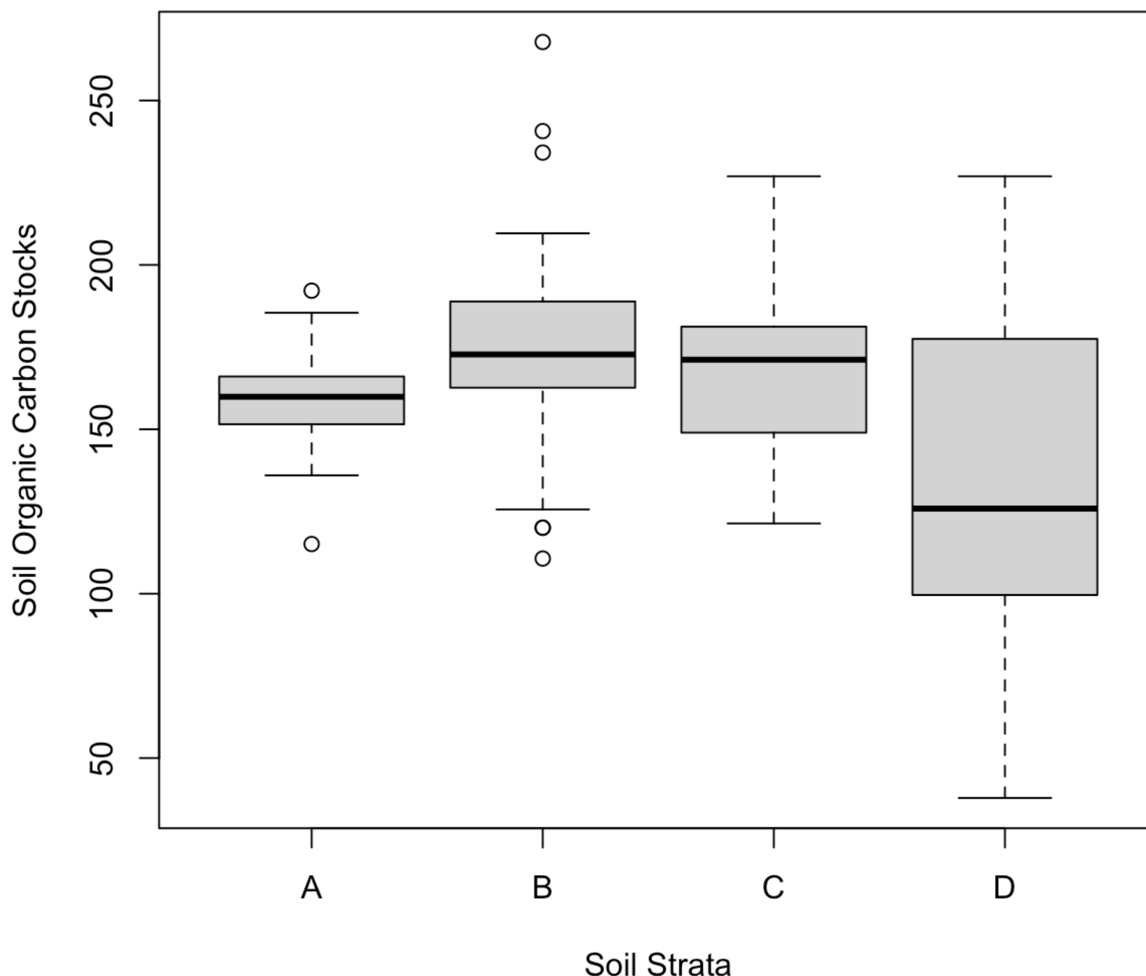


Figure 12: A box plot of SOCs sampled to a depth of 0 – 30 cm depth measured in each stratum.

When SOCS data from the surface 30 cm depth were combined, once again, stratum B had the highest SOCS at 175.49 t C ha^{-1} while stratum D had the lowest at 136.2 t C ha^{-1} (Figure 12). A t-test and Tukey test indicated that in the surface 30 cm there was a significant difference between stratum D and all other strata.

As anticipated, these results show that overall, the Kavanagh farm has very high SOCS compared to both the NZ average across land use and also to dairy farms in other parts of the country. Comparing the carbon stocks to a depth of 30 cm, with 162.14 t C ha^{-1}, the Kavanagh farm has 60% more SOCS than the nationwide average SOCS across all land uses of 98.7 t C ha^{-1} (Minasny et al., 2017).

4.1.3 Comparison of SOC for each stratum for the 0 – 60 cm depth

The box and whisker plot shown in Figure 13 shows the distribution of SOCS for the full 0 – 60 cm depth grouped by strata. This plot shows that the median SOCS in strata A, B and C are similar while stratum D has a larger range and has a lower SOCS content than the other strata. Based on the results of a Tukey test, median SOCS measured in strata D were significantly lower than the median of strata B and C, with P-values of 0.0094 and 0.0131 respectively. However, there was no significant difference between the median SOCS in stratum D compared to A (P = 0.1754).

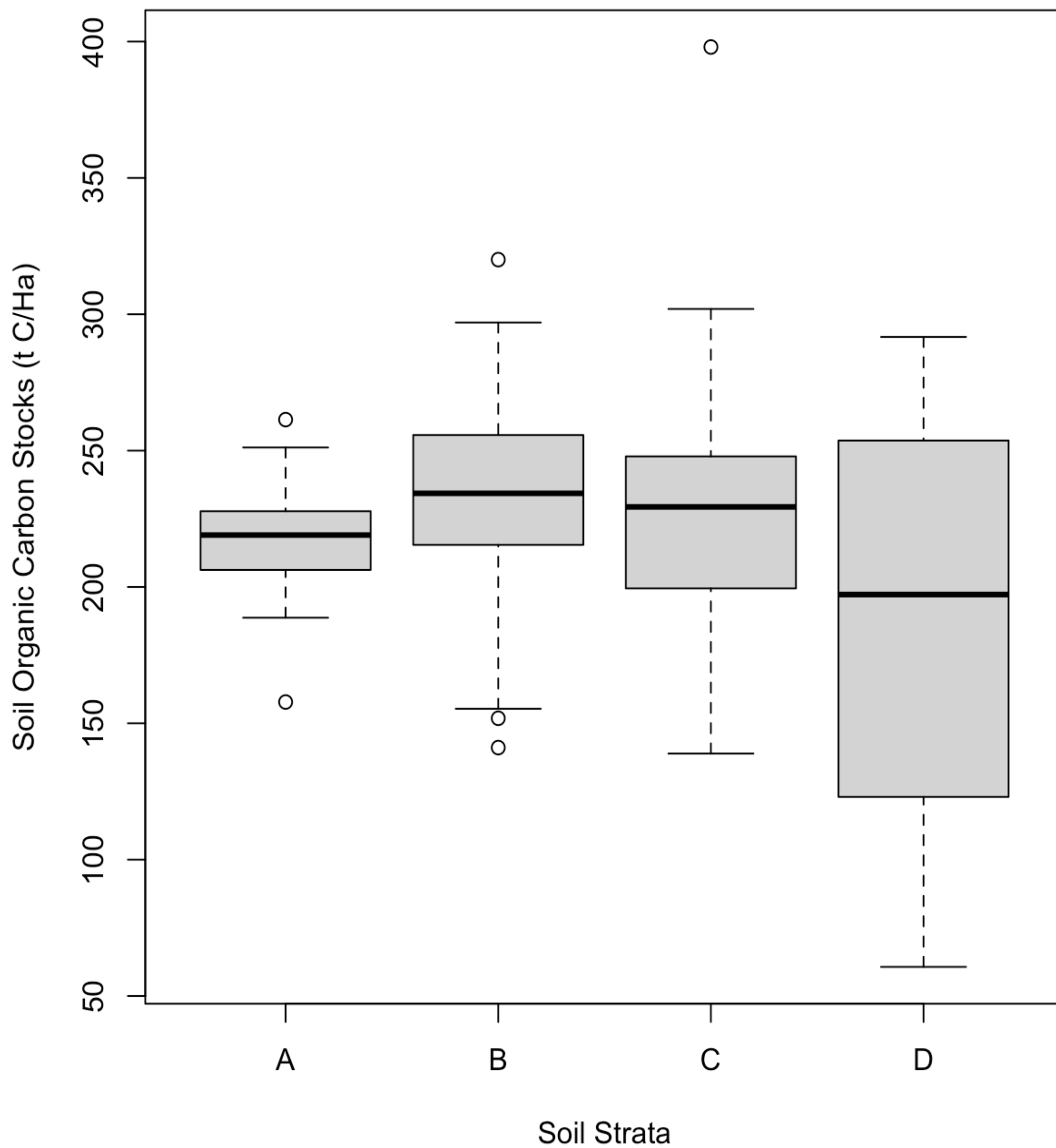


Figure 13: A box plot comparing the SOCS by strata (combined 0 – 60 cm depth).

Comparing the full 60 cm results to other NZ dairy farms once again shows that the Kavanagh farm has very high SOCS. Kavanagh's 219.57 t C ha^{-1} is significantly higher than the 173 t C ha^{-1} average found by a 2014 survey of 25 dairy farms in the Waikato by Barnett et al. (2014) This is despite the majority of the soils on these Waikato dairy farms also being Allophanic Soils.

Compared to other dairy farms in Taranaki, the carbon stocks on the Kavanagh farm are high. For reference, SOCS are ~7% higher than the 201.7 t C ha^{-1} of SOCS found on the DTT Waimate West farm which is situated 15 kilometres away between Okaiawa and Manaia on similar ring plain soils. Furthermore, the Waimate West farm doesn't have any low carbon reclaimed black sand soils like Kavanagh which pulls down the full farm average considerably. For reference, the SOCS data from the Waimate West farm is an average of 100 samples taken from 20 paddocks (5 cores per paddock) over the 43 ha farm. The only other dairy farm SOCS data we could find from the Taranaki region was provided by Kenneth and Rachel Short of Shortland Farms who run two dairy farms on two different sites in coastal South Taranaki. Their Oaonui farm and Opunake farm are 50 minutes and 30 minutes respectively northwest along the South Taranaki coastline from Hawera. Despite this, they have very similar soils to the Kavanagh farm with both farms being predominantly well to moderately draining dark brown loams derived from volcanic parent material. The average SOCS across both farms to a depth of 60 cm was 211.7 t C ha^{-1} as of January 2024, once again, slightly lower than the levels seen on the Kavanagh farm (Rachel Short, *pers. com.*, July 20, 2024).

A more detailed examination of different depths within each strata shows a difference between both 0 – 15 cm and 15 – 30 cm depths for strata D vs B and D vs C, much like the differences observed in Figure 13. However, at deeper depths, (30 – 45 cm and 45 – 60 cm) there are no significant differences between strata (Figure 14). This is a surprising result given that a large proportion of the cores in stratum D were almost entirely black sand which has significantly different properties to the Egmont black loam making up most of the other strata. Despite this, the impact of this different soil type is visible in Figure 13 where there is a large standard deviation as a result of a combination of both black sand and Egmont black loam being present in the stratum.

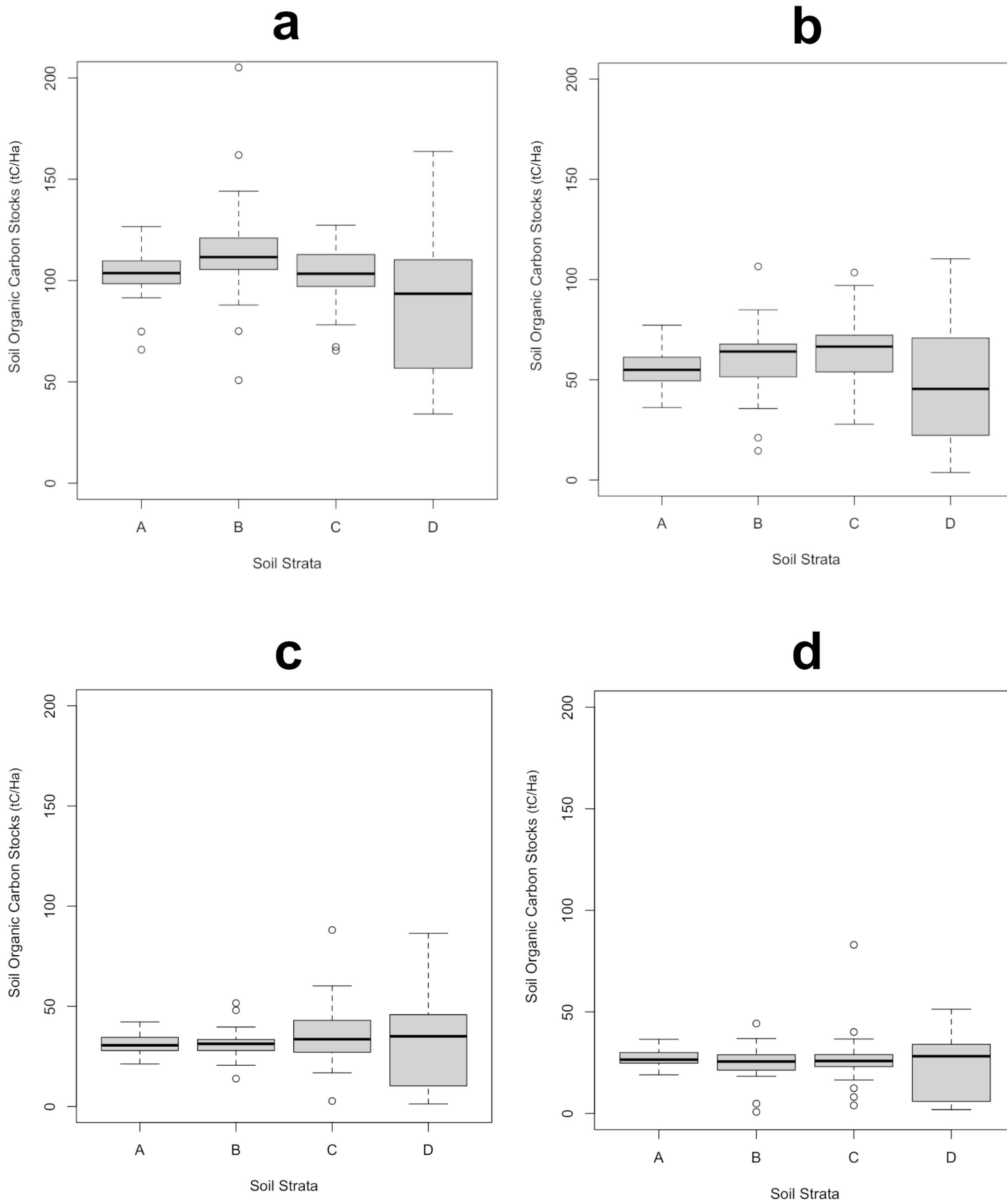


Figure 14: A boxplot comparing the SOCS by strata at different sample depths. a: 0 – 15 cm sampling depth. b: 15 – 30 cm sampling depth. c: 30 – 45 cm sampling depth. d: 45 – 60 cm sampling depth.

4.1.4 SOCS in the bund

Looking beyond the strata, it is worth analysing the data collected from the bund, the paddock with an anthropogenic soil on a large man-made bund to create a barrier from the neighbouring Whareroa dairy factory. This paddock was left out of the SOC survey due to the anthropogenic nature of this paddock being likely to be significantly different from the rest of the farm in unpredictable ways. However, comparing the data from the bund to the other strata shows that the bund largely conforms with the rest of the farm-wide data. The SOCS within the bund are just over 200 t C ha^{-1} and the depth distribution is largely the same with one notable exception. The 45 – 60 cm carbon stocks in the bund are a mere 58% of the farm-wide average SOCS at this depth. While this is almost certainly related to the anthropogenic nature of this soil, the exact reason for this low carbon content in this part of the soil is not clear. However, with just 4 samples at this depth, it is possible that variation between samples is having an effect.

4.2 Effectiveness of strata

A post-hoc power analysis was performed to assess the statistical power of the survey results to detect a difference between the soil strata for total SOCS to a depth of 60 cm. With only strata B and D and C and D being significantly different as identified by a Tukey test in section 4.1.3, we have already established that the initial stratification was ineffective at grouping areas of high and low SOCS together. Regardless, this power analysis will further assess the effectiveness of the initial stratification.

Table 1: A table displaying the statistical power for each pair of the initial strata to detect a significant difference. A post-hoc power of >80% indicates that the trial can detect a significant difference.

Strata	A + B	A + C	A + D	B + C	B + D	D + C
Post-Hoc Power	39.9%	28.1%	53.2%	3.4%	80.0%	74.2%

The results of this power analysis indicates that the only strata combination with enough statistical power to detect a significant difference between the two is strata B and D which has 80% statistical power, right on the 80% threshold of significance. All other strata combinations were below 80%, indicating that the strata were not drawn in an optimal way which grouped the areas of high and low SOCS.

Chapter 5 – Soil respiration experiment results and discussion

5.1 Data reliability

As discussed in section 3.4.3, there were concerns about a possible impact on the results due to some samples being incompletely dried. In theory, this may result in a loss of SOC in the sample while it was in storage ahead of the lab analysis. This chapter investigated this possibility by incubating the wettest samples with soil moisture content values ranging between 19.8 – 26.3%. The carbon respiration from these samples was measured and compared to the respiration of fully air dried subsamples from the same wet samples. The methods for this experiment can be found in Appendix 4.

The soil respiration method relies on the use of a blank jar to measure CO_2 emissions in the absence of soil. Unfortunately, it appeared that the blank jar used in this study had a leak as it required 16.75 mL of HCl to neutralise the remaining NaOH and this amount was higher than a significant number of jars with soil in them. In numerous previous experiments of the same design, the blank jar requires approximately 19.9 mL of HCl (Paramsothy Jeyakumar *pers. com.*). Therefore, we speculated that the blank jar was leaking, allowing atmospheric CO_2 into the jar during the experiment. There is also a chance that this issue affected other samples, but it is not possible to confirm this. Consequently, we have assigned a value for the blank of 19.9 mL based on extensive experience undertaking this experiment (Paramsothy Jeyakumar *pers. com.*). While we would ideally have preferred to investigate this further to determine the reliability of this data and further investigate respiration in stored samples, we were unable to do this within the duration of this study.

5.2 Sample Storage Respiration Experiment Results

The box plot in Figure 15 shows a significant variation within each of the four treatments. This is evident by the substantial overlap across each of the central quartile boxes. Furthermore, the range of values within each treatment is very large varying from 6.22 to 54.53 μg CO_2^{-1} g soil^{-1} day^{-1} in the dry (0 – 15 cm) samples and 16.77 to 71.04 μg CO_2^{-1} g soil^{-1} day^{-1} in the wet (0 – 15 cm) sample. The deep depths also have similarly large ranges from 12.49 to 72.77 μg CO_2^{-1} g soil^{-1} day^{-1} in the dry (45 – 60 cm) samples and 29.45 to 70.90 μg CO_2^{-1} g soil^{-1} day^{-1} in the wet (45 – 60 cm) sample.

The median values of the dry treatments (32.07 µg CO_2^{-1} g soil^{-1} day^{-1}) for both depths were not significantly different from the median values of the wet treatments, with the dry treatments having a median value of 32.07 (0 – 15 cm) and 41.57 (45 – 60 cm) and the wet treatments having medians of 33.11 (0 – 15 cm) and 54.43 (45 – 60 cm).

