The effects of varying intensity cultivation on soil quality in a maize cropping system

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Abstract

Maize is the primary crop grown on arable land in the Waikato region, predominantly established on Allophanic soils due to their well-drained and resilient properties. Full cultivation (FC) is universally adopted in cropping systems and associated with increased soil aeration and successful seed establishment, however, has been shown to reduce soil quality through declines in soil organic matter (SOM) and soil structure. SOM (TC & TN) decline and aggregate stability are considered important indicators of soil quality in cropping systems as they pose the greatest risk to long term productivity and profitability. Soil degradation can be reduced through conservation tillage such as no-till (NT) and strip-till (ST). Previous studies have investigated the effect of cultivation intensity on soil quality and consistently found that NT systems have greater carbon (C) levels and aggregate stability at the soil surface than higher intensity cultivation systems.

The main aim of this thesis was to determine whether there were significant differences in soil quality between varying intensity cultivation systems (FC, ST, NT) on Allophanic soils in the Hamilton Basin. Further aims were to determine whether differences in the inherent soil properties of the Horotiu silt loam and Bruntwood silt loam would influence the soil quality within the study area, and to identify whether soil quality was influenced by an interaction between cultivation intensity and soil type.

Twelve plots with four replicates of each cultivation treatment were sampled and soil quality measured using seven soil quality indicators (total C (TC), total nitrogen (TN), mineralisable nitrogen (N), soil pH, Olsen P, bulk density (BD), and macroporosity (MP)) and three additional cropping indicators (aggregate stability, penetration resistance, and visual soil assessment). Mechanically driven cores for TC and TN analysis were taken from 0 – 7.5 cm, 7.5 – 15 cm, and 15 – 30 cm. Significant differences in TC, TN, and aggregate stability in the top 10 cm were detected between cultivation treatments ($p < 0.05$). NT was shown to be the most beneficial cultivation for a maize cropping system, indicated by significantly greater TC (3.98 %), TN (0.41 %), and aggregate stability (0.97 mm, MWD) at the soil surface than higher intensity cultivation systems (For FC; TC = 3.56 %, TN = 0.37 %, aggregate stability = 0.62 mm). Additionally, significant differences in TC and TN were found between soil types, where Horotiu silt

loam had significantly greater TC and TN (e.g. for 0 – 10 cm; Horotiu: TC = 4.02 %, TN = 0.42 %; Bruntwood TC = 3.52 %, TN = 0.36 %). There were also significant differences in aggregate stability, MP, and BD between soil types, where the Horotiu silt loam had higher aggregate stability (0.82 mm, MWD), MP (14 %) and lower BD (0.96 t m^{-3}) and Olsen P (82.9 μg g^{-1}) than the Bruntwood silt loam (Aggregate stability = 0.73 mm, MP = 12 %, BD = 1.05 t m^{-3}, Olsen P = 105.5 μg g^{-1}). Where there were interactions between cultivation intensity and soil type, significant differences were detected in aggregate stability and penetration resistance, where the Horotiu silt loam under NT had higher aggregate stability (1.07 mm, MWD) and penetration resistance (2.00 MPa) than all other combinations. Conversely, the Bruntwood silt loam under FC had the lowest aggregate stability (0.55 mm, MWD) and penetration resistance (1.63 MPa).

Many of the soil quality values in the study area fell below or exceeded target ranges set for cropping systems, regardless of cultivation treatment or soil type. This is due to the intensive nature of cropping systems, use of heavy machinery, removal during harvest, and poorly defined target ranges. This study highlights how differences in inherent soil properties between two soil types within the same soil order can greatly influence soil quality. Previous data showed cultivation intensity did not significantly influence maize yield at this stage in the trial. This research therefore suggests NT systems result in higher SOM content and greater aggregate stability and therefore may be a more suitable cultivation system for continuous maize cropping without decreasing productivity or profitability.

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Chapter 1

Introduction

1.1 Background

Soil quality is defined as "the capacity of a specific soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Soil Science Society of America, as cited in Lilburne *et al.*, 2004). Or more simply, "fitness for use" where a soil's quality is determined by its ability to match soil conditions suited to a certain land use and to maintain this fitness in the long term (Schipper & Sparling, 2000). Soil quality is essential to the overall productivity and health of land as it supports a range of ecosystem services that primary production relies on (Mackay *et al.*, 2013), including food and fiber production, nutrient provisioning and cycling, climate regulation and carbon storage, water provision and quality maintenance, pollutant degradation and pest control, and conservation of biodiversity (Vogel *et al.*, 2018). Where soil quality is degraded, the capability to support these essential services and its fitness for use is reduced, therefore reducing productivity and profitability, and implicating other domains of the environment such as water quality (Ministry for the Environment (MfE) & Statistics New Zealand (StatsNZ), 2018).

In New Zealand (NZ), specific pressures are applied to soils as a result of land use intensification and land use changes that impact quality and versatility of soil resources through changes in soil physical, chemical, and biological properties (MfE & StatsNZ, 2018). These include inadequate vegetation cover during cultivation and harvesting of crops and poor matching of land use to soil capability (Ministry for Primary Industries (MPI), 2015). A nationally consistent set of soil quality indicators are used to monitor soil quality in NZ, comprising a range of soil physical, chemical, and biological properties that can indicate changes in soil quality in response to land use, as identified in the "500 Soils" project (Lilburne *et al.*, 2004; Sparling & Schipper, 2004; Sparling *et al.*, 2004). These indicators include total carbon, total nitrogen, mineralisable nitrogen, soil pH, Olsen P, bulk density, and macroporosity. Other indicators have been identified as

valuable for cropping systems by the Land Monitoring Forum (2009), and include aggregate stability, penetration resistance, and visual soil assessments (VSA). The seven soil quality and additional cropping indicators allow for interpretation of data and comparison with target ranges to identify trends and issues in soil quality.

A large focus in cropping systems is the preservation of soil organic matter (SOM). SOM is essential for life and productivity in soil, made up largely of carbon and nitrogen from organic matter and its decomposition (Abreu *et al.*, 2011; Taylor *et al.*, 2017). SOM increases soil fertility and improves biological and physical soil properties (West & Post, 2002; Diekow *et al.*, 2005; Deb *et al.*, 2015). SOM enhances soil microbial activity and biodiversity through an additional metabolic energy source (Black & Bauer, 1983; Haddaway *et al.*, 2016). SOM is strongly related to aggregate formation and stability, where SOM helps to bind and form soil aggregates, and in turn aggregates aid in physical protection and preservation of SOM (Deb *et al.,* 2015; Landcare Research Manaaki Whenua (LCRS-MW), 2020). Improved soil structure and soil conditions allow for efficient air and water movement and productive plant growth (McLaren & Cameron, 1996; Diekow *et al.*, 2005). Loss of SOM is of large concern under cropping systems as it is accelerated through cultivation and harvesting, resulting in the rate of organic matter removal being much higher than that being put in (McLaren & Cameron, 1996; Haddaway *et al.*, 2016).

Maize is the primary crop grown on arable land in the Waikato region (Foundation for Arable Research (FAR), 2019). Maize silage and grain are high value, cost effective, and high carbohydrate crops that are used for animal feeds, human food, and industrial products and are grown predominantly on the Allophanic soils of the Waikato region such as the Horotiu and Bruntwood soil series due to their well-drained and resilient properties (FAR, 2008; Nicholls *et al.*, 2009; Reid & Morton, 2019). Maize is also established on Gley soils in Waikato such as the Te Kowhai soil series, however Gley soils are more sensitive to continuous cropping than Allophanic soils due to their poor drainage characteristics and associated properties (FAR, 2008). Maize production in the Waikato makes up approximately 50 % of NZ maize silage production and 38 % of the maize harvest occurring within the Waikato region (StatsNZ, 2017). Soil compaction and

reductions in soil quality due to intensive cultivation have been identified to be major limitations to continuous maize production in NZ (Sparling *et al.,* 1992; FAR, 2018).

Full cultivation (FC) or conventional cultivation is universally adopted in cropping systems and has been associated with increased soil aeration, successful seed establishment, and mechanical weed control. However, FC has been shown to reduce soil quality through significant loss of SOM by accelerated decomposition and declines in soil structure, therefore risking reduced long-term productivity and profitability (Arshad, 1999; Sparling *et al.*, 2000a; Zuber *et al.*, 2015; Zuber *et al.*, 2018). Soil degradation can be reduced by the adoption of conservation tillage such as no-till or direct drill, and strip-till or minimum tillage (Holland, 2004).

No-till (NT) or direct drill is a system where there is limited soil disturbance, alternatively a seed is directly drilled into the undisturbed soil (Haynes & Knight, 1989; McLaren & Cameron, 1996). In this system, residues from the previous crop remain on the soil surface rather than being incorporated into the soil (Kumar & Goh, 1999). This increases SOM, provides additional metabolic sources for soil microorganisms, and improves soil aggregation and stability (Doran & Zeiss, 2000; Zuber *et al.*, 2018). Strip-till (ST) is a reduced version of cultivation, only disturbing the portion of the soil that is to have a crop row, consequently gaining the benefits of both FC and NT systems (FAR, 2019b). The establishment of maize crops using reduced cultivation methods such as NT have been adopted internationally, however is not yet a widely used cropping system in NZ regardless of the numerous recognized benefits (FAR, 2019b).

The soils in the study area are Allophanic soils, which are significantly influenced by clay minerals such as allophane, with enhanced binding with SOM therefore improving soil structure and quality (McLaren & Cameron, 1996). Allophanic soils typically have higher aggregate stability and better soil structure and therefore are better suited to continuous maize cropping than Gley soils (FAR, 2008). The Horotiu silt loam, found on slight raises of the landscape, is exceptionally versatile, resilient, well-drained and porous, with moderately deep rooting depth and moderate permeability (Singleton, 1991; Waikato Regional Council (WRC), 2011b). The Bruntwood soil series has soil properties intermediate of both Allophanic and Gley soils due to its position in the

landscape (Lowe, 2020). The Bruntwood silt loam's upper subsoil is made up of well-drained allophanic material and therefore has advantageous allophanic properties such as stable fine aggregates and low bulk density and is suited to maize production (WRC, 2011a; Lowe, 2020). The Bruntwood silt loam is less versatile than the Horotiu silt loam due to its limiting higher density subsoil and less porous structure, however the Bruntwood silt loam is more widespread throughout the Waikato region (WRC, 2011a).

This thesis will compare the effect of varying intensity cultivation on soil quality in a cropping system on Allophanic soils of the Hamilton Basin of the Waikato region, NZ. This thesis will also compare soil quality between two soil types – the Horotiu silt loam and Bruntwood silt loam – to identify whether inherent differences within the Allophanic soil order influence the soil quality of the study area, as well as measuring differences in the soil type responses to varying intensity cultivation. Seven soil quality indicators (total carbon, total nitrogen, mineralisable nitrogen, soil pH, Olsen P, bulk density, and macroporosity) and three cropping specific indicators (aggregate stability, penetration resistance, and visual soil assessment) were measured to distinguish differences between treatments and/or soil type. Although this trial is relatively young (five years old), data reported in this study provides a useful baseline to identify trends in cultivation intensity-related changes in soil quality over time, and highlight which soil quality parameters are most affected by cultivation intensity. The data from this study will contribute to ongoing soil quality monitoring for the Foundation for Arable Research (FAR) at their Northern Cropping Research Site (NCRS) as part as an ongoing trial.

1.2 Aims and objectives

The overarching aim of this thesis was to determine whether cultivation intensity has a significant influence on soil quality on Allophanic soil, in the Hamilton Basin. Further aims were to determine whether soil type would dominate soil quality in a cropping system, and whether soil types respond differently to varying intensity cultivations.

The specific objectives were to:

- Compare the soil quality under three cultivation treatments including full cultivation (FC), strip tillage (ST), and no tillage (NT) to determine whether lower intensity cultivation improves soil quality;

- Compare the soil quality of the Horotiu silt loam and the Bruntwood silt loam to determine whether soil type dominates soil quality in the study area; and

- Determine if there is a significant interaction between soil type, cultivation intensity, and soil quality.

1.3 Thesis layout

Chapter two reviews the literature on soil quality and cultivation in NZ, the effects of cultivation intensity on soil quality, and the soils of the Hamilton Basin.

Chapter three describes the detailed methodology used for soil sampling, laboratory analysis, and statistical analyses undertaken for this thesis.

Chapter four presents results from the study and has been written in the form of a paper for later submission to a suitable peer-reviewed journal. Methods are abbreviated however there is some repetition of material from previous chapters.

Chapter five contains the summary of the main conclusions of this research and recommendations for further research.

Appendices A- C, contain additional supplementary information.

Chapter 2

Literature review

2.1 Introduction

Land is the foundation of the New Zealand economy, with land based primary production including agriculture and horticulture bringing $35.4 billion in exports in 2016 (MPI, 2015, as cited in Ministry for the Environment (MfE) & StatsNZ, 2018). Agriculture (inclusive of pastoral farming, horticulture, and cropping) covered 12.1 million hectares of New Zealand land in 2016, with large increases in horticulture and vegetable growing in recent years (MfE & StatsNZ, 2018).

Soil quality is essential to the overall productivity and health of land, as it supports a range of functions that primary production relies on (Vogel *et al.*, 2018). These include the growing of food and providing raw resources, hosting significant biodiversity, storing and recycling nutrients, regulating drainage and flow and storage of water, storing carbon, and the filtering of contaminants such as nitrogen and phosphorus that in turn can reduce contaminants entering waterways (Mackay *et al.,* 2013; MfE & StatsNZ, 2018). Poor land management and intensive land use can impact these functions through changes in soil quality, reducing soil productivity and its ability to carry out essential functions (Doran & Zeiss, 2000). Intensive cultivation or tilling of soil is widely adopted in New Zealand and has been highlighted as one of the major pressures facing the sustainability of our soils (MfE & StatsNZ, 2018). Taylor *et al.* (2017) suggests that reducing cultivation is a major way to maintain and improve soil quality.

This literature review investigates soil quality and the effects of varying intensity cultivation on soil quality, with a focus on the differences observed in reduced cultivation systems. Firstly, I will discuss soil quality in New Zealand and how this is assessed and monitored with focus on important soil properties and their effect on productivity with specific interest on cropping and horticulture land uses and Allophanic soils (Section 2.2). I will then provide a brief overview of cultivation in New Zealand and review literature and previous studies that have investigated the effects of tillage and cultivation on soil quality, with a focus on those that compare intensive cultivation with

reduced cultivation (Section 2.3). I will then provide a background on soils found in the Hamilton Basin with focus on soils of the plains (Section 0), and finally I will discuss research needs within these themes (Section 2.5).

2.2 Soil quality in New Zealand

Soil quality is defined as "the capacity of a specific soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Soil Science Society of America as cited in Lilburne *et al.*, 2004). More recently, soil quality is defined in terms of its "fitness for use" where a soils quality is determined by its ability to match soil conditions suited to a certain land use and its capability to maintain this fitness in the long term (Schipper & Sparling, 2000). Soils provide a range of ecosystem services, simply defined as the benefits that humans obtain from ecosystems (Mackay *et al.*, 2013). These services include food and fiber production, nutrient provisioning and cycling, climate regulation and carbon storage, water provision and quality maintenance, pollutant degradation and pest control, and conservation of biodiversity (Vogel *et al.*, 2018). Where soil quality is degraded, the capability to support these essential services and its fitness for use is reduced, therefore reducing productivity, production, profitability, and implicating other domains of the environment such as water quality (MfE & StatsNZ, 2018).

Key pressures lead to declines in soil quality, including intensification, land use change, climatic pressure, and effects and contamination from past land uses (Ministry for Primary Industries (MPI), 2015). Combined, these pressures affect quality and versatility of soil resources through changes in soil physical, chemical, and biological properties. In New Zealand, specific pressures are applied to soils as result of rapid land use intensification and land use changes (MfE & StatsNZ, 2018). These include irrigation, addition of chemicals, inadequate vegetation cover through cultivation and harvesting of crops, fragmentation of land and urban expansion reducing availability of versatile and high quality soils, poor matching of land use to the soil capability, and past deforestation (MPI, 2015).

The Resource Management Act (1991) and the Environmental Reporting Act (2015) are the legislative frameworks for the sustainable management and monitoring of natural and physical resources in New Zealand (Land Monitoring Forum (LMF), 2009). These legislations require regional authorities to monitor and report on the state of the environment in their region. State of the environment reporting (SOE) monitors the pressures on the environment, the current state of the environment, and what is being done about these. These are described in a State of the New Zealand Environment report every three years, as well as a state of each domain report every three years. Environmental domains include land, air, atmosphere and climate, freshwater, and marine (MfE, 2015).

An interpretative framework for soil quality monitoring and assessment in New Zealand was implemented through the "500 soils project" (Lilburne *et al.*, 2004; Sparling & Schipper, 2004; Sparling *et al.*, 2004). The aim of the 500 soils project was to construct a quantitative soil quality monitoring system that could be used at a national scale by implementing uniform protocols, soil quality indicators, and target ranges to report on national and regional soil quality (Lilburne *et al.*, 2004; Cavanagh *et al.*, 2017). The 500 soils project identified seven key soil properties that could act as indicators of soil quality by best showing changes in soil physical, chemical, and biological properties. This was achieved through sampling over 500 soils throughout New Zealand, under a range of land uses (Sparling *et al.*, 2004). Target ranges for these seven recommended indicators were established to show how each indicator could support fitness for use, productivity between different soil types and land use, and have the capability to meet production and environmental requirements (Lilburne *et al.*, 2004; Sparling *et al.*, 2008). These target ranges have since been refined as seen in the Land Monitoring Forum (2009), as well as additional indicators suggested for specific land uses such as pastoral, forestry, and cropping and horticulture. These soil quality indicators and target ranges will be discussed further in Section 2.2.1.

2.2.1 Soil quality indicators

To measure soil quality, a range of soil properties can be used as indicators. Soil quality indicators are required to identify land management effects, where each soil indicator can indicate a different aspect of land management and/or soil type (Sparling *et al.*,

2008). Seven key soil quality indicators that represent key properties of soil were recommended through the 500 soils project (Lilburne *et al.*, 2004). These soil indicators include key soil physical, chemical, and biological properties that individually indicate impacts of land use, and combined can indicate land use impacts and overall soil quality. These include total carbon, total nitrogen, mineralisable nitrogen, soil pH, Olsen P, bulk density, and macroporosity (Sparling & Schipper, 2002; Lilburne *et al.*, 2004; Sparling *et al.*, 2004). These seven key soil quality indicators allow for interpretation of data with target values and to be used in identifying and reporting trends in soil quality (Taylor & Hill, 2018). Land Monitoring Forum (2009) also suggests two additional indicators for intensively cultivated land, including aggregate stability and soil profile description to more than 0.5 m. Penetration resistance is another commonly used soil quality indicator in studies with cultivated soils, such as in Crittenden *et al.* (2015) and Hart *et al.* (1988). Visual Soil Assessment (VSA) is also an on-farm assessment of soil quality, designed to be used and interpreted by landowners (Shepherd, 2009).

Soil quality indicators must fit a criteria to be useful for soil quality monitoring and reporting. They must be quantitative and measurable, responsive within a timeframe (track change), interpretable, cost effective, scientifically justifiable, socially acceptable, internationally recognised, and preferably part of historical monitoring procedures and studies (Doran *et al.,* 2000; LMF, 2009). The 500 soils recommended seven soil quality indicators fit this criteria, hence why they are most suitable for nationally consistent monitoring.

Provisional target ranges for the seven key soil quality indicators were defined by Sparling *et al.* (2008), and refined by the Land Monitoring Forum (2009). Target ranges are suggested for each indicator and are categorized by land use or soil type, depending on which has been identified to have the largest impact on that soil property. A single cropping and horticultural class was created by expert panels as it was unfeasible to accurately classify the large number of horticultural and cropping land uses. However, this was a significant generalization giving very broad targets and for this reason cropping and horticulture target ranges are “poorly defined” (LMF, 2009; Sparling *et al.,* 2008). Thus, the additional indicators aggregate stability and penetration resistance can help define soil quality within this land use. Methodology for the following soil quality indicators are further discussed in Chapter 3.

2.2.1.1 Total carbon

Total carbon (C) is a very important soil chemical property, and commonly used internationally as a soil quality indicator (Cavanagh *et al.*, 2017). Carbon is a major component of soil organic matter (SOM), which is essential for life and productivity in soil (Taylor *et al.*, 2017). SOM aids in retaining soil moisture and nutrients and is known to improve and preserve soil structure and soil conditions allowing for efficient air and water movement and therefore plant growth (McLaren & Cameron, 1996; Diekow *et al.*, 2005). Soil C is known to have a number of associated benefits, such as increased soil fertility, improved biological and physical soil properties through a reduction in soil bulk density, increased soil aggregation resulting in increased physical protection of SOM (Deb *et al.*, 2015), improved water holding capacity, enhanced soil microbe activity and increased soil biodiversity through an additional metabolic energy source (Black & Bauer, 1983; Haddaway *et al.*, 2016). These benefits in turn enhance productivity by allowing efficient nutrient cycling, aiding in soil structure formation, and improving crop resistance to pests and diseases (Zuber *et al.*, 2018). Total organic C has been identified to be one of the major soil attributes that are most likely to control soil structural vulnerability (Hewitt, 1998). Total C measures the amount of carbon in soil, including carbonates and SOM C. New Zealand soils typically contain very low carbonates, therefore total C is a good measure of SOM C (Sparling *et al.*, 2008).

Total C is used as an indicator of soil quality as low levels of C in soil has a number of associated negative effects on soil quality and therefore on productivity (LMF, 2009). A direct effect of low soil C is seen in soil biological properties, with reduced microbial biomass, microbial activity, and nutrient cycling due to a limited supply of a metabolic energy source and loss of habitat (McLaren & Cameron, 1996; Taylor *et al.*, 2017). All the associated physical benefits of soil C are reduced with declining soil C, such as soil strength and aggregate formation and stability, which in turn limits water and air movement, and therefore plant growth (Reeves, 1997). Total C is an important indicator to consistently monitor as once SOM has been depleted in soils it can take many years to replace. Intensive conservation and sustainable land management practices are recommended for SOM depleted soils (Sparling *et al.*, 2008).

According to Sparling and Schipper (2002), total C levels in soil are primarily influenced by Soil order, rather than land use. Allophanic soils typically have significantly higher C content than other soils under the same land use because SOM and its C portion is stabilised through allophane, imogolite, and ferrihydrite (Sparling *et al.*, 2008; Yuan, 2010). Land use and management however does have a large impact on C levels in soil, as the amount of organic matter in soil is determined by the rate at which it is being added, and the rate at which it is being decomposed (Hart *et al.*, 1988). Loss of SOM and its component C is of major concern under cropping and horticulture systems due to loss of C through cultivation and harvesting, where the rate of organic matter (OM) input is much lower than that being removed (McLaren & Cameron, 1996; Haddaway *et al.*, 2016). Target ranges for total C in New Zealand soils have been categorised by soil order and are applicable to all land uses (Table 2.1).

Table 2.1. Total Carbon target ranges expressed in units of %w/w. Target ranges are classified ranging from very depleted to ample levels of Total Carbon for each soil order (LMF, 2009).

	Very depleted	Depleted	Normal	Ample	
Allophanic	0.5	**3**	4	9	12
Semi-arid, Pumice & Recent	0	**2**	3	5	12
Organic	exclusion				
All other Soil Orders	0.5	**2.5**	3.5	7	12

2.2.1.2 Total nitrogen

Total nitrogen (N) is an important soil quality indicator as nitrogen is an essential nutrient for all plants and animals (LMF, 2009). Total N measures all forms of N, which is useful as N comes in various forms including dinitrogen gas in the atmosphere, ammonia and gaseous oxides of nitrogen, ammonium, nitrate and nitrate salts, and organic forms such as proteins (Landcare Research - Manaaki Whenua (LCRS-MW), 2020). Much of these forms of N however are not directly available to plants, the plant available forms of N are nitrate (NO_3^-) and ammonium (NH_4^+). N is an important component of SOM, with approximately 90 % of total soil N typically found within SOM (Sparling *et al.*, 2008) because the majority of N has been added to soil through biological fixation of atmospheric N_2 by soil microorganisms, and their death and incorporation into the SOM (McLaren & Cameron, 1996). SOM N is unavailable to plants

and must be mineralised by soil microorganisms into the plant available forms (Sparling *et al.*, 2008). The amount of N available to be mineralised in soil is known as mineralisable N (Section 2.2.1.3). N contents are typically highest in soils with significant SOM accumulation and biological N-fixation, and therefore is usually associated with high C contents (LCRS-MW, 2020). As total N is highly related to SOM content, the benefits of high N levels in soil will be similar to those discussed in Section 2.2.1.1, such as improved water holding capacity and soil conditions for plant growth (Diekow *et al.*, 2005).

Total N is a useful indicator of soil quality as low levels indicate potentially insufficient levels of this major nutrient and therefore limit microbial activity and plant growth and productivity (McLaren & Cameron, 1996; Sparling *et al.*, 2008; LMF, 2009). Low N levels also indicate low SOM, resulting in a number of associated negative effects on soil quality such as those discussed in Section 2.2.1.1, and therefore also impacting productivity. Loss of N and C are one of the main concerns for arable land due to the associated loss of SOM (Taylor *et al.*, 2017). Alternatively, very high total N levels can indicate excessive use of nitrate fertilisers and promote leaching of nitrate, which in turn can cause water quality issues as seen recently in New Zealand (MfE & StatsNZ, 2018). Retaining N in soil to reduce impacts on soil quality is of significant importance in the Waikato Region (Taylor *et al.*, 2017).

According to Sparling and Schipper (2002), total N is more largely influenced by land use, rather than soil order. This is because the amount of SOM is determined by the rate organic matter is being added, and the rate at which it is being decomposed (Hart *et al.*, 1988). Loss of SOM is of major concern under cropping and horticulture systems due to cultivation and harvesting, where the rate of OM input is much lower than that being removed (McLaren & Cameron, 1996; Haddaway *et al.*, 2016). Target ranges for total N in New Zealand cropping and horticulture soils have not been defined as target values will depend on the specific crop grown (Table 2.2).

Table 2.2. Total nitrogen target ranges expressed in units of %w/w. Target ranges are classified ranging from very depleted to high levels of total nitrogen for each Land use, excluding cropping and horticulture (LMF, 2009).

	Very depleted	Depleted	Normal	Ample	High	
Pasture	0	**0.25**	0.35	0.65	**0.70**	1.0
Forestry	0	**0.10**	0.20	0.60	**0.70**	
Cropping and horticulture	exclusion					

2.2.1.3 Mineralisable nitrogen

Mineralisable nitrogen (N) is one of the key soil quality indicators used in New Zealand soil quality monitoring and is also known as "readily decomposed organic N" or "potentially available N" (LMF, 2009). As mentioned in Section 2.2.1.2, N comes in many forms, however not all N can be used or is available to plants (McLaren & Cameron, 1996; LCRS-MW, 2020). Although the majority of soil N is found in SOM, soil organisms must mineralise N found in SOM into forms that can be taken up by plants (Sparling *et al.*, 2008). This plant available form of N is known as inorganic N and is in the forms of nitrate and ammonium (LCRS-MW, 2020). Mineralisable N is a measure of how much N can potentially be supplied to plants through the decomposition or mineralisation of SOM nitrogen into inorganic N (Sparling *et al.*, 2008).

Mineralisable N is a useful indicator of soil quality as it is a practical measure of SOM quality and soil microbial efficiency, in relation to the ability to mineralise and store N that can be used by plants, and therefore optimise productivity (McLaren & Cameron, 1996; LCRS-MW, 2020). A low mineralisable N indicates that the potential to produce plant available N is low, and therefore could result in insufficient N for plant growth, limiting productivity (Sparling *et al.*, 2008). Lower mineralisable N levels are typical in cropping soils compared to those under pasture due to the high removal rate of SOM (Hart *et al.*, 1988; Schipper & Sparling, 2000). Alternatively, a high or excessive mineralisable N indicates that there is an excess of N in the soil, likely through excessive or high inputs of N fertilizers, which is a more common issue of pastoral systems (McLaren & Cameron, 1996; LMF, 2009; MfE & Stats NZ, 2018). This can give rise to leaching of excess nitrate, posing risk for surrounding waterways, a large issue in New Zealand as identified in Our Land 2018 (MfE & StatsNZ, 2018).

Target ranges for mineralisable N are categorized by land use and are applicable to all soil orders (Table 2.3). Sparling *et al.* (2000a) recommended mineralisable N to be a property suitable to monitor cropping systems, due to its indication of SOM quality.

Table 2.3. Mineralisable nitrogen target ranges expressed in units of μg g^{-1}. Target ranges are classified ranging from very low to excessive levels of mineralisable nitrogen for each Land use, applicable to all soil orders (LMF, 2009).

	Very low	Low	Adequate	Ample	High	Excessive	
Pasture	25	**50**	100	200	200	**250**	300
Forestry	5	**20**	40	120	150	**175**	200
Cropping and horticulture	5	**20**	100	150	150	**200**	225

2.2.1.4 Soil pH

Soil pH is an important indicator of soil quality that indicates the acidity or alkalinity of a soil (Sparling *et al.,* 2008; LMF, 2009). Most plants and animals have an optimum pH range for growth and productivity; therefore, soil pH will determine which species will have the most successful growth (MfE & StatsNZ, 2018). Soil pH also influences the availability and solubility of a range of compounds in soil such as heavy metals like aluminum, which if soluble or in excess can cause ecotoxicity to microorganisms and therefore loss of productivity (Fageria & Moreira, 2011). Soil pH is also noted to influence the availability of essential nutrients, such as phosphorus (McLaren & Cameron, 1996). New Zealand soils are typically naturally acidic (McLaren & Cameron, 1996; Sparling & Schipper, 2002), hence native plant species are typically tolerant of more acidic soil conditions, however, introduced crop and pasture species require a more alkaline soil (LMF, 2009). The common remediation of soils with acidic pH is to use Lime ($CaCO_3$) to raise the pH to a more neutral or alkaline state (Sparling *et al.*, 2008; Fageria & Moreira, 2011).

Soil pH is a useful soil quality indicator as a pH outside of an optimum range will result in limited growth and productivity. It can also indicate where there may be risk of limited nutrients such as calcium or phosphorus, or an excess of compounds such as aluminum. A significant crop in New Zealand is maize, which requires a pH range of around 5 – 7, where higher yields are typically achieved (Sithole & Magwaza, 2019). Ongoing

monitoring of soil pH is important for agricultural systems to indicate when liming is necessary so to not have negative impacts on productivity (LMF, 2009).

Target ranges for soil pH in New Zealand are categorized primarily by land use (Table 2.4) as Sparling and Schipper (2002) found land use to have a larger impact. The defined target ranges for cropping and horticulture are general averages as the target ranges will depend on the specific crop grown, such as maize.

Table 2.4. Soil pH target ranges from very acid to very alkaline soil pH for each Land use. Target ranges for cropping and horticulture are general averages as the target ranges will depend on the specific crop grown (LMF, 2009).

	Very acid	Slightly acid	Optimal	Sub-optimal	Very alkaline	
Pastures on all soils except Organic	4	**5**	5.5	6.3	**6.6**	8.5
Pastures on Organic soils	4	**4.5**	5	6	**7.0**	
Cropping and horticulture on all soils except Organic	4	**5**	5.5	7.2	**7.6**	8.5
Cropping and horticulture on Organic soils	4	**4.5**	5	7	**7.6**	
Forestry on all soils except Organic		**3.5**	4	7	**7.6**	
Forestry on Organic soils	exclusion					

2.2.1.5 Olsen P

Phosphorus (P) is a key nutrient for plants and animals, however New Zealand soils naturally have low phosphorus levels, and a large amount is not available for plant uptake (McLaren & Cameron, 1996; LMF, 2009). Olsen P measures the amount of plant available P in a soil (Olsen *et al.*, 1954; LCRS-MW, 2020). P is taken up by plants through that found in the soil solution in available forms such as H_2PO_4 and HPO_4^{2-}, however much of this available phosphorus is adsorbed onto clays and OM, known as P retention. Soils with high clay and OM contents will have higher P retention, such as Allophanic soils which typically have high to very high P retention, noted to be as high as 98 % in the Horotiu silt loam (Singleton, 1991; McLaren & Cameron, 1996; Sparling *et al.*, 2008; LCRS-MW, 2020). P retention has been identified to be one of the four soil attributes that control soil structural vulnerability (Hewitt, 1998).

Olsen P is an important soil quality indicator as it indicates whether there is enough P that can actually be used by soil microbes and plants, and hence determines soil and plant productivity. P is essential for storage and transfer of energy and is a structural component of many plant biochemicals, hence a limited supply of available P can seriously impact plant growth and reproduction seen in resulting small stunted plants and limited root growth (McLaren & Cameron, 1996). Olsen P therefore indicates where there is a deficient supply of available P in the soil, and indicates requirements for phosphate fertilisers that can input plant available forms of P into the soil (Sparling *et al.,* 2008; LMF, 2009). Alternatively, Olsen P can indicate an excessive amount of available P in the soil, risking excess phosphate leaching from the soil and contaminating surrounding waterways (Sparling *et al.*, 2008; Taylor *et al.*, 2017). Olsen P levels are a large issue in New Zealand soils, either by being too low or too high, however excess P is more frequently observed under intensive land uses such as cropping and horticulture (Taylor *et al.,* 2017; MfE & StatsNZ, 2018).

Soil quality programmes in New Zealand between 2014 and 2017 identified that 33 % of tested sites had excess phosphorus levels (MfE & StatsNZ, 2018). Target ranges for Olsen P are categorized by land use and soil order (Table 2.5) as land use determines phosphate inputs and soil order determines P retention. Although target ranges have been defined, the optimum Olsen P range for Allophanic soils is noted to be between 20 – 30 µg g^{-1} (Morton & Roberts, 2018).

Table 2.5. Target ranges for Olsen P expressed in units of µg g^{-1} for land uses and soil orders. Target ranges are classified ranging from very low to high (LMF, 2009).

	Very low	Low	Adequate	Ample	High	
Pasture on Sedimentary and Allophanic soils	0	**15**	20	**50**	**100**	200
Pasture on Pumice and Organic soils	0	**15**	35	**60**	**100**	200
Cropping and horticulture on Sedimentary and Allophanic soils	0	**20**	50	**100**	**100**	200
Cropping and horticulture on Pumice and Organic soils	0	**25**	60	**100**	**100**	200
Forestry on all Soil Orders	0	**5**	10	**100**	**100**	200

2.2.1.6 Bulk density

Bulk density is one of the indicators of soil physical quality and soil structure. Soil physical condition can in some cases have a larger influence on plant growth, regardless of soil fertility (McLaren & Cameron, 1996). Soil structure is essential to productivity of soil, as structure controls water and air movement and hence essential aerobic activity (Dexter, 1997). Bulk density gives a measure of how dense a soil is and is a major indicator of compaction (LMF, 2009). Compacted soils have poor aeration, are poorly drained, limit root growth and penetration, and have the potential to become anaerobic therefore limiting essential functions and processes within soils carried out by soil organisms (Sparling *et al.,* 2008; LCRS-MW, 2020). Compaction is caused by poor and intensive land management such as animal treading, heavy machinery, cultivation, and loss of SOM, or a combination of these (LMF, 2009; LCRS-MW, 2020). Bulk density is affected by a soils natural properties such as soil texture, fundamental materials, and porosity (Sparling *et al.*, 2008).

Bulk density is an important soil quality indicator as it indicates soil physical quality which is essential to the productivity of soil and plants. It is a useful indicator of how land management is influencing the soil (LMF, 2009). Compaction also impacts availability and transport of nutrients to plant roots. Compaction reduces air-flow throughout the soil, contributing to denitrification and nitrogen gas losses, decreases mineralised N, and promotes leaching of nutrients such as nitrate and phosphate (Lipiec & Stępniewski, 1995). A high bulk density indicates compaction which can reduce soil productivity by potentially limiting or even stopping plant growth (McLaren & Cameron, 1996). Poor soil structure is typically associated with other undesirable changes in soil properties such as loss of SOM and decreased microbial activity (Sparling *et al.*, 2000b). Alternatively, soils with a low bulk density are considered to be 'loose', porous, and open textured which can result in higher erosion rates, susceptibility to drying out, and a lack of water holding capacity and water availability for plant roots (Sparling *et al.*, 2008). Reductions in soil physical quality seen in high bulk density compaction are common for intensive land uses such as cropping and horticulture (Schipper *et al.,* 2000; MfE & StatsNZ, 2018).

Sparling and Schipper (2002) found bulk density to be majorly influenced by soil order, and it is known that bulk density is typically inversely related to soil porosity. Allophanic soils have naturally low bulk density, hence their versatility for land use (McLaren & Cameron, 1996). Target ranges for bulk density are therefore categorized by soil order, which is applicable to all land uses (Table 2.6).

Table 2.6. Bulk density target ranges expressed in units of t m^{-3}. Target ranges are classified ranging from very loose soil to very compact soil for each soil order (LMF, 2009).

	Very loose	Loose	Adequate	Compact	Very compact	
Semi-arid, Pallic and Recent soils	0.3	**0.4**	0.9	1.25	**1.4**	1.6
Allophanic soils		**0.3**	0.6	0.9	**1.3**	
Organic soils		**0.2**	0.4	0.6	**1.0**	
All other soils	0.3	**0.7**	0.8	1.2	**1.4**	1.6

2.2.1.7 Macroporosity

Macroporosity is a measure of the proportion of large pores in soil, defined as pores larger than 60 μm (Sparling *et al.*, 2008). These are measured by calculating the proportion of soil that is drained between the pressure levels of 0 and -10 kPa (Chapter 3). Macropores are essential for the transportation of oxygen throughout soil and drain most rapidly after rainfall events. They are the most important pores to monitor as they are the first to be lost when soil is compacted (Sparling *et al.,* 2008; LMF, 2009). Macroporosity is typically inversely related to bulk density, where a low macroporosity is associated with a high bulk density, indicating soil compaction (McLaren & Cameron, 1996). As mentioned in Section 2.2.1.6, compacted soils have poor aeration, are poorly drained, limit root growth and penetration, and have the potential to become anaerobic therefore limiting essential functions and processes carried out by soil organisms (Sparling *et al.,* 2008; LCRS-MW, 2020). Compaction is caused by poor and intensive land management such as animal treading, heavy machinery, cultivation, and loss of SOM, or a combination of these (LMF, 2009; LCRS-MW, 2020). Macroporosity is thought to be a more sensitive measure of changes in soil physical quality (McLaren & Cameron, 1996; MfE & StatsNZ, 2018).

Macroporosity is an important soil quality indicator as it indicates if a soil is compacted and is a sensitive measure of changes in soil quality most typically due to poor land management. The effects of low macroporosity and hence compacted soils are reduced

availability and transportation of nutrients to plant roots, due to reduced air-flow throughout the soil (Lipiec & Stępniewski, 1995; McLaren & Cameron, 1996). This contributes to denitrification and nitrogen gas losses, decreases mineralised N, and it also promotes leaching of nutrients such as nitrate and phosphate (Lipiec & Stępniewski, 1995). These effects could limit or even stop plant or crop growth and productivity, which highlights importance of monitoring these changes. Low macroporosity is common in intensive land uses such as dairy and cropping systems (MfE & StatsNZ, 2018). Low macroporosity under intensive land uses is a major soil quality issue for New Zealand (MfE & StatsNZ, 2018). Alternatively, soils with high macroporosity are considered to be "loose", porous and open textured which can result in higher erosion rates, susceptibility to drying out, and low water holding capacity and availability for plant roots (Sparling *et al.*, 2008).

Macroporosity is a more sensitive measure of soil physical quality as it is more responsive to changes in land use (LMF, 2009). A soil with macroporosity less than 10 % will adversely affect plant growth (McLaren & Cameron, 1996; Dexter, 1997). Soil quality programmes in New Zealand between 2014 and 2017 found that 44 % of tested sites had macroporosity of less than 10 % (MfE & StatsNZ, 2018). Although Allophanic soils typically have relatively high natural porosity (McLaren & Cameron, 1996) soils with high clay contents are more susceptible to changes in pore structure when they are wet (LCRS-MW, 2020). Target ranges are categorized by land use and applicable to all soil orders (Table 2.7).

Table 2.7. Macroporosity target ranges expressed in units of % and measured at -10 kPa. Target ranges are classified ranging from very low to high, categorised by land use (LMF, 2009).

	Very low	Low	Adequate	High	
Pastures, cropping and horticulture	0	**6**	10[1]	**30**	40
Forestry	0	**8**	10	**30**	40

2.2.1.8 Aggregate stability

Aggregate stability is a soil quality indicator typically used only for cropping and horticultural soils (LMF, 2009; Cavanagh *et al.*, 2017). Aggregate stability is a measure of the resistance of soil aggregates or crumbs to damage, and is a useful indicator of soil

physical quality and soil structural stability (Haynes & Knight, 1989). Aggregate stability is an important indicator for cropping systems as it is associated with SOM (Sparling *et al.*, 2003). Improved SOM content in soils is known to significantly improve aggregation and aggregate stability and declines in SOM is a large concern in cropping systems (Hart *et al.*, 1988). Aggregate stability is important for preserving soil structure and SOM, and is essential for the transportation of water and air throughout the soil (Haynes & Knight, 1989).

Aggregate stability is a useful soil quality indicator for cropping and horticulture systems as it is an early and sensitive indicator of soil physical quality. It is correlated to a number of important properties in soil such as SOM, bulk density and macroporosity (FAR, 2019b). High aggregate stability is indicated by a stable, crumbly soil texture. High aggregate stability enhances water infiltration, prevents drying out of soil, allows for efficient and deep plant root growth and indicates a more versatile soil (Bay of Plenty Regional Council (BOPRC), 2020). As aggregate stability is a measure of resistance to compaction, slaking, and capping of seedbeds which are all essential to monitor for arable soils (LMF, 2009). Soils with high aggregate stability are more resistant to impacts of cultivation, treading and heavy traffic, and rainfall (Haynes & Knight, 1989). Low aggregate stability indicates poor soil structure and susceptibility to compaction, which is common for cropping systems as harvesting and cultivating breaks up and disrupts aggregates. This significantly reduces SOM that is protected inside aggregates, which in turn reduces stability and formation of aggregates due to limited SOM to bind aggregates (MfE & StatsNZ, 2018; FAR, 2019b). Soils with high natural clay contents and organic matter such as Allophanic soils have improved bindings and formation of aggregates and consequently have higher aggregate stability and resistance to breakage (Yuan, 2010).

New Zealand cropping soils typically have an aggregate stability of around 1.2 to 2 mm mean weight diameter (MWD) (BOPRC, 2020). There are no uniform target ranges for aggregate stability in New Zealand, however lower limits have been recommended as displayed in Table 2.8, with the majority indicating that an aggregate stability above 1.5 mm MWD is desired.

Table 2.8. Table displaying suggested lower limits for aggregate stability, expressed in units of mm, mean weight diameter (MWD).

	Reference					
	Sparling *et al.* (2008)	Mackay *et al.* (2013)	Plant & Food Research (2018)	Foundation for Arable Research (2019b)	Bay of Plenty Regional Council (2020)	Landcare Research - Manaaki Whenua (2020)
Aggregate Stability (mm, MWD)	2	1.5	1.5	1.5	1.5	< 1 = very poorly stable soil

2.2.1.9 Penetration resistance

Penetration resistance is a parameter used to indicate soil structure and strength by measuring the resistance of a soil to penetration (Pachepsky *et al.*, 1998). Penetration resistance is an easily measured indicator that is related to porosity and density, therefore it can indicate compaction and is a common technique for evaluating effects of land management on soils (Murphy & Firth, 2004; Kuhwald *et al.*, 2016).

Penetration resistance is a useful indicator as it is easy to measure in the field and can give another indication of compaction. An aerated soil such as a recently cultivated soil will have a reduced penetration resistance (Burgess *et al.*, 2000). Alternatively, a soil that is compacted through heavy stocking or machinery, or an uncultivated soil such as in a no till system will have an increased penetration resistance (FAR, 2019b).

The critical limit for penetration resistance is 3 MPa where root growth is limited (McQueen & Shepherd, 2002; Murphy & Firth, 2004). A soil with high penetration resistance makes it difficult for roots to penetrate the soil and can increase susceptibility to waterlogging and poor aeration, which can lead to root death and decreased and limited plant growth (Murphy & Firth, 2004). Increased penetration resistance can also reduce infiltration of water into and throughout soil, and the transportation of nutrients (Pachepsky *et al.*, 1998).

2.2.1.10 Visual soil assessment

The visual soil assessment (VSA) is a field based method to assess the condition of soil and plant performance to determine impacts from land use and management (Shepherd, 2009). VSA uses a number of visual observations from a sample area of soil, including soil texture, structure, and porosity, number and colour of soil mottles, soil

colour, number and average size of earthworms, soil smell, potential rooting depth, surface ponding, and surface relief. It assesses plant performance using a number of plant indicators such as pasture quality and growth, and presence and type of weeds. A score is given for each property, different properties are assigned different weightings, and combined give an overall score of soil and plant quality, ranging from poor, moderate, and good (Shepherd, 2009).

A soil with a high VSA score will likely have the most successful production, with the lowest establishment and operational costs (Shepherd, 2009). VSA is a useful soil quality tool as it provides a simple and easy method to assess soil condition, and can be used on a paddock scale and requires no training or technical skills, allowing it to be utilised by landowners (FAR, 2019a). VSA can help give insight into potential issues or limitations and indicate requirements for further monitoring (Shepherd, 2009). As it is a visual assessment, it is limited in its ability to provide an in depth or definitive assessment of soil quality. Variables such as macroporosity and bulk density are not accurately represented, and there is no insight of soil biological or chemical quality (Cavanagh *et al.*, 2017). The commonly used VSA is that by Shepherd (2009), and more specific variables are used for cropping systems, such as the cropping VSA designed by Foundation for Arable Research (2019a) that includes more specific soil structural tests. For more detail on the FAR VSA used in this study, see Chapter 3 and Appendix A.

2.2.2 Soil quality sampling in NZ

As discussed in Section 2.2, multiple legislations require regional authorities to monitor and report on the state of the environment in their region. The nationally consistent set of indicators previously discussed in Section 2.2.1 are monitored using standard sampling methods and protocols. Regional authorities follow standard sampling methods from *Land and Soil Monitoring: A guide for SoE and Regional Council Reporting* (LMF, 2009). The regional authority will then either analyse soil samples independently following the same guide and methodology, or will contract an external laboratory that may use a variation of or different methodology to analyse for the key soil quality indicators. Independent researchers or organisations may use different sampling and laboratory methodology.