A Tukey test comparing the soil respiration means of all treatments indicated that neither pair of wet and dry samples from the same depth were significantly different from one another (P = 0.36). This suggests that there is no difference in respiration between the wet and dry samples. Consequently, it is unlikely that there is a discrepancy between the measured SOCS and the actual SOCS in the field for the improperly dried soil samples.

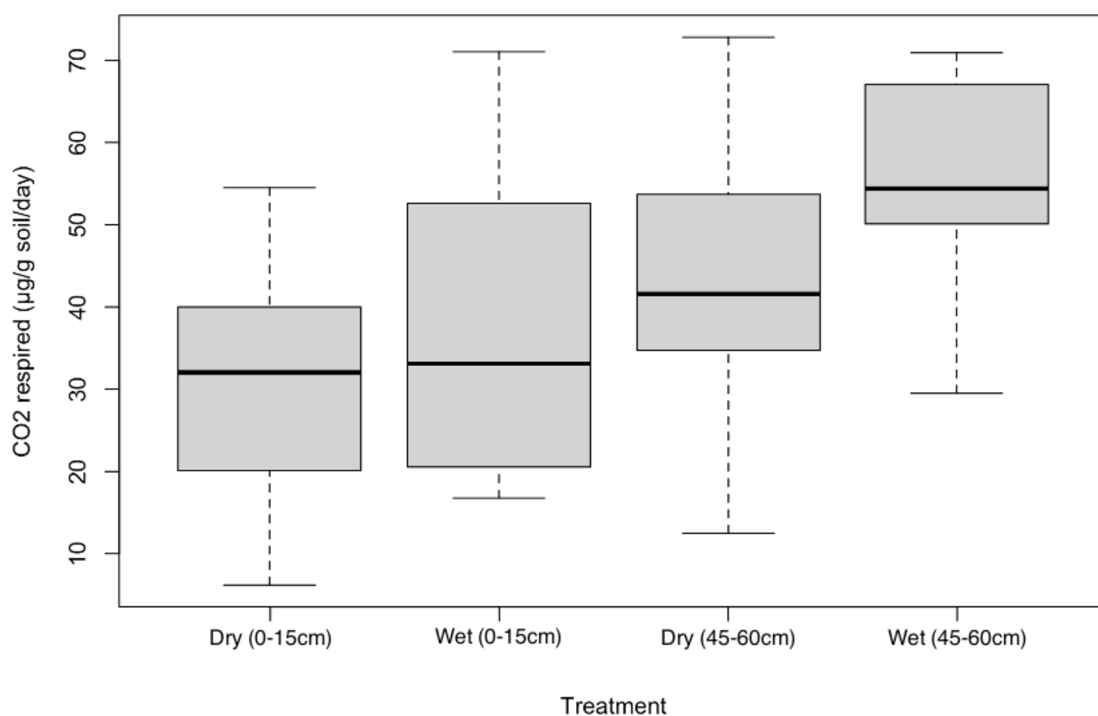


Figure 15: A box plot comparing the amount of CO_2 respired by soil in different treatments in the sample storage respiration trial.

Despite this finding, the average quantity of carbon respired per gram of soil per day in this experiment (including both wet and dry samples) translates to a potential loss of 0.73 t C ha^{-1} in the top 0 – 15 cm soil and 1.03 t C ha^{-1} in the 45 – 60 cm of soil. Extrapolating linearly between these values estimates carbon losses in the 15 – 30 cm and 30 – 45 cm depths to be ~0.83 and 0.93 t C ha^{-1} respectively. This could lead to a total loss of 3.52 t C ha^{-1} over the full sampling depth due to respiration of the samples before analysis, meaning that in-field carbon content is possibly about 1.6% higher than this benchmarking study indicates. Since the carbon loss occurred in both the wet and dry soils equally, there

is no reason to suspect that some samples were affected more than others. This carbon loss occurred while following standard practice, so if real, has the potential to also impact other soil carbon benchmarking surveys. This finding questions our long-held assumption that air drying soils completely suspends carbon respiration and highlights the need for future studies to explore this issue in more detail.

Assuming that the data collected in this experiment is accurate, it suggests that the carbon loss during the sampling and analysis process is relatively low at ~1.6%. Consequently, we believe that the respiration of carbon while samples were in storage had minimal impact on the results of this current carbon benchmarking study on Allophanic soils.

Chapter 6 – General discussion

6.1 Rationale for revised strata

With one of the largest limiting factors of SOCS benchmarking being the cost and labour required for sample collection and analysis (Mudge et al., 2020), it is important that the benchmarking and monitoring system is optimally designed to minimise cost by reducing the number of samples needed for a desired degree of accuracy. As previously outlined, the most effective way to do this is using stratification (de Gruijter et al., 2018). However, stratification requires having a good understanding of the distribution of SOCS throughout the farm before drawing the strata and in this case, the preliminary data available prior to this current benchmarking was lacking. Furthermore, the results have shown little difference between most of the strata, indicating that the initial stratification did not effectively differentiate between the areas of low and high SOCS. Even the stratum which did show a difference, stratum D, measured a large range and standard deviation (Table 5C, Appendix 5), suggesting that the targeted low soil carbon area was poorly defined by the strata borders. Because of this, it is recommended that for future soil carbon surveys, the strata be redrawn using the recently collected SOCS data.

The following section of this report outlines the methods used to develop the revised strata, summarises the revised strata and quantifies the efficacy of the revised strata if they are to be used going forward. The rationale for stratification and grouping areas of higher and lower SOCS together is to reduce the number of samples required to attain an accurate estimate of SOCS on the farm (de Gruijter et al., 2018). If the initial stratification did not group these areas effectively then it is best to revise them.

6.2 Method for revising strata

With new data from the benchmarking survey, the strata were able to be redrawn with a much greater degree of precision than with the preliminary data at the beginning of the study. Using the kriging heat map produced with the survey data, the heat map was converted into a raster. Then the data were grouped into four zones using a “natural breaks” selection which uses an algorithm to identify groups of similar value. From here, a manual comparison of the new strata based on the heat map was reviewed and compared with the other ancillary variables such as soil type and slope. This allows the manual cleaning of the heat map based strata to better align with the likely reality of the SOCS on

the farm, since outliers and random variability can have an outsized influence on the soil heat map.

Once the new proposed strata were drawn, sample data were grouped with the new strata and another sensitivity analysis was performed. This allowed quantification of the improvement that was achieved by redrawing the strata. Finally, the 95% confidence intervals for the mean of all iterations of the strata (no strata, first strata and redrawn strata) were compared to quantify the efficacy of stratifying the farm. The calculations involved in this process are outlined in Appendix 1. From there, the best version of stratification was adopted and the number of samples required for future surveys to be able to detect a change of a certain size between surveys (were one to occur) also known as a minimum detectable difference (MDD) was calculated.

6.3 Proposed revised strata

The strata were redrawn using a combination of the farm SOCS heat map (Figure 11) and then manually adjusting strata borders to align with other ancillary variables such as soil type, paddock boundaries and slope. The number of strata is determined based on how much the marginal stratum that is added reduces the standard variation of the dataset. In this case, full calculations were unable to be made due to time constraints. However, the optimal number of four strata was approximated by comparing the distribution of the data under different number of strata in ArcGIS.

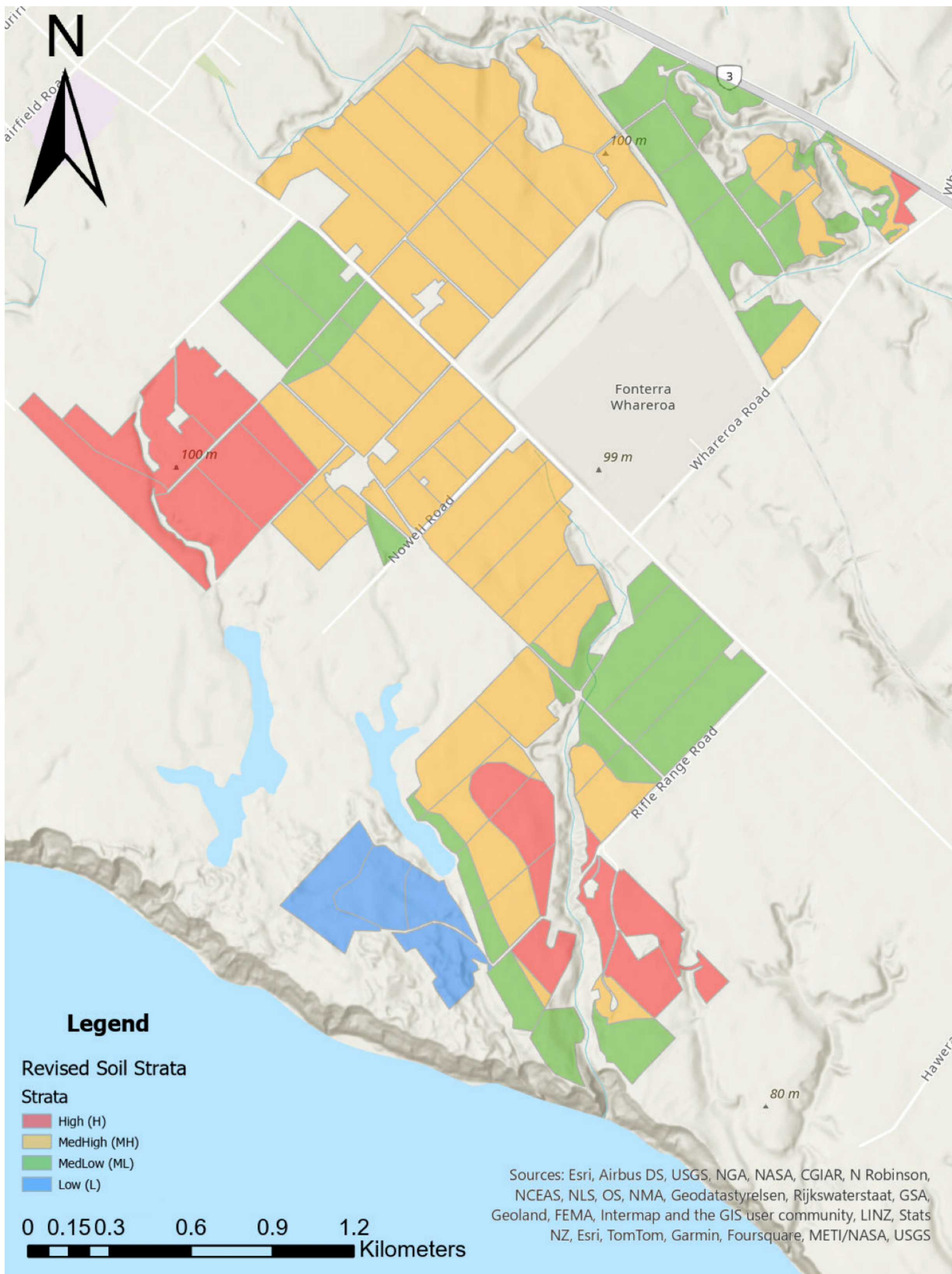


Figure 16: A map of the revised SOCS strata. The revised strata grouped areas of the farm into low SOCS (L), medium-low SOCS (ML), medium-high SOCS (MH) and high SOCS (H) based on the initial benchmarking survey and the farm soil map.

These new strata separate the areas of high and low SOCS more effectively (Figure 16) with each stratum being significantly ($P < 0.0001$) different from each other. This is a

material improvement over the initial strata where a significant difference was only found between just two strata combinations. This more effective stratification is due to a better alignment with soil type and topographical changes on the farm compared to the previous strata. Specifically, stratum A primarily encompasses the flat sections of the Egmont black loam soil with the highest SOCS, though some very small sections are located on steeper rolling slopes around paddock boundaries. Stratum B has a combination of flat Egmont black loam soil and a small amount of slightly rolling land. It generally encompasses a second tier of SOCS through the centre of the farm which are lower than the SOCS found in stratum A. Stratum C contains a mixture of steeper slopes, hill soils and Egmont black loam soil on flat land with the lowest SOCS associated with this soil type. Finally, stratum D strictly encompasses the Patea black sand soils which have varying topography.

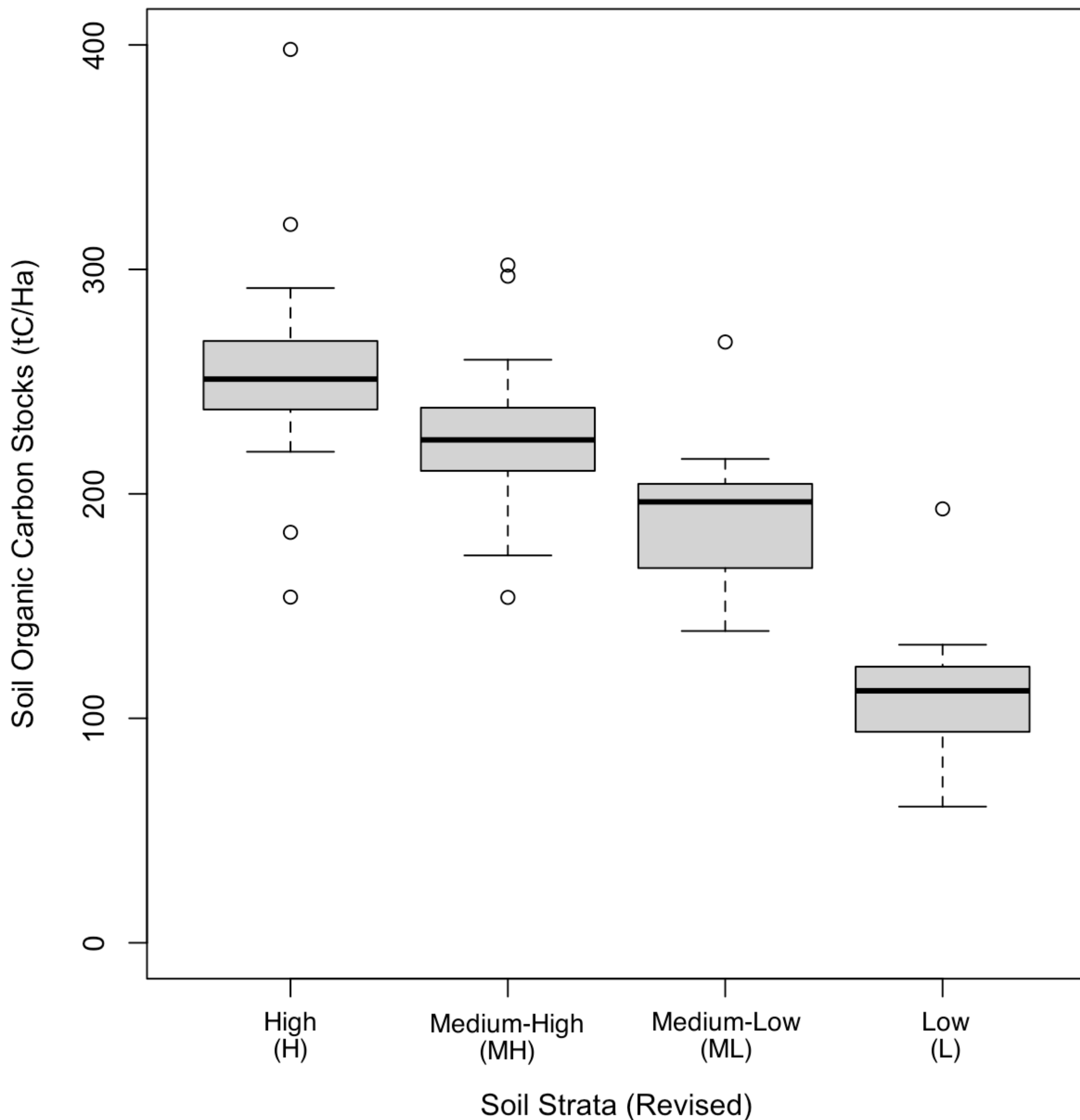


Figure 17: Box plot comparing the SOCS of the revised strata from 0 – 60 cm. H: High SOCS strata. MH: Medium-high SOCS strata. ML: Medium-low SOCS strata. L: Low SOCS strata.

It is important to quantify the impact the revised strata have on the confidence interval of the mean and the MDD of the data set. This is because the desired degree of accuracy determines the number of samples required for ongoing SOCS monitoring. MDD is calculated using equation 5 from Appendix 1 (FAO, 2020).

$$MDD \geq (S/\sqrt{n})*(t\alpha+t\beta) \qquad \text{Equation 5}$$

Where:

MDD = The desired MDD

S = Standard deviation of the change in SOCS at all static sampling locations between two surveys

n = Number of sample cores (sample locations)

t_α = is the two-sided critical value of the t-distribution at a given significance level (α). In this example α = 0.05

t_β = the one-sided quartile of the t-distribution corresponding to a probability of type II error β (being 1 − β the statistical power). In this example, β = 0.8 or 80%.

The FAO equation for calculating the MDD uses the standard deviation of the change in SOCS observed at each static sampling site between two surveys (S). The standard deviation of the change in SOCS at sampling points captures short-range spatial variability measurement error and the variability of any changes in SOCS. However, since data are only available for Kavanagh's benchmarking survey, data for changes in SOCS are not available to input into the MDD equation. Instead, the pooled standard deviation of the SOCS values across all strata (S_p) which is calculated in Appendix 1 has been used. This should be a conservative estimate as the standard deviation of the change in SOCS at sampling sites between two surveys is unlikely to exceed the pooled standard deviation of SOCS across all strata. This therefore means that this initial estimation of the MDD should be an upper bound. Upon conducting the next SOCS survey with the same static sampling sites, the MDD should be recalculated inputting S into the MDD equation where S_p was input for this initial estimate. This will likely result in a smaller and more precise MDD value which will allow future surveys to be further optimised for cost effectiveness and accuracy.

Table 2: A table comparing the means, confidence intervals and minimum detectable difference for both iterations of the stratification and the unstratified data. SOC stock values are cumulative to 60 cm. All values in this table were calculated using the method

	No Stratification		Initial Strata		Revised Strata	
95% Confidence Intervals (t C ha^{-1})	Lower	Upper	Lower	Upper	Lower	Upper
	204.65	230.43	209.15	230.04	211.35	227.84
Mean (t C ha^{-1})	217.54		219.60		N/A	
Confidence Interval Range (t C ha^{-1})	25.78		20.89		16.49	
Minimum Detectable Difference (t C ha^{-1})	12.89		10.44		8.25	
MDD (% of mean)	5.93%		4.76%		3.75%	

Table 2 shows that the revised strata substantially decreases the MDD in the dataset when compared to no stratification, with the MDD decreasing from 12.89 t C ha^{-1} to 8.25 t C ha^{-1}.

The improvement over the initial strata is also substantial, reducing the MDD from 10.44 t C ha^{-1} in the initial strata to 8.25 t C ha^{-1} in the revised strata. Another way of quantifying this difference is by comparing the number of samples required to attain the same 8.25 t C ha^{-1} MDD if stratification was not used. In this scenario, a total of 293 cores would be required instead of the current 120 cores (calculated using equation 6 from Appendix 1). Strictly based on sample analysis costs at commercial rates (excluding labour for taking and processing samples which can be another 50% – 100% added to the total cost), not stratifying the farm would add an extra $21,798 to the cost of undertaking a benchmarking survey.

It is worth highlighting the effectiveness of revising the strata in this example. Using the revised strata going forwards will increase survey accuracy by 21%. This is of substantial benefit to the farm through reduced sampling costs. The ability to make an adjustment like this is a considerable advantage to performing a larger survey and not bulking samples for the initial benchmarking.