The Land Monitoring Forum (2009) recommends that typical field sampling includes multiple steps. These include describing the site, digging a small pit to identify and characterise the soil profile and set out a 50 metre transect. Soil samples for chemical analyses are collected at 2 m spacing along the transect using a bucket sampler to collect samples to 10 cm depth. Three undisturbed soil cores are collected at 15 m, 30 m, and 45 m along the transect for physical analyses using metal cores (~5 cm x 6 cm). Typically, at these same points along the transect, three spade samples to around 7.5 cm depth are collected for aggregate stability samples. VSA's are not typically carried out by regional authorities as it is designed to be a monitoring tool for landowners, however when used for soil assessment in New Zealand, the methods are those from Shepherd (2009). Further detail on sampling and laboratory methodology is discussed in Chapter 3, where the recommended regional council methodology was used or adapted for this project.

2.3 Cultivation

For many years, cultivation or tillage has been used in cropping systems to prepare the seedbed for successful establishment and growth of crops (Arshad, 1999). Cultivation is also used to control weeds and bury the residues from previous crops (Haynes & Knight, 1989; McLaren & Cameron, 1996). Full cultivation (FC) or conventional tillage is a system where typically there is deep cultivation or inverting the soil such as mouldboard ploughing, followed by another cultivation to create the seedbed (Holland, 2004).

A significant crop in New Zealand is maize, first recorded in New Zealand from the late 18th century (Bansal & Eagles, 1984). Maize silage and grain are high value, cost effective, high carbohydrate crops that are used for animal feeds, human food, and industrial products (FAR, 2019b). Maize production in the Waikato region grew rapidly from 1966 to 1976 due to the economic advantages of maize production over dairy and meat farming at that time (Bansal & Eagles, 1984). Maize is now the primary crop grown on arable land in the Waikato, grown predominantly on the Allophanic soils of the region such as the Horotiu and Bruntwood soil series due to their well-drained and resilient properties (FAR, 2008; Nicholls *et al.*, 2009; Reid & Morton, 2019). Maize is also largely established on Gley soils in Waikato such as the Te Kowhai series (Section 2.4.2), however Gley soils are more sensitive to continuous cropping than Allophanic soils (FAR,

2008). Maize production in Waikato is significant in comparison to wider New Zealand, with approximately 50 % of New Zealand maize silage production and 38 % of overall maize harvest occurring within the Waikato region (StatsNZ, 2017). Soil compaction and reductions in soil quality due to intensive cultivation have been identified to be major limitations to continuous maize production (Sparling *et al.*, 1992; FAR, 2018).

Full cultivation (FC) is most commonly used in cropping systems and has been associated with a number of benefits, such as soil aeration, successful seed establishment, and weed control (Section 2.3.1). For sustainable arable cropping, management practices must be able to be profitable while avoiding environmental degradation (Sparling *et al.*, 2000a). FC has been identified to have a number of negative effects on soil quality and therefore risks losses in long term productivity and profitability (Sparling *et al.*, 2000a). Environmental and specifically soil degradation can be reduced by the adoption of conservation tillage (McLaren & Cameron, 1996). Eminent methods of conservation tillage or reduced cultivation are no-till (NT) or direct drill, and strip-till (ST) or minimum tillage (Holland, 2004).

No-till (NT) or direct drill is a system where there is limited soil disturbance, alternatively a seed is directly drilled into the undisturbed soil (Haynes & Knight, 1989; McLaren & Cameron, 1996). In this system, there is no tillage or cultivation, therefore the residues from the previous crop remain on the soil surface rather than being incorporated and soil inverted as in a FT system (Kumar & Goh, 1999). Strip-till (ST) is a reduced version of cultivation that only disturbs a portion of the soil that is to have a crop row, resulting in "strips" of cultivated soil. Consequently, ST systems gain the benefits of both FC and NT systems (FAR, 2019b). This requires use of strip-till cultivators typically with multiple passes, such as the *Soil Warrior* used in various FAR trials (FAR, 2018; FAR, 2019b). The establishment of maize crops using reduced cultivation methods such as NT have been adopted internationally, however it is not yet a widely used cropping system in New Zealand regardless of the numerous recognized benefits (FAR, 2019b).

The effects of FC, ST, and NT on soil quality are discussed below in Sections 2.3.1 and 2.3.2. Relevant results from previous studies comparing the effects of FC and reduced cultivation systems on soil quality are summarised in Table 2.10.

2.3.1 Effects of conventional cultivation on soil quality

Conventional or full cultivation (FC) has been used widely in cropping systems due to a number of benefits for crop growth, yields, and profitability (FAR, 2009). Tillage or cultivation of soil can increase aeration and porosity, and reduce density of the topsoil, thus reducing susceptibility to compaction and enabling the establishment of crops (Zuber *et al.*, 2015; Haddaway *et al.*, 2016). This is especially important in continuous maize cropping systems as soil compaction can be a major limitation for maize production (Sparling *et al.*, 1992). However, it has been found that although cultivation may improve soil structure in the short term, in the long term these benefits are lost with continuous cropping (Cotching *et al.*, 1979). Soil cultivation incorporates previous crop residues throughout the soil profile, distributing nutrients and SOM (McLaren & Cameron, 1996). Cultivation mechanically destroys and reduces weeds in the inversion and tillage processes (Haynes & Knight, 1989; Haddaway *et al.*, 2016). Although cultivation is associated with a number of benefits, New Zealand soils are under significant threat due to intensive cultivation degrading soil quality (MfE & StatsNZ, 2018).

The largest concern of FC systems is the significant loss of SOM. As discussed in Section 2.2.1.1, SOM is essential for life and productivity in soil (Taylor *et al.*, 2017). Cultivation accelerates the decomposition of SOM when crop residues are fragmented into smaller pieces when aggregates are destroyed during the cultivation process, exposing SOM to oxidation and allowing easier decomposition by soil microorganisms (Zuber *et al.*, 2018). In FC cropping systems, the loss of SOM from accelerated decomposition is not balanced by increased inputs of organic matter, hence resulting in reduced SOM contents (Hart *et al.*, 1988; Diekow *et al.*, 2005). The loss of SOM from cultivated soils results in a number of successive impacts on soil quality due to loss of a significant source of carbon as an energy source for soil microorganisms, essential nutrients for soil and plant productivity, and the structural binding abilities of SOM (Black & Bauer, 1983; Zuber *et al.*, 2018).

The effects of SOM loss due to intensive disruption of soil through cultivation and inversion are seen in other aspects of soil quality such as soil biology and chemistry (Arshad, 1999). Associated with reduced SOM and the loss of the carbon energy source,

are reduced soil microorganisms and biological activity (McLaren & Cameron, 1996). This results in reduced cycling of essential nutrients within soil, such as mineralisable N (Section 2.2.1.3) hence reducing plant available nutrients, limiting plant growth and productivity (Hart *et al.*, 1988).

Declines in soil structure and stability are common in intensive cropping systems such as maize, due to the intensive nature of cultivation and the loss of SOM (Cotching *et al.*, 1979). Loss of soil structure in intensive cultivation systems are reflected in a range of soil quality indicators such as reduced aggregate stability (MfE & StatsNZ, 2018; Zuber *e al.,* 2018), commonly observed in many studies comparing FC systems with reduced cultivation systems (Table 2.10). This occurs through excessive breakdown of soil aggregates during cultivation and due to the loss of SOM that is essential for maintaining the stability of soil aggregates (McLaren & Cameron, 1996). Continuous cultivation, soil inversion, and the use of heavy machinery can also lead to degradation of soil structure through increased bulk density and reduced macroporosity, thus compacting soils (FAR, 2009; Haddaway *et al.*, 2016; Vogel *et al.*, 2018). Soil compaction and reduced soil physical, biological, and chemical quality have been identified to be major limitations to continuous maize production (Sparling *et al.*, 1992; FAR, 2018).

2.3.2 Effects of reduced cultivation on soil quality

Internationally, reduced or conservation cultivation and tillage systems such as ST and NT have been widely adopted, however there is still minimal use of these in New Zealand (FAR, 2019b). This is of particular interest in maize cropping systems which, although nationally widespread, are noted to be one of the most intensive cropping systems in regards to changes in soil quality (Cotching *et al.*, 1979). There are a significant number of benefits associated with reduced cultivation such as reduced costs and energy use, however arguably the most significant is the marked improvement in soil quality (Haddaway *et al.,* 2016; FAR, 2019).

Reduced cultivation typically reduces SOM losses as soil aggregates and crop residues are not disturbed by cultivation practices, therefore SOM remains protected within soil aggregates from accelerated decomposition (Doran & Zeiss, 2000; Zuber *et al.*, 2018). There are also higher SOM contents in reduced cultivation especially NT systems,

because the rate of OM input versus output is more balanced as crop residues are not broken up and incorporated into the soil, instead remaining on the soil surface providing a significant SOM source in the topsoil (Haynes & Knight, 1989). A vast number of studies have observed the significant accumulation of SOM in the top 10 cm of soils under NT (Table 2.10). Increased SOM content in reduced cultivation systems has a number of benefits for soil quality (see Section 2.2.1.1), such as improved soil structure and stability, improved nutrient cycling, water infiltration, and higher microbial diversity and productivity due to an increased carbon energy source (Lal, 2008).

Reduced cultivation systems improve soil structure, which is important as soil structure is vital for continuous cropping systems (Sparling *et al.*, 1992). The increased presence of SOM improves soil structure as it is essential for the strength, binding, and stability of soil aggregates (McLaren & Cameron, 1996). Improved soil structure in NT and ST systems is reflected with significantly improved aggregate stability, which is important in cropping systems as it provides higher resistance to impacts of cultivation (if using a ST system), treading and heavy traffic, and rainfall (Hart *et al.*, 1988; Haynes & Knight, 1989) (see Section 2.2.1.8). Improved aggregate stability has been observed in many studies of soil quality under NT systems (Table 2.10).

ST or minimum tillage systems are forms of reduced cultivation that have advantages and disadvantages of both FC and NT systems (FAR, 2019b). ST is beneficial compared to FC as it conserves soil moisture and reduces soil erosion due to half of the soil surface covered with crop residue, resulting in improved levels of SOM on the soil surface (FAR; 2009; 2019). ST can be beneficial compared to NT as it will result in properties associated with cultivation, such as increased aeration and porosity, and decreased bulk density (Haddaway *et al.,* 2016; FAR, 2019).

Although NT and ST systems improve soil structure, they commonly have decreased macroporosity and increased bulk density due to the lack of mechanical break up of soil aggregates (Lipiec & Stępniewski, 1995). NT systems are also noted to have decreased plant available N due to a decreased rate of mineralisation as SOM is not exposed or broken down during cultivation and therefore not rapidly mineralised by soil microorganisms (Lipiec & Stępniewski, 1995; McLaren & Cameron, 1996) (see Section 2.2.1.3).

Table 2.9. Summary table displaying the comparative effects of NT compared to a FC system (McLaren & Cameron, 1996). Effects have been categorised as whether it is good/improved; green = good, orange = variable, red = poor.

Soil Property	Effect
Soil structural stability	Higher
Bulk density	Higher
Nitrogen availability	Lower
Soil pH	Lower
SOM	Higher
Soil strength + bearing capacity	Higher
Total porosity	Lower
Risk of erosion	Lower
Earthworm numbers	Higher
Moisture content	Higher

2.3.3 Previous studies comparing cultivation intensity and the effects on soil quality

Review of previous studies involving comparisons between FC and reduced cultivation systems on soil quality identified a number of consistent results (Table 2.10). The majority of studies found the accumulation of SOM or soil organic carbon (SOC) in the topsoil under NT systems, typically in the top 10 cm. However, multiple studies found that below 10 cm SOM was lower under NT systems and SOM is distributed more uniformly down the soil profile under FC systems. Higher aggregate stability and improved soil structure under NT were found in a number of studies, likely associated with the accumulation of SOM in the topsoil. However, numerous studies identified that FC systems had a lower bulk density than NT systems. Multiple studies from FAR also recorded that there were no significant differences in maize yields between FC, NT and ST, regardless of differences in soil quality attributes. Multiple studies focused on the effect of FC on soil quality in various soil types or soil orders, showing how a well-drained soil had decreased soil physical quality very early into the studies, however these soils may form an equilibrium state where they no longer reduce in quality after a few years. One study found that a poorly drained soil showed improved soil structure after a few years, however these benefits were lost after long term cropping.

Table 2.10. Table displaying relevant soil quality results from previous studies involving comparisons of FC systems versus reduced cultivation systems such as ST and NT.

Reference	Study	Results
Foundation for Arable Research (2019b)	FC vs. ST vs. NT under maize Waikato, NZ	• No significant differences in maize yields • Differences in soil quality attributes such as aggregate stability
Foundation for Arable Research (2019b)	FC vs. ST vs. NT under maize Hinuera & Poverty Bay, NZ	• No significant differences in maize yields
Foundation for Arable Research (2019b)	FC vs. ST vs. NT Christchurch, NZ	• Intensity of cultivation affected distribution of C, with greater C in top 0 – 10 cm in NT • Improved soil structure, water storage & Olsen P in NT
Seitz *et al.* (2019)	FC vs. ST vs. NT & organic farming vs. conventional farming, Switzerland	• Higher aggregate stability in NT systems • Lower soil erosion in reduced cultivation systems
Sithole and Magwaza (2019)	FC vs. rotational tillage (RT) vs. NT under maize South Africa	• Reduced BD and less acidification under FC and RT • High SOM in NT soil surface, distributed in FC profile • Higher maize yields in NT if increased N application
Zuber *et al.* (2015); Zuber *et al.* (2018)	NT vs. Chisel Tillage (FC) USA	• Greater levels of soil organic carbon (SOC) and Total N in 0 – 10 cm in NT
Si *et al.* (2018)	NT vs. FC under maize Northern China	• Higher C, esp. in topsoil in NT, but reduced further down profile, enhanced C cycling & macroaggregates in NT, but lower maize yields • Higher BD in NT upper soil
Arai *et al.* (2018)	NT vs. FC Japan	• No earthworms present in FC after 2 years • Higher C in topsoil and earthworms present in NT

Reference	Study	Results
Crittenden *et al.* (2015)	NT vs. FC & organic vs. conventional farming The Netherlands	• Increased SOM from 0 – 20 cm, inc. aggregate stability & inc. penetration resistance in NT • Increased porosity in FC in short term
Himmelbauer *et al.* (2012)	NT vs. FC under maize Eastern Austria	• Larger horizontal extension of maize root system in FC • Higher aggregate stability, SOC from 0 – 10 cm, BD, plant available water, & deeper root depth in NT
Blanco-Canqui and Lal (2008)	NT vs. FT USA	• Increased SOM from 0 – 10 cm, inc. N from 0 – 5 cm, both dec. below 10 cm in NT • Higher SOM and N below 10 cm in FC
Francis and Knight (1993)	NT vs. FC, Canterbury, NZ	• Significantly higher SOC, Total N, and Min N in 0 – 7.5 cm in NT, higher below 7.5 cm in FC • Higher BD and lower macroporosity in NT, however more earthworms
Haynes and Knight (1989)	NT vs. FC, Canterbury, NZ	• Higher SOM and aggregate stability in 0 – 5 cm in NT • Much lower aggregate stability in FC, but higher SOM below 5 cm and uniform distribution of SOM in profile
Sparling *et al.* (1992)	Continuous maize & cereal cropping FC Well drained soil vs. Poorly drained soils Manawatu, NZ	• Well drained soil had the largest losses in C and aggregate stability under long term FC compared to the poorly drained soils
(Cotching *et al.*, 1979)	Maize cropping FC Horotiu silt loam (Allophanic) vs. Puniu silt clay loam (Gley) Waikato, NZ	• Horotiu silt loam had large decline in C in topsoil after 9 years cropping • Slight increase in BD under Horotiu silt loam, however minimal physical changes after 3 years (goes into an equilibrium of soil structure) • Puniu silt loam initially decreased BD then increased with increasing years under maize and compacted, decreased ag stab after long term. • Benefits of cultivation for compacted Puniu soil were lost with long term cropping

2.4 Soils of the Hamilton Basin

The Hamilton Basin area is located in the Waikato region of New Zealand and is made up of four distinct landforms which are linked to various soil series, allowing for prediction of soil types within Hamilton (Lowe, 2020). These include low rolling hills, flat alluvial plains, low terraces, and gullies (Figure 2.1). Low rolling hills of the Hamilton Basin are fragments from landscapes formed over a million years ago (Lowe, 2020). The plains are made up of alluvium originating from volcanic catchments in the central North Island deposited by the ancestral Waipa and Waikato Rivers over the past 100,000 years, known as the Hinuera Formation (Lowe, 2020). Gullies are infrequently cut into the Hinuera Surface and drain towards the Waikato River.

The alluvial plains are known as the Hinuera Surface, comprising of a range of low ridges and depressions or swales (Figure 2.2). The most recent deposition in the Hamilton Basin was around 20,000 years ago, after which the ancestral Waikato River began to entrench, resulting in the formation of terraces and into its modern channel. Since that most recent deposition, multiple thin tephra layers have covered a vast area of the Hinuera Surface in the Hamilton Basin and the soil pattern on the Hinuera Surface reflects the depositional environments (Lowe, 2020). Soils of the plains in the Hamilton Basin are the result of developmental upbuilding pedogenesis with three most common soil orders found that are reflective of their depositional environments as they are dominated by Allophanic or Halloysitic material (Singleton, 1991; Lowe, 2020) (Figure 2.2). The soils of the plains are most commonly used for maize production and form the soils of this study (FAR, 2008).

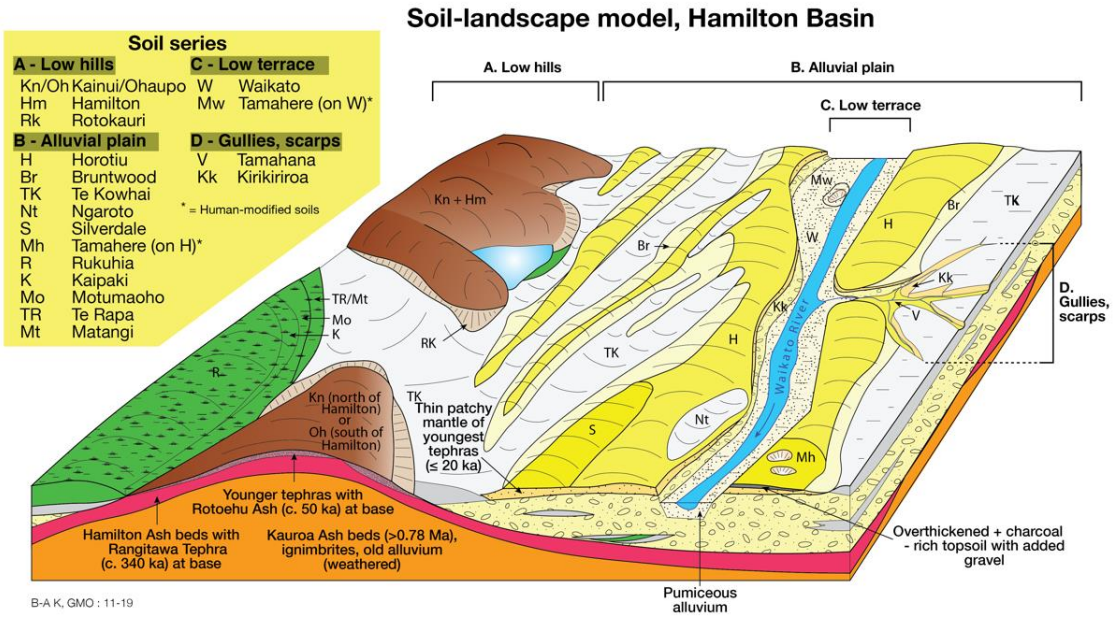

Figure 2.1. Soil-landscape model of the Hamilton Basin in the Waikato region of New Zealand (Lowe, 2020).

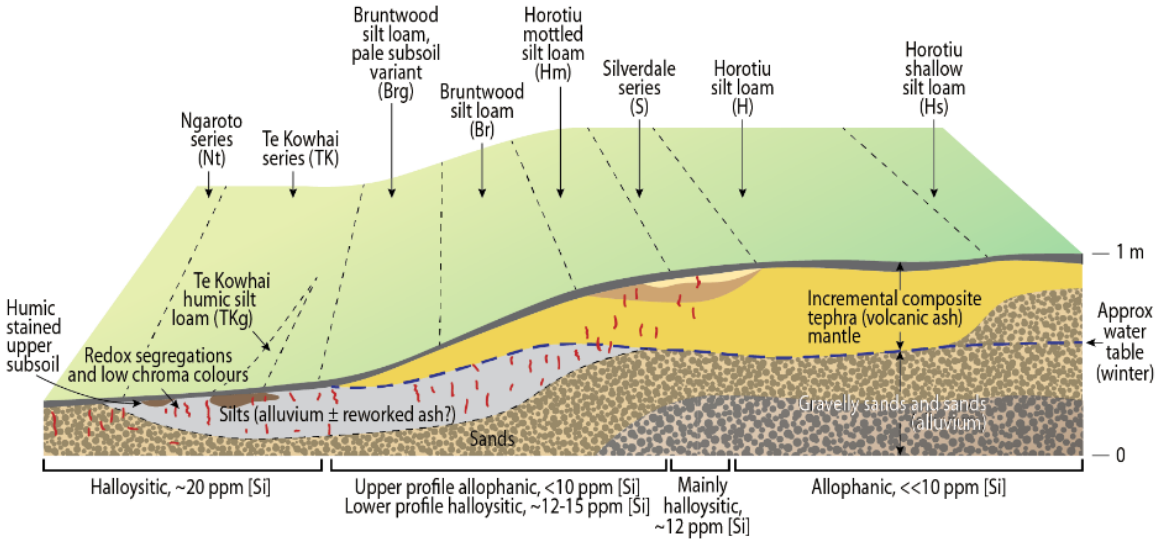

Figure 2.2. Model of soil types and variations found on the alluvial plains in the Hamilton Basin in the Waikato region of New Zealand (Lowe, 2020)

2.4.1 Horotiu series

On slightly raised channels overlying coarse alluvium of the Hinuera Surface is where the Horotiu series is found (Figure 2.1). The Horotiu series are Allophanic soils known for being well-drained and versatile for land use (Singleton, 1991; WRC, 2011; Lowe, 2020). Allophanic soils have properties that are significantly influenced by clay minerals such as allophane, imogolite and ferrihydrite. These clay minerals enhance binding with SOM thus improving soil structure and quality, and result in high P retention noted to be as high as 98 % (LCRS-MW, 1978). Allophanic soils are the predominant soils used for maize production within the Waikato region (FAR, 2008; Reid & Morton, 2019). Allophanic soils typically have a higher aggregate stability and better soil structure under cropping systems, therefore are better suited to continuous maize cropping than Gley soils (FAR, 2008). A dominant soil type within the Horotiu series is the Horotiu silt loam (Figure 2.2), classified as a Typic Orthic Allophanic Soil (New Zealand Soil Classification (NZSC)) (WRC, 2011b). The Horotiu silt loam is known to be exceptionally versatile, resilient, well-drained and porous, with moderately deep rooting depth and moderate permeability (Singleton, 1991; WRC, 2011).