6.4 Survey accuracy

The final part of the analysis involves determining the number of samples required to achieve different thresholds of data accuracy. The goal of this study is to propose a SOCS benchmarking and monitoring system for the DTT team. However, one of the biggest factors in the decision-making process is cost and the optimal budget for their monitoring system is unknown. Consequently, the best recommendation would be one which has multiple different options for the team to choose from to allow them to optimise their system to fit their needs. Such an approach was also recommended by Mudge et al. (2020) who stated the following:

> *[Regarding the desired survey accuracy]... "This can only be determined by the landowner/manager, but as a general rule, we believe that designing a system whereby repeat measurements of SOCS could detect a change of 2–5% (should such a change occur) would be a good starting point. A 2–5% change in SOC corresponds to a change of about 2 or 5 Mg.ha^{-1} for the top 30 cm of New Zealand's agricultural soils."*

Table 3: The number of sample cores required to attain a corresponding minimum detectable difference along with the optimal distributions of cores across the strata.

	MDD (t C Ha)	Total # of cores required	Number of cores required in each stratum				Estimated laboratory analysis costs	Estimated labour hours of sampling in field	Estimated labour hours of sample processing
			High	Medium-High	Medium-Low	Low			
2t C/Ha sensitivity	2	2039	474	898	526	141	$ 256,975.10	1530	1122
2% sensitivity	4.39	423	98	186	109	29	$ 53,289.86	317	233
5t C/Ha sensitivity	5	326	76	144	84	23	$ 41,116.02	245	179
5% sensitivity	10.98	68	16	30	17	25	$ 8,526.38	51	37
Current # of cores	8.25	120	28	53	31	8	$ 15,120.00	90	66

The estimated cost of the laboratory analysis shown does not include sample preparation and is based on September 2023 pricing at a commercial laboratory (Hill Laboratories, *pers. com*., September, 2023). The estimated labour hours for taking samples from the field are also included but this could vary by 50% or more depending on soil type, farm size and accessibility and field technician expertise. The estimated labour hours for sample processing includes drying, weighing, grinding, splitting and measuring moisture content.

Consequently, a range of MDD thresholds have been calculated based on this guidance. These include; a 5% change, a 5 t C ha^{-1} change, a 2% change, a 2 t C ha^{-1} change. A status quo 120 core survey was also included for reference. Additionally, a chart depicting the number of samples required to attain a desired MDD for a sampling survey on the Kavanagh farm has been created in case DTT wish to pick a different MDD threshold to the ones listed above (Figure 18).

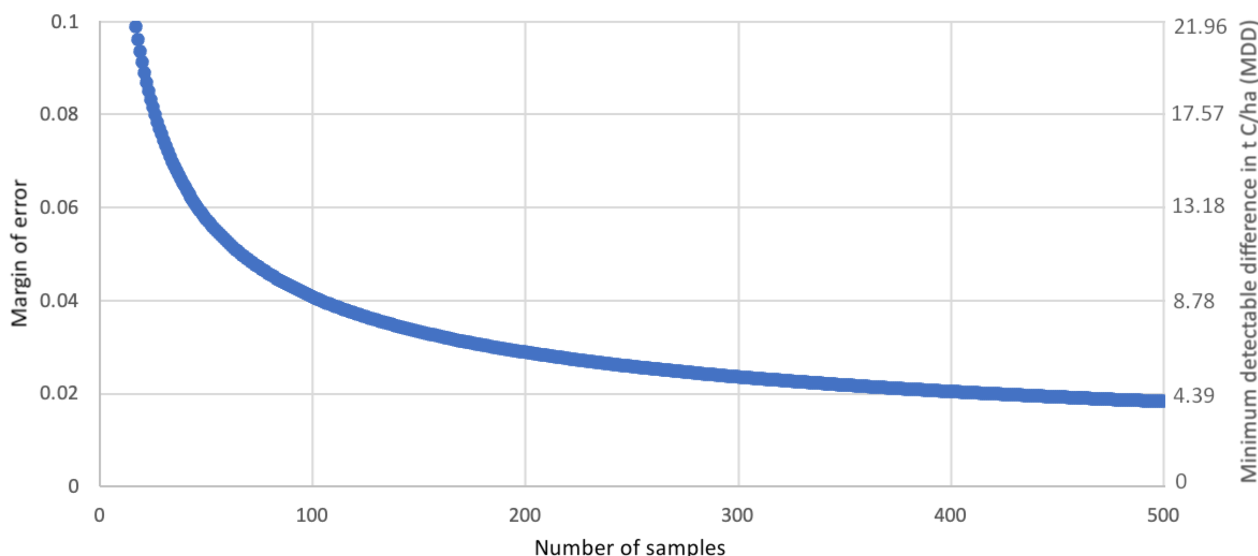


Figure 18: A chart depicting the number of samples required to attain a desired margin of error for a sampling survey on the Kavanagh farm. This curve will vary from farm to farm due to a different standard deviation in the dataset. This curve was calculated using equation 5 in Appendix 1 using the value S_p and it should be updated after future surveys to use S once the value of S is known.

The results in Table 3 show the number of sample cores required for these different MDD thresholds. Based on this, depending on DTT's budget, they may wish to go with the 5% sensitivity option or maintain the current number of 120 samples for an MDD of 8.25 t C ha^{-1}. Going one threshold higher in terms of accuracy is the 5 t C ha^{-1} threshold which would require an impractical and expensive 326 sample cores per survey. If no sample bulking strategy was used, this would result in 1,304 samples being analysed in a laboratory.

Finally, with the number of samples determined, the last step is to distribute the samples into the strata where they will be most effective. This is achieved by using a method known as a Neyman allocation which is outlined in Appendix 1. This distributes the total number of samples optimally between all the different strata to achieve the greatest impact on accuracy from each additional core sampled. This is done by allocating more cores to strata with a larger percentage of the total land area of the farm, as well as to strata with a higher standard deviation between cores. These numbers are displayed in Table 3 in the "Number of cores required in each stratum" columns.

6.5 Building the optimal ongoing SOCS monitoring system

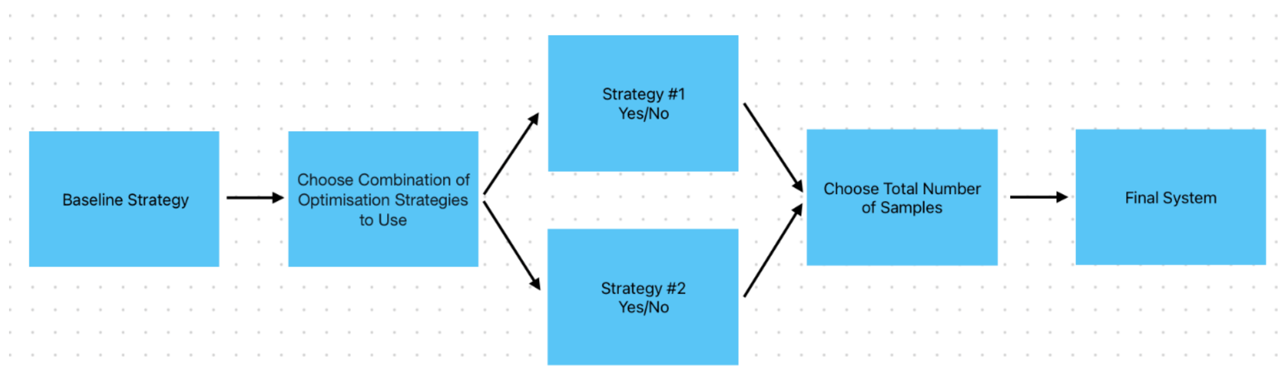


Figure 19: A flow chart outlining a decision-making framework to determine the optimal SOC survey approach for Kavanagh farm.

The SOCS monitoring system which best suits the Kavanagh farm going forward will be dependent on DTT's priorities and budget for soil carbon monitoring. Therefore, the following section of this study will outline the variables in system design which have already been determined and are not recommended to be changed. Following this, variables which may change to account for DTT's specific needs will be outlined and the

strategies behind these changes along with their advantages and disadvantages will be discussed.

While this study will not provide a specific recommendation for a future SOCS monitoring system to be used on the Kavanagh farm, this section does provide a framework with clear guidance to allow DTT to quickly and easily find a solution which is optimised for their needs. In the section below, a baseline strategy has been recommended which can then be modified using any combination of two strategies designed to optimise this system to meet DTT's priorities. Finally, the system they select can then be appropriately scaled to the desired degree of accuracy and the desired budget of the project by selecting the total number of samples that they will take with each survey, as outlined in Figure 18.

6.5.1 Variables to be kept consistent

Based on the initial Kavanagh farm SOCS benchmarking survey, existing SOCS benchmarking and monitoring standards, and established scientific evidence, the following variables will be required in any future farm SOCS survey.

Stratified random sampling and static synchronous sampling

While other methods such as grid based or systematic sampling do exist, stratified random sampling is easier to establish and is, in most cases, superior and has been strongly recommended by FAO (2020); Australian Government et al. (2021) and Mudge et al. (2020). This method is used to generate the sample locations for the first benchmarking, and static synchronous sampling means that ongoing monitoring surveys resample positions close to but in a random direction from the original sites. This approach results in the lowest number of sampling sites to detect how SOCS on the farm change over time (de Gruijter et al., 2018).

Stratification

The statistical analysis performed on the Kavanagh farm SOCS benchmarking survey has demonstrated that the redrawn strata will improve the accuracy of future surveys and should be adopted.

Sampling depth

The 60 cm depth with four 15 cm increments depth used in the initial survey has been successful and has provided insight into the distribution of soil carbon at different depths while also allowing the data to be compared to the standard depth on 30 cm (FAO, 2020; Australian Government, 2021 and Mudge et al. 2020). This approach achieved the desirable balance of measuring key depths associated with standard approaches, whilst minimising cost.

Time of sampling

For accurate assessment of SOCS over time, it is critical that the surveys are done at a similar time of year to avoid any potential seasonal changes in SOC and to ensure soil conditions (particularly moisture) are similar between samplings as this could lead to differences in how soils are extracted from the corer. Because of this, the FAO, (2020) recommends ensuring that the median calendar day of the sample taking process is no more than a month away from the median calendar day of the original survey. For reference, the median day of this benchmarking survey was the 3rd of September, so all future surveys should have a median day between the 3rd of August and the 3rd of October.

6.5.2 Variables to be changed

Total number of samples

The total number of soil cores can be changed to optimise the balance between the cost of a SOCS survey and the accuracy of the data collected (Table 3). A graph showing the number of samples required to attain a desired MDD is outlined in Figure 18. If the estimated price per sample of a survey is known, then that can be added to the x axis of Figure 18 to help with the decision-making process.

Frequency of ongoing monitoring surveys

There is no single standard for the frequency of monitoring surveys. Generally, they are performed every 1-5 years (Mudge et al., 2020) but they can vary in frequency depending on the goals of the farm. The FAO SOCS protocol recommends repeating SOCS surveys every four years as a minimum and while the Australian soil carbon protocol doesn’t specify a time frame, it does recommend a maximum time between surveys of 5 years (FAO, 2020; Australian Government, 2021).

Sample bulking

Sample bulking is an effective way of significantly reducing the number of samples needed to accurately represent the overall SOCS of the farm. However, the trade-off is that the ability to precisely map soil carbon throughout the farm is compromised. This could be an issue if DTT wish to use some of the SOCS cores sampled in the initial survey to examine the effects of different management treatments over time, or if they wish to further investigate the spatial distribution of SOCS beyond this initial survey. Therefore, this decision is best made by DTT themselves.

6.5.3 Baseline strategy: regular stratified sampling

This strategy is the simplest and most conventional approach to SOCS monitoring. This system utilises stratified simple random sampling where there are a specified number of samples in specific locations that are resampled no more than 5 m away from the site of the previous sample in each successive survey. Based on guidance from FAO (2020), surveys should be undertaken every 4 years to track SOCS changes with a moderate frequency, giving more insight into shorter term changes on the farm but minimising the cost and labour associated with more intensive annual or biennial surveys.

This baseline system attempts to find a middle ground between the range of established sample system designs and remains flexible if changes need to be made in the future. For example, by not bulking samples and leaving successive survey locations static (static synchronous sampling), it is easier to later change farm strata or to compare two sections of the farm which may have been under different management regimes. However, this system can be further optimised to make trade-offs in exchange for a cheaper or more accurate survey. These options are outlined in the next two sections.

6.5.4 Optimisation strategy #1: less frequent, higher precision sampling surveys

This strategy involves reducing the frequency of the ongoing monitoring surveys from once every 4 years to once every 5 years. Compared to the baseline sampling system, this would allow for about 25% more samples to be taken for the same cost, or for sampling cost to be reduced by 20% for the same degree of accuracy. This means that for the same

expense, rather than taking 120 samples every 4 years for an MDD of 8.25 t C ha^{-1} (Figure 18), instead, 150 samples could be taken every 5 years to achieve an MDD of 7.38 t C ha^{-1}. This improves the confidence interval for detecting longer term changes in SOCS on the farm. However, the disadvantage to this strategy is that there is less information on how the SOCS are changing on a shorter time frame, so more dynamic SOCS changes may be missed. Furthermore, there will be a larger impact of any variation in a survey which might be caused by extreme seasonal weather patterns or other short term SOCS changes which aren't representative of long-term changes occurring. This is because the surveys are less frequent and therefore, one single survey can have more influence over how the long-term SOCS trend appears.

6.5.5 Optimisation strategy #2: sample bulking

This strategy offers significant cost savings at the expense of losing a lot of data flexibility. Depending on the number of samples in each composite sample (typically 3 – 10), the cost savings are due to a reduction in laboratory analysis costs of 66 – 90%. This is substantial since laboratory analysis costs in this benchmarking survey were approximately 55 – 75% of the total cost of sampling. In total, that could see a full cost reduction of the monitoring survey in the range of 36 – 70%. Such a saving could also allow more samples in total to be analysed for the same price, significantly reducing the MDD for the total SOCS within the dataset.

Unfortunately, this substantial cost saving also comes with numerous disadvantages. Starting with increasing technical limitations that bulking the samples creates. With bulking, the strata can no longer be changed or further revised without starting over with another benchmarking survey and new sampling locations (Mudge et al., 2020). Secondly, data from the same individual sample sites can no longer be used to calculate the MDD as accurately as possible. Without an accurate MDD calculation, the total number of samples required can't be optimised quite as precisely (FAO, 2020). Third, there is a greater risk of error introduced during the laboratory analysis (de Gruijter et al., 2018). Finally, and most importantly, bulked samples provide no insight into the spatial distribution of SOCS, nor can specific sample locations be referenced to provide the SOCS at a specific location. Since samples are mixed before analysis, data can only be referenced on a strata wide basis or as the average across a group of all samples in the same composite. This also means that features from this analysis such as the SOCS heat map of the farm could not

be updated with subsequent surveys. Consequently, the data couldn't be used to identify how different management practices might influence SOCS. However, if any future research studies that might influence soil carbon were conducted on the farm, it would be advisable that SOCS measurements be taken specifically for that study area, separate from the ongoing SOCS monitoring system, although some alignment may be possible and desirable.

With everything considered, bulking is an effective option for reducing costs on the condition that no future stratification changes are to be made and if the primary goal of the project is simply to assess total SOCS and not the spatial distribution of SOCS. Given that the strata for this farm have been redrawn to optimise future sampling strategies (Figure 16), it is unlikely that they will need to be revised any further. Consequently, if the DTT team want to prioritise cost effectiveness and accuracy per dollar spent on measuring SOCS and they don't require data on spatial distribution of SOCS for Kavanagh farm, then sample bulking is advisable.

6.5.6 Number of samples

The final step required to plan the ongoing SOCS monitoring system is to decide on the total number of samples required. There are two ways from which DTT can calculate the number of samples they need to use. These are:

- Decide on a budget
- Decide on a desired MDD

Deciding on a budget

For this method, we recommend that the cost of sampling is quantified through expected labour hours and laboratory costs on a per sample basis. From there, it is quite simple to divide the budget by the cost per sample to determine the number of samples that can be afforded. If sample bulking is used, then the laboratory analysis costs will be significantly reduced.

The challenge with this method is that the cost of taking one sample is hard to estimate as it depends on how fast the field technician takes the samples, their pay rate and if sample

preparation is done in-house or at the commercial laboratory. For reference, this benchmarking study took approximately 80 – 110 hours to take all 124 cores from the field using a manual coring system, and to divide them into 4 different depths to then air dry the 496 samples. However, this can be substantially faster or slower depending on the tools and experience of the field technician. Following this, sample preparation (grinding, splitting, bagging and weighing) took a further 60 – 80 hours. This can be done by commercial laboratories, but it costs an extra ~$8.80 per sample as per a 2023 price quote from Hill Laboratories in Hamilton. Finally, at the time of the benchmarking survey (September 2023), the price of soil carbon analysis for one sample was $31.50 per sample (pre-dried and ground) and $40.30 per sample including sample preparation (drying and grinding) but excluding moisture content measurements.

Once the number of sample cores (total number of samples ÷ 4 samples per core) has been determined based on budget, it would be prudent to calculate the corresponding MDD which this number of samples provides to ensure that it is sufficient to detect a minimum threshold of accuracy (2 – 5% of total SOCS). This can be done using equation 5 from Appendix 1 (FAO, 2020). Note, the number of sample cores in this calculation is 1/4th of the number of total samples since there are 4 different depths in each core which are analysed individually. Hence there are 4 samples per core.

Deciding on a minimum detectable difference

The other way to determine the number of samples required is by deciding on a specific MDD in order to detect a change in SOCS of a specific minimum size, were such a change to occur. Mudge et al. (2020) recommends aiming to detect a 2 – 5% change, should one occur. This would equate to an MDD of 4.39 – 10.98 t C ha^{-1}. If surveys were done every 5 years, then a change of 0.88 – 2.2 t C ha^{-1} $year^{-1}$ or greater could be detected, should it occur. This degree of sensitivity would be sufficient to detect the impact of many management practices which are known to increase SOCS. Anything in this range would be a sensible choice but a final number should be easier to reach when considering both cost and anticipated future SOCS changes.

The required sample size to meet the desired MDD can be calculated using equation 6 found in Appendix 1, taken from FAO (2020):

$$n \geq (S^*(t\alpha + t\beta)/MDD)^2 \quad \text{Equation 6}$$

Where:

n = the number of samples

S = Standard deviation of the change in SOCS at all static locations between two surveys

MDD = minimum detectable difference

$t\alpha$ = is the two-sided critical value of the t-distribution at a given significance level (α). In this example $\alpha = 0.05$

$t\beta$ = the one-sided quartile of the t-distribution corresponding to a probability of type II error β (being $1 - \beta$ the statistical power). In this example, $\beta = 0.8$ or 80%.

Due to this being the Kavanagh farm's first SOCS survey, as with equation 5, in this instance S was substituted with the pooled standard deviation of the SOCS values across all strata (S_p). We encourage DTT to recalculate the required number of samples after a repeat survey with static sampling sites has been performed, allowing for a more accurate MDD and n value to be calculated using S.

6.5.7 Finalising the new plan

Once the number of samples to be taken in the ongoing monitoring system has been decided and the rest of the system has been designed using a combination of the strategies laid out above, the last step will be to proportionally distribute the samples across the strata as efficiently as possible. This process is done using a statistical method known as a Neyman allocation which has been outlined in Appendix 1. Since the number of samples will differ from the number used in the initial benchmarking survey, new sample sites will have to be randomly generated.

It is worth noting that if the new strata are adopted as recommended, this will mean that the previously visited sample sites will not be revisited in the next survey. Consequently, this means that DTT will have to wait for two surveys at the new static sampling sites to be completed before they can calculate the S value in equation 5. However, once they do have this value, they will be able to further optimise the number of samples they are taking

as this value allows the MDD to be more precise, allowing future surveys to require less samples. Alternatively, DTT could revisit the same sites and once again use the initial strata for the next survey to calculate this number, but we believe that implementing the revised strata first is the optimal approach as it has a clear, quantified benefit, whereas the benefit of calculating the more precise MDD with the value S cannot yet be quantified.

6.6 Outlook and implications for the Kavanagh farm greenhouse gas budget

6.6.1 Outlook for future SOCS changes

In an effort to estimate the scale of possible future SOCS changes on the Kavanagh farm, we reviewed existing literature for any monitoring of SOCS on farms on Taranaki Allophanic soils similar to those found on the Kavanagh farm, but such data was limited. Given this limitation, any estimates are mostly based on the available literature on SOC sequestration in other parts of the country relating to specific management practices.

The only data on SOCS changes on Taranaki dairy farms which we could find came from a short-term comparison between two SOCS surveys performed on Shortland Farms in coastal South Taranaki (Rachel Short, *pers. com.*, July 20, 2024). However, these data only reflect changes over a 1.5-year period and had a change in the sampling sites and sampling methods between the two surveys. The methods of the initial survey were similar to the preliminary survey rather than a full benchmarking survey. While they did observe a significant increase in SOCS between the surveys, since the first survey did not utilise standard benchmarking survey methods and sites were not static between surveys, no conclusions can be drawn at this stage. However, their most recent survey followed a method very closely resembling international standards (Australian Government, 2021; FAO, 2020; Mudge et al., 2020).

Because Shortland Farms is a certified organic operation with a myriad of regenerative practices which have all been implemented in the last few years, it is likely that their farms are currently undergoing SOCS changes due to the significant management changes. While studies aren't being performed on their farms to identify specific practices to

increase SOCS, we recommend that DTT get in contact with Shortland Farms and track any ongoing SOCS changes as their results could be indicative of the potential for Taranaki farms to increase SOCS under regenerative farm management practices. This could provide valuable insight into what practices DTT could consider trialling on the Kavanagh farm in the future and what capacity Taranaki soils have to increase SOCS.

6.6.2 Recommended management practice changes

Assuming the adoption of all recommended practices to increase SOCS, our baseline estimate shows the potential for DTT to increase the SOCS on Kavanagh farm by approximately 1.66 t C ha^{-1} $year^{-1}$ over the next 20 – 30 years. We anticipate that the rate of sequestration will initially be lower as the new strategy will take time to be implemented across the whole farm under best practice. We then expect the sequestration rate to peak after 5 – 10 years as more of the farm has been managed using inversion tillage and other recommended practices before dropping off over time towards the end of the 20 – 30-year period, at which point, a new SOCS equilibrium is reached (Caruso et al., 2018). However, with little research on the long-term impacts of these management practices, there may be sustained gains or some losses beyond this 20 – 30 year period. As more research is performed on NZ farms, new practices may also be able to further increase SOCS beyond baseline levels. Estimates were calculated based on documented SOCS changes attributed to different beneficial management practices (Table 4). The methods by which estimations shown in Table 4 were calculated are outlined in Appendix 7.

Table 4: The baseline, optimistic and highest range estimates for the number of t C ha^{-1} $year^{-1}$ which could be sequestered by various management practices.

	Baseline sequestration estimate (t C ha^{-1} $year^{-1}$)	Optimistic sequestration estimate (t C ha^{-1} $year^{-1}$)	Highest sequestration estimate (t C ha^{-1} $year^{-1}$)	Notes	References
Inversion Tillage	0.56	1.7	2	Actual sequestration will be lower initially since inversion tillage is done on small sections of the farm at a time. These estimates are long-term, full-farm averages.	Low: Lawrence-Smith et al., (2021) Medium: Schiedung et al., (2019) High: Calvelo-Pereira et al., (2018)
Biochar	1.1	2.5	4.4	The highest sequestration estimate is based on extrapolating percentage increases in SOCS and is therefore quite speculative. Baseline and optimistic estimates are based on real recorded sequestration rates on different soils.	Low: Gross et al., (2021) Medium: Blanco-Canqui et al. (2020)., Gross et al., (2022) High: Gross et al., (2021)

Some of the estimates in Table 4 are somewhat speculative due to significant differences between the studies from which the estimates were derived and the conditions on the Kavanagh farm. Alongside a lack of relevant existing research into these management practices, the main issue was how to apply the findings of other studies to Taranaki's high SOCS Allophanic soils. With the Kavanagh farm having over twice the national average SOCS to a depth of 30 cm, it is unclear how to apply findings from studies performed in soils with lower SOCS to the Kavanagh farm.

The decision to use the observed values of SOCS changes in t C ha^{-1} $year^{-1}$ from other studies or to take them in terms of the relative change in SOCS is an important one. This is because if the change in SOCS was taken from a study performed on an NZ farm with average SOCS, then the difference between the expected change in SOCS would be more than twice as large if it were applied to the Kavanagh farm by taking the percentage change over the observed change in SOCS (Minasny et al., 2017). Both methods of applying these findings can be rationalised and there is no literature addressing this topic so there is no clear best practice.

The rationale in favour of using the same precise sequestration numbers (in t C ha^{-1}) as shown in the relevant studies would be that the rate of carbon input into the soil from pasture would not scale proportionally with the soil's SOCS, rather with other factors such as fertility or not at all. However, the reasoning in favour of applying the percentage increase in SOCS would be that high SOCS Allophanic soils will be able to retain carbon more effectively and also would likely be more fertile, resulting in more SOC inputs and better SOC retention. With no existing literature defining this relationship, we therefore utilised both methods in our estimates.

In our estimates we have given a baseline SOCS estimate, an optimistic estimate and a highest estimate for potential SOCS changes on the Kavanagh farm. The baseline estimates primarily utilise the observed change in SOCS demonstrated by other studies and the optimistic and highest estimates utilise a combination of percentage and the observed changes to varying degrees. Furthermore, the highest estimates were based more heavily off the studies demonstrating higher sequestration rates. All rationale behind how these numbers were reached is detailed in Appendix 7.

6.6.3 Management practices to increase soil carbon stocks

The following management practices are worth considering on Kavanagh farm if an increase in SOCS is desired. These practices have been selected due to their expected impact on SOCS and due to their low cost and for their capacity to provide other co-benefits.

When adopting new farm management practices, we recommend trialling at small scale first before implementing them fully into the farm system. This is because there is still a shortage of local scientific literature covering many of these practices and their impacts on SOCS. Such trials taking place on smaller farm plots may also require extra SOCS testing beyond what is included in the ongoing monitoring system to more accurately assess the impact of these practices.

Inversion tillage

Inversion tillage shows promise for its potential to increase SOCS in the years following its use. However, the impact it might have on the Kavanagh farm is unclear due to a large variance in the SOC sequestration rates found in studies done across NZ. This is exacerbated by the fact that there is no existing research on inversion tillage in Taranaki and many of the studies performed in the rest of NZ have been based on modelling rather than direct measurements over long periods. Finally, the Kavanagh farm has a significantly higher SOCS than most of the other studies referenced, which raises a question around the best way to apply their findings to the Kavanagh farm. One could either directly take the observed sequestration numbers in t C ha^{-1} and apply them to the Kavanagh farm or, one could take the percentage increase in SOCS relative to the farm's SOCS. Due to all this uncertainty, we believe that the best strategy is to utilise the rates and amount of sequestration observed by local studies for the baseline estimation and consider a combination of observed sequestration values and the percentage increases for the more optimistic estimates.

Modelling by Lawrence-Smith et al. (2021) predicted a total increase in SOCS of 9.6 – 12.7 t C ha^{-1} following inversion tillage on Allophanic soils, corresponding to a 9.6 – 12% increase in SOCS in the top 30 cm of the soil. Applied to the Kavanagh farm's SOCS in the

top 30cm, this would result in a 15.36 – 19.2 t C ha^{-1} over a 20-year period or 0.77 – 0.96 t C ha^{-1} $year^{-1}$. This is similar to sequestration seen in a study performed on farmland on the West Coast of the South Island which saw an average of 1.2 – 1.8 t C ha^{-1} $year^{-1}$ on a podzol soil (Schiedung et al., 2019). With the average SOCS in the podzol soil of 119 t C ha^{-1}, this is a 1% – 1.5% annual increase in SOCS. A rate of 1% – 1.5% increase in SOCS on the Kavanagh farm would correspond to a 2.2 – 3.3 t C ha^{-1} $year^{-1}$.

More significant sequestration has been demonstrated on a Tokomaru silt loam soil which saw a 3.5 t C ha^{-1} $year^{-1}$ increase in the top 30 cm over 4 years after inversion tillage. This equated to a 4.5% increase per year (Calvelo-Pereira et al., 2018). However, since this study was only over 4 years, it doesn't account for the annual increases in SOCS decreasing significantly in later years after inversion (Lawrence-Smith et al., 2021). It is worth noting that this was for a Tokomaru silt loam soil which has a much lower SOCS than Kavanagh's Egmont black loam, so in the most optimistic case, a 4.5% increase in SOCS might be seen in the first few years. However, this extrapolation doesn't seem to be credible as this would equate to a maximum initial sequestration rate of 7.2 – 9.86 t C ha^{-1} $year^{-1}$. Such a rate would be highly unlikely as it exceeds the rate of carbon inputs into the soil from pasture which adds approximately 1.32 t C ha^{-1} $year^{-1}$ directly to the soil and an additional 6.82 t C ha^{-1} $year^{-1}$ into root biomass, of which, a much smaller fraction will end up in the soil as SOCS as root biomass turns over (Saggar & Hedley, 2001). Also, contrasting this with the estimated 9.6 – 12.7 t C ha^{-1} total increase on Allophanic soils over 20 years estimated by Lawrence-Smith et al. (2021), makes it seem highly unlikely that such a high rate of 7.2 – 9.86 t C ha^{-1} $year^{-1}$ could realistically be attained on these Allophanic soils from inversion tillage alone. Furthermore, this rate was an initial rate over the first 4 years, so even if it were possible, it is likely to decrease over time until a new equilibrium is reached (Caruso et al., 2018).

The practicality of implementing inversion tillage will result in less immediate SOCS gains and more of a long-term increase in SOCS. This is because inversion tillage is typically done when pasture renewal is due to minimise carbon loss during pasture renewal. On most dairy farms, pasture renewal rotates with a subset of paddocks being renewed each year. Consequently, inversion tillage would typically be applied to small sections of a farm each year such as 7 – 10% of the farm (Calvelo-Pereira et al., 2022). Consequently, only a small portion of the farm would benefit from it at first, but as more of the farm's soil has

been inverted, the annual rate of sequestration would increase, and SOCS increases would continue until approximately 20 years after the final paddock has been inverted.

Biochar

Biochar is widely seen as a reliable method of increasing SOCS and also has denitrification inhibiting properties which help to reduce nitrous oxide emissions (Cayuela et al., 2013; Gross et al., 2021). However, its cost and the lack of infrastructure to produce and distribute this product in NZ is a key issue limiting its adoption (Whitehead et al., 2018). However, if these hurdles can be overcome, we believe that biochar has the potential to increase SOCS by about 1.1 t C ha^{-1} $year^{-1}$. More optimistic estimates put this potential as high as 2.5 – 4.4 t C ha^{-1} $year^{-1}$, with these larger gains being primarily the result of large, repeat applications over long periods of up to 10 years (Gross et al., 2021; Gross et al., 2022). A significant portion of the SOC added through these biochar amendments is coming from the biochar itself, so it is worth conducting a full life cycle assessment of the biochar source used. However, this will likely not be an issue as in most cases, the full life cycle of biochar production sees other sources of net carbon sequestration (Patel & Panwar, 2023; Roberts et al., 2010).

It is also worth noting that due to a tendency for the biochar to leach down the soil profile, it offers increased carbon sequestration at lower soil depths (Dai et al., 2005; Rumpel et al., 2009). However, the downside to this leaching propensity is that biochar is less effective on large-grained soils such as the Patea black sand soils along the coastline on the Kavanagh farm (Yang et al., 2019).

6.6.4 Additional recommendations

The following recommendations are not specifically recommended for the Kavanagh farm, but worth considering if they fit in with the farm system and are appropriate.

Pasture varieties and diverse pasture

Despite mixed evidence, small trials to investigate the impact of diverse pastures on SOCS on the Kavanagh farm could be beneficial. While small measured or estimated SOCS gains of no more than 1.2 t C ha^{-1} $year^{-1}$ have been achieved through the establishment of diverse pastures with deeper roots and a higher fine root density

(McNally et al., 2015; Steinbeiss et al., 2008; Whitehead et al., 2018), no change or even small SOCS losses have also been observed (Rutledge et al., 2017; Wall et al., 2024). This variation is likely due to different pasture mixtures and local environments leading to a range of reported results. This means it will likely be very important to find a diverse pasture mixture which can be established under the local conditions and farm management on the Kavanagh farm. If a diverse pasture can be successfully established, then it may be possible that small gains in SOCS could be seen due to the deeper root systems and increased resilience to climatic events (Wall et al., 2021).

Importing feed

Importing of animal feed from other farms has been shown to increase SOCS when only accounting for the importing farm. More specifically, 27% of the carbon contained in the feed is returned to the soil through animal excreta while the rest is lost through respiration, milk production and enteric fermentation, respectively (Kirschbaum et al., 2017). However, when accounting for the farm acting as the source of the feed, there is no net SOCS increase. So, while this may be useful for an individual farm's carbon accounting, it does not achieve net sequestration on a global carbon cycle scale and if anything would lead to net emissions due to transportation of the feed.

Deferred grazing

Very small SOCS gains can be achieved through the use of deferred grazing, but with increases on the scale of just 0.1 t C ha^{-1} $year^{-1}$, its benefits are limited if only considered through the lens of SOCS (Kirschbaum et al., 2015).

Reduced tillage and pasture renewal

One of the primary management practices leading to the loss of SOCS is through tillage (Whitehead et al., 2018). In dairy pastures, the only time this is relevant is if a fodder crop is grown or when pasture comes up for renewal. When tillage events do occur, a few strategies can be employed to minimise SOC losses. Use of minimally disruptive tillage methods, reducing the time the soil is left fallow and avoid tillage when the soil is wet can all reduce the SOCS losses (Whitehead et al., 2018). Furthermore, if the farm is intending on undertaking inversion tillage in an attempt to increase SOCS, timing it to coincide with pasture renewal is a very efficient way to reduce potential soil carbon losses from tillage.

Summertime irrigation

The use of irrigation in temperate regions like NZ's prime dairying regions can lead to SOC losses as high as 26% (Condron et al., 2014). This is due to the increased microbial activity and subsequent metabolisation of soil carbon in warm summer weather that is facilitated by increased soil moisture levels from irrigation. This phenomenon is backed up by a significant body of evidence (Kirschbaum et al., 2017; Mudge et al., 2017, 2021; Schipper et al., 2019). However, Condron et al. (2014) did demonstrate that there is an optimal irrigation schedule which can increase pasture growth without significant SOC losses. In their experiment they saw no significant carbon loss when irrigating 100 mm when soil moisture content dropped to 10%, but the productivity benefits were still clear with this irrigation resulting in a 44% increase in pasture growth. While the Kavanagh farm doesn't currently utilise irrigation, the impacts of irrigation are important to consider if they ever consider utilising it in the future.

One potentially related factor to consider is the impact of effluent application. It has been established that effluent application increases SOCS by recycling carbon and other nutrients which would otherwise be lost from the farm system (Maillard & Angers, 2014). However, there is no existing research around whether water based effluent application in summer months has the same effect as irrigation. If effluent is applied during hot and dry periods, then the effect of increased soil moisture could theoretically lead to SOC losses through the same mechanism as SOC due to irrigation, but there is currently a knowledge gap in the research here. Since a positive relationship between effluent application and SOCS has been demonstrated, we recommend continuing the existing effluent application regime.

6.7 Full farm carbon budget

DTT have existing emissions data on the Kavanagh farm. Animal GHG emissions (biological emissions) were assessed using the NZ GHG inventory methodology. All other GHG emissions were calculated using a life cycle assessment (LCA) to account for all 'cradle-to-farm-gate' emissions, including those from the production and use of farm inputs. The annual emissions from the Kavanagh farm in the 2022/23 season was 2796.48 t CO_2e for the 213 effective ha farm (this excludes the dry stock enterprise which is

included in the CEA). If the baseline estimation for potential SOCS sequestration of 1.66 t C ha^{-1} $year^{-1}$ were to be attained, this alone would offset 46% of the Kavanagh farm's GHG emissions over the next 20 years (see Appendix 7 for calculation method). However, there may be practical limitations to the Kavanagh farm being able to get the full benefits from these practices. A lack of infrastructure for biochar is a potential barrier inhibiting its adoption and the slow rollout of inversion tillage across the whole farm could also be problematic since best practice for inversion tillage involves only inverting small sections of the farm each year as different pastures come due for pasture renewal. Both of these issues could potentially delay the implementation of these practices, this being particularly problematic with regards to DTT's goal of getting the Kavanagh farm to achieve net zero emissions by 2032.

Using the more optimistic estimates could see a greater rate of sequestration for the Kavanagh farm if either inversion tillage or biochar application are particularly successful. We anticipate that if the more optimistic sequestration rates are attained for one of these practices, this lessens the likelihood of the more optimistic rates being seen for the other practice since SOC inputs from pasture are limited (Saggar & Hedley, 2001). Taking the optimistic estimates for inversion tillage and the baseline increase from biochar puts the sequestration potential at 2.8 – 3.1 t C ha^{-1} $year^{-1}$ which would offset 78 – 87% of the farm's annual emissions. The optimistic estimates for biochar combined with the baseline inversion tillage numbers put potential sequestration at 3.06 – 4.96 t C ha^{-1} $year^{-1}$ which would offset 85% – 139% of the farm's annual emissions. For reference, in order to be fully net zero emissions, the Kavanagh farm requires a sequestration rate of 3.58 t C ha^{-1} $year^{-1}$ to be achieved.

Based on the literature reviewed in this study, it seems very unlikely that the farm's current emissions could be completely offset by SOC sequestration. All the estimates in this study are made under the assumption that the Kavanagh farm immediately rolls out both biochar and inversion tillage management practices across the entire farm. It is highly unlikely that this will be possible for numerous reasons. First, the Kavanagh farm has ongoing trials occurring on the farm which they will not want to disrupt, likely preventing some paddocks from being eligible for management changes. Secondly, biochar requires infrastructure for it to be produced. This infrastructure must be located close enough to the farm to be cost effective, and it must also be able to scale with the desired volume of applications on the

farm. This could be a big challenge with NZ biochar infrastructure currently being a limiting factor to its widespread adoption (Whitehead et al., 2018). Third, inversion tillage may not be viable on all areas of the farm due to steep slopes, obstacles or already disturbed soils. Finally, it would be prudent for these practices to be trialled on a smaller scale to assess their efficacy before implementing them throughout the farm, delaying the implementation of these practices with relation to the 2032 net zero emissions target. With all of this considered, due to the practicalities of implementing on-farm changes, the real rate of sequestration which the Kavanagh farm might see in practice over the next decade may be lower than the estimated 1.66 t C ha^{-1} $year^{-1}$ which could theoretically be achieved.