2.4.2 Te Kowhai series

The dominant soil order on the low lying swales in the Waikato region are the Gley Te Kowhai soils, overlying poorly drained fine alluvium, predominantly halloysitic and poorly drained due to compacted subsoil layers with slow permeability, and typically have fluctuating and high water tables (Singleton, 1991; Lowe, 2020) (Figure 2.2). These soil properties cause anoxic conditions for periods of the year in Te Kowhai soils, resulting in iron reduction and removal, producing a very white or light grey subsoil and mottles throughout the soil profile (WRC, 2011a). The low permeability and poor drainage of Te Kowhai soils make them unsuitable for many land uses as soil microorganisms and many plants cannot tolerate anoxic or low oxygen conditions in these wet soils (WRC, 2011a). Regardless, maize production is commonly found on Gley soils in Waikato because they are interspersed with Allophanic soils on the flat alluvial plains (Figure 2.1). The properties of Gley soils make them more sensitive to continuous cropping, however much land in Waikato will have a complex arrangement of Allophanic and Gley soils that does not allow for separation or exclusion of one soil type (FAR,

2008). The dominant soil of the Te Kowhai series is the Te Kowhai silt loam, classified as a Typic Orthic Gley Soil (NZSC), known for being poorly drained, unsuitable for horticultural use, and susceptible to wet conditions and related issues such as pugging (Singleton, 1991; WRC, 2011b).

2.4.3 Bruntwood series

The Bruntwood series are found between the slightly raised channels and low-lying swales of the alluvial plains (Figure 2.2). Due to their intermediate position on the plains, the Bruntwood series have soil properties intermediate of both Horotiu and Te Kowhai series soils (Singleton, 1991; Lowe, 2020). The Bruntwood series has an upper subsoil made up of well-drained allophanic material, therefore the upper profile is associated with advantageous allophanic properties such as stable fine aggregates and low bulk density (WRC, 2011a; Lowe, 2020). The lower subsoil is however typically at the same level as the swales or has a slow permeable layer that limits drainage, resulting in a halloysitic, poorly drained subsoil (WRC, 2011a; Lowe, 2020). The dominant soil of the Bruntwood series is the Bruntwood silt loam, classified as a Typic Impeded Allophanic Soil (NZSC) (WRC, 2011a). The upper soil is well drained with moderate permeability, therefore is suited to a range of land uses including maize production (FAR, 2008). The Bruntwood series is not as versatile as the Horotiu series due to its limiting subsoil and less porous structure, but it is more widespread throughout the Waikato region (WRC, 2011a).

2.5 Research needs

A significant New Zealand arable crop research organisation, FAR (2019) have found that although the establishment of maize crops using NT planting has been widely taken up internationally, there is a limited uptake in New Zealand. New Zealand agricultural scientist and engineer, Dr John Baker, states that New Zealand is “slipping behind in no-till” because the mild climate, soils, and animal-based rotations conceal much of the negative effects of FC, and New Zealand could be leading the world in reducing greenhouse gas emissions and increasing food production through the adoption of NT farming (Baker, 2012, 2019). A significant focus of studies and trials using NT and reduced cultivation systems in New Zealand has been the impact on crop yields, where

many found no change in yields under NT farming, hence growers and farmers cannot justify changing from FC to NT or ST systems in terms of increased profitability or improved production. This is potentially why there is such limited uptake of these reduced tillage systems in New Zealand. A greater understanding of the effects of NT and ST systems on soil quality and therefore long term soil and plant productivity is required, so New Zealand farmers and growers can understand the large number of positive benefits that a reduced cultivation system could have on their soil quality, erosion risk, plant productivity, and also impacts on surrounding water quality through decreased soil losses.

There is also a limited understanding of the interaction between soil order and soil type, cultivation intensity, and soil quality. Many studies of FC versus NT and ST in New Zealand have not considered the soil order or soil type, instead assuming the soil response is primarily from the cultivation treatment and not affected by the inherent characteristics of the soil order. The majority of maize production is on flat or undulating land, and in the Waikato region this is predominantly on Allophanic soils, which are of natural high quality and versatility. However, as described in Section 0, the soil-landscape pattern of the Hamilton Basin means that maize is actually grown on a continuum of Horotiu, Bruntwood and Te Kowhai soil series, each with varying degrees of versatility and limitations. It is therefore critical that we understand how different soil types respond to cultivation intensity and if adopting reduced cultivation strategies will be beneficial for one soil order or soil type over another.

Chapter 3

Methods

3.1 Introduction

The main objective of this thesis was to compare soil quality under three cultivation treatments including full cultivation, strip tillage, and no tillage. The overarching methodology of this thesis was to:

- Identify soil types at the study area (Section 3.4);
- Use sampling methods adapted from Regional Council reporting (Land Monitoring Forum, 2009) and university methods to collect soil samples (Section 3.5) for subsequent laboratory analysis of soil quality indicators (Section 3.6); and
- Identify any statistically significant differences in soil quality between treatments, between soil types, and between soil types within treatments (Section 3.7).

This chapter explains the full methods carried out during this thesis. This will begin by describing the study area, the soil sampling design, laboratory analysis of soil quality, and then statistical analysis of the results.

3.2 Study area

The study area was a long-term maize crop establishment trial managed by the Foundation for Arable Research (FAR) located in Tamahere, Hamilton in the Waikato region of New Zealand (Figure 3.1). This trial has three treatments of cultivation practices which are full cultivation (FC), strip-till (ST), and no-till planting (NT) or direct drill. The study area consists of four replicates of each treatment in 97 m x 6.1 m plots (8 crop rows) in a random order. Maize is established from mid spring to late summer and a cover crop in between (Refer to appendix C for further details on trial). The general climate is temperate with a mean annual temperature of 14.4 °C and mean annual rainfall of 1225 mm (NIWA, 2020).

A soil map of the study area (Section 3.3), identified two primary soil types in the study area – the Horotiu silt loam, and the Bruntwood silt loam (Figure 3.3). Landforms in the Hamilton Basin are identified either as low rolling hills, alluvial plains, low terraces, or gullies. The soils found in the study area are formed on alluvial plains. The plains are made up of volcanic alluvium deposited during the Hinuera Formation *c.* 22,000 cal. years ago by the ancient Waipa and Waikato rivers (Lowe, 2020). These surfaces are referred to as the Hinuera Surface, and the soil patterns follow the pattern of alluvial deposition, where the well-drained soils such as Horotiu soils (Allophanic soil order) are on slightly raised channels, poorly drained soils such as Te Kowhai (Gley soil order) on low lying swales, and Bruntwood soils (Allophanic soil order) found in between (Singleton, 1991; Molloy, 1998; Lowe, 2020). See Section 2.4 for more information on soils of the Hamilton Basin.

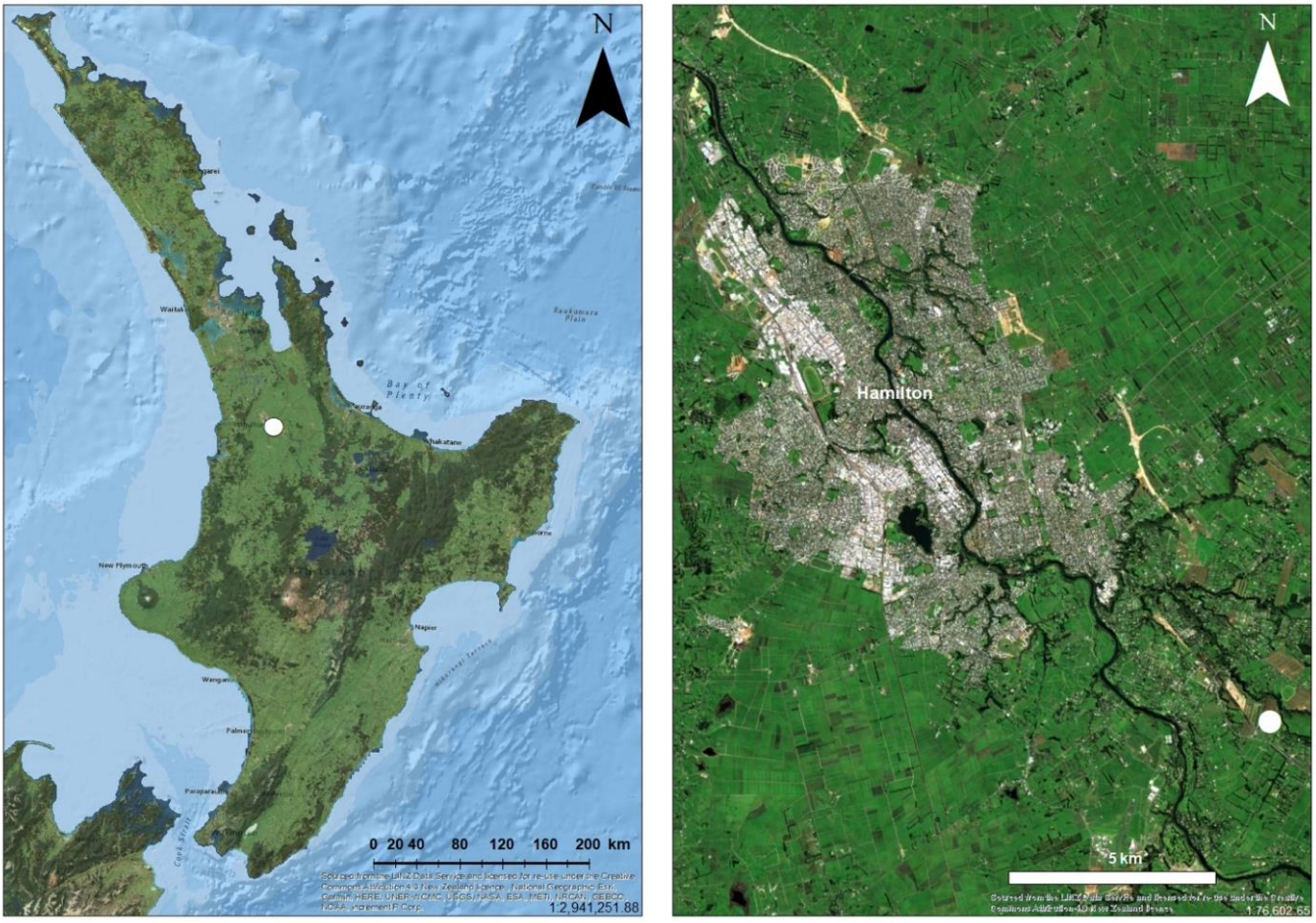

Figure 3.1. Maps displaying study area location; Left - wider North Island, New Zealand; Right - Hamilton, Waikato, New Zealand. Study area is represented by white dot.

3.3 Soil mapping

3.3.1 Field methods

As there were 12 plots in the study area, it was decided to treat these plots separately and identify the soil types and proportions of each soil type in each plot. This was done through auger sampling, where a sample would be collected by augering to at least 30 cm and laid out on a wooden board to identify soil type. Soil identification methods were adapted from Hewitt (1993) and Milne *et al.* (1995) including an allophane test (Sodium fluoride, NaF) to identify allophanic soils and distinguish between Horotiu and Bruntwood soils, as Horotiu silt loam tested more strongly for allophane. These methods identified four soil types present in the study area as seen in Figure 3.2. As each soil type was identified, landforms were used to predict where changes in soil type would likely be, such as slight raises would likely be Horotiu soils, for flats and the majority of the study area it would likely be Bruntwood soils, and small swales or depressions would likely be Te Kowhai soils, following common patterns identified by Lowe (2020) and Hewitt (1993). Where landforms changed from one form to another, e.g., from flat to swale, more concentrated augering was undertaken to ensure the transition between soil types was captured. Soil types were recorded for each plot by sketching onto a map, and recording the distance from the beginning of the transect, sides of each plot, and end of each plot.

Figure 3.2. A) Horotiu silt loam – warm brown topsoil (NaF test: strongly allophanic), vibrant orange subsoil (NaF test: moderately to weakly allophanic); B) Bruntwood silt loam – dark brown topsoil (NaF test: moderate to weakly allophanic), light brown subsoil (NaF test: weakly/non-allophanic); C) Te Kowhai silt loam – blackish brown topsoil (non-allophanic), grey subsoil sometimes with mottles present (non-allophanic).

3.3.2 Digitizing the soil map

ArcMap (GIS) was used to digitize the soil map. Points were added on the map where there had been an auger sample and identified soil sample, and these were later connected to form the portions of each soil type as seen in the final map (Figure 3.3). The 12 plots were overlaid on the map to easily show the soil proportions and sample areas in each plot. As seen in Figure 3.3, the proportion of each soil type in each plot differed. The study area was dominated by Bruntwood and Horotiu soils, and areas where there were indistinguishable changes in soil type or potential complexes of soil types were excluded.

Figure 3.3. Soil map of the study area, displaying the soil types for the entire study area, as well as within each plot.

3.4 Sampling design

Preliminary data analysis provided by FAR on previous soil quality assessments from the study area gave insight into the number of samples necessary to potentially provide statistically significant results. The soil map (Figure 3.3) was used to distinguish the proportions of each soil type in each plot to allow for appropriate numbers of samples to be taken from each soil portion. For this study, samples were only collected from proportions of Horotiu silt loam and Bruntwood silt loam (inclusive of Bruntwood silt loam, deep topsoil variant) as the portions of Te Kowhai were very small therefore not representative of the study area (Figure 3.3). Definitive areas of Bruntwood and Horotiu soils were mapped, excluding any areas where there may be "complexes" of the various soil types or Te Kowhai silt loam (Figure 3.4).

The soil sampling design varied depending on which soil quality indicator and associated parameters were measured, and was split into six different sampling schemes:

- Soil quality samples (using a bucket sampler as in Section 3.5.1)
- Total C/N soil cores (mechanically driven to 30 cm as in Section 3.5.2)
- Intact soil cores (for bulk density and particle density as in Section 3.5.3)
- Aggregate stability samples (Section 3.5.4)
- Penetrometer (Section 3.5.5)
- Visual soil assessment (VSA) (Section 3.5.6)

Each soil quality indictor sampled had a different number of samples to be collected depending on that suggested by preliminary data analysis (Table 3.1 & Table 3.2), and each plot had to have different sampling locations rather than a replicative system depending on the soil proportions as seen in Figure 3.4.

Figure 3.4. Map displaying the exact areas of Bruntwood and Horotiu soils that were sampled in each plot, excluding any areas where there may be "complexes" of the various soil types and Te Kowhai silt loam.

Each sample design was based on a "zig-zag" approach to ensure samples were collected from crop-rows, and between-rows, so as to capture the variability created during cultivation, planting and use of heavy machinery (tractor tyres). The sampling area within each plot excluded 1 m from each edge of the plot, so to exclude the areas where there may be effects seen from the adjacent plots. Soil quality sampling used a unique approach to identify sample locations (Figure 3.5), whereas the remaining soil sampling used the same approach to identify sample locations with randomly generated numbers to define where to sample along each zig-zag (Figure 3.6).

Table 3.1. Table showing number of samples collected per plot. *Note: Soil cores were further split into three depths resulting in three times the number of samples.

Sample Type	No. of Bruntwood samples	No. of Horotiu Samples	Total Number of Samples
Soil Quality samples	12	12	24
Intact soil cores	5	5	10
Total C/N soil cores*	3*	3*	6*
Aggregate stability	3 (bulked)	3 (bulked)	2
Penetrometer	8	8	16
Visual Soil Assessment	1	1	2

Table 3.2. Table showing total number of samples collected for each treatment. *Note: Soil cores were further split into three depths resulting in three times the number of samples.

Sample Type	Treatment (4 x plots)
Soil Quality samples	96
Intact soil cores	40
Total C/N soil cores*	24*
Aggregate stability	8
Penetrometer	64
Visual Soil Assessments	8

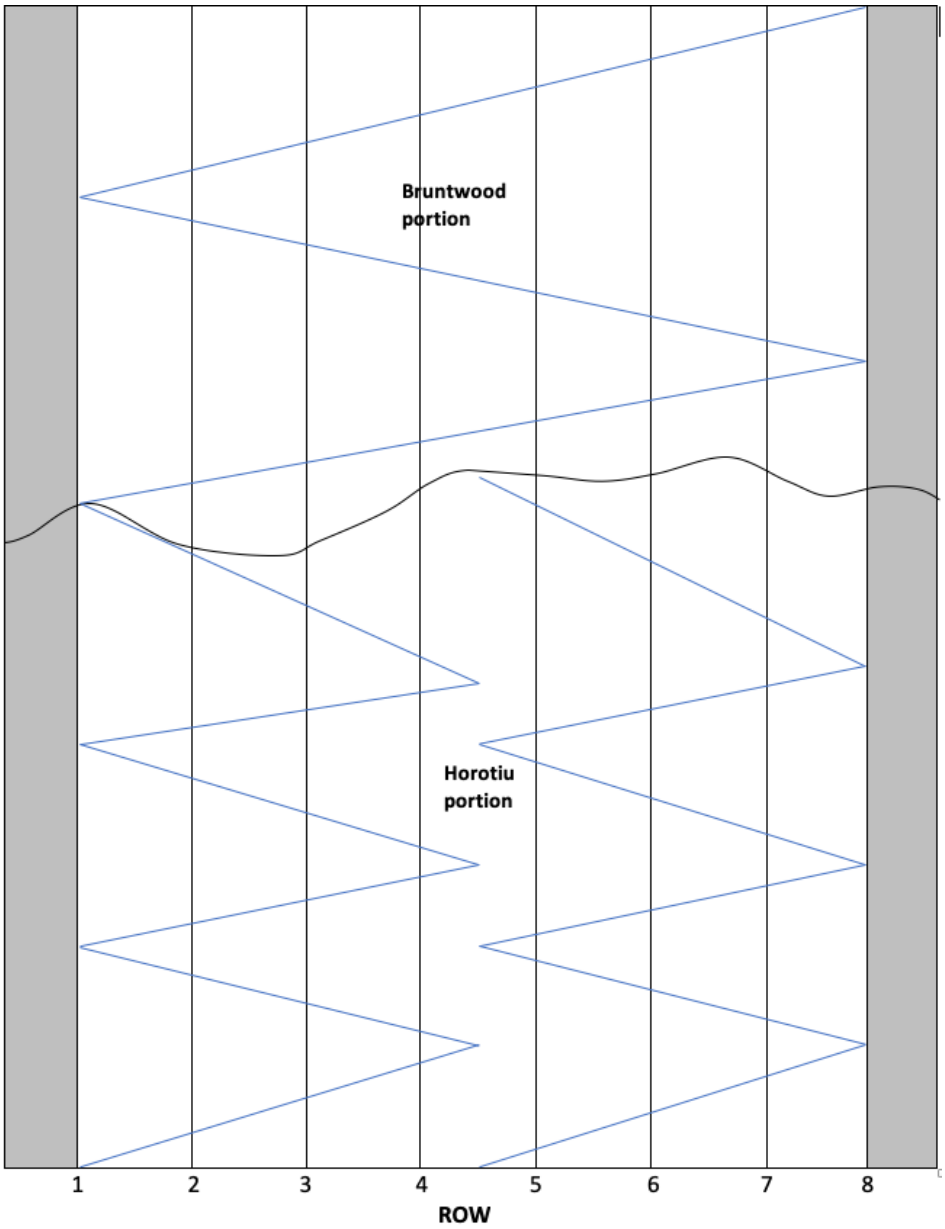

Figure 3.5. Sampling design for soil quality sampling. Image represents a portion of one plot, with a portion of Horotiu silt loam, and a portion of Bruntwood silt loam. The grey shaded area represents the 1 m on either edge of the plot being excluded from sampling. The blue zig-zags are the sampling area, which are different systems for Horotiu and Bruntwood. As Horotiu portions in each plot are much smaller than the Bruntwood, the Horotiu portion is further split into two areas, using two zig-zag systems to allow for 12 samples to be collected from the area. The bucket sampler takes approx. 10 - 12 samples randomly along one zig-zag line to fill the bucket for one sample. The location of zig-zags are calculated as the size of the portion divided by 12 samples (Bruntwood) or divided by 6 samples x 2 areas to be sampled (Horotiu).

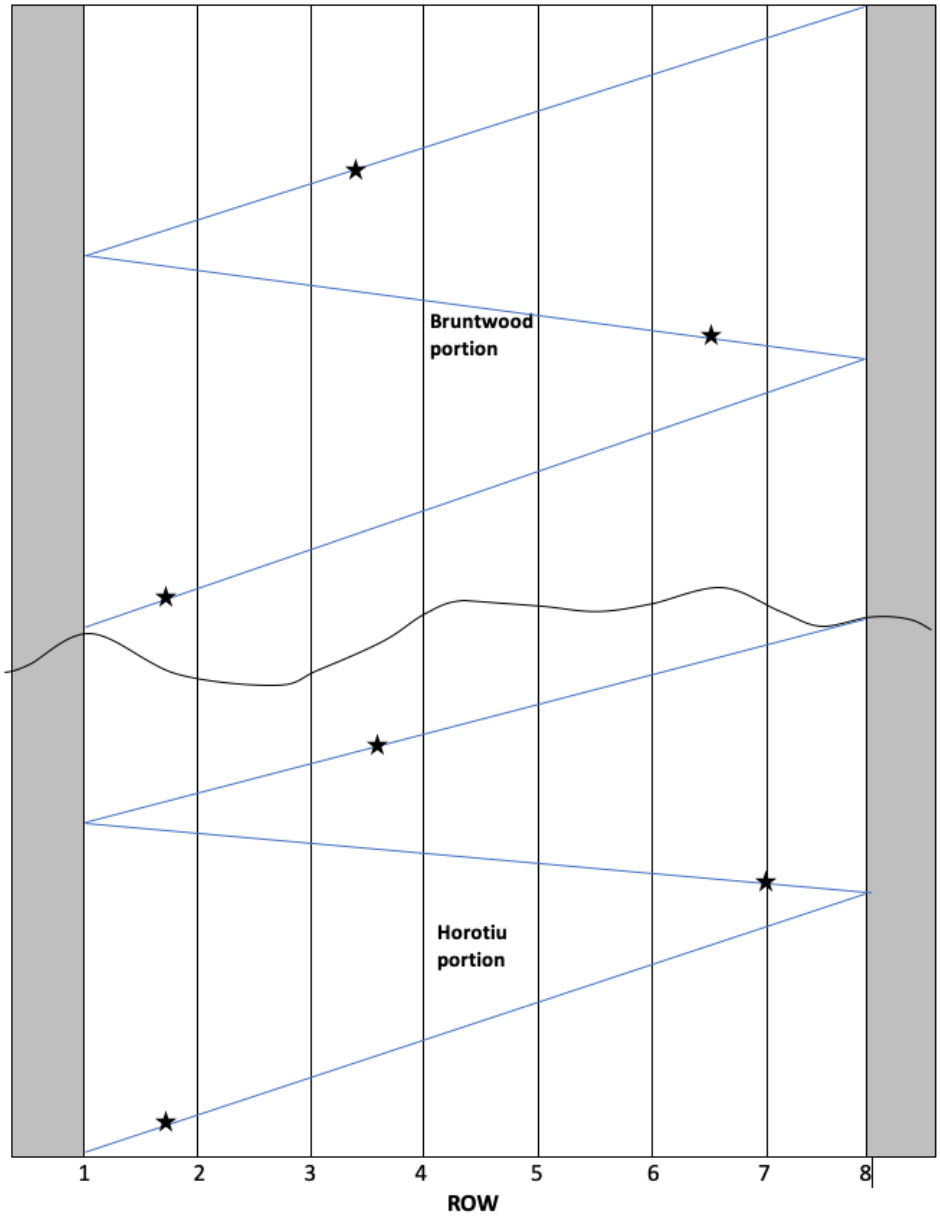

Figure 3.6. Sampling design for intact soil cores, Total C/N soil cores, aggregate stability, VSA, and penetrometer sampling. Image represents part of one plot, with a portion of Horotiu silt loam, and a portion of Bruntwood silt loam. The grey shaded area represents the 1 m on either edge of the plot being excluded from sampling. The blue zig-zags are the sampling area, which are different systems for Horotiu and Bruntwood. The amount of zig-zags that are used is determined by the length of the sampling area is divided by the amount of samples identifying where to zigzag, this image is an example of if there were 3 samples collected per soil type. Random numbers were generated before sampling to identify where to sample along each zig-zag (shown as stars in this image).