An important consideration beyond the potential sequestration rate is also the potential for the farm to decrease net emissions in the future. While SOCS sequestration alone is likely not enough to offset the farm's emissions, it can play a significant role in the path to net zero. When combined with other practices to reduce emissions, the net zero emissions goal may be within reach for the DTT team. Consequently, it will be critical that DTT employs an integrated approach of increasing SOCS and pioneering the latest practices in reducing on-farm emissions to achieve net zero emissions on the Kavanagh farm in the next decade.

The primary remaining challenge with regards to this opportunity is the long-term sustainability of constantly increasing SOCS. When a management change is implemented which increases or decreases SOCS, in most cases the change occurs over time in a non-linear fashion with the largest SOCS change occurring immediately following the management change. Eventually, after 20 – 50 years, a new dynamic ecological equilibrium in SOCS is reached and that management practice no longer continues to increase SOCS, rather it keeps SOCS stable at a level above the baseline levels (Caruso et al., 2018). While there is variation in the rate of SOCS change across different management changes, it seems unlikely that there will be management practices which can continuously increase SOCS year after year, indefinitely. Hence, despite the significant potential opportunity posed by soil carbon sequestration to offset farm emissions in the medium term, this is not a permanent opportunity, and so other technological advances will have to be made for a long-term sustainable net zero farming system.

Overall, carbon sequestration through SOCS provides a significant opportunity to offset farm GHG emissions by approximately 46%. Alongside this, it also provides an opportunity to improve other aspects of the farm including improving soil structure, facilitating soil microbial activity and increasing nutrient retention (Batjes, 2014; Stockmann et al., 2013; Whitehead et al., 2018). Consequently, employing new SOC optimising management practices to increase SOCS on the Kavanagh farm will be a key strategy on the road to becoming a net zero emissions dairy farm without compromising on productivity.

References

Anderson, D. W., & Paul, E. (1984). Organo-mineral complexes and their study by radiocarbon dating. *Soil Science Society of America Journal*, *48*(2), 298–301.

Arbestain, M. C., Jones, J. R., Condron, L. M., & Clough, T. J. (2016). Research and application of biochar in New Zealand. *Agricultural and Environmental Applications of Biochar: Advances and Barriers*, *63*, 423–443.

Australian Government. (2021). *Carbon Credits (Carbon Farming Initiative—Carbon Capture and Storage) Methodology Determination 2021.* https://www.legislation.gov.au/Details/F2021L01379

Bain, L. J., & Engelhardt, M. (1992). *Introduction to probability and mathematical statistics (Vol. 4)*. Duxbury Press. Belmont, CA.

Balesdent, J., Chenu, C., & Balabane, M. (2000). Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and Tillage Research*, *53*(3–4), 215–230. https://doi.org/10.1016/S0167-1987(99)00107-5

Bangroo, S., Najar, G., & Rasool, A. (2017). Effect of altitude and aspect on soil organic carbon and nitrogen stocks in the Himalayan Mawer Forest Range. *Catena*, *158*, 63–68.

Barnett, A. L., Schipper, L. A., Taylor, A., Balks, M. R., & Mudge, P. L. (2014). Soil C and N contents in a paired survey of dairy and dry stock pastures in New Zealand. *Agriculture, Ecosystems & Environment*, *185*, 34–40. https://doi.org/10.1016/j.agee.2013.12.008

Batjes, N. H. (2014). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, *65*(1), 10–21. https://doi.org/10.1111/ejss.12114_2

Beare, M. H., McNeill, S. J., Curtin, D., Parfitt, R. L., Jones, H. S., Dodd, M. B., & Sharp, J. (2014). Estimating the organic carbon stabilisation capacity and saturation deficit of

soils: A New Zealand case study. *Biogeochemistry*, *120*(1–3), 71–87. https://doi.org/10.1007/s10533-014-9982-1

Berman, H. B. (2024). *Sample size: Stratified random samples.* StatTrek. Retrieved June 5, 2024, from https://stattrek.com/sample-size/stratified-sample

Blanco-Canqui, H., Laird, D. A., Heaton, E. A., Rathke, S., & Acharya, B. S. (2020). Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. *GCB Bioenergy*, *12*(4), 240–251. https://doi.org/10.1111/gcbb.12665

Blodau, C. (2002). Carbon cycling in peatlands A review of processes and controls. *Environmental Reviews*, *10*(2), 111–134.

Bobbitt, Z. (2020). *How to calculate a pooled standard deviation (with example).* Statology. Retrieved May 30, 2024, from https://www.statology.org/pooled-standard-deviation/

Bunt, J. S., & Rovira, A. D. (1955). The effect of temperature and heat treatment on soil metabolism. *Journal of Soil Science*, *6*(1), 129–136. https://doi.org/10.1111/j.1365-2389.1955.tb00837.x

Calvelo-Pereira, R., Hedley, M. J., Arbestain, M. C., Bishop, P., Enongene, K. E., & Otene, I. J. J. (2018). Evidence for soil carbon enhancement through deeper mouldboard ploughing at pasture renovation on a Typic Fragiaqualf. *Soil Research*, *56*(2), 182. https://doi.org/10.1071/SR17039

Calvelo-Pereira, R., Hedley, M. J., Hanly, J. A., Beare, M. H., McNally, S. R., & Bretherton, M. R. (2022). Spring pasture renewal involving full inversion tillage and a summer crop can facilitate soil C storage, improve crop yields and lower N leaching. *Soil and Tillage Research*, *219*, 105347. https://doi.org/10.1016/j.still.2022.105347

Campbell, D. I., Wall, A. M., Nieveen, J. P., & Schipper, L. A. (2015). Variations in CO2 exchange for dairy farms with year-round rotational grazing on drained peatlands.

Agriculture, Ecosystems & Environment, *202*, 68–78. https://doi.org/10.1016/j.agee.2014.12.019

Caruso, T., De Vries, F. T., Bardgett, R. D., & Lehmann, J. (2018). Soil organic carbon dynamics matching ecological equilibrium theory. *Ecology and Evolution*, *8*(22), 11169–11178.

Cayuela, M. L., Sánchez-Monedero, M. A., Roig, A., Hanley, K., Enders, A., & Lehmann, J. (2013). Biochar and denitrification in soils: When, how much and why does biochar reduce N2O emissions? *Scientific Reports*, *3*(1), 1732.

Chappell, A., & Viscarra Rossel, R. A. (2013). The importance of sampling support for explaining change in soil organic carbon. *Geoderma*, *193–194*, 323–325. https://doi.org/10.1016/j.geoderma.2012.09.011

Chase, F. E., & Gray, P. H. H. (1957). Application of the warburg respirometer in studying respiratory activity in soil. *Canadian Journal of Microbiology*, *3*(2), 335–349. https://doi.org/10.1139/m57-038

Chevallier, T., Woignier, T., Toucet, J., & Blanchart, E. (2010). Organic carbon stabilization in the fractal pore structure of Andosols. *Geoderma*, *159*(1-2), 182-188.

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Routledge.

Conant, R. T., Cerri, C. E. P., Osborne, B. B., & Paustian, K. (2017). Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, *27*(2), 662–668. https://doi.org/10.1002/eap.1473

Condron, L. M., Hopkins, D. W., Gregorich, E. G., Black, A., & Wakelin, S. A. (2014). Long-term irrigation effects on soil organic matter under temperate grazed pasture: Pasture production and soil organic matter. *European Journal of Soil Science*, *65*(5), 741–750. https://doi.org/10.1111/ejss.12164

Curtin, D., Beare, M. H., & Hernandez-Ramirez, G. (2012). Temperature and Moisture Effects on Microbial Biomass and Soil Organic Matter Mineralization. *Soil Science*

Society of America Journal, *76*(6), 2055–2067. https://doi.org/10.2136/sssaj2012.0011

Dai, X., Boutton, T. W., Glaser, B., Ansley, R. J., & Zech, W. (2005). Black carbon in a temperate mixed-grass savanna. *Soil Biology and Biochemistry*, *37*(10), 1879–1881. https://doi.org/10.1016/j.soilbio.2005.02.021

DairyNZ. (2023). *Deferred grazing.* Retrieved from https://www.dairynz.co.nz/feed/fundamentals/deferred-grazing/

Davis, M., Wilde, R., Garrett, L., & Oliver, G. (2004). New Zealand carbon monitoring system soil data collection manual. *Wellington, Ministry for the Environment*.

de Gruijter, J. J., McBratney, A. B., Minasny, B., Wheeler, I., Malone, B. P., & Stockmann, U. (2018). Farm-Scale Soil Carbon Auditing. In Alex. B. McBratney, B. Minasny, & U. Stockmann (Eds.), *Pedometrics* (pp. 693–720). Springer International Publishing. https://doi.org/10.1007/978-3-319-63439-5_23

De Gruijter, J. J., Minasny, B., & Mcbratney, A. B. (2015). Optimizing Stratification and Allocation for Design-Based Estimation of Spatial Means Using Predictions with Error. *Journal of Survey Statistics and Methodology*, *3*(1), 19–42. https://doi.org/10.1093/jssam/smu024

Dwivedi, D., Tang, J., Bouskill, N., Georgiou, K., Chacon, S. S., & Riley, W. J. (2019). Abiotic and Biotic Controls on Soil Organo–Mineral Interactions: Developing Model Structures to Analyze Why Soil Organic Matter Persists. *Reviews in Mineralogy and Geochemistry*, *85*(1), 329–348. https://doi.org/10.2138/rmg.2019.85.11

Egli, M., Sartori, G., Mirabella, A., Favilli, F., Giaccai, D., & Delbos, E. (2009). Effect of north and south exposure on organic matter in high Alpine soils. *Geoderma*, *149*(1–2), 124–136.

Food and Agriculture Organization. (2020). *A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes*. FAO. https://doi.org/10.4060/cb0509en

Ford, H., Healey, J. R., Webb, B., Pagella, T. F., & Smith, A. R. (2019). How do hedgerows influence soil organic carbon stock in livestock-grazed pasture? *Soil Use and Management*, *35*(4), 576–584. https://doi.org/10.1111/sum.12517

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., … Zheng, B. (2023). Global Carbon Budget 2023. *Earth System Science Data*, *15*(12), 5301–5369. https://doi.org/10.5194/essd-15-5301-2023

Goodman, J., Dunn, N. R., Ravenscroft, P. J., Allibone, R. M., Boubee, J., David, B. O., Griffiths, M. H., Ling, N., Hitchmough, R., & Rolfe, J. R. (2014). *Conservation status of New Zealand freshwater fish, 2013*. Publishing Team, Department of Conversation.

Gross, A., Bromm, T., & Glaser, B. (2021). Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. *Agronomy*, *11*(12), 2474. https://doi.org/10.3390/agronomy11122474

Gross, C. D., Bork, E. W., Carlyle, C. N., & Chang, S. X. (2022). Biochar and its manure-based feedstock have divergent effects on soil organic carbon and greenhouse gas emissions in croplands. *Science of The Total Environment*, *806*, 151337. https://doi.org/10.1016/j.scitotenv.2021.151337

Haney, R. L., Franzluebbers, A. J., Jin, V. L., Johnson, M. V., Haney, E. B., White, M. J., & Harmel, R. D. (2012). Soil Organic C:N vs. Water-Extractable Organic C:N. *Open Journal of Soil Science*, *02*(03), 269–274. https://doi.org/10.4236/ojss.2012.23032

Heckenmüller, M., Narita, D., Klepper, G. (2014). *Global availability of phosphorus and its implications for global food supply: An economic overview*. Kiel Working Paper, No. 1897, Kiel Institute for the World Economy (IfW), Kiel

Hedley, C., Manderson, A., Mudge, P., Roudier, P., Fraser, S., Parfitt, R., Smaill, S., Schipper, L., & Kelliher, F. (2015). Improved Measurements of Hill Country Soil Carbon—To Assist Carbon Change Studies. *Ministry for Primary Industries: Wellington, New Zealand*, *2*.

Hedley, C., Payton, I., Lynn, I., Carrick, S., Webb, T., & McNeill, S. (2012). Random sampling of stony and non-stony soils for testing a national soil carbon monitoring system. *Soil Research*, *50*(1), 18–29.

Hewitt, A., Forrester, G., Fraser, S., Hedley, C., Lynn, I., & Payton, I. (2012). Afforestation effects on soil carbon stocks of low productivity grassland in New Zealand: *Soil C effects of afforestation*. *Soil Use and Management*, *28*(4), 508–516. https://doi.org/10.1111/j.1475-2743.2012.00439.x

Hoogendoorn, C. J., De Klein, C. A., Rutherford, A. J., Letica, S., & Devantier, B. P. (2008). The effect of increasing rates of nitrogen fertiliser and a nitrification inhibitor on nitrous oxide emissions from urine patches on sheep grazed hill country pasture. *Australian Journal of Experimental Agriculture*, *48*(2), 147–151.

Hossain, Md. B. (2021). Glomalin and Contribution of Glomalin to Carbon Sequestration in Soil: A Review. *Turkish Journal of Agriculture - Food Science and Technology*, *9*(1), 191–196. https://doi.org/10.24925/turjaf.v9i1.191-196.3803

Hunt, J. E., Kelliher, F. M., McSeveny, T. M., Ross, D. J., & Whitehead, D. (2004). Long-term carbon exchange in a sparse, seasonally dry tussock grassland: *Global Change Biology*, *10*(10), 1785–1800. https://doi.org/10.1111/j.1365-2486.2004.00842.x

IPCC (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies.

Jakšić, S., Ninkov, J., Milić, S., Vasin, J., Živanov, M., Jakšić, D., & Komlen, V. (2021). Influence of Slope Gradient and Aspect on Soil Organic Carbon Content in the Region of Niš, Serbia. *Sustainability*, *13*(15), 8332. https://doi.org/10.3390/su13158332

Jastrow, J. D. (1996). Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. *Soil Biology and Biochemistry*, *28*(4–5), 665–676. https://doi.org/10.1016/0038-0717(95)00159-X

Jenny, H. (1980). *The soil resource: Origin and behavior*. Springer Science & Business Media.

Kane, S. P. (2024). *ClinCalc.* Retrieved May 30, 2024, from https://clincalc.com/stats/power.aspx

Kern, J., & Johnson, M. (1993). Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal*, *57*(1), 200–210.

Kirschbaum, M. U. F., Schipper, L. A., Mudge, P. L., Rutledge, S., Puche, N. J. B., & Campbell, D. I. (2017). The trade-offs between milk production and soil organic carbon storage in dairy systems under different management and environmental factors. *Science of The Total Environment*, *577*, 61–72. https://doi.org/10.1016/j.scitotenv.2016.10.055

Kirschbaum, M. U., Rutledge, S., Mudge, P. L., Puche, N., Schipper, L. A., & Campbell, D. I. (2015). Changes in soil carbon stocks of New Zealand's grazed pasture in response to variations in management and environmental factors. *28th Annual FLRC Workshop*, 1–19.

Kleber, M., Eusterhues, K., Keiluweit, M., Mikutta, C., Mikutta, R., & Nico, P. S. (2015). Mineral–Organic Associations: Formation, Properties, and Relevance in Soil Environments. In *Advances in Agronomy* (Vol. 130, pp. 1–140). Elsevier. https://doi.org/10.1016/bs.agron.2014.10.005

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*(1–2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

LaMorte, W. W. (2020). *Sample size for one sample, continuous outcome.* Boston University School of Public Health. Retrieved June 5, 2024, from https://sphweb.bumc.bu.edu/otlt/MPH-Modules/BS/BS704_Power/BS704_Power3.html

Lawrence-Smith, E. J., Curtin, D., Beare, M. H., McNally, S. R., Kelliher, F. M., Calvelo Pereira, R., & Hedley, M. J. (2021). Full inversion tillage during pasture renewal to increase soil carbon storage: New Zealand as a case study. *Global Change Biology*, *27*(10), 1998–2010. https://doi.org/10.1111/gcb.15561

Lee, J.-M., Park, D.-G., Kang, S.-S., Choi, E.-J., Gwon, H.-S., Lee, H.-S., & Lee, S.-I. (2022). Short-Term Effect of Biochar on Soil Organic Carbon Improvement and Nitrous Oxide Emission Reduction According to Different Soil Characteristics in Agricultural Land: A Laboratory Experiment. *Agronomy*, *12*(8), 1879. https://doi.org/10.3390/agronomy12081879

Leining, C., Kerr, S., & Bruce-Brand, B. (2020). The New Zealand Emissions Trading Scheme: Critical review and future outlook for three design innovations. *Climate Policy*, *20*(2), 246–264. https://doi.org/10.1080/14693062.2019.1699773

Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *177*(5), 651–670. https://doi.org/10.1002/jpln.201400058

Mackay, A. D., Vibart, R., McKenzie, C., Costall, D., Bilotto, F., & Kelliher, F. M. (2021). Soil organic carbon stocks in hill country pastures under contrasting phosphorus fertiliser and sheep stocking regimes, and topographical features. *Agricultural Systems*, *186*, 102980.

Maillard, É., & Angers, D. A. (2014). Animal manure application and soil organic carbon stocks: A meta-analysis. *Global Change Biology*, *20*(2), 666–679. https://doi.org/10.1111/gcb.12438

Marschner, B., Brodowski, S., Dreves, A., Gleixner, G., Gude, A., Grootes, P. M., Hamer, U., Heim, A., Jandl, G., Ji, R., Kaiser, K., Kalbitz, K., Kramer, C., Leinweber, P., Rethemeyer, J., Schäffer, A., Schmidt, M. W. I., Schwark, L., & Wiesenberg, G. L. B. (2008). How relevant is recalcitrance for the stabilization of organic matter in soils? *Journal of Plant Nutrition and Soil Science*, *171*(1), 91–110. https://doi.org/10.1002/jpln.200700049

Mazzetto, A., Falconer, S., & Ledgard, S. (2021). *Mapping the carbon footprint of milk for dairy cows.* Report for DairyNZ (No. RE450/2020/081). AgResearch, Hamilton, 22.

McDowell, R., Muirhead, R., & Monaghan, R. (2006). Nutrient, sediment, and bacterial losses in overland flow from pasture and cropping soils following cattle dung deposition. *Communications in Soil Science and Plant Analysis*, *37*(1–2), 93–108.

McIntosh, P., Gibson, R., Saggar, S., Yeates, G., & McGimpsey, P. (1999). Effect of contrasting farm management on vegetation and biochemical, chemical, and biological condition of moist steepland soils of the South Island high country, New Zealand. *Soil Research*, *37*(5), 847–866.

McNally, S. R., Beare, M. H., Curtin, D., Meenken, E. D., Kelliher, F. M., Calvelo Pereira, R., Shen, Q., & Baldock, J. (2017). Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. *Global Change Biology*, *23*(11), 4544–4555. https://doi.org/10.1111/gcb.13720

McNally, S. R., Laughlin, D. C., Rutledge, S., Dodd, M. B., Six, J., & Schipper, L. A. (2015). Root carbon inputs under moderately diverse sward and conventional ryegrass-clover pasture: Implications for soil carbon sequestration. *Plant and Soil*, *392*, 289–299.

McNeill, S. J. E., Golubiewski, N., & Barringer, J. (2014). Development and calibration of a soil carbon inventory model for New Zealand. *Soil Research*, *52*(8), 789. https://doi.org/10.1071/SR14020

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., … Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Ministry for the Environment. (2017). *National Planning Standards Discussion Paper B – District Plan Structure.* Wellington: Ministry for the Environment.

Ministry for the Environment. (2024). *New Zealand's greenhouse gas inventory 1990–2022.* https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2022/

Mudge, P. L., Kelliher, F. M., Knight, T. L., O'Connell, D., Fraser, S., & Schipper, L. A. (2017). Irrigating grazed pasture decreases soil carbon and nitrogen stocks. *Global Change Biology*, *23*(2), 945–954. https://doi.org/10.1111/gcb.13448

Mudge, P. L., McNeill, S., Hedley, C., Roudier, P., & Poggio, M. (2020). *Design of an on-farm soil carbon benchmarking and monitoring approach for individual pastoral farms*. https://www.agmatters.nz/assets/Reports/On-farm-soil-carbon-benchmarking-and-monitoring-approach_final-report_June2019-v2.pdf

Mudge, P. L., Millar, J., Pronger, J., Roulston, A., Penny, V., Fraser, S., Eger, A., Caspari, T., Robertson, B., Mason, N. W. H., & Schipper, L. A. (2021). Impacts of irrigation on

soil C and N stocks in grazed grasslands depends on aridity and irrigation duration. *Geoderma*, *399*, 115109. https://doi.org/10.1016/j.geoderma.2021.115109

Naylor, D., Sadler, N., Bhattacharjee, A., Graham, E. B., Anderton, C. R., McClure, R., Lipton, M., Hofmockel, K. S., & Jansson, J. K. (2020). Soil Microbiomes Under Climate Change and Implications for Carbon Cycling. *Annual Review of Environment and Resources*, *45*(1), 29–59. https://doi.org/10.1146/annurev-environ-012320-082720

New Zealand Government. (2021). New Zealand's submission under the Paris Agreement: New Zealand's first nationally determined contribution. https://unfccc.int/sites/default/files/NDC/2022-06/New%20Zealand%20NDC%20November%202021.pdf

Olson, K. R., & Al-Kaisi, M. M. (2015). The importance of soil sampling depth for accurate account of soil organic carbon sequestration, storage, retention and loss. *Catena*, *125*, 33–37. https://doi.org/10.1016/j.catena.2014.10.004

Parfitt, R. L. (2009). Allophane and imogolite: role in soil biogeochemical processes. *Clay minerals*, *44*(1), 135-155.

Parfitt, R. L., Stevenson, B. A., Dymond, J. R., Schipper, L. A., Baisden, W. T., & Ballantine, D. J. (2012). Nitrogen inputs and outputs for New Zealand from 1990 to 2010 at national and regional scales. *New Zealand Journal of Agricultural Research*, *55*(3), 241-262.

Patel, M. R., & Panwar, N. L. (2023). Biochar from agricultural crop residues: Environmental, production, and life cycle assessment overview. *Resources, Conservation & Recycling Advances*, *19*, 200173. https://doi.org/10.1016/j.rcradv.2023.200173

Pennsylvania State University. (2023). *Conversions commonly used when comparing timber and carbon values.* Retrieved from https://extension.psu.edu/conversions-commonly-used-when-comparing-timber-and-carbon-values

Reisinger, A., Ledgard, S. F., & Falconer, S. J. (2017). Sensitivity of the carbon footprint of New Zealand milk to greenhouse gas metrics. *Ecological Indicators*, *81*, 74–82. https://doi.org/10.1016/j.ecolind.2017.04.026

Rillig, M. C. (2004). Arbuscular mycorrhizae, glomalin, and soil aggregation. *Canadian Journal of Soil Science*, *84*(4), 355–363.

Roach, C., & Morton, J. (2005). Impacts of intensive dairying on soil and pasture sustainability in Taranaki. *Proceedings of the New Zealand Grassland Association*, 109–116.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science & Technology*, *44*(2), 827–833.

Rodríguez, A. R., Arbelo, C. D., Guerra, J. A., Mora, J. L., Notario, J. S., & Armas, C. M. (2006). Organic carbon stocks and soil erodibility in Canary Islands Andosols. *Catena*, *66*(3), 228-235.

Rumpel, C., Ba, A., Darboux, F., Chaplot, V., & Planchon, O. (2009). Erosion budget and process selectivity of black carbon at meter scale. *Geoderma*, *154*(1–2), 131–137. https://doi.org/10.1016/j.geoderma.2009.10.006

Rutledge, S., Wall, A. M., Mudge, P. L., Troughton, B., Campbell, D. I., Pronger, J., Joshi, C., & Schipper, L. A. (2017). The carbon balance of temperate grasslands part I: The impact of increased species diversity. *Agriculture, Ecosystems & Environment*, *239*, 310–323. https://doi.org/10.1016/j.agee.2017.01.039

Saggar, S., & Hedley, C. (2001). Estimating seasonal and annual carbon inputs, and root decomposition rates in a temperate pasture following field 14C pulse-labelling. *Plant and Soil*, *236*, 91–103.

Schiedung, M., Tregurtha, C. S., Beare, M. H., Thomas, S. M., & Don, A. (2019). Deep soil flipping increases carbon stocks of New Zealand grasslands. *Global Change Biology*, *25*(7), 2296–2309. https://doi.org/10.1111/gcb.14588

Schipper, L. A., Dodd, M. B., Pronger, J., Mudge, P. L., Upsdell, M., & Moss, R. A. (2013). Decadal Changes in Soil Carbon and Nitrogen under a Range of Irrigation and Phosphorus Fertilizer Treatments. *Soil Science Society of America Journal*, *77*(1), 246–256. https://doi.org/10.2136/sssaj2012.0126

Schipper, L. A., Mudge, P. L., Kirschbaum, M. U. F., Hedley, C. B., Golubiewski, N. E., Smaill, S. J., & Kelliher, F. M. (2017). A review of soil carbon change in New Zealand’s grazed grasslands. *New Zealand Journal of Agricultural Research*, *60*(2), 93–118. https://doi.org/10.1080/00288233.2017.1284134

Schipper, L. A., Parfitt, R. L., Fraser, S., Littler, R. A., Baisden, W. T., & Ross, C. (2014). Soil order and grazing management effects on changes in soil C and N in New Zealand pastures. *Agriculture, Ecosystems & Environment*, *184*, 67–75. https://doi.org/10.1016/j.agee.2013.11.012

Schipper, L. A., Parfitt, R. L., Ross, C., Baisden, W. T., Claydon, J. J., & Fraser, S. (2010). Gains and losses in C and N stocks of New Zealand pasture soils depend on land use. *Agriculture, Ecosystems & Environment*, *139*(4), 611–617. https://doi.org/10.1016/j.agee.2010.10.005

Schipper, L. A., Petrie, O. J., O’Neill, T. A., Mudge, P. L., Liáng, L. L., Robinson, J. M., & Arcus, V. L. (2019). Shifts in temperature response of soil respiration between adjacent irrigated and non-irrigated grazed pastures. *Agriculture, Ecosystems & Environment*, *285*, 106620. https://doi.org/10.1016/j.agee.2019.106620

Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*(14), 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Smith, P., Soussana, J., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J. E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*(1), 219–241. https://doi.org/10.1111/gcb.14815

Steinbeiss, S., Beßler, H., Engels, C., Temperton, V. M., Buchmann, N., Roscher, C., Kreutziger, Y., Baade, J., Habekost, M., & Gleixner, G. (2008). Plant diversity positively affects short-term soil carbon storage in experimental grasslands: *Global Change Biology*, *14*(12), 2937–2949. https://doi.org/10.1111/j.1365-2486.2008.01697.x

Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A. B., Courcelles, V. D. R. D., Singh, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Bird, M., Brookes, P. C., Chenu, C., Jastrow, J. D., Lal, R., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment*, *164*, 80–99. https://doi.org/10.1016/j.agee.2012.10.001

Tate, K., Wilde, R., Giltrap, D., Baisden, W., Saggar, S., Trustrum, N., Scott, N., & Barton, J. (2005). Soil organic carbon stocks and flows in New Zealand: System development, measurement and modelling. *Canadian Journal of Soil Science*, *85*(Special Issue), 481–489.

Wall, A., Goodrich, J., & Schipper, L. (2021). Importance of resilient pastures for New Zealand's agricultural soil carbon stocks. *NZGA: Research and Practice Series*, *17*, 191–200.

Wall, A. M., Laubach, J., Campbell, D. I., Goodrich, J. P., Graham, S. L., Hunt, J. E., Mudge, P. L., Whitehead, D., & Schipper, L. A. (2024). Effects of dairy farming management practices on carbon balances in New Zealand's grazed grasslands: Synthesis from 68 site-years. *Agriculture, Ecosystems & Environment*, *367*, 108962.

Wang, Y., Hu, C., Dong, W., Li, X., Zhang, Y., Qin, S., & Oenema, O. (2015). Carbon budget of a winter-wheat and summer-maize rotation cropland in the North China Plain. *Agriculture, Ecosystems & Environment*, *206*, 33–45. https://doi.org/10.1016/j.agee.2015.03.016

Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science*, *64*(1), 58–65. https://doi.org/10.1111/ejss.12002

Whitehead, D., Schipper, L. A., Pronger, J., Moinet, G. Y. K., Mudge, P. L., Calvelo Pereira, R., Kirschbaum, M. U. F., McNally, S. R., Beare, M. H., & Camps-Arbestain, M. (2018). Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. *Agriculture, Ecosystems & Environment*, *265*, 432–443. https://doi.org/10.1016/j.agee.2018.06.022

Wilson, C. H., Strickland, M. S., Hutchings, J. A., Bianchi, T. S., & Flory, S. L. (2018). Grazing enhances belowground carbon allocation, microbial biomass, and soil carbon in a subtropical grassland. *Global Change Biology*, *24*(7), 2997–3009. https://doi.org/10.1111/gcb.14070

Yang, X. Y., Chang, K.-H., Kim, Y. J., Zhang, J., & Yoo, G. (2019). Effects of different biochar amendments on carbon loss and leachate characterization from an agricultural soil. *Chemosphere*, *226*, 625–635.

Appendices

Appendix 1 – Calculations for pooled mean, pooled standard deviation, margin of error and 95% confidence interval.

Calculating the pooled mean and pooled standard deviation

1. First, the means and standard deviations for each stratum must be calculated. This can be achieved using the "mean" and "sd" commands in R.

   R Code Sample 1

   ```
   mean_stratum1 <- mean(stratum1)
   mean_stratum2 <- mean(stratum2)
   mean_stratum3 <- mean(stratum3)
   mean_stratum4 <- mean(stratum4)
   sd_stratum1 <- sd(stratum1)
   sd_stratum2 <- sd(stratum2)
   sd_stratum3 <- sd(stratum3)
   sd_stratum4 <- sd(stratum4)
   ```

2. With the means for each strata calculated, the means are then combined and weighted proportionally to the land area covered by each stratum to ensure that there is proportional representation of each stratum. The land area and other numbers from the Kavanagh farm used in this section can be found in appendix 5.

   Equation 1

   $$m_w = (m_1 * a_1 + m_2 * a_2 + m_3 * a_3 + m_4 * a_4) / (a_1 + a_2 + a_3 + a_4)$$

   Where;

   $m_1, m_{2...}$ = the means of strata 1 and 2 etc respectively.

   $a_1, a_2...$ = the land area covered by strata 1 and 2 etc respectively.

   m_w = weighted mean SOCS

R Code Sample 2

```
total_mean <- (mean_stratum1 * strata_1_proportional_area +
    mean_stratum2 * strata_2_proportional_area + mean_stratum3 *
    strata_3_proportional_area + mean_stratum4 * strata_4_proportional_area)
```

3. Next, the pooled standard deviation is calculated. This is the standard deviation of the full data set based on the standard deviations from within each stratum. Equation 2 was adapted from Bobbitt, (2020).

Equation 2

$$S_p = \sqrt{((a_1*S_{s1})^2 + (a_2*S_{s2})^2 + (a_3*S_{s3})^2 + (a_4*S_{s4})^2 / (a_1+a_2+a_3+a_4))}$$

Where:

S_p = Pooled standard deviation

a_1, a_2... = Land area covered by strata 1 and 2 etc respectively.

S_{s1}, S_{s2}... = Standard deviation of the corresponding strata (strata 1, strata 2...etc)

R Code Sample 3

```
total_sd <- sqrt((strata_1_area * sd_stratum1^2 + strata_2_area *
    sd_stratum2^2 + strata_3_area * sd_stratum3^2 + strata_4_area *
    sd_stratum4^2) / total_area)
```

Calculating the margin of error

The margin of error is calculated using the following formula which is rearranged from LaMorte (2020) and has the type 2 error t-value added in as per the formula for MDD in (FAO, 2020):

Equation 3:

$$e \geq (S_p/\sqrt{n})*(t\alpha+t\beta)$$

Where:

e = The desired margin of error

S_p = Pooled standard deviation

n = Number of sample cores (sample locations)

$t\alpha$ = is the two-sided critical value of the t-distribution at a given significance level (α). In this example α = 0.05

$t\beta$ = the one-sided quartile of the t-distribution corresponding to a probability of type II error β (being $1 - \beta$ the statistical power). In this example, β = 0.8 or 80%.

Calculating 95% confidence intervals of the mean

Calculate the 95% confidence intervals using the margin of error and the mean.

Equation 4:

$$\text{Lower CI} = m_w - (e * m_w)$$

$$\text{Upper CI} = m_w + (e * m_w)$$

Where:

m_w = weighted mean SOCS

e = the margin of error

Calculating the desired MDD

MDD is calculated using equation 1 (FAO, 2020).

Equation 5:

$$MDD \geq (S/\sqrt{n})*(t\alpha+t\beta)$$

Where:

MDD = The desired MDD

S = Standard deviation of the change in SOCS at all static locations between two surveys

n = Number of sample cores (sample locations)

$t\alpha$ = is the two-sided critical value of the t-distribution at a given significance level (α). In this example α = 0.05

tβ = the one-sided quartile of the t-distribution corresponding to a probability of type II error β (being 1 − β the statistical power). In this example, β = 0.8 or 80%.

Note: If S is not known, S_p can be used to provide a less precise upper bound of the MDD which the real MDD will not be higher than. However, recalculating this once S is known is beneficial and highly recommended.

Calculating the sample size required for a desired MDD

This equation is taken from (FAO, 2020)

Equation 6:

$$n \geq (S^*(t\alpha + t\beta)/MDD)^2$$

Where:

n = the number of samples

S = Standard deviation of the change in SOCS at all static locations between two surveys

MDD = minimum detectable difference

tα = is the two-sided critical value of the t-distribution at a given significance level (α). In this example α = 0.05

tβ = the one-sided quartile of the t-distribution corresponding to a probability of type II error β (being 1 − β the statistical power). In this example, β = 0.8 or 80%.

Note: If S is not known, S_p can be used to provide a less precise upper bound of the desired sample size which the real sample size required for the desired MDD will not be higher than. However, recalculating this once S is known is beneficial and highly recommended.

Distributing the samples optimally between strata

Once the sample size required for the desired MDD has been calculated, the remaining question is where to optimally allocate all the samples since some strata will require more samples than others for an optimal utilisation of samples. This is calculated using a Neyman allocation which utilises the following formula modified from Berman, (2024):

Equation 7:

$$n_h = n * (a_h * \sigma_h) / [\Sigma (N_i * \sigma_i)]$$

Where:

n_h = The optimal sample size for the stratum being calculated

n = Total sample size

a_h = The population size for stratum being calculated

σ_h = The standard deviation of stratum being calculated

N_i = The population size for any stratum i

σ_i = The standard deviation for any stratum i.

Note: The denominator of the Neyman allocation formula which is $\Sigma (N_i * \sigma_i)$ is the sum of the population size and standard deviation of ***all strata calculated individually****. While the use of i in this context is common mathematical notation, that may not be known to the entire target audience of this report.*

Other notes

- The 95% confidence interval for the revised strata in Table 2 should not be calculated until a new survey has been done with samples generated specifically for the new revised strata boundaries.

Appendix 2 – ArcGIS and Kriging

The farm SOCS heat map was created using kriging through the geostatistical wizard in ArcGIS Pro version 3.1.2. All default settings were used.

Key Settings:

- Data source: Sample site coordinates and corresponding SOCS values
- Kriging type: Simple
- Variogram model: Covariance
- Transformation: Normal Score Transformation
- Search neighbourhood: Standard
- Neighbours to include: 5
- Include at least: 2
- Sector type: Four and 45 degree
- Model Type: Stable
- Output cell size: 8 x 8 metres
- Extent: Large enough to cover all of the paddocks

Screenshot of kriging method report:

Method Report

Input datasets	
⊟ **Dataset**	
Type	Feature Class
Data field 1	AllLocationsOrganised_XYTableToPoint.TotalSOCSforKriging
Records	123
⊟ **Method**	**Kriging**
Type	Simple
Output type	Prediction
⊟ **Dataset #**	1
Trend type	None
⊟ **Transformation**	Normal Score Transformation
Approximation	DensitySkew
Kernels	4
BaseDistribution	Student's t-distribution
⊟ **Searching neighborhood**	Standard
Neighbors to include	5
Include at least	2
Sector type	Four and 45 degree
Major semiaxis	442.476750301845
Minor semiaxis	442.476750301845
Angle	0
⊟ **Variogram**	Covariance
Number of lags	12
Lag size	58.210750720857
Nugget	0.722036148477
Measurement error %	100
⊟ **Model type**	Stable
Parameter	2
Range	442.476750301845
Anisotropy	No
Partial sill	0.380581831811

Appendix 3 – Sampling equipment list

- 4.2cm diameter, 1 metre long corer
- Waratah rammer
- Large jack
- Long pole
- Clean water
- Damp cleaning cloth
- Half pipe
- Knife
- Plastic sample bags
- Sample labelling paper
- Chilly bins for sample storage
- RTKGPS system
- Inclinometer
- Backup GPS system
- Bung for corer
- Plank of wood

Appendix 4 – Soil sample respiration experiment methods

Objective

To set up an experiment to quantify the loss of soil organic carbon in soil samples kept in storage before analysis and compare any difference between fully air-dried and imperfectly dried soil samples.

Context

During a larger study to assess the total SOCS on a Taranaki dairy farm, a subset of samples in the trial were imperfectly dried, leaving them with 10 – 26% moisture content for approximately 2 months of storage in air-tight bags. In theory, microbial respiration could continue while the moist samples are in storage. Meanwhile properly dried samples are the least conducive to microbial respiration. If true, this could cause a loss of carbon from the moist samples to airborne CO_2, resulting in inaccurate readings of the carbon content of moist samples, especially relative to the properly dried samples.

Duration of experiment

The experiment duration was intended to last approximately 3 weeks since this was as long as the experiment could be run while leaving sufficient time to analyse the data and incorporate the results into the larger study. Three weeks was enough to accurately reflect any changes which may have happened within the two-month storage period without having to run this experiment for two months. Due to practical reasons while running the experiment, the final experiment length was 26 days.

Treatments

The experiment consisted of 40 samples which were taken from 20 original soil samples. 10 of the 20 original soil samples were the 10 highest soil moisture content samples from a depth of 0 – 15 cm depth and the other 10 of the 20 original soil samples were from a depth of 45 – 60 cm deep. With 20 samples prepared, each one was then split into two so that there was one moist subsample and a dry subsample which was air dried before the

experiment. Alongside a blank control sample which had no soil in it, this resulted in a total of 41 samples.