3.5 Soil sampling

Soil sampling for soil quality investigations on the two major soil types (Bruntwood silt loam and Horotiu silt loam) took place at the long-term maize crop establishment trial at the FAR NCRS in Tamahere, Hamilton, Waikato (Figure 3.1), on the 9th to 20th September 2019. Samples were collected in the late winter period to be consistent with previous FAR sample collection and allow for accurate comparisons with previous years. During this period, the site was in a cover crop (oats) with the maize crop residue still present. To prepare the site for sampling, the soil map was used and markers placed into the ground to mark the Horotiu and Bruntwood sampling areas in each plot (including marking the excluded 1 m from the edge of each plot) (Figure 3.7).

Figure 3.7. Photo of site with markers seen throughout the study area

3.5.1 Soil quality sampling

A bucket sampler was used to sample soil to 10 cm depth, requiring the sampler to be pushed into the soil approximately 10 - 12 times along the transect to fill the bucket. The samples were stored in plastic snaplock bags in a 4°C fridge before being processed and analysed.

3.5.2 Soil coring

To collect soil cores, a motorised post driver (Christie Engineering) with a tube (core) was used to drill to a depth of 30 cm (Figure 3.8). Soil cores were extracted from the tubes and placed into half pipes to be sectioned from 0 - 7.5 cm, 7.5 - 15 cm, and 15 - 30 cm. These depth increments were used to compare to previous FAR soil quality

assessments using these depths. These samples were stored in plastic snaplock bags in a 4°C fridge until processed and analysed.

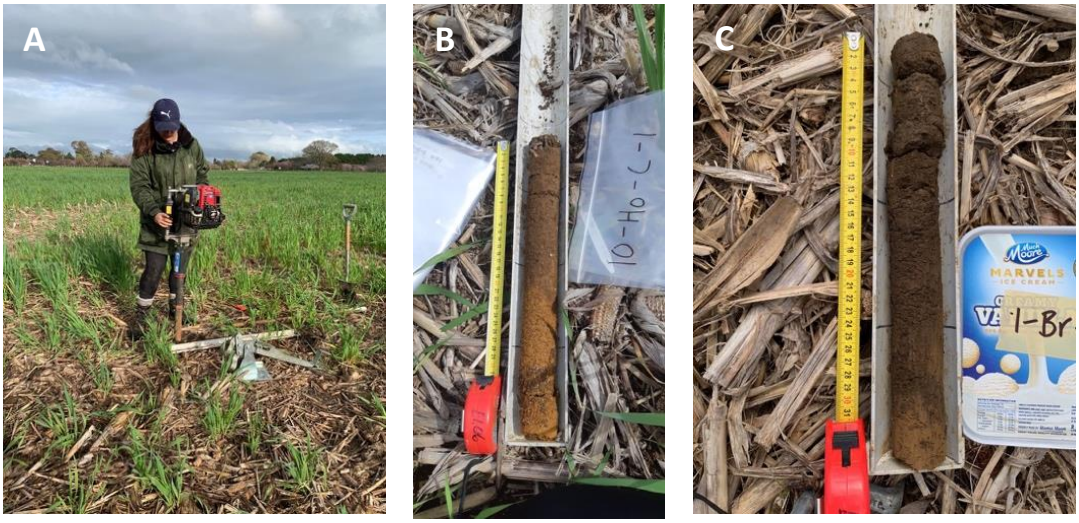

Figure 3.8. A) Christie post driver corer in use B) Horotiu core extracted from 30 cm depth to be later sectioned into three increments (0 - 7.5 cm, 7.5 - 15 cm, 15 - 30 cm), C) Bruntwood silt loam core extracted from 30 cm depth to be later sectioned into 3 depth increments (0 - 7.5 cm, 7.5 - 15 cm, 15 - 30 cm).

3.5.3 Bulk density cores & particle density sampling

Intact soil cores (5 cm x 6 cm) were collected for bulk density and macroporosity analysis. Ground cover was removed, and the cores were gently hammered into the soil to 5 cm depth, then carefully extracted. The excess soil around the core was scraped off and collected into a plastic snaplock bag for particle density analysis. The cores were wrapped in plastic film and stored at 10°C until processed and analysed.

3.5.4 Aggregate stability

To collect aggregate stability samples, a spade was used to carefully extract a 5 cm x 5 cm block of soil to approximately 7.5 cm depth (trimmed if necessary). In each plot, three samples from each soil type were then bulked together and stored in an ice cream container and stored firstly at 4°C before being processed and analysed.

3.5.5 Penetration resistance

Penetration resistance was measured in the field using a penetrometer from Manaaki Whenua - Landcare Research. The penetrometer was manually pushed into the ground

to measure the resistance of soil to the penetration, these results were recorded and later digitised.

3.5.6 Visual soil assessment (VSA)

Visual soil assessments (VSA) were taken to provide a visual and understandable way to assess the soil quality. A simplified cropping farm VSA was used, created by FAR, to assess soil structure and porosity, turbidity, and earthworm counts. To do a VSA, a hole was dug using the farmer spade method (Figure 3.9) to approximately 20 cm depth and 35 cm wide, with the contents from the hole placed onto a tarpaulin. The first assessment for structure and porosity was taken by parting clods of soil and looking for signs of nutty aggregates, and given a score (Figure 3.9). Turbidity was assessed by first collecting an "undisturbed" sample from out of the trial area (such as under a fence line), and placed into a container of water, giving an indication of what the turbidity of an undisturbed soil can look like. A sample from the tarpaulin was then put into a container of water and compared to the undisturbed sample, to give a score (Figure 3.10). Earthworms in the sample were then counted and given a score. These scores are then added up to provide a total and average score for each VSA (Appendix A).

Figure 3.9. A) Equipment required for VSA including tarpaulin, spade, water, container, and a VSA score sheet; B) Example of how to assess structure and porosity with this example given a score of 1.5 or moderate to good condition.

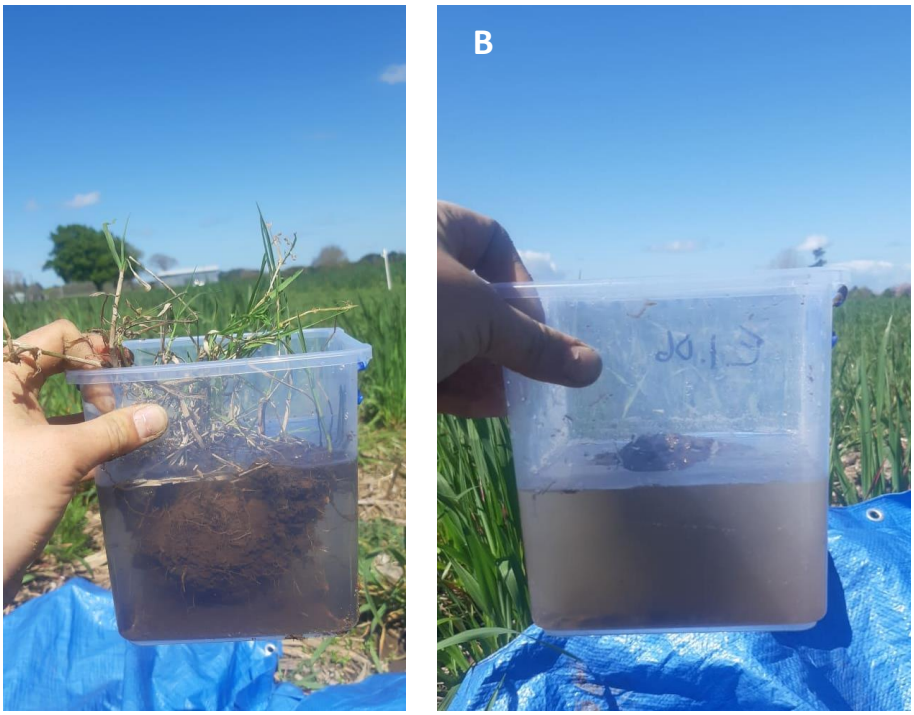

Figure 3.10. A) Turbidity sample from under the fence line given a turbidity score of 1.5 or moderate to good condition used to compare with samples taken in the study area. B) Example of a sample given a turbidity rating of 0.5 or moderate to poor condition.

3.6 Laboratory analysis

Below are summaries of the laboratory analysis methods. Details of various reagents and chemicals have not been included, refer to the listed references for these details.

3.6.1 Sample preparation

3.6.1.1 Soil quality samples

Due to multiple laboratory analysis for soil quality requiring field moist soil, the soil quality samples were first passed through a 2 mm sieve and remaining roots were removed by hand. These samples were then subsampled for mineralisable nitrogen (5 g) into plastic bags to be frozen at approximately -18 ˚C until analysis. A subsample was then taken for chemical analysis to be air-dried in an oven at 35 ˚C for around five days, or until a constant weight, then stored in plastic containers at room temperature. The oven was used to dry soil rather than at room temperature due to the significant number of samples to allow for a more rapid and consistent drying process. A subsample from half of the soil quality samples was then taken to be used for total carbon and nitrogen analysis, with any visible roots removed, a portion was used to measure water content

and moisture factor, and the remaining portion was finely ground using a mortar and pestle and stored in plastic containers stored at room temperature.

3.6.1.2 Total C/N soil cores

Soil core samples were first air-dried in an oven at 35 ˚C for around five days, or until a constant weight. These were then passed through a 2 mm sieve directly into a mortar and pestle, with all visible roots removed, a subsample was taken to measure water content and moisture factor. The remaining sample was then finely ground and stored in plastic containers stored at room temperature.

3.6.1.3 Aggregate Stability Samples

Aggregate stability samples were first carefully sieved to < 4 mm, then sieved through a 2 mm sieve. The aggregates remaining on the 2 mm sieve (2 – 4 mm aggregates) were then air-dried in an oven at 35 ˚C for around five days, or until a constant weight. Samples were then analysed immediately once air-dried to avoid any damage to the aggregates.

3.6.2 Particle density

Particle density is required to calculate total porosity, macroporosity and air-filled porosity (see Section 3.6.3). Particle density was measured using clean, dry 50 mL density bottles and vacuum desiccators in Manaaki Whenua – Landcare Research (MWLR) laboratories as well as following MWLR methodology.

Approximately 15 g of < 2 mm ground oven dried soil was put into each density bottle with its bottle stopper inserted, weighed, and then saturated with a small amount of distilled water. The bottles were placed into a vacuum desiccator and vacuum gradually applied and released until bubbling had settled and vacuum continuously applied. Over a period of two to three hours, more distilled water was gradually added until the bottles were filled to the base of the neck (Figure 3.11). At this stage, a beaker of distilled water was placed in the desiccator to be deoxygenated for use the following day. The samples and water were left under vacuum for at least another hour, then the vacuum was turned off, however the samples and water remained in the deoxygenated desiccators overnight allowing for full settling of the soil. The following day the bottles were placed into a 25 ˚C water bath and topped up using the deoxygenated water, and left for 30

minutes. After 30 minutes, the bottles were sealed with the bottle stoppers, dried, and weighed. Using the weight of the bottle and soil before analysis and again after, particle density can be calculated using Equation 3-1.

$$PD\ (t\ m^{-3}) = \frac{0.99707\ x\ (BS - B)}{BW - \big(BWS - (BS - B)\big)}$$

Equation 3-1

Where:

0.99707 = Density of water at 25 ˚C (t m^{-3})

BS = Mass of bottle + soil (g)

B = Mass of bottle (g)

BW = Mass of bottle + water (g)

BWS = Mass of bottle + water + soil (g)

Figure 3.11. Particle density bottles in desiccators under vacuum

3.6.3 Macroporosity, air-filled porosity, & bulk density

The intact soil cores (5 cm x 6 cm) were firstly used to measure macroporosity (-5 kPa) and air-filled porosity (-10 kPa) using MWLR methodology and equipment. To prepare the samples for analysis, ceramic plates were saturated with water over a period of two to three days and the cores were trimmed to be flush with the top and bottom of the metal core, with no soil remaining on the outside, and then weighed. The cores were placed on the plates and put in a sink with a small amount of water over a few days. After three days, the ceramic plate hoses were released to allow pressure to be applied to the plates, which were then placed into plastic bags 50 cm above a bottle where the

hoses could drain, therefore applying -5 kPa pressure to the cores, where they were left for around three days (Figure 3.12 A). After three days, the cores were reweighed and re-wet, and then placed 1 m above the draining bottle, therefore applying -10 kPa pressure, where they were left for seven days (Figure 3.12 B). After seven days, the cores were reweighed. For bulk density analysis, the cores were then oven-dried at 105 °C for a few days and then reweighed, then calculated for gravimetric water content (Equation 3-2), mass of dry soil (Equation 3-3), and dry bulk density (Equation 3-4). Once bulk density was calculated, this could be used with particle density calculations (equations) to calculate total porosity (Equation 3-5), macroporosity (Equation 3-6) and air-filled porosity (Equation 3-7). Units for bulk density were expressed in $t\ m^{-3}$, and macroporosity and air-filled porosity expressed in *% v/v.*

$$\mathrm{GWC} = \left(\frac{(Mass\ of\ liner\ \&\ wet\ soil - Mass\ of\ liner\ \&\ dry\ soil)}{Mass\ of\ liner}\right) x\ 100$$

Equation 3-2

$$DS = \frac{(GWC - Mass\ of\ liner)}{(1 + \left(\frac{GWC}{100}\right))}$$

Equation 3-3

$$BD\ (t\ m^{-3}) = \frac{DS}{Volume\ of\ liner}$$

Equation 3-4

$$TP\ (\%) = \left(1 - \left(\frac{BD}{Particle\ Density}\right)\right) x\ 100$$

Equation 3-5

$$Macroporosity\ (\%) = TP - Volumetric\ water\ content\ at\ 5kPa$$

Equation 3-6

$$Air - filled\ porosity\ (\%) = TP - Volumetric\ water\ content\ at\ 10kPa$$

Equation 3-7

Figure 3.12. Intact soil cores on ceramic plates with hoses draining into a bottle of water with A) -5 kPa pressure applied to produce macroporosity results, and B) -10 kPa pressure applied to produce air-filled porosity results.

3.6.4 Aggregate Stability

Aggregate stability was measured using a wet sieving method by the Land Monitoring Forum (2009) using a mechanical sieve. Ten grams of the 2 – 4 mm aggregate samples were dried overnight at 105 ˚C to derive moisture content to be used in later calculations. Sieve nests were placed in the mechanical siever with the sieves in order of 2 mm, 1 mm, and then 0.5 mm (Figure 3.12). Water was added to the wet siever and 50 g of air-dried 2 - 4mm aggregates were carefully placed onto the top sieve (2 mm). After 20 minutes of wet sieving, the nest of sieves was carefully removed and using a low pressure hose the remaining aggregates on each sieve transferred into pre-weighed pottles. The pottles were left to settle for a few minutes, then as much excess water as possible was removed. The pottles were then dried in the oven at 105 ˚C overnight, or

until dried depending on how much excess water was present. The samples were then re-weighed and using moisture content data, aggregate stability is calculated as mean weight diameter (MWD, mm) and percentage of aggregates larger than 1 mm using a range of equations as seen below.

$$Total\ oven\ dry\ weight = \frac{Wet\ sieving\ sample\ weight}{MC\ wet\ weight * MC\ dry\ weight}$$

Equation 3-8

Where:

Wet sieving sample weight = Approximately 50 g (pre-recorded)

MC = moisture content (g)

$$\%\ aggregates\ 2-4\ mm = \left(\frac{2-4\ mm\ weight}{Total\ oven\ dry\ weight}\right) x\ 100 \quad \textbf{A}$$

$$\%\ aggregates\ 1-2\ mm = \left(\frac{1-2\ mm\ weight}{Total\ oven\ dry\ weight}\right) x\ 100 \quad \textbf{B}$$

$$\%\ aggregates\ 0.5-1\ mm = \left(\frac{0.5-1\ mm\ weight}{Total\ oven\ dry\ weight}\right) x\ 100 \quad \textbf{C}$$

$$\%< 0.5\ mm = 100 - (\%2-4\ mm) - (\%1-2\ mm) - (\%0.5-1\ mm) \quad \textbf{D}$$

Equation 3-9 A - D

$$Aggregate\ stability\ MWD\ (mm) = \frac{(A * 3) + (B * 1.5) + (C * 0.75) + (D * 0.25)}{100}$$

Equation 3-10

$$Aggregate\ stability\ \%< 1\ mm = \%\ 2-4\ mm + \%\ 1-2\ mm$$

Equation 3-11

Figure 3.13. Wet sieving mechanical siever, with nest of sieves (2 mm, 1 mm, 0.5 mm) in water and mechanically moved up and down for 20 minutes.

3.6.5 Mineralisable Nitrogen

To measure mineralisable nitrogen, anaerobic methods based on those of Blume (1985) were used. Five grams of field moist, < 2 mm soil was used and each sample was duplicated, where one duplicate was tested for mineralisable nitrogen at Day 0, and one was incubated with 10 mL distilled water for seven days at 40 ˚C.

Day 0 samples were measured by adding 10 mL of distilled water, then adding 40 mL of the ammonium extractant Potassium chloride (KCl). These were shaken for one hour, then filtered and collected into another falcon tube. Ammonium concentration was then measured using a manual colorimetric procedure analysed in a spectrophotometer as in Baethgen and Alley (1989). This added small amounts of solutions to 1 mL of the filtered samples that allowed for colorimetric detection of ammonium. Once the solutions were added, samples were left to rest for 45 minutes and for colour to develop (green), then absorbance levels were read at 650 nm on the spectrophotometer. After seven days, the incubated samples followed the same procedures beginning from the addition of the 40 mL extractant.

Ammonium standards provided a daily standard curve on the spectrophotometer using six standards with 0, 2, 4, 6, 8, and 10 μg NH_4-N / mL. Once a standard curve was created using the standards, the linear equation for the standard curve was used to calculate ammonium concentrations. An example of this can be seen in Equation 3-12.

$$y = 0.0821x + 0.0407$$

Equation 3-12

Where:

y = absorbance of sample (nm)

x = ammonium concentration (μg / mL)

As the absorbance was the known variable (*y*), the equation was rearranged to solve for *x* or ammonium concentration as seen in Equation 3-13.

$$x = \frac{y - 0.0407}{0.0821}$$

Equation 3-13

Equation 3-13 gives ammonium concentration of each sample in μg / mL, these are then converted into μg N / g using Equation 3-14.

$$Ammonium\ conc\ \left(\frac{\mu gN}{g}\right) = \frac{x * 40}{5}$$

Equation 3-14

Where:

x = ammonium concentration (μg / mL) calculated in Equation 3-13

40 = amount of KCl extractant used (mL)

5 = amount of soil used (g)

Finally, to calculate mineralisable nitrogen the ammonium concentration in the Day 0 sample was subtracted from the Day 7 incubated sample to give total mineralisable nitrogen (μgN / g) for that sample.

3.6.6 Soil pH

Soil pH was measured using the soil pH in water method based on those by Blakemore *et al.* (1987). Approximately 8 g of < 2 mm field moist soil was placed in falcon tubes, and 20 mL distilled water added. Caps were placed on the falcon tubes and manually shaken until the contents were mixed thoroughly. The samples were then left to settle overnight. The following day, pH meters were calibrated using pH 4, 7, and 10 buffers, and soil pH was measured by placing the electrode halfway between the soil and water interface.

3.6.7 Olsen P

Olsen P or plant available phosphorus was measured using methods based on those by Olsen *et al.* (1954) and Murphy and Riley (1962). This method involves the addition of an extractant for phosphorus, and a colorant to colourmetrically measure phosphorus. Forty mL of the phosphorus extractant ($NaHCO_3$) was added to 2 g of < 2 mm air-dried soil and shaken for around 30 minutes. The samples were then filtered, and 10 mL of the filtered samples transferred into 100 mL volumetric flasks. 0.5 M H_2SO_4, distilled water, and Murphy and Riley Solution were added and left to rest for around 20 minutes for colour to develop (Figure 3.14). The samples were then absorbance levels were read using a spectrophotometer at 880 nm.

Six Olsen P standards with 0, 1, 2, 3, 4, and 5 ppm P were used to produce a daily standard curve on the spectrophotometer. Once a standard curve was created using the standards, the linear equation for the standard curve was used to calculate Olsen P concentrations. An example of this can be seen in Equation 3-15.

$$y = 0.077x - 0.0007$$

Equation 3-15

Where:

y = absorbance of sample (nm)

x = Olsen P concentration (μg / mL)

As the absorbance was the known variable, the equation was rearranged to solve for *x* or Olsen P concentration as seen in Equation 3-16.

$$x = \frac{y + 0.0007}{0.077}$$

Equation 3-16

Equation 3-16 gives Olsen P concentration of each sample in µg / mL, these are then converted into µg / g using Equation 3-17.

$$Olsen\ P\ conc\ \left(\frac{\mu g}{g}\right) = \frac{x * 40}{2}$$

Equation 3-17

Where:

x = Olsen P concentration (µg / mL) calculated in Equation 3-13

40 = amount of extractant ($NaHCO_3$) used (mL)

2 = amount of soil used (g)

Figure 3.14. A) Olsen P standards with colourant to be used to create standard curve, showing colour difference from 0 – 5 ppm P. B) Set of samples being tested for Olsen P, showing colours are very blue indicating they are high in Olsen P.

3.6.8 Total carbon and nitrogen

Total soil carbon (C) and nitrogen (N) from each increment (0 – 7.5 cm, 7.5 – 15 cm, and 15 – 30 cm) and the soil quality samples from 0 – 10 cm, was measured using a combustion method with the University of Waikato LECO TruSpec CN Elemental Analyser. For samples to be analysed in the LECO, a colour scheme was allocated to allow each colour of soil to have a certain weight to be put through the LECO. It was determined that light coloured soil was to use 70 mg, medium coloured soil use 60 mg, and dark coloured soil to use 30 mg. Soil was weighed into small tinfoil boats and carefully folded and rolled into small balls to be analysed in the LECO. The rest of the combustion method in the LECO was carried out by the Waikato Stable Isotope Unit, and results were given as a percentage of Total C and Total N in each sample.