This allows the impact of soil moisture during sample storage to be assessed at both extremes of the soil depth spectrum, maximising the applicability of our findings to the original trial. Furthermore, the highest soil moisture content samples were selected as opposed to selecting a range of different samples because the highest moisture content samples are all Egmont black loam due to its high moisture retention. Egmont black loam also has the highest soil carbon concentration and consequently, these samples are likely to have the highest microbial counts, increasing potential carbon loss to respiration. This means that if any samples were to lose soil carbon to respiration in storage, it was most likely going to be these samples.

The sub-samples were dried to the following moisture contents:

- A high moisture content treatment which remained at its initial moisture content between 19.8 – 26.3%.
- A fully air-dried control treatment where the sample was dried until it reached a stable weight.

The target sample weight was 20g for each sub-sample as this is sufficiently large for all measurements to be reliable while leaving some soil remaining as an archive sample.

Equipment

- Incubator which can be set to 15°C
- 41 x 500 mL jars and corresponding lids
- 41 x 50 mL conical flasks
- Volumetric dispenser
- 1L of 0.5 M NaOH solution
- 20 mL burette
- 200 mL 1 M BaCl
- 1L 0.5 M HCl
- Phenolphthalein indicator
- Weighing scales

Experimental Setup

First, the incubator should be turned on to 15°C to best replicate the storage conditions for samples in the Kavanagh farm SOCS benchmarking. Once all soil samples have been prepared and the incubator is set up, the next few steps must be performed consecutively, one jar/sample at a time to ensure minimal exposure of soil and NaOH solution to the air. First, each soil sample is to be poured into its own jar and the empty conical flask is placed on top of the soil inside the jar. Finally, using the volumetric dispenser, 20 mL of 0.5 M NaOH solution is added to the conical flask before the lid of the jar is placed on top and screwed on tight. Once all 41 jars have been prepared, they are placed inside the incubator which is set to 15°C until the experiment is finished.

Once the incubation period is complete, jars can be removed from the incubator and the following steps are once again to be completed one jar at a time to minimise exposure of the NaOH solution to air. First, the jar is opened, and the conical flask is removed. 4 mL of 1 M BaCl is added using a volumetric dispenser before being mixed by gently shaking the flask. This removes Na2CO3 from the solution, leaving just NaOH which will react with HCl in a later step. Following this, three drops of phenolphthalein solution is added to the flask to act as an indicator. Next, a 20 mL burette is filled with 0.5 M HCl solution and this is used to titrate the remaining NaOH in the conical flask. It is important during this titration process to constantly mix the solution in the flask gently and slowly add more HCl until the solution changes colour. Once this is done, the volume of HCl used is recorded to calculate the quantity of CO_2 in the jar which was absorbed by the NaOH solution in the jar throughout incubation.

Calculations

After data from the experiment was collected, the carbon respired by the soil in the experiment was converted from µg CO_2/g soil/day into the loss of carbon in t C ha^{-1} which the loss of carbon from the sample in storage would be equivalent to for the field reading.

Statistical Analysis

RStudio version 2023.12.1+402 was again used for the statistical analysis. First, a summary of the data was produced including the following microbial activity values;

minimum, 1st quartile, median, mean, 3rd quartile and maximum. Following this, a box and whisker plot was made visually compare the different treatments. Next, a one-way F-test with ANOVA was performed comparing all 4 treatments to see if there was a statistically significant difference between the means of the treatments. Finally, we performed a Tukey test to identify which treatments were significantly different from each other.

Appendix 5 – Data tables

Table 5A: Data summary of the revised strata, including the pooled standard deviation of each stratum, the optimum sample size for each stratum for a 120-sample survey (based on a Neyman distribution) and the land area of each stratum.

Strata	High	Medium-High	Medium-Low	Low	Total
Standard deviation (t C ha^{-1})	39.26	25.94	30.28	37.93	31.93
Sample size	34	56	20	10	120
Proportion of land area of farm (m^2)	412408	1182852	593200	127145	2315605

Table 5B: The average SOCS content of each stratum by depth for the initial stratification (t C ha^{-1}).

Depth	Strata				
	A	B	C	D	Bund
0 – 15 cm	103.20	114.86	103.14	89.30	90.30
15 – 30 cm	56.27	60.67	64.09	46.90	64.71
30 – 45 cm	31.14	31.23	36.06	30.72	38.01
45 – 60 cm	26.94	25.03	27.01	23.55	14.92
Total 0 – 60 cm	217.56	231.79	230.30	190.48	207.95

Table 5C: The standard deviation of the SOCS values within each stratum from the initial stratification (t C ha^{-1}).

Depth	Strata				
	A	B	C	D	Bund
0 – 15 cm	12.21	26.74	14.62	31.22	4.27
15 – 30 cm	9.31	18.41	17.17	30.03	26.43
30 – 45 cm	4.90	7.51	15.53	21.38	19.93
45 – 60 cm	4.08	8.23	13.03	16.38	4.36
Total 0 – 60cm	20.54	40.88	46.22	69.69	N/A

Table 5D: Data summary of the initial strata, including the pooled standard deviation, the sample size, the land area of each stratum and the weighted mean SOCS of the full data set.

Strata	A	B	C	D	Total
Standard deviation	20.54	40.88	46.22	69.69	40.43
Sample size	30	30	30	30	120
Proportion of land area of farm (m^2)	999,273	754,922	229,312	332,145.89	2,315,653.13
Weighted mean SOCS (t C ha^{-1})					219.57

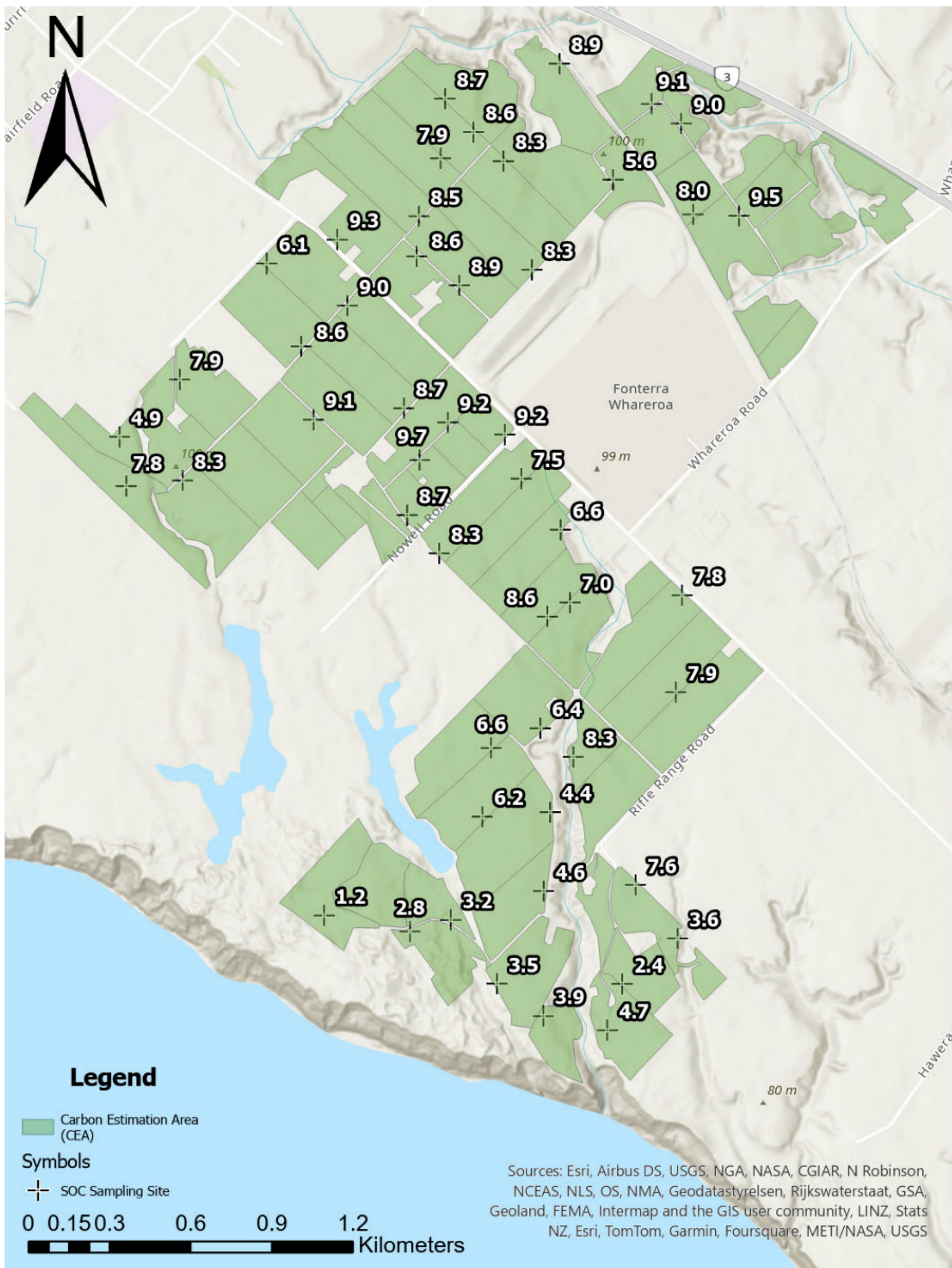
Appendix 6 – Preliminary SOCS data

The preliminary SOCS data was sourced from a pre-existing data set from soil carbon samples taken along fence lines to a depth of 15 cm in January 2022. SOCS was estimated by also using data from an incomplete set of bulk density measurements taken in April 2022. The soil %C was mapped on its own due to the incomplete soil bulk density data. With only 12 samples for 50 soil carbon samples, the data on estimated SOCS down to 15 cm was very limited. However, when combined with other ancillary variables such as soil type, for the purpose of identifying areas of significantly different SOCS values to the rest of the farm, this data was helpful in the initial strata drawing process.

Table 6A. The carbon concentration (%C) and GPS co-ordinates of all of the data points in the preliminary SOCS data.

0-15 cm Total Carbon %	NZTM Easting	NZTM Northing	0-15 cm Total Carbon %	NZTM Easting	NZTM Northing	0-15 cm Total Carbon %	NZTM Easting	NZTM Northing
9.5	1711795	5615492	7.8	1710036	5614749	4.6	1711210	5613581
8.0	1711664	5615498	4.9	1710019	5614889	2.8	1710827	5613472
9.0	1711634	5615757	9.1	1710573	5614930	1.2	1710583	5613521
9.1	1711550	5615814	8.7	1710831	5614959	2.4	1711430	5613314
5.6	1711437	5615600	9.2	1710956	5614917	3.2	1710944	5613503
8.9	1711289	5615932	9.7	1710874	5614811	3.5	1711073	5613320
8.3	1711202	5615347	9.2	1711118	5614880	3.9	1711204	5613226
8.9	1710994	5615306	8.7	1710836	5614655	4.7	1711386	5613183
8.5	1710882	5615504	8.3	1710926	5614545	3.6	1711590	5613441
8.7	1710961	5615837	7.5	1711163	5614754	7.6	1711472	5613595
8.6	1711041	5615741	6.6	1711273	5614607			
8.3	1711125	5615657	8.6	1711232	5614361			
9.3	1710648	5615441	7.0	1711297	5614400			
8.6	1710874	5615390	7.8	1711617	5614416			
9.0	1710674	5615253	7.9	1711595	5614141			
6.1	1710446	5615376	8.3	1711300	5613961			
8.6	1710541	5615139	6.4	1711207	5614044			
7.9	1710946	5615668	6.6	1711066	5613990			
7.9	1710193	5615050	4.4	1711232	5613805			
8.3	1710197	5614763	6.2	1711038	5613795			

Figure 6A. A map showing all sampling sites from the preliminary SOCS data and their corresponding carbon concentrations (%C). This data was taken in January 2022.



Appendix 7 – Calculations to make future SOCS change estimates and CO_2 to C conversion

Future SOCS change estimates

Inversion tillage

Base estimate: 0.56 t C ha^{-1} $year^{-1}$

"In the 20 years following FIT pasture renewal, soil C was predicted to increase by an average of 7.3–10.3 (Sedimentary soils) and 9.6–12.7 t C ha^{-1} (Allophanic soils), depending on the assumptions applied." – Lawrence-Smith et al., (2021).

This value was calculated by taking the mean value (11.15) of the predicted SOCS increase for Allophanic soils (9.6 – 12.7 t C ha^{-1}) and dividing it by the 20-year time frame this was quoted for.

$$11.15 / 20 = 0.56 \text{ t C ha}^{-1} \text{ year}^{-1}$$

Optimistic estimate: 1.7 t C ha^{-1} $year^{-1}$

The average rate of sequestration on a podzol soil on the West Coast of the South Island was 1.2 t C ha^{-1} $year^{-1}$ (Schiedung et al., 2019). However, proportional to the total SOCS, this is a 1% increase in SOCS per year. A 1% increase on the Kavanagh farm would be 2.2 t C ha^{-1} $year^{-1}$. The average between these two values created by two different extrapolation methods is 1.7 t C ha^{-1} $year^{-1}$.

Highest estimate: 2 t C ha^{-1} $year^{-1}$

An increase of 13.9 t C ha^{-1} was observed over a four-year period (Calvelo-Pereira et al., 2018). This equated to an 18% increase in SOCS over 4 years. This is a 3.5 t C ha^{-1} $year^{-1}$ increase or a 4.5% annual increase. A 4.5% annual increase equates to a 9.88 t C ha^{-1} $year^{-1}$ increase for the Kavanagh farm, but this does not seem plausible. This is because this rate of sequestration exceeds the rate of carbon input into soil by pasture. Pasture inputs approximately 1.32 t C ha^{-1} $year^{-1}$ directly to the soil and an additional 6.82 t C ha^{-1} $year^{-1}$ into root biomass, of which, a much smaller fraction will end up in the soil as SOCS as root biomass turns over (Saggar & Hedley, 2001). Consequently, it would seem improbable for SOCS increases to

scale proportionally at the rate observed in the study by Calvelo-Pereira et al. (2018), so we will use the already relatively high rate of 3.5 t C ha^{-1} $year^{-1}$. The values for this section of the report are the average annual sequestration across the approximately 20-year period before SOCS find a new equilibrium after changes are made (Caruso et al., 2018). So, for simplicity of calculation, we will assume a linear decay of the annual increase in SOCS (the real decay would likely not be linear, but this is only an estimation). Starting from a high of 3.5 t C ha^{-1} $year^{-1}$ in years 1-4 and a low of 0 t C ha^{-1} $year^{-1}$ in year 20, the average annual increase in SOCS over 20 years is 2.0125 t C ha^{-1} $year^{-1}$ or approximately 2 t C ha^{-1} $year^{-1}$.

Biochar

Base estimate: 1.1 t C ha^{-1} $year^{-1}$

4.5 t C ha^{-1} is the low end of the 95% confidence interval for field studies of a duration between 3 – 5 years. Taking an average duration of 4 years, 4.5 t C ha^{-1} / 4 years = 1.125 t C ha^{-1} $year^{-1}$ or approximately 1.1 t C ha^{-1} $year^{-1}$ (Gross et al., 2021).

Optimistic estimate: 2.5 t C ha^{-1} $year^{-1}$

Application of biochar at a relatively low rate of 7 t ha^{-1} $year^{-1}$ increased soil organic carbon sequestration by 2.5 t C ha^{-1} $year^{-1}$ relative to the control treatment. This sequestration is on top of the carbon content of the applied biochar (Gross et al., 2022). 2.65 t C ha^{-1} $year^{-1}$ was also sequestered over a 6-year study in the US excluding the carbon added directly through the biochar (Blanco-Canqui et al., 2020).

Highest estimate: 4.4 t C ha^{-1} $year^{-1}$

The one-off application of 7.25 t C ha^{-1} on cropping land in the Midwest US lead to a ~ 2% annual increase in SOCS over the control treatment (Blanco-Canqui et al., 2020). Applying this to Kavanagh's 219.6 t C ha^{-1} would mean a 4.4 t C ha^{-1} $year^{-1}$ increase in SOCS. The increase in SOCS in this study includes carbon added directly through the application of biochar and it is worth noting that the one-off application in this study of 7.25 t C ha^{-1} is low relative to other studies reviewed by Gross et al. (2021) which see applications of over 30 t ha^{-1} over 3 – 10 years. Another key consideration to large applications of biochar is a life cycle assessment

of the source of the biochar. The production of the biochar may have a carbon footprint or other environmental or farm management impacts which changes the net impact of biochar amendments when considering the full carbon footprint beyond just the scope of SOCS.

CO_2 to SOC conversion

The equivalent CO_2 emissions from the Kavanagh farm was converted into the corresponding mass of SOCS needed to be sequestered to offset those emissions and vice versa. Doing this involves using a conversion factor due to carbon being measured directly by the mass of carbon in the soil while CO_2 emissions are measured in t of CO_2 molecules, of which, only a fraction is carbon. Hence, a conversion factor based on the mass of carbon in a CO_2 molecule is used (Pennsylvania State University, 2023). This is the same conversion factor used for converting CO_2 to t C sequestered in trees.

Approximate mass of a carbon atom: 12
Approximate mass of a CO_2 molecule: 44
Conversion factor = 44 / 12 = 3.6667
Inverse conversion factor = 12 / 44 = 0.2727

Examples:

*1 t C ha^{-1} * 100 ha = 100 t C sequestered across the full farm.*
*100 t C * 3.6667 = 366 t CO_2 equivalent sequestered.*

*1,000 t CO_2 equivalent in emissions across the full farm * 0.2727 = 272.7 t C sequestered in soil to offset emissions.*
272.7 t C / 100 ha = 2.727 t C ha^{-1} in sequestration required to offset emissions.

Appendix 8 – Raw survey data

Table 8A. NZTM 2000 GPS co-ordinates of final soil core sampling positions for Kavanagh Farm (Dairy Trust Taranaki) located near Hawera, South Taranaki and sampled from the 17th August – 20th September 2023.