3.6.9 Moisture Content

Subsamples were taken from < 2 mm air-dried soil quality and soil core samples to be used to calculate Total C and N. Tins were pre-weighed and a spoonful of the subsample was added and weighed. The subsample was then dried overnight in the oven at 105 °C. The samples were then reweighed, and calculated for gravimetric water content (GWC) (Equation 3-18) and moisture factor (MF) (Equation 3-19).

$$GWC\ (g\ g^{-1}) = \frac{Air\ dry\ sample\ weight - Oven\ dry\ sample\ weight}{Oven\ dry\ sample\ weight}$$

Equation 3-18

$$MF = \frac{Air\ dry\ sample\ weight}{Oven\ dry\ sample\ weight}$$

Equation 3-19

3.7 Statistical Analysis

Data was analysed through the analysis of variance (ANOVA) using GenStat and Minitab software to test the statistical significance of the observed differences in soil properties between the three cultivation treatments (full cultivation, strip-till, no-till), as well as between the two soil types (Horotiu silt loam, Bruntwood silt loam), and where there was an interaction of both treatment and soil type. *P* values of less than 0.05 were reported as statistically significant (Appendix B).

Chapter 4

The effects of varying intensity cultivation on soil quality in a maize cropping system

4.1 Abstract

Maize is the primary crop grown on arable land in the Waikato region, predominantly established on Allophanic soils due to their well-drained and resilient properties. Full cultivation (FC) is universally adopted in cropping systems and associated with increased soil aeration and successful seed establishment, however, has been shown to reduce soil quality through declines in soil organic matter (SOM) and soil structure. Soil degradation can be reduced through conservation tillage such as no-till (NT) and strip-till (ST). A number of studies have investigated the effect of cultivation intensity on soil quality and consistently found that NT systems have greater carbon (C) levels and aggregate stability at the soil surface than higher intensity cultivation systems.

This study aimed to identify differences in soil quality between cultivation intensities (FC, ST, and NT) on Allophanic soils of the Hamilton Basin. NT was shown to be most beneficial for a maize cropping system as indicated by significantly greater total C (TC) (3.98 %), total nitrogen (TN) (0.41 %), and aggregate stability (0.97 mm, MWD) at the soil surface than higher intensity cultivation systems (For FC; TC = 3.56 %, TN = 0.37 %, Agstab = 0.62 mm). Additionally, soil quality was compared between soil types (Horotiu silt loam & Bruntwood silt loam) finding that Horotiu silt loam had significantly greater TC and TN from 0 – 10 cm, 0 – 7.5 cm, and 7.5 – 15 cm (For 0 – 10 cm; TC = 4.02 %, TN = 0.42 %), aggregate stability (0.82 mm, MWD), macroporosity (14 %) and lower bulk density (0.96 t m^{-3}) and Olsen P (82.9 µg g^{-1}) than the Bruntwood silt loam (TC = 3.52 %, TN = 0.36 %, Agstab = 0.73 mm, MP = 12 %, BD = 1.05 t m^{-3}, Olsen P = 105.5 µg g^{-1}). Interactions of cultivation intensity and soil type had minimal influence on soil quality, however, the Horotiu silt loam under the least intensive cultivation (NT) had significantly higher aggregate stability (1.07 mm) than all other combinations. Conversely, the Bruntwood silt loam under FC had the lowest aggregate stability (0.55 mm, MWD) and penetration resistance (1.63 MPA).

Many of the soil quality values in the study area fell below or exceeded target ranges regardless of cultivation treatment or soil type due to the intensive nature of cropping systems, heavy machinery, and poorly defined target ranges. Regardless, this study identified NT as the most beneficial cultivation for a maize cropping system, and highlights how inherent soil properties can dominate soil quality. As there were no differences in maize yields with cultivation intensities, the improvements in soil quality seen in increased SOM and aggregate stability under NT indicates that NT may be a more suitable cultivation system for continuous maize cropping without decreasing productivity or profitability.

4.2 Introduction

Soil quality is defined as "the capacity of a specific soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Soil Science Society of America, as cited in Lilburne *et al.*, 2004). Or more simply, "fitness for use" where a soil's quality is determined by its ability to match soil conditions suited to a certain land use and its capability to maintain this fitness in the long term (Schipper & Sparling, 2000). Soil quality is essential to the overall productivity and health of land as it supports a range of ecosystem services that primary production relies on (Mackay *et al.*, 2013), including food and fiber production, nutrient provisioning and cycling, climate regulation and carbon storage, water provision and quality maintenance, pollutant degradation and pest control, and conservation of biodiversity (Vogel *et al.*, 2018). Where soil quality is degraded, the capability to support these essential services and its fitness for use is reduced, therefore reducing productivity and profitability, and implicating other domains of the environment such as water quality (Ministry for the Environment (MfE) & Statistics New Zealand (StatsNZ), 2018).

In New Zealand (NZ), specific pressures are applied to soils as a result of land use intensification and land use changes that impact quality and versatility of soil resources through changes in soil physical, chemical, and biological properties (MfE & StatsNZ, 2018). These include inadequate vegetation cover during cultivation and harvesting of crops, and poor matching of land use to soil capability (Ministry for Primary Industries (MPI), 2015). A nationally consistent set of soil quality indicators are used to monitor

soil quality in NZ, comprised of a range of soil physical, chemical, and biological properties that can indicate changes in soil quality in response to land use, as identified in the "500 Soils" project (Lilburne *et al.*, 2004; Sparling & Schipper, 2004; Sparling *et al.*, 2004). These indicators include total carbon, total nitrogen, mineralisable nitrogen, soil pH, Olsen P, bulk density, and macroporosity. Other indicators identified to be valuable for cropping systems by the Land Monitoring Forum (2009) include aggregate stability, penetration resistance, and visual soil assessments (VSA). The seven soil quality and additional cropping indicators allow for interpretation of data with target ranges and can identify trends and issues in soil quality.

A large focus in cropping systems is the preservation of soil organic matter (SOM). SOM is essential for life and productivity in soil, made up largely of carbon and nitrogen from organic matter and its decomposition (Abreu *et al.*, 2011; Taylor *et al.*, 2017). SOM increases soil fertility and improves biological and physical soil properties (West & Post, 2002; Diekow *et al.*, 2005; Deb *et al.*, 2015). SOM enhances soil microbial activity and biodiversity through an additional metabolic energy source (Black & Bauer, 1983; Haddaway *et al.*, 2016). SOM is strongly related to aggregate formation and stability, where SOM helps to bind and form soil aggregates, and in turn aggregates aid in physical protection and preservation of SOM (Deb *et al.,* 2015; Landcare Research – Manaaki Whenua (LCRS-MW), 2020). Improved soil structure and soil conditions allow for efficient air and water movement and productive plant growth (McLaren & Cameron, 1996; Diekow *et al.*, 2005). SOM decline is of large concern under cropping systems as SOM loss is accelerated through cultivation and harvesting, resulting in the rate of organic matter removed being much higher than that being put in (McLaren & Cameron, 1996; Haddaway *et al.*, 2016).

Maize is the primary crop grown on arable land in the Waikato region (Foundation for Arable Research (FAR), 2019) as maize grain and silage are high value, cost effective, and high carbohydrate crops that are used for animal feeds, human food, and industrial products. Maize is predominantly grown on the Allophanic soils of the Waikato region such as the Horotiu and Bruntwood soil series due to their well-drained and resilient properties (FAR, 2008; Nicholls *et al.*, 2009; Reid & Morton, 2019). It is also established on Gley soils in Waikato such as the Te Kowhai soil series, however Gley soils are more sensitive to continuous cropping than Allophanic soils due to their poor drainage

characteristics and associated properties (FAR, 2008). Maize production in the Waikato makes up approximately 50 % of NZ maize silage production and 38 % of overall maize harvest occurring within the Waikato region (StatsNZ, 2017). Soil compaction and reductions in soil quality due to intensive cultivation have been identified as major limitations to continuous maize production in NZ (Sparling *et al.,* 1992; FAR, 2018).

Full cultivation (FC) or conventional cultivation is universally adopted in cropping systems and has been associated with increased soil aeration, successful seed establishment, and mechanical weed control. However, full cultivation has been shown to reduce soil quality through significant loss of SOM by accelerated decomposition and declines in soil structure, therefore threatening long-term productivity and profitability (Arshad, 1999; Sparling *et al.*, 2000a; Zuber *et al.*, 2015; Zuber *et al.*, 2018). Soil degradation can be reduced by the adoption of conservation tillage such as no-till (NT) or direct drill, and strip-till (ST) or minimum tillage (Holland, 2004).

No-till (NT) or direct drill is a system where there is limited soil disturbance, alternatively a seed is directly drilled into the undisturbed soil (Haynes & Knight, 1989; McLaren & Cameron, 1996). In this system, residues from the previous crop remain on the soil surface rather than being incorporated into the soil (Kumar & Goh, 1999). This increases SOM, provides additional metabolic sources for soil microorganisms, and improves soil aggregation and stability (Doran & Zeiss, 2000; Zuber *et al.*, 2018). Strip-till (ST) is a reduced version of cultivation, only disturbing a portion of the soil that is to have a crop row, consequently gaining the benefits of both FC and NT systems (FAR, 2019b). The establishment of maize crops using reduced cultivation methods such as NT have been adopted internationally, however is not yet a widely used cropping system in New Zealand regardless of the numerous recognized benefits (FAR, 2019b).

The soils in this study are Allophanic soils, which are significantly influenced by clay minerals such as allophane, with enhanced binding with SOM therefore improving soil structure and quality (McLaren & Cameron, 1996). Allophanic soils typically have a higher aggregate stability and superior soil structure and better suited to continuous maize cropping than Gley soils (FAR, 2008). The Horotiu silt loam, found on slight raises of the landscape, is exceptionally versatile, resilient, well-drained and porous, with moderately deep rooting depth and moderate permeability (Singleton, 1991; Waikato

Regional Council (WRC), 2011b). The Bruntwood soil series has soil properties intermediate of both Allophanic and Gley soils due to its position in the landscape (Lowe, 2020). The Bruntwood silt loam's upper subsoil is made up of well-drained allophanic material and therefore has advantageous allophanic properties such as stable fine aggregates and low bulk density and suited to maize production (WRC, 2011a; Lowe, 2020). Bruntwood silt loam is less versatile due to its limiting higher density subsoil and less porous structure, however the Bruntwood silt loam is more widespread throughout the Waikato region (WRC, 2011a).

This study investigates the effect of varying intensity cultivation on soil quality in a cropping system on Allophanic soils of the Hamilton Basin of the Waikato region, New Zealand. The main objective of this study was to compare soil quality under three cultivation treatments, including full cultivation (FC), strip tillage (ST), and no tillage (NT). A second objective was to compare soil quality between two soil types – the Horotiu silt loam and Bruntwood silt loam, to identify whether inherent differences within the Allophanic soil order influence a soil's ability to resist the effects of cultivation and whether the individual soil types respond differently to cultivation intensity. Seven soil quality indicators (total carbon, total nitrogen, mineralisable nitrogen, soil pH, Olsen P, bulk density, and macroporosity) and three cropping specific indicators (aggregate stability, penetration resistance, and visual soil assessment) were measured to distinguish differences between treatments and/or soil type. Although this trial is relatively young (five years), data reported in this study provides a useful baseline to identify trends in cultivation intensity-related changes in soil quality over time, and highlight which soil quality parameters are most affected by cultivation intensity. Furthermore, any differences in the response to cultivation across the two soil types will be determined. This will inform land managers on whether reduced cultivation cropping systems such as no tillage or strip tillage can be beneficial to growers in New Zealand, if soil types should or could be practically cultivated differently, and where efforts should be focused to mitigate soil quality degradation in cropping systems.

4.3 Materials and methods

4.3.1 Study area

The study area is located on a long-term maize crop establishment trial managed by the Foundation for Arable Research (FAR), in the Waikato region of New Zealand (Figure 4.1) in the area known as the Hamilton Basin. Hamilton has a temperate climate with a mean annual temperature of 14.4°C and mean annual rainfall of 1225 mm (NIWA, 2020). This trial has three cultivation treatments, which are full cultivation (FC), strip-till (ST), and no-till (NT) or direct drill. The study area is approximately one hectare with four replicates of each treatment in 97 m x 6.1 m plots in a random order. Before 2007, the study area was part of a long-term vegetable cropping system using FC methods. From 2007, it was in maize under various cultivation systems until the trial was established in 2014. Maize is established across the whole study area from mid spring to late summer and a cover crop in between. Soil quality sampling has been carried out annually prior to this study, typically collected in late winter. The primary soil types in the study area are the Horotiu silt loam and the Bruntwood silt loam, both of the Allophanic soil order however with contrasting natural soil properties.

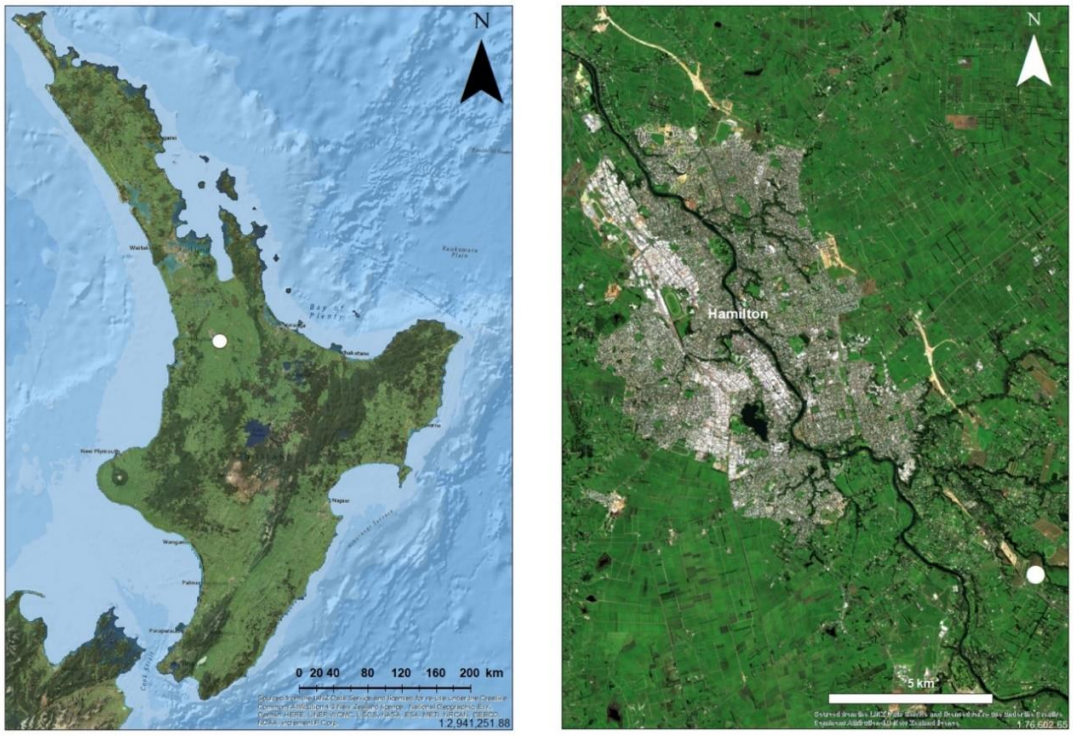

Figure 4.1. Maps displaying study area location; Left - wider North Island, New Zealand; Right - Hamilton, Waikato, New Zealand. Study area is represented by the white dot.

4.3.2 Soil mapping

A soil map was created of the study area to determine the primary soil types and variability. Using landforms, knowledge of soils of the Hamilton Basin (Section 4.2) and soil identification methods adapted from Hewitt (1993) and Milne *et al.* (1995), auger samples were taken to approximately 30 cm and soil type was identified. A number of samples were taken in each plot to identify the proportions of each soil type and allow for soil samples to be collected from the correct soil. These methods identified four soil types in the study area including the Horotiu silt loam, Bruntwood silt loam, Bruntwood silt loam deep topsoil variant, and Te Kowhai silt loam (Figure 4.2). The area was dominated by the Bruntwood silt loam (inclusive of the variant) covering 63 % of the study area, and the Horotiu silt loam covering 15 %. The remaining area (21 %) is made up of complexes of the various soil types or Te Kowhai silt loam.

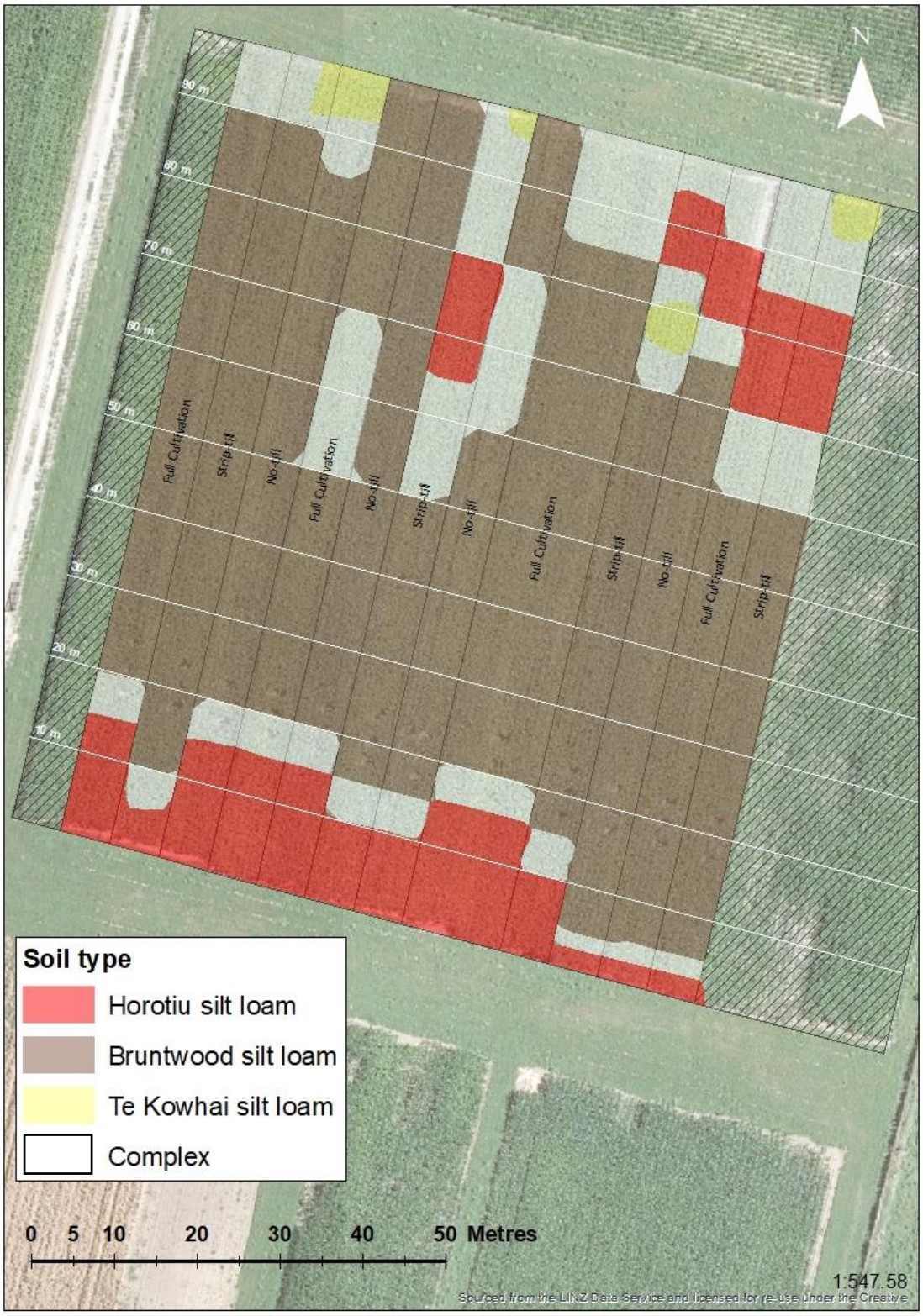

Figure 4.2. Map produced using ArcMap GIS displaying soil types found within the study area, including Horotiu silt loam, Bruntwood silt loam (inclusive of Bruntwood silt loam, deep topsoil variant), Te Kowhai silt loam, and areas where there are potential complexes of these various soil types, or there is no distinguishable change in soil type.

4.3.3 Soil sampling

Samples were collected in late winter (September 2019) to be consistent with previous annual sampling. Each plot was sampled separately and an equal number of samples taken from each soil type. Only the Bruntwood silt loam (inclusive of Bruntwood silt loam, deep topsoil variant) and the Horotiu silt loam were sampled in this study (Figure 4.2). Samples were collected using a zig zag formation across each plot to collect samples from crop rows and between crop rows, so as to capture the variation caused by cultivation, planting, and use of heavy machinery.

For each plot, on-site soil assessments were carried out including penetration resistance using a penetrometer, and a modified VSA to score soil physical quality (FAR, 2019a). For chemical and biological analysis, soil cores were collected to 10 cm using a bucket sampler, where approximately 10 soil cores filled the bucket, representing one sample. Intact soil cores were collected for soil physical measurements using stainless steel rings (5 cm diameter x 6 cm depth). Further soil cores were collected to 30 cm depth to be used for Total C and N analyses using a motorized post driver with a core attached; the cores were sectioned into depth increments of 0 - 7.5 cm, 7.5 - 15 cm, and 15 - 30 cm. Three spade samples to approximately 7.5 cm were collected for aggregate stability measurements.

4.3.4 Sample preparation

Prior to analysis, bucket sampler composite samples were well-mixed and sieved to < 2 mm, subsamples air-dried for Olsen P analyses, and further subsamples finely ground for Total C and N analyses. Soil cores to 30 cm were split into depth increments, air-dried and sieved to < 2 mm, and finely ground for Total C and N. Soil water content was determined by oven drying at 105 ˚C. Aggregate stability samples were sieved to retain 2 – 4 mm aggregates, then air-dried. Particle density samples were sieved to < 2 mm, oven-dried at 105 ˚C, then finely ground.

4.3.5 Laboratory analysis

Analyses included particle density, macroporosity, bulk density, aggregate stability, mineralisable N, soil pH, Olsen P, and Total C and N. Physical analyses were measured using Landcare Research – Manaaki Whenua methodology (Claydon, 1997). Particle

density was analysed by deoxygenating soil and water to calculate total porosity. Intact soil cores were saturated and equilibrated firstly at -5 kPa on ceramic tension plates, and again at –10 kPa to determine macroporosity. Dry bulk density and total porosity were calculated through 105 °C oven-dried weights. Aggregate stability was measured through the wet sieving method as in Land Monitoring Forum (2009).

Mineralisable nitrogen (N) was measured using methods adapted from Blume (1985) and Baethgen and Alley (1989) using anaerobic incubation of field moist samples and concentrations determined using colourmetric analysis. Soil pH was determined using methods as in Blakemore *et al.* (1987), where field moist soil was measured in deionized water. Olsen P was determined using methods by Olsen *et al.* (1954) and Murphy and Riley (1962), extracting Olsen P from samples and measured using colourmetric analysis. Total C and N were measured using a combustion method using a LECO TruSpec CN Elemental Analyser.

4.3.6 Statistical analysis

Data was analysed through the analysis of variance (ANOVA) using GenStat and Minitab software to test the statistical significance of the observed differences in soil properties between the three cultivation treatments (full cultivation, strip-till, no-till), as well as between the two soil types (Horotiu silt loam, Bruntwood silt loam). *P* values of less than 0.05 were reported as statistically significant. ANOVA was carried out for each soil quality variable testing differences between treatments, between soil types, or an interaction of both treatment and soil type. Standard error of difference (SED) was calculated through the ANOVA analysis to give comparisons between treatments and soil types.

4.4 Results

Mean values for the seven soil quality variables, aggregate stability, penetration resistance and VSA are shown in Table 4.1. Mean values for mechanically drilled soil cores to 30 cm split into depth increments (0 – 7.5 cm, 7.5 – 15cm, and 15 – 30 cm) are shown in Table 4.2. The majority of soil variables followed a similar trend in decreasing or increasing values with cultivation intensity (i.e. NT > ST > FC or NT < ST < FC) (Tables 4.1 & 4.2). Significant error of differences between the means (SED) identified variables

that showed high variability such as mineralisable N, Olsen P and macroporosity (Table 4.1). Average values were categorised by target values for each variable as seen in Table 4.1. ANOVA identified statistically significant differences between cultivation treatments, soil types, and where there is an interaction of both treatment and soil type. These were indicated by *p* values of less than 0.05 (Tables 4.3 & 4.4). The most significant differences were observed between the two soil types.

Table 4.1. Table displaying mean values for soil quality variables measured from 0 – 10 cm, including total carbon & nitrogen, mineralisable nitrogen, Olsen P, bulk density, macroporosity, aggregate stability, penetration resistance, and visual soil assessment. FC = Full cultivation, ST = Strip till, NT = No till; Ho = Horotiu silt loam, Br=Bruntwood silt loam; FC x Ho = Only Horotiu samples within full cultivation, etc. *BD & MP were measured from approx. 0 – 5 cm. [1]. S.E.D = Standard error of differences of means. Traffic light system represents target ranges (LMF, 2009; LCRS-MW, 2020); Green = adequate/good; orange = low/high; red = very high/very low

Treatment	Total C (%) 0 – 10 cm	Total N (%) 0 – 10 cm	Min N ($\mu g\ g^{-1}$)	pH	Olsen P ($\mu g\ g^{-1}$)	BD * ($t\ m^{-3}$)	MP * (%)	Ag Stab (mm, MWD)	PR (MPa)	VSA (Total score)
FC	3.56	0.37	16.24	6.52	87.0	0.99	14.8	0.62	1.76	3.3
ST	3.77	0.39	17.69	6.21	86.4	0.99	13.8	0.73	1.87	3.6
NT	3.98	0.41	33.51	6.10	109.2	1.03	11.8	0.97	1.95	4.5
S.E.D [1]	0.106	0.011	8.985	0.090	8.290	0.022	1.672	0.080	0.128	0.140
Ho	4.02	0.42	21.59	6.30	82.9	0.96	14.9	0.82	1.94	4.2
Br	3.52	0.36	23.37	6.26	105.5	1.05	12.0	0.73	1.79	3.6
S.E.D [1]	0.125	0.015	1.381	0.049	2.030	0.015	0.800	0.037	0.016	0.090
FC x Ho	3.87	0.40	14.57	6.55	76.6	0.94	16.6	0.70	1.89	3.9
FC x Br	3.24	0.33	17.92	6.49	97.5	1.04	13.0	0.55	1.63	3.0
ST x Ho	3.88	0.40	16.86	6.28	75.5	0.96	12.9	0.68	1.93	3.9
ST x Br	3.66	0.37	18.53	6.15	97.3	1.03	12.9	0.79	1.82	3.6
NT x Ho	4.31	0.45	33.36	6.06	96.8	0.99	13.4	1.07	2.00	4.5
NT x Br	3.66	0.37	33.67	6.14	121.7	1.07	10.2	0.86	1.91	4.2
S.E.D [1]	0.187	0.022	9.143	0.109	8.650	0.029	1.938	0.092	0.129	0.180

Table 4.2. Table displaying mean values for total carbon and total nitrogen from 0 – 30 cm, split into three depth increments of 0 – 7.5 cm, 7.5 – 15 cm, & 15 – 30 cm. FC = Full cultivation, ST = Strip till, NT = No till; Ho = Horotiu silt loam, Br = Bruntwood silt loam; FC x Ho = Only Horotiu samples within full cultivation, etc. [1]S.E.D = Standard error of differences of means. Traffic light system represents target ranges (LMF, 2009; LCRS-MW, 2020); Green = adequate/good; orange = low/high; red = very high/very low.

	Total C (%)			Total N (%)		
	Depth (cm)			Depth (cm)		
Treatment	**0 – 7.5**	**7.5 – 15**	**15 - 30**	**0 – 7.5**	**7.5 – 15**	**15 - 30**
FC	3.55	3.49	2.41	0.37	0.37	0.25
ST	3.69	3.45	2.07	0.38	0.36	0.22
NT	3.89	3.47	2.04	0.41	0.37	0.22
S.E.D [1]	0.153	0.104	0.153	0.015	0.009	0.018
Ho	3.99	3.69	2.26	0.42	0.40	0.24
Br	3.43	3.25	2.09	0.35	0.34	0.22
S.E.D [1]	0.155	0.140	0.187	0.017	0.016	0.021
FC x Ho	3.94	3.81	2.49	0.42	0.40	0.26
FC x Br	3.16	3.18	2.32	0.33	0.33	0.24
ST x Ho	3.82	3.58	2.15	0.40	0.39	0.23
ST x Br	3.57	3.32	1.20	0.36	0.34	0.21
NT x Ho	4.22	3.69	2.13	0.44	0.39	0.22
NT x Br	3.57	3.25	1.95	0.36	0.34	0.21
S.E.D [1]	0.244	0.200	0.276	0.025	0.022	0.031

Table 4.3. Table displaying relationship between soil quality variables and treatment, soil type, or an interaction of both. Where FC x ST x NT investigates the difference in soil quality between treatments, Ho x Br investigates the difference in soil quality between soil types (Ho = Horotiu; Br = Bruntwood), Treat + Soil investigates differences in soil quality associated with an interaction of both treatment and soil type. *BD & MP were measured from approx. 0 – 5 cm. Values in red indicate a statistically significant difference ($p < 0.05$).

	Soil Quality results (0 – 10 cm)									
Treat	**Total C (%)**	**Total N (%)**	**Min N ($\mu g\ g^{-1}$)**	**pH**	**Olsen P ($\mu g\ g^{-1}$)**	**BD* ($t\ m^{-3}$)**	**MP* (%)**	**Ag Stab (mm, MWD)**	**PR (MPa)**	**VSA (total score)**
FC x ST x NT	0.020	0.029	0.184	0.009	0.054	0.219	0.262	0.013	0.377	0.127
Ho x Br	0.003	0.003	0.230	0.455	< 0.001	< 0.001	0.006	0.043	< 0.001	0.071
Treat + Soil	0.324	0.418	0.678	0.271	0.700	0.627	0.629	0.016	0.005	0.570

Table 4.4. Table displaying relationship between Total C & N and treatment, soil type, or an interaction of both. Where FC x ST x NT investigates the difference in soil quality between treatments, Ho x Br investigates the difference in soil quality between soil types (Ho = Horotiu; Br = Bruntwood), Treat + Soil investigates differences in soil quality associated with an interaction of both treatment and soil type. Values highlighted in red indicate a statistically significant difference ($p < 0.05$).

	Total C (%)				Total N (%)			
	Depth (cm)				Depth (cm)			
Treat	**0 – 7.5**	**7.5 – 15**	**15 – 30**	**0 – 30 (cumulative)**	**0 – 7.5**	**7.5 – 15**	**15 – 30**	**0 – 30 (cumulative)**
FC x ST x NT	0.165	0.919	0.100	0.205	0.238	0.938	0.167	0.129
Ho x Br	0.006	0.011	0.396	0.032	0.003	0.006	0.385	0.043
Treat + Soil	0.372	0.562	0.999	0.926	0.513	0.740	0.966	0.789

4.4.1 Influence of cultivation intensity on soil quality

There were statistical differences between varying intensity cultivation treatments and soil quality variables including total C and N (TC & TN), aggregate stability, and soil pH (Table 4.3). There was a trend in soil quality variables decreasing or increasing with cultivation intensity (i.e. NT > ST > FC or NT < ST < FC) (Table 4.1 & 4.2). TC & TN were significantly different between the three treatments in the top 10 cm ($p < 0.05$) (Table 4.1), with NT having the highest average of both TC (3.98 %) and TN (0.41 %). FC had the lowest average of both TC (3.56 %) and TN (0.37 %) (Figure 4.3 & Table 4.1). Total C from 0 – 10 cm ranged from 2.66 % the minimum in FC ('very depleted'), to 5.06 % the maximum in NT ('normal') (Figure 4.3). The majority of FC data falls into 'depleted' ranges for TC, whereas a larger proportion of NT data falls into 'normal' levels of TC (Figure 4.3). Aggregate stability had significant differences between the three treatments ($p < 0.05$) (Table 4.3). NT had the highest average aggregate stability mean weight diameter (MWD) (0.97 mm) and the maximum (1.2 mm), whereas FC had the lowest MWD (0.62 mm) and the minimum (0.50 mm) (Figure 4.3 & Table 4.1).

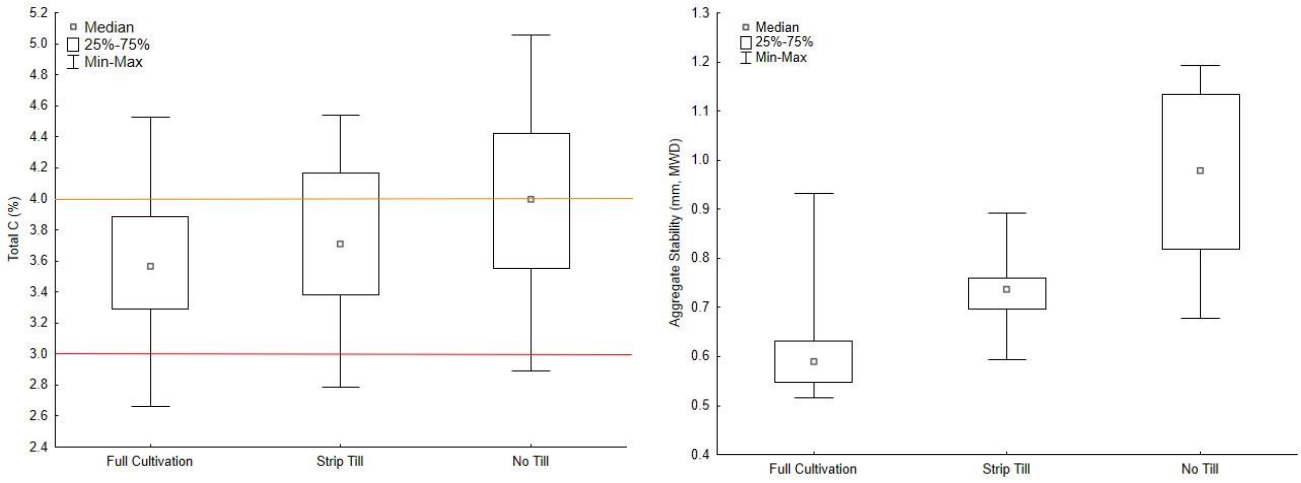

Figure 4.3. Boxplots displaying – Left: Total C % from 0 – 10 cm for each treatment with target ranges (LMF, 2009) indicated by coloured lines where 0.5 – 3 % = very depleted, 3 – 4 % = depleted, 4 – 9 % = normal; Right: Aggregate stability for each treatment. Graphs display median values, 25th & 75th percentiles, and minimum and maximum values.

There was a significant difference between cultivation treatments and soil pH ($p < 0.05$) (Table 4.3) where FC had the highest average soil pH (6.52) and NT had the lowest (6.10) (Table 4.1). Although TC and TN was significantly different between treatments at 0 – 10 cm (Table 4.3), there were no statistical differences in TC and TN between

treatments for any of the depth increments in Table 4.4 (0 – 7.5 cm, 7.5 – 15 cm, 15 – 30 cm). There were no statistical differences in mineralisable N, Olsen P, bulk density, macroporosity, penetration resistance, or VSA (Table 4.3).

4.4.2 Influence of soil type on soil quality

There were statistically significant differences between soil types and the majority of soil quality variables including TC, TN, Olsen P, bulk density, macroporosity, aggregate stability and penetration resistance (Tables 4.3 & 4.4). The Horotiu silt loam had a higher average TC (4.02 %) and TN (0.42 %) compared to the Bruntwood silt loam (TC = 3.52 %, TN = 0.36 %) for all depth increments (0 – 10 cm, 0 – 7.5 cm, 7.5 – 15 cm, and cumulative depth of 0 – 30 cm) (Tables 4.1 – 4.4). The minimum TC was observed in Bruntwood silt loam at 2.66 % ('very depleted') and the maximum in Horotiu silt loam at 5.06 % ('normal') (Figure 4.4). The majority of 0 – 10 cm Bruntwood silt loam data falls into 'depleted' levels of TC, whereas a large portion of the Horotiu silt loam data falls into 'normal' levels (Figure 4.4). Aggregate stability was significantly higher in the Horotiu silt loam (mean = 0.82 mm, max = 1.2 mm) compared to the Bruntwood silt loam (mean = 0.73 mm, max = 1.15 mm) (Table 4.1 & Figure 4.4).

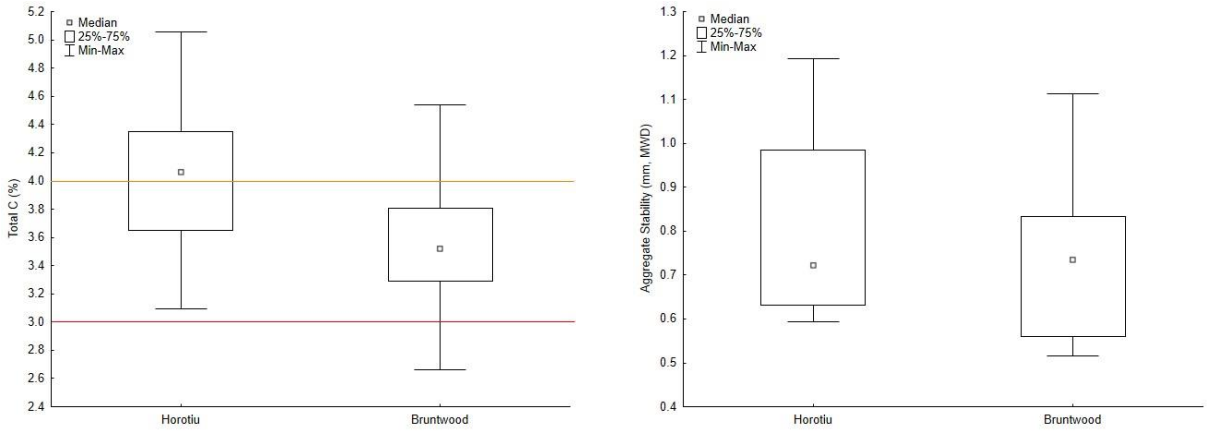

Figure 4.4. Boxplots displaying – Left: Total C % from 0 – 10 cm for each soil type with target ranges (LMF, 2009) indicated by coloured lines where 0.5 – 3 % = very depleted, 3 – 4 % = depleted, 4 – 9 % = normal; Right: Aggregate stability for each soil type. Graphs display median values, 25th & 75th percentiles, and minimum and maximum values.

Olsen P was significantly higher in the Bruntwood silt loam (105.5 µg g^{-1}) compared to the Horotiu silt loam (82.9 µg g^{-1}) (Table 4.1). Penetration resistance was significantly higher in the Horotiu silt loam (1.95 MPa) (Table 4.1) and a high level of significance ($p < 0.001$) between the soil types (Table 4.3).

Bulk density and macroporosity were both significantly different between soil types (Table 4.3). Bulk density was significantly higher in the Bruntwood silt loam (1.05 t m^{-3}) compared with the Horotiu silt loam (0.96 t m^{-3}). Consequently, the Bruntwood silt loam had the lowest average macroporosity (12 %) compared to the Horotiu silt loam (14.9 %) (Table 4.1). However, macroporosity data showed significant variation with a SED of 0.8 for soil type comparisons (Table 4.1) which is relevant when considering the lower limit for 'adequate' macroporosity is 10 % (Figure 4.5).

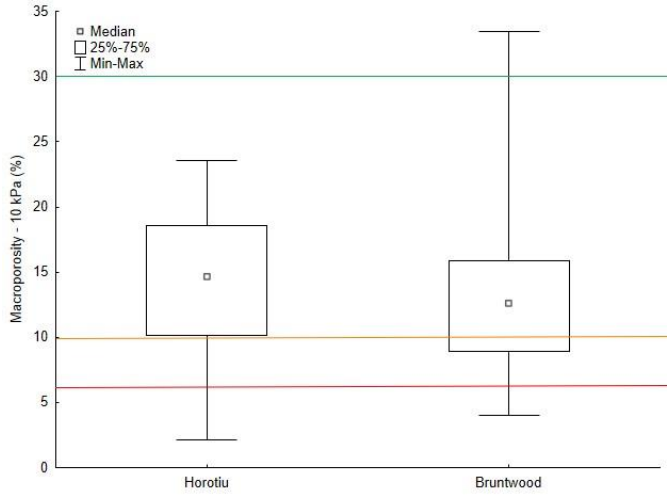

Figure 4.5. Boxplots displaying – Left: Total C % from 0 – 10 cm for each soil type with target ranges (LMF, 2009) indicated by coloured lines where 0.5 – 3 % = very depleted, 3 – 4 % = depleted, 4 – 9 % = normal; Right: Aggregate stability for each soil type. Graphs display median values, 25th & 75th percentiles, and minimum and maximum values.

4.4.3 Influence of cultivation intensity and soil type on soil quality

ANOVA analysis identified a significant interaction between cultivation treatment and soil type in aggregate stability and penetration resistance (Table 4.3). Aggregate stability was significantly higher in the Horotiu silt loam under a NT treatment (1.07 mm) and significantly lower in Bruntwood silt loam under a FC treatment (0.55 mm) (Table 4.1 & Figure 4.6). This follows the trend in Sections 4.4.1 & 4.4.2, where NT and Horotiu silt loam have the highest average aggregate stability (Table 4.1). Penetration resistance had a high level of significance where there was an interaction of cultivation treatment and soil type (p = 0.005) (Table 4.1). Penetration resistance was highest in the Horotiu silt loam under a NT treatment (2.00 MPa), and the lowest in Bruntwood silt loam under a FC treatment (1.63 MPA) (Table 4.1).

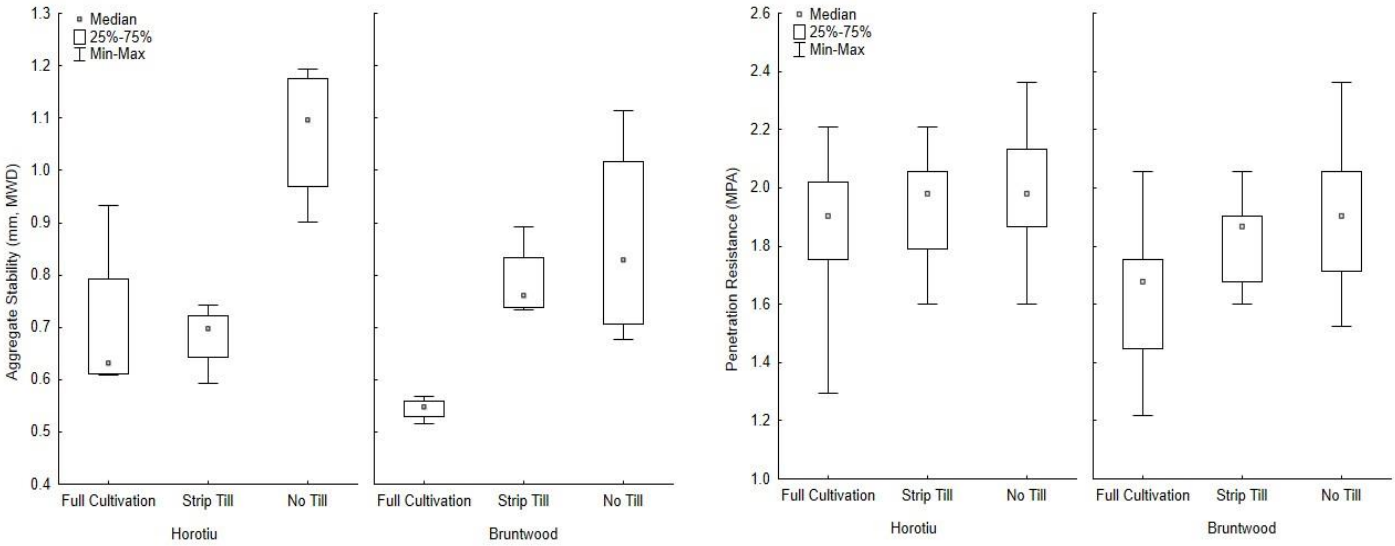

Figure 4.6. Boxplots displaying Left; aggregate stability for each treatment within each soil type. Right; penetration resistance for each treatment within each soil type. Graphs display median values, 25th & 75th percentiles, and minimum and maximum values

4.4.4 Influence of cultivation intensity on maize yields

ANOVA analysis did not identify any significant differences in maize yields between cultivation treatments for the period of 2015 – 2019 or for any of the years individually (p > 0.05). As seen in Figure 4.8, maize yields did not differ between treatments over time and they follow the same trends for each year, with average maize yields in 2019 ranging from 7.3 to 8.3 t ha^{-1}, lower than the previous year (13.1 – 14.1 t ha^{-1}).

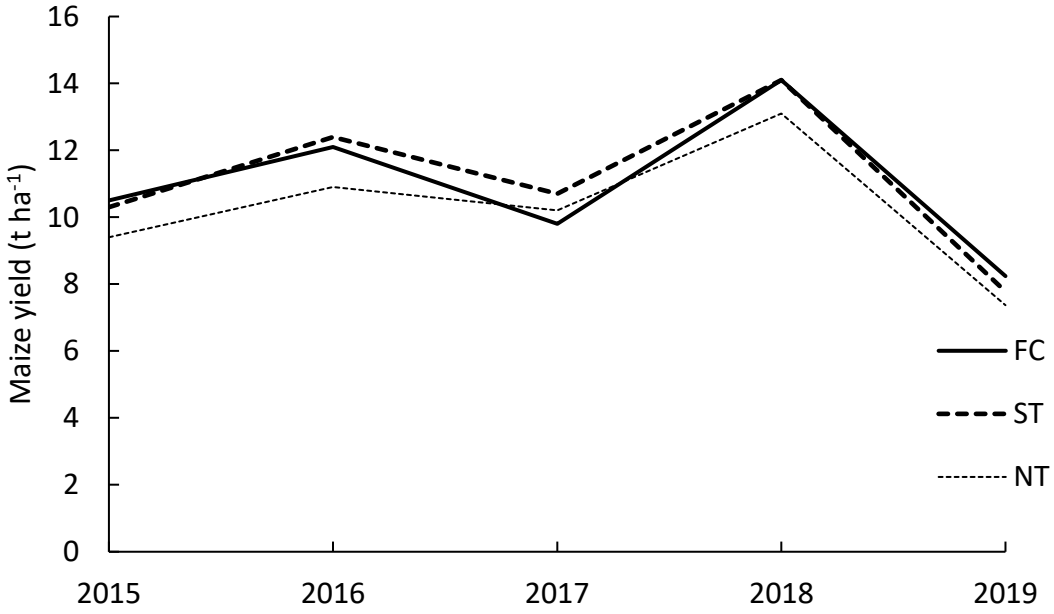

Figure 4.7. Graph displaying change in maize yield over time (2015 – 2019) for each treatment. Data from Foundation for Arable Research (2019).