	Strata A		Strata B		Strata C		Strata D			Bund	
Sample No.	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Bund No.	Latitude	Longitude
1	5615927.25	1711550.06	5614642.96	1711059.97	5614103.62	1711084.14	5613442.31	1711182.82	1	5615142.95	1711061.64
2	5615148.21	1710578.54	5615433.89	1712220.33	5613871.01	1711138.14	5613498.46	1711350.31	2	5615159.07	1711112.23
3	5615759.57	1710746.44	5614644.59	1710093.48	5613679.47	1711120.79	5613568.11	1711000.97	3	5615282.13	1711264.87
4	5614985.98	1710568.37	5614617.00	1710744.78	5613945.05	1711065.73	5613315.80	1711400.27	4	5615314.10	1711333.83
5	5614200.96	1711548.55	5615820.26	1711143.49	5614012.67	1710977.86	5613338.81	1710989.05			
6	5614343.02	1711515.63	5615877.81	1711227.45	5613976.39	1711074.56	5613443.07	1711045.74			
7	5615873.50	1710897.86	5614452.27	1711360.70	5614100.24	1711004.01	5613270.73	1711480.18			
8	5615536.24	1710904.38	5615329.33	1711895.69	5613957.33	1710978.11	5613577.49	1710649.02			
9	5615268.17	1711087.83	5614791.68	1710451.30	5614199.36	1711219.98	5613788.56	1711163.39			
10	5614933.95	1710374.39	5614542.17	1711052.63	5613912.26	1711006.65	5613523.17	1710514.75			
11	5614900.16	1710873.18	5614863.50	1710332.08	5614017.21	1711412.36	5613176.69	1711529.27			
12	5614672.19	1710835.20	5614613.60	1711105.07	5614066.38	1711090.34	5613486.00	1710589.15			
13	5614640.61	1710689.21	5615761.00	1711458.33	5613775.67	1711363.43	5613374.51	1710938.68			
14	5614589.92	1710530.83	5614530.94	1710297.76	5613734.78	1711345.89	5613366.64	1711436.30			
15	5615852.85	1710861.40	5614654.49	1710424.61	5613493.43	1711457.09	5613532.90	1711124.31			
16	5615027.72	1710695.57	5614871.10	1710269.00	5613888.03	1710876.50	5613433.35	1711420.71			
17	5614893.87	1711079.99	5615453.02	1712239.48	5613952.92	1711489.52	5613565.27	1710937.01			
18	5615201.28	1710900.76	5614568.95	1710165.79	5613745.23	1710956.85	5613575.04	1710891.71			
19	5614978.25	1710461.04	5615548.83	1711170.62	5614202.24	1711095.32	5613350.32	1711584.65			
20	5613868.33	1711466.07	5614821.43	1710071.22	5614063.77	1711363.77	5613367.77	1711230.22			
21	5615491.39	1711035.44	5614672.23	1710355.59	5614027.15	1711047.76	5613512.96	1710827.23			
22	5614810.76	1710493.59	5614644.59	1711244.23	5613864.09	1710891.16	5613359.98	1711491.39			
23	5615123.18	1711904.34	5615585.55	1711984.03	5613721.90	1711095.68	5613202.36	1711257.38			
24	5615413.14	1711059.07	5615465.63	1712005.02	5614093.83	1711029.63	5613582.17	1710481.16			
25	5614033.46	1711604.95	5614390.43	1711102.41	5613495.97	1711509.29	5613327.30	1711660.40			
26	5615262.98	1710848.35	5614442.48	1711237.08	5613726.27	1711057.39	5613330.74	1711513.93			
27	5615163.88	1711856.81	5615495.61	1712269.68	5613852.42	1710988.80	5613300.83	1711210.89			
28	5615271.53	1710813.32	5615591.00	1711445.03	5613712.39	1711175.99	5613283.32	1711661.97			
29	5614227.04	1711410.17	5614753.74	1710030.28	5613642.48	1711382.04	5613430.83	1711124.54			
30	5615149.14	1710436.95	5615888.39	1711149.79	5613992.56	1710931.37	5613629.56	1710579.70			

Table 8B. Soil carbon concentration (%C moisture adjusted) for each sampling strata and depth for Kavanagh Farm (Dairy Trust Taranaki) located near Hawera, South Taranaki and sampled from the 17th August – 20th September 2023.

	Strata A				Strata B				Strata C				Strata D			
Sample No.	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**
1	7.80	5.11	1.74	1.66	10.82	4.75	2.28	2.00	8.96	4.98	2.63	2.11	7.98	5.25	2.63	2.31
2	6.78	4.93	2.07	1.51	7.56	6.17	1.39	0.04	8.54	6.04	3.19	1.64	6.70	2.77	1.10	0.74
3	8.58	4.70	2.08	1.84	10.32	4.89	2.14	1.67	5.67	4.63	2.27	1.92	2.00	2.85	1.70	2.23
4	9.10	6.43	2.98	2.10	7.77	1.25	0.79	1.42	9.11	5.22	2.05	1.82	6.81	1.19	1.51	0.45
5	9.05	4.02	2.06	2.03	9.25	4.00	2.30	1.92	7.35	4.98	2.36	2.16	1.84	0.41	0.15	0.14
6	8.34	4.59	2.21	2.07	11.12	3.81	2.26	1.65	7.17	4.69	2.78	2.20	2.20	2.26	2.56	1.40
7	9.04	5.15	2.77	2.56	6.82	7.08	3.50	2.19	7.43	3.54	2.13	1.48	7.69	4.09	3.06	2.57
8	10.20	4.23	2.58	2.14	4.73	1.76	1.26	1.53	7.78	5.16	2.58	1.84	1.72	0.21	0.36	1.48
9	10.26	4.69	2.30	1.86	8.69	4.38	2.27	2.06	7.50	4.84	1.84	0.35	8.31	5.43	2.46	1.87
10	8.54	5.40	3.39	2.40	9.19	5.03	3.18	3.11	7.81	5.01	2.92	2.11	4.20	0.87	0.16	0.11
11	9.73	4.90	2.69	1.84	8.73	5.63	3.28	2.03	8.13	3.13	1.21	0.90	6.77	3.31	3.63	3.48
12	9.79	4.41	2.86	2.41	10.29	5.95	1.99	1.79	9.88	4.39	2.35	2.37	2.28	1.33	2.00	0.45
13	9.18	5.22	3.70	2.52	8.44	0.60	1.44	1.81	7.82	3.57	1.85	1.45	3.84	1.11	0.29	0.12
14	8.38	4.05	1.99	2.21	9.15	4.51	2.28	1.69	8.96	7.93	6.26	6.07	6.54	3.90	2.99	2.47
15	7.61	4.41	2.21	1.85	11.13	5.43	2.52	1.99	9.03	5.77	3.97	2.86	6.86	2.05	0.64	0.73
16	10.62	3.91	2.22	2.00	9.20	5.19	3.42	2.99	5.23	3.19	2.39	1.84	8.47	5.10	2.73	2.18
17	10.71	5.06	2.42	1.96	9.79	5.85	2.78	2.25	7.29	4.53	1.67	1.63	5.23	1.12	0.18	0.13
18	9.36	4.50	2.88	2.00	11.73	3.12	1.76	1.64	2.83	2.18	2.64	1.77	4.23	0.18	0.10	0.07
19	9.42	4.00	1.89	1.60	11.52	9.93	2.86	1.66	8.58	7.03	4.84	2.32	3.19	0.78	3.90	3.68
20	8.19	4.23	2.15	2.11	9.93	5.75	2.44	1.51	7.36	1.63	0.14	0.21	7.14	3.56	2.89	2.60
21	10.24	3.95	2.24	2.12	10.18	4.51	2.70	1.99	6.92	3.78	2.84	1.71	2.31	0.20	0.10	0.07
22	9.53	4.67	2.23	2.23	9.74	5.41	2.84	2.03	5.74	5.13	3.19	2.43	7.93	5.26	3.39	2.88
23	9.05	6.79	4.14	2.53	9.28	4.38	1.87	1.56	6.70	5.47	3.32	2.50	4.56	1.85	2.47	1.76
24	9.42	2.80	2.15	2.16	11.36	5.40	3.04	2.08	8.72	4.71	2.29	1.85	6.56	2.80	0.34	0.16
25	8.61	5.09	2.56	1.73	9.84	6.39	3.02	2.41	9.29	5.20	2.57	1.74	2.53	3.21	6.91	3.85
26	9.65	4.97	2.12	1.93	9.58	3.23	1.91	1.58	3.00	2.89	2.87	2.32	7.59	5.55	3.19	2.39
27	8.52	4.32	2.64	2.16	10.18	6.96	4.22	3.28	8.36	4.59	2.57	2.05	3.75	1.79	1.18	1.72
28	9.47	5.53	3.67	2.38	7.04	4.23	3.06	1.95	7.27	5.94	3.46	2.85	9.98	7.65	2.91	2.02
29	4.62	3.88	1.53	1.59	8.92	4.61	2.58	1.83	8.83	4.60	2.88	2.07	9.29	1.17	2.22	2.13
30	7.64	3.45	1.80	1.62	9.38	5.00	2.66	2.07	8.43	1.95	1.12	0.62	3.59	0.46	0.04	0.05

Table 8C. Soil bulk density (g/m^3) for each sampling strata and depth for Kavanagh Farm (Dairy Trust Taranaki) located near Hawera, South Taranaki and sampled from the 17th August – 20th September 2023.

	Strata A				Strata B				Strata C				Strata D			
Sample No.	0-15cm	15-30cm	30-45cm	45-60cm	0-15cm	15-30cm	30-45cm	45-60cm	0-15cm	15-30cm	30-45cm	45-60cm	0-15cm	15-30cm	30-45cm	45-60cm
1	0.81	0.81	1.33	0.87	0.64	0.80	0.84	0.90	0.76	0.82	0.67	0.88	0.96	1.06	0.92	0.81
2	0.74	0.83	1.36	0.84	0.45	0.81	1.22	1.25	0.89	0.89	0.85	0.95	0.79	1.13	1.11	0.80
3	0.80	0.78	0.87	0.93	0.86	0.90	0.78	0.81	1.08	0.98	0.85	0.86	1.54	1.66	1.44	1.19
4	0.77	0.78	0.76	0.72	0.85	1.13	1.17	1.00	0.88	0.86	0.88	0.96	1.00	1.19	1.04	1.05
5	0.82	0.82	0.90	0.87	0.75	0.83	0.82	0.91	0.96	0.97	0.85	0.89	1.49	2.01	1.60	1.65
6	0.79	0.83	0.85	0.91	0.71	0.78	0.85	0.96	0.92	0.77	0.79	0.88	1.59	1.75	1.52	1.47
7	0.78	0.79	0.84	0.84	0.86	0.80	0.98	0.88	0.91	0.90	0.80	0.87	1.03	1.01	0.96	0.86
8	0.75	0.80	0.88	0.87	1.06	1.35	1.36	0.21	0.88	0.87	0.84	0.83	1.32	1.18	2.05	2.03
9	0.75	0.79	0.86	0.90	0.86	0.88	0.93	0.94	0.92	0.95	1.33	1.52	0.89	0.87	0.85	0.92
10	0.85	0.95	0.83	0.94	0.84	0.82	0.74	0.76	0.95	0.96	0.91	0.92	1.44	1.72	1.93	2.32
11	0.73	0.80	0.82	0.93	0.82	0.80	0.81	0.95	0.88	0.95	0.93	1.23	1.02	1.17	1.01	0.98
12	0.74	0.79	0.81	0.88	0.76	0.80	0.94	0.90	0.86	0.82	0.83	0.92	1.42	1.35	1.59	1.39
13	0.72	0.78	0.63	0.85	0.83	1.62	1.33	1.00	0.88	0.86	0.90	1.00	1.39	1.69	1.50	2.50
14	0.78	0.87	0.91	0.90	0.78	0.90	0.82	0.90	0.92	0.87	0.94	0.91	0.93	1.52	0.81	0.78
15	0.80	0.72	0.99	0.90	0.82	0.90	0.84	0.89	0.81	0.94	0.91	0.93	1.37	0.87	1.08	1.17
16	0.75	0.80	0.85	0.87	0.88	0.85	0.65	0.82	1.00	1.07	0.98	0.86	0.92	1.44	0.83	0.94
17	0.79	0.86	0.87	0.93	0.76	0.77	0.78	1.32	0.87	0.83	0.97	0.96	1.26	0.98	2.09	1.22
18	0.75	0.80	0.89	1.03	0.82	0.93	0.79	0.97	1.54	1.71	1.17	1.05	1.49	1.93	2.19	2.51
19	0.71	0.83	0.94	0.95	0.74	0.72	0.88	1.00	0.88	0.92	0.83	0.89	1.19	1.93	0.98	0.84
20	0.89	0.84	0.89	0.86	1.09	0.91	0.85	0.81	0.95	1.14	1.31	1.27	1.03	1.24	0.98	0.90
21	0.75	0.82	0.92	0.94	1.34	0.93	0.77	0.70	0.94	0.89	0.80	0.89	1.46	2.16	2.16	2.50
22	0.83	0.88	0.80	0.91	0.78	0.80	0.78	0.88	1.04	1.12	1.02	0.96	0.85	0.97	0.90	0.77
23	0.75	0.76	0.53	0.96	0.80	0.78	0.94	0.90	1.03	0.89	0.73	0.72	1.26	1.41	1.34	1.07
24	0.74	0.86	0.89	0.88	0.75	0.81	0.81	0.86	0.88	0.89	0.87	0.91	1.17	1.43	2.47	2.46
25	0.77	0.71	0.79	0.86	0.73	0.68	0.70	0.86	0.78	0.88	0.91	0.90	1.21	1.08	0.83	0.87
26	0.71	0.75	0.85	0.86	0.78	0.77	0.72	0.86	1.49	1.53	1.02	1.05	0.81	0.93	0.84	0.88
27	0.75	0.75	0.74	0.82	0.70	0.78	0.76	0.69	0.98	0.97	0.85	0.82	1.83	1.63	1.68	1.32
28	0.67	0.77	0.63	0.69	0.93	1.02	0.86	0.94	0.87	0.93	0.83	0.70	0.73	0.90	0.87	0.91
29	0.95	0.85	0.93	0.90	0.81	0.92	0.84	0.90	0.76	0.89	1.30	0.92	1.18	1.82	1.46	1.30
30	0.86	0.88	0.83	0.92	0.80	0.80	0.76	0.70	0.89	0.99	1.09	1.33	1.48	1.94	2.12	2.49

Table 8 D. Soil organic carbon stocks (kg C/ha) by strata and depth for Kavanagh Farm (Dairy Trust Taranaki) located near Hawera, South Taranaki and sampled from the 17th August – 20th September 2023

	Strata A				Strata B				Strata C				Strata D			
Sample No.	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**	**0-15cm**	**15-30cm**	**30-45cm**	**45-60cm**
1	94.50	61.97	34.62	21.56	103.95	56.89	28.64	26.85	102.23	61.01	26.39	27.65	115.17	83.61	36.13	28.17
2	74.80	61.20	42.22	19.02	50.80	74.83	25.45	0.77	114.07	80.32	40.78	23.54	79.84	47.03	18.23	8.91
3	103.41	55.32	27.25	25.71	133.70	66.24	25.13	20.34	91.59	67.79	28.90	24.90	46.23	70.87	36.81	39.71
4	104.87	75.09	33.87	22.60	99.01	21.08	13.90	21.33	120.98	67.42	27.07	26.28	102.30	21.10	23.47	7.01
5	111.66	49.49	27.91	26.49	103.90	49.64	28.15	26.16	106.07	72.24	30.25	28.66	41.11	12.45	3.62	3.49
6	98.57	56.98	28.13	28.18	118.31	44.36	28.86	23.90	99.40	54.36	33.11	29.00	52.56	59.10	58.31	30.83
7	105.80	61.06	34.81	32.21	87.91	84.86	51.60	29.00	101.34	47.61	25.64	19.34	118.62	62.29	44.02	33.03
8	115.45	50.62	33.91	27.90	75.04	35.65	25.57	4.83	103.06	67.23	32.60	23.05	34.14	3.73	11.12	45.01
9	116.13	55.77	29.66	25.16	112.12	57.55	31.61	28.90	103.40	68.65	36.52	8.09	111.25	70.85	31.49	25.98
10	108.63	76.81	42.08	33.85	115.16	62.02	35.06	35.56	111.40	71.88	39.96	29.01	90.95	22.28	4.64	3.84
11	107.23	58.60	32.95	25.73	107.49	67.77	39.68	29.14	106.76	44.73	16.80	16.49	103.31	58.03	54.99	51.33
12	107.96	52.12	34.67	31.86	117.80	71.62	28.14	24.05	127.32	53.91	29.38	32.67	48.50	26.99	47.83	9.45
13	98.99	61.28	35.20	32.09	105.47	14.58	28.77	27.28	102.82	46.15	25.03	21.87	79.75	28.19	6.55	4.51
14	98.34	53.19	27.16	29.72	107.29	60.69	27.94	22.84	123.45	103.49	88.07	83.00	91.05	88.91	36.27	28.88
15	91.48	47.75	32.75	25.03	136.64	72.97	31.76	26.74	109.85	81.18	54.34	40.12	141.26	26.68	10.28	12.78
16	119.23	46.79	28.19	26.20	121.01	66.18	33.43	36.88	78.17	50.96	35.03	23.79	116.58	110.35	33.91	30.83
17	126.61	65.55	31.53	27.46	111.58	67.55	32.29	44.29	95.29	56.30	24.28	23.61	98.57	16.35	5.68	2.40
18	104.69	53.78	38.35	30.95	144.12	43.39	20.95	23.75	65.43	55.94	46.44	27.83	94.38	5.22	3.29	2.64
19	100.88	49.88	26.59	22.70	127.65	106.51	37.90	24.92	113.72	97.05	60.19	30.97	56.76	22.69	57.18	46.24
20	109.71	53.48	28.51	27.36	161.94	78.75	31.25	18.31	104.38	27.84	2.73	3.96	110.27	65.88	42.58	34.96
21	114.78	48.38	30.71	29.99	205.16	62.64	31.31	20.92	97.09	50.27	34.07	22.88	50.57	6.49	3.25	2.63
22	118.53	61.80	26.81	30.45	114.26	65.25	33.28	26.87	89.65	86.22	48.78	35.10	100.58	76.91	45.85	33.28
23	102.22	77.22	32.85	36.51	111.20	51.44	26.47	21.07	103.33	73.09	36.19	26.92	85.89	39.02	49.56	28.17
24	103.95	36.14	28.61	28.52	128.08	65.45	37.00	26.75	115.06	62.60	29.80	25.30	114.72	60.01	12.66	5.92
25	99.00	54.58	30.42	22.26	108.16	65.47	31.65	31.17	109.26	68.89	35.18	23.54	45.85	51.73	86.43	50.02
26	102.93	55.95	27.04	25.06	112.64	37.07	20.58	20.43	67.24	66.18	43.99	36.68	92.63	77.77	40.00	31.53
27	95.63	48.58	29.27	26.49	107.64	81.23	48.02	33.91	123.04	66.92	32.62	25.32	102.80	43.82	29.66	34.05
28	95.81	63.88	34.55	24.77	98.17	64.56	39.50	27.57	94.59	82.50	43.01	29.91	109.95	103.22	37.97	27.61
29	65.88	49.23	21.24	21.46	107.99	63.61	32.54	24.67	101.33	61.06	56.30	28.42	163.71	32.03	48.64	41.51
30	98.44	45.69	22.30	22.29	112.04	60.21	30.37	21.61	112.86	28.87	18.41	12.43	79.67	13.46	1.28	1.87

Table 8E. Soil carbon concentration (%C moisture adjusted), bulk density (g/m^3) and organic carbon stocks (kg C/ha) for each depth of the bund area for Kavanagh Farm (Dairy Trust Taranaki) located near Hawera, South Taranaki and sampled from the 17th August – 20th September 2023.

Soil carbon concentration (%C moisture adjusted)				
	0-15cm	**15-30cm**	**30-45cm**	**45-60cm**
Bund 1	6.97	6.75	2.32	1.16
Bund 2	7.50	5.80	4.44	0.79
Bund 3	6.89	5.70	1.65	0.35
Bund 4	7.65	1.23	1.43	1.15
Soil bulk density (g/m^3)				
Bund 1	0.83	0.82	0.98	0.97
Bund 2	0.79	0.90	1.00	1.40
Bund 3	0.86	0.85	1.20	1.60
Bund 4	0.84	1.39	1.00	1.03
Soil organic carbon stocks (kg C/ha)				
Bund 1	86.97	82.89	34.21	16.88
Bund 2	88.57	77.92	66.83	16.56
Bund 3	89.10	72.45	29.65	8.43
Bund 4	96.57	25.58	21.37	17.81