4.4.5 Full cultivation versus reduced cultivation

Further ANOVA analysis was used to identify any differences in soil quality between full cultivation and reduced cultivation (strip tillage & no tillage) (Table 4.5). This identified significant differences that were not found between treatments when treating NT and ST as separate treatments as in Table 4.3 & 4.4. TC and TN was significantly higher from 0 – 10 cm under reduced cultivation (3.88 %) compared to FC (3.24 %), however TC was significantly higher in FC at the 15 – 30 cm depth (2.41 %). Reduced cultivation had significantly higher mineralisable N (25.6 µg g^{-1}), Olsen P (97.57 µg g^{-1}), bulk density (1.03 t m^{-3}), MWD aggregate stability (0.85 mm), and penetration resistance (1.91 MPa) compared to FC, whereas, FC had significantly higher soil pH (6.52) compared to reduced cultivation (6.16).

Table 4.5. Table displaying mean values and differences in soil quality variables between full cultivation and reduced cultivation (ST + NT), including total carbon & nitrogen, mineralisable nitrogen, Olsen P, bulk density, macroporosity, aggregate stability, penetration resistance, and visual soil assessment.

	Full Cultivation	Reduced Cultivation	*p*-value
Total C % (0 - 10 cm)	3.24	3.88	< 0.001
Total C % (0 - 7.5 cm)	3.55	3.78	0.092
Total C % (7.5 - 15 cm)	3.49	3.45	0.796
Total C % (15 - 30 cm)	2.41	2.06	0.044
Total C % (cumulative 0 - 30 cm)	3.15	3.10	0.694
Total N % (0 - 10 cm)	0.33	0.40	< 0.001
Total N % (0 - 7.5 cm)	0.37	0.39	0.216
Total N % (7.5 - 15 cm)	0.37	0.37	0.960
Total N % (15 - 30 cm)	0.25	0.22	0.072
Total N % (cumulative 0 - 30 cm)	0.33	0.33	0.703
Min N (µg g^{-1})	16.24	25.60	< 0.001
pH	6.52	6.16	< 0.001
Olsen P (µg g^{-1})	87.11	97.57	< 0.005
Bulk Density (t m^{-3})	0.95	1.03	< 0.001
Macroporosity (%)	14.83	12.81	0.060
Aggregate Stability (mm, MWD)	0.62	0.85	0.005
Penetration resistance (MPa)	1.76	1.91	< 0.001
VSA (total score)	3.38	4.00	0.124

4.5 Discussion

This study shows that cultivation intensity, soil type, and an interaction of both have a significant effect on soil quality (Table 4.3 & 4.4). NT had significantly greater TC and TN at the soil surface and aggregate stability than higher intensity cultivation systems. Soil quality within each cultivation treatment identified a common trend in decreasing or increasing values with cultivation intensity (i.e. NT > ST > FC or NT < ST < FC). This study identified that soil quality is dictated by intrinsic soil properties. Although both are Allophanic soils, the Horotiu silt loam had superior soil quality than the Bruntwood silt loam, as indicated by significantly greater TC from 0 – 15 cm, aggregate stability, macroporosity and significantly lower bulk density. An interaction of cultivation intensity and soil type has a minimal influence on soil quality. However, the important cropping indicator aggregate stability was significantly higher in the Horotiu silt loam under the least intensive cultivation (NT). Numerous soil quality values fell below or exceeded target ranges (LMF, 2009; LCRS-MW, 2020). Therefore, the overall soil quality in this study area is considered to be poor regardless of cultivation treatment or soil type.

4.5.1 Influence of cultivation intensity on soil quality

Cultivation intensity had a significant influence on various soil quality variables, including TC and TN in the top 0 – 10 cm, aggregate stability, and soil pH showing significant differences between treatments (Table 4.3). Soil quality within each cultivation treatment identified a common trend in decreasing or increasing values with cultivation intensity (i.e. NT > ST > FC or NT < ST < FC) (Tables 4.1 & 4.2). This is reflective of the notable contrasts in cultivation methodology in the FC and NT systems, whereas ST is an intermediate of both methods and therefore is consistently found to be 'intermediate' in soil quality (FAR, 2019).

4.5.1.1 Cultivation effects on soil organic matter (SOM)

Cultivation intensity has a significant influence on TC and TN at the soil surface (Table 4.3). On average, NT had significantly higher TC (3.98 %) and TN (0.41 %) than both ST (3.77 % & 0.39 %) and FC (3.56 % & 0.37 %) (Table 4.1. & 4.3 & Figure 4.3). This indicates significant accumulation of SOM in the topsoil of NT, which is consistent with numerous studies (Blanco-Canqui & Lal, 2008; Arai *et al.*, 2018; Zuber *et al.*, 2018; Sithole & Magwaza, 2019). Significantly higher SOM at the soil surface in NT is due to reduced loss

of SOM as soil aggregates and crop residues are not destroyed by cultivation practices, therefore SOM remains protected from accelerated decomposition within soil and accumulates (Doran & Zeiss, 2000; Zuber *et al.*, 2018). The rate of organic matter input versus output (maize harvest) is more balanced in the NT treatment as crop residues are not broken up and incorporated into the soil, instead remaining on the surface providing a significant SOM source in the topsoil (Hart *et al.*, 1988; Haynes & Knight, 1989; Diekow *et al.*, 2005). The significantly higher SOM in the topsoil of NT systems has a number of associated benefits such as improved binding and stability of soil aggregates, improved water holding capacity, and enhanced soil microbe activity biodiversity through an additional metabolic energy source (Black & Bauer, 1983; Haddaway *et al.*, 2016). Studies have shown that these benefits in turn enhance productivity by aiding efficient nutrient cycling, soil structure formation, and improving crop resistance to pests and diseases (Zuber *et al.*, 2018).

Although NT had significantly higher TC than the higher intensity cultivation methods in the top 10 cm, according to Land Monitoring Forum (2009) guidelines the average TC values for all three treatments are considered to be 'depleted' for an Allophanic soil (Table 4.1). However, a large proportion of NT data is in 'normal' TC ranges, whereas the majority of FC and ST has 'depleted' levels of TC (Figure 4.3).

Numerous studies note that TC and TN levels typically decrease with depth, observed in this study within each treatment (Table 4.2), however it was not possible to identify significant differences between treatments from any depth increment of the 0 – 30 cm mechanically drilled core samples. This was despite a significant difference between treatments in the 0 – 10 cm samples taken via bucket sampling. This is likely due to more intensive sampling through bucket sampling where approximately 12 small cores equate to one sample, and 144 samples were analysed compared to just 72 cores across the entire three treatments and two soil types (Section 4.3.3).

Although there were no significant differences in TC and TN between treatments in the 0 – 30 cm mechanically drilled core samples, the trend for NT to have higher TC and TN compared to FC is reversed from 15 – 30 cm depth (Table 4.2). FC has the highest TC and TN below the soil surface (7.5 – 30 cm) due to crop residues being incorporated throughout the soil profile through cultivation, whereas NT only gains organic matter (OM) inputs through the soil surface.

4.5.1.2 Cultivation effects on aggregate stability

NT had significantly higher aggregate stability (0.97 mm) than both ST (0.73 mm) and FC (0.62 mm) (Table 4.1 & 4.3 & Figure 4.3). This is consistent with a large number of studies such as, Peigné *et al.* (2018), Himmelbauer *et al.* (2012), and Blanco-Canqui and Lal (2008). Aggregate stability is higher in NT as there is minimal disruption and breaking of aggregates through cultivation, and the significantly lower aggregate stability in FC is reflective of the intensive cultivation and disturbance of aggregates (Doran & Zeiss, 2000; Zuber *et al.*, 2018). The increased presence of SOM in NT also contributes to the strength, binding, and stability of soil aggregates (McLaren & Cameron, 1996). Aggregate stability is important for preserving soil structure and SOM, and transportation of water and air throughout the soil (Haynes & Knight, 1989). Higher aggregate stability enhances water infiltration, prevents drying out, allows for efficient and deep plant root growth and indicates a more versatile soil (Bay of Plenty Regional Council (BOPRC), 2020). The higher aggregate stability in NT makes these soils more resistant to impacts of cultivation, treading and heavy traffic, and rainfall (Haynes & Knight, 1989).

Although NT has significantly higher average aggregate stability than ST and FC, it is still below the lower limit of 1.5 mm (MWD) recommended by a number of authors such as the Bay of Plenty Regional Council (2020), Plant & Food Research (2018) and Mackay *et al.* (2013). Landcare Research – Manaaki Whenua (2020) suggests that a soil with a MWD aggregate stability below 1 mm is “very poorly stable”, thus all treatments in this study are considered to have unstable soil.

Although VSA total score did not show any significant differences between cultivation intensity, when comparing the individual scores (structure & porosity, turbidity, earthworm count), the turbidity score is significantly higher in NT compared to ST and FC. As turbidity was designed to be a visual measure of aggregate stability, this corroborates the results found for aggregate stability.

4.5.1.3 Cultivation effects on soil pH

NT had significantly lower soil pH (6.1) than both ST (6.21) and FC (6.52) (Table 4.1 & 4.3). Various studies have noted this difference between NT and FC, such as Sithole and Magwaza (2019) and McLaren and Cameron (1996). The significantly higher SOM at the soil surface in NT contributes to the lower soil pH at the NT soil surface (Sithole &

Magwaza, 2019). This is due to SOM having an acidic pH and the process of decomposition of the highly accumulated SOM results in a lower pH in the soil (McLaren & Cameron, 1996). Soil pH influences the availability and solubility of a range of compounds in soil such as heavy metals like aluminum, which if soluble or in excess can cause ecotoxicity to microorganisms and therefore loss of productivity (Fageria & Moreira, 2011). Soil pH can influence the availability of essential nutrients, such as phosphorus (McLaren & Cameron, 1996). The common remediation of soils with a more acidic pH is to use lime ($CaCO_3$) to raise the pH to a more neutral or alkaline state, therefore increasing costs for production (Sparling *et al.*, 2008; Fageria & Moreira, 2011).

Although NT has a significantly lower average soil pH than ST and FC, according to Land Monitoring Forum (2009) guidelines it is still considered to be within 'optimal' target ranges for cropping and horticultural soils (Table 4.1) and the required pH range for maize of 5 – 7 where higher yields are typically achieved (Sithole & Magwaza, 2019).

4.5.1.4 Cultivation effects on maize yields

Cultivation intensity did not have a significant influence on maize yield in this study (Figure 4.8). Previous studies by the Foundation for Arable Research (FAR) throughout New Zealand have investigated this effect (FAR, 2019). A short-term trial in Kaipara comparing NT and FC found that in the second year (2019) FC had significantly higher maize grain yield compared to NT. Another FAR trial in the Waikato region that compares the effect of NT and ST on maize silage, found that during higher than average rainfall, ST had significantly higher maize silage yields compared to NT. However, various other FAR trials such as another in Kaipara, Waikato, and Poverty Bay, found no significant differences in maize yield between FC, ST, and NT, consistent with this trial's findings. The longest FAR trial (15 years) in Chertsey (Canterbury, NZ) compares the effects of NT, ST, and FC on irrigated and dryland sites. This study found that there were only significantly greater maize yields under NT if in a dryland system and when water was limiting.

A number of international studies have found that NT systems can have a loss of yield in comparison to FC systems (Lipiec & Stępniewski, 1995; Haddaway *et al.*, 2016; Si *et al.*, 2018). However, Arshad (1999) and Francis and Knight (1993) note that over time (> 5 years) the crop yields under NT increase substantially from FC. This suggests

that although this study and comparable FAR studies have found no differences in maize yields between cultivation treatments this may be due to the short duration of the trials (< 5 years) and there may be an increase in yields under NT over the coming years.

The results from this study indicate that a grower may be able to achieve sufficient maize yields using a less intensive cultivation regime and also improve SOM and aggregate stability and therefore improve soil quality and maintain long-term productivity and profitability.

4.5.1.5 Full cultivation versus reduced cultivation

Reduced cultivation (RC) was significantly higher in TC and TN in the top 10 cm (RC = 3.88 % & 0.40 %, FC = 3.24 % & 0.33 %), mineralisable N (RC = 25.6 µg g^{-1}; FC = 16.24 µg g^{-1}), Olsen P (RC = 97.57 µg g^{-1}, FC = 87.11 µg g^{-1}), bulk density (RC = 1.03 t m^{-3}, FC = 0.95 t m^{-3}), aggregate stability MWD (RC = 0.85 mm, FC = 0.62 mm), and penetration resistance (RC = 1.91 MPa, FC = 1.76 MPa). These are consistent with previous studies, where NT systems have increased SOM at the soil surface as crop residues remain on the surface and decomposition is not accelerated through cultivation (Doran & Zeiss, 2000; Zuber *et al.*, 2018). Similarly in ST, approximately 50 % of this system will be having the same effect (FAR, 2019b). FC had significantly higher TC from 15 - 30 cm (FC =2.41 %, RC = 2.06 %) and soil pH (FC = 6.52, RC = 6.16) (Table 4.5). FC has significantly higher TC in the 15 – 30 cm depth due to the mixing of soil and inversion through cultivation that moves SOM down the soil profile, whereas NT does not move SOM down the profile and ST only moves a proportion (McLaren & Cameron, 1996).

Mineralisable N is higher under RC potentially due to the increased SOM content that improves nutrient cycling (Lal, 2008), however some studies note that NT systems had decreased plant available N due to decreased rates of mineralisation as SOM is not broken down during cultivation or rapidly mineralised by soil microorganisms (Lipiec & Stępniewski, 1995; McLaren & Cameron, 1996). Olsen P is higher under RC as the majority of phosphate fertilisers remain and accumulate at the soil surface, whereas under FC, nutrients are mixed further down the soil profile (McLaren & Cameron, 1996). Soil pH is significantly lower in RC as there is significantly higher SOM at the soil surface which contributes to lower soil pH (Sithole & Magwaza, 2019).

Although RC can improve soil structure such as significantly higher aggregate stability, for the same reason, RC can have increased bulk density and penetration

resistance due to the lack of mechanical break up of soil aggregates (Lipiec & Stępniewski, 1995).

Although a higher number of differences can be detected when grouping ST and NT into RC, it is important to note that each cultivation treatment is significantly different in methodology and consequently have different associated impacts on soil quality, therefore it is unreasonable to group them together. It could also be argued that ST could be grouped with FC as it is technically 50 % FC and NT, therefore it is more unbiased to treat these three treatments separately.

4.5.2 Influence of soil type on soil quality

Soil type had a significant influence on the majority of soil quality variables, including TC and TN from 0 – 10 cm, 0 – 7.5 cm, 7.5 – 15 cm, and the cumulative depth of 0 – 30 cm (Table 4.3 & 4.4). There were also notable differences in aggregate stability, Olsen P, bulk density, macroporosity, and penetration resistance (Table 4.3). Despite both being Allophanic soils, differences between the Horotiu silt and the Bruntwood silt loam are reflective of the contrasts in soil composition. Horotiu silt loam is more porous, well drained, and well-structured, with high allophane contents particularly in the topsoil, whereas the Bruntwood silt loam is moderately porous and structured in the topsoil, with a limiting subsoil and lower allophane contents throughout (Singleton, 1991; WRC, 2011b; WRC, 2011a; Lowe, 2020). This study highlights that soil quality in the study area is primarily dominated by soil type, regardless of cultivation intensity.

4.5.2.1 Soil type effects on SOM

Soil type had a significant influence on SOM (TC & TN) at various depths including 0 – 10 cm, 0 – 7.5 cm, 7.5 – 15 cm, and for the cumulative depth of 0 – 30 cm (Table 4.3 & 4.4). The Horotiu silt loam had significantly higher TC (For 0 – 10 cm = 4.02 %) and TN (For 0 – 10 cm = 0.42 %) compared to the Bruntwood silt loam for all measured depths (For 0 – 10 cm; TC = 3.52 %, TN = 0.36 %) (Table 4.1 & 4.2). The significantly higher SOM in the Horotiu silt loam is due to the higher allophane content than the Bruntwood silt loam which prevents organic matter breakdown (Singleton, 1991). According to Sparling and Schipper (2002), TC in soil is primarily influenced by soil order. Allophanic soils typically have significantly higher C content than other soils because SOM and its C portion is stabilised through allophane, imogolite, and ferrihydrite (Sparling *et al.*, 2008;

Yuan, 2010). Significantly higher SOM in the Horotiu silt loam has a number of associated benefits on other soil properties such as aggregate formation and stability, improved water holding, greater soil microbe activity and biodiversity through an increased metabolic energy source (Black & Bauer, 1983; Haddaway *et al.*, 2016).

According to Land Monitoring Forum (2009) guidelines, the significantly higher TC at the soil surface in the Horotiu silt loam is in 'normal' ranges. Over 50 % of the 0 – 10 cm TC data falls within the 'normal' range for Allophanic soils, whereas the average TC in the Bruntwood silt loam at 0 – 10 cm and 0 – 7.5 cm and the majority of the 0 – 10 cm data is considered to fall into the 'depleted' range (Table 4.1 & Figure 4.4). The significant difference in SOM between soil types suggests that regardless of cultivation intensity the natural soil composition may dominate the ability to retain TC.

4.5.2.2 Soil type effects on physical soil quality

Significant differences between soil types were observed in various soil physical properties including aggregate stability, bulk density, macroporosity, and penetration resistance (Table 4.3). The Horotiu silt loam had significantly higher MWD aggregate stability (0.82 mm), penetration resistance (1.94 MPa) and macroporosity (14.93 %), and significantly lower bulk density (0.96 t m^{-3}) compared to the Bruntwood silt loam (Ag stab = 0.73 mm; PR = 1.79 MPa; MP = 12.0 %; BD = 1.05 t m^{-3}) (Table 4.1).

4.5.2.2.1 Aggregate stability

Soils with high natural clay contents and OM such as Allophanic soils have improved bindings and formation of aggregates and consequently higher aggregate stability and resistance to breakage (Yuan, 2010). The higher allophane content in the Horotiu silt loam contributes to the higher aggregate stability in comparison to the Bruntwood silt loam which has lower allophane content and less versatile natural structure (Waikato Regional Council, 2011a; Lowe, 2020). Although the average aggregate stability in the Horotiu silt loam is higher (0.82 mm) in comparison to the Bruntwood silt loam (0.73 mm) (Table 4.1 & Figure 4.4), both soil types are still below 1 mm and considered to be "very poorly stable".

4.5.2.2.2 Bulk density and macroporosity

The lower bulk density and inversely higher macroporosity in the Horotiu silt loam is reflective of its natural physical properties. Bulk density has been shown to be governed

by a soil's natural properties such as soil texture, fundamental materials, and porosity (Sparling *et al.*, 2008). The Horotiu silt loam typically has lower bulk density and higher macroporosity than other soils under the same land use (WRC, 2011b). Although the Horotiu silt loam has a lower average bulk density (0.96 t m^{-3}) compared to the Bruntwood silt loam (1.05 t m^{-3}) (Table 4.1), both of the soil types are considered to be 'compacted' (Table 4.1). Compact soils have poor aeration, poorly drainage, limit root growth, and have the potential to become anaerobic therefore limiting essential functions and processes within soils carried out by soil organisms (Sparling *et al.,* 2008; LCRS-MW, 2020).

A study by Cotching *et al* (1979) that compared the Horotiu silt loam and a Gley soil under long-term cropping noted that the Horotiu silt loam initially increased in bulk density however minimal physical changes had occurred after three years under cropping, and conversely the Gley soil initially decreased in bulk density however then bulk density increased with increasing years under cropping. This may be the trend seen in this study, where the Horotiu silt loam is lower in bulk density than the Bruntwood silt loam which in comparison has lower natural quality and more comparable to the Gley soil in Cotching's study.

Although the Bruntwood silt loam had significantly lower macroporosity (12.04 %) compared to the Horotiu silt loam (14.93 %), according to Land Monitoring Forum (2009) guidelines both fall into the 'adequate' target ranges for a cropping soil (Table 4.1). However, macroporosity data showed significant variation with a SED of 0.8 for soil type comparisons (Table 4.1) which is relevant when considering the lower limit for adequate macroporosity is 10 % (Figure 4.5) where it can adversely affect plant growth (McLaren & Cameron, 1996; Dexter, 1997). The variation in macroporosity data is likely because samples had been collected from both between and on crop rows, and crop rows in the ST and FC plots have been cultivated, hence will likely have a higher macroporosity, whereas in between crop rows this will likely be lower.

4.5.2.2.3 Penetration resistance

The Horotiu silt loam had significantly higher penetration resistance (1.94 MPa) than the Bruntwood silt loam (1.79 MPa) (Table 4.1). This difference however contradicts previous studies where a more aerated soil (Horotiu) has a reduced penetration resistance (Burgess *et al.*, 2000). Alternatively, a soil that is more compact (Bruntwood)

has an increased penetration resistance (FAR, 2019b). It is therefore difficult to conclude why the Horotiu silt loam has higher penetration resistance than the Bruntwood silt loam, other than the effect of treatment may be influencing the data as there is an identified interaction between soil type and cultivation intensity (Section 4.5.3).

However, regardless of the differences between soil types, penetration resistance for both soil types is well below the critical limit of 3 MPa where root growth is limited, therefore we can assume root growth is not limited in this study area (McQueen & Shepherd, 2002; Murphy & Firth, 2004).

4.5.2.3 Soil type effects on Olsen P

The Bruntwood silt loam had significantly higher Olsen P (105.5 μg g^{-1}) compared to the Horotiu silt loam (82.9 μg g^{-1}) (Table 4.1). Phosphorus (P) is taken up by plant available forms (H_2PO_4 and HPO_4^{2-}), however much of this is adsorbed onto clays and organic matter, known as P retention (McLaren & Cameron, 1996). Soils with high clay and organic matter contents will have higher P retention, such as Allophanic soils which typically have high to very high P retention (McLaren & Cameron, 1996; Sparling *et al.*, 2008; LCRS-MW, 2020). The significantly lower Olsen P in the Horotiu silt loam is due to its higher P retention as it has a higher clay and allophane content than the Bruntwood silt loam, noted to be as high as 98 % in the topsoil compared to the Bruntwood silt loam with an average topsoil P retention of 88 % (LCRS-MW, 1978; Degens *et al.*, 2000; Dodd *et al.*, 2014a, 2014b).

Although the Horotiu silt loam has lower Olsen P than the Bruntwood silt loam, according to Land Monitoring Forum (2009) it is considered to fall into 'adequate' target ranges for an Allophanic cropping soil, whereas the Bruntwood silt loam is considered to have 'high' or excessive Olsen P levels (Table 4.1). However, the optimum Olsen P range for Allophanic soils is noted to be between 20 – 30 μg g^{-1} (Morton & Roberts, 2018), therefore both are well above this optimum level. Excess P can lead to leaching from the soil and contaminating surrounding waterways, a large issue for NZ soils and the wider environment that is frequently observed in cropping and horticulture due to intensive phosphate fertilizer use (Taylor *et al.,* 2017; MfE & StatsNZ, 2018).

4.5.3 Influence of cultivation intensity and soil type on soil quality

Soil quality is significantly influenced by an interaction of cultivation intensity and soil type (Table 4.3 & 4.4). Phillips and Phillips (1984) suggest that NT is best suited to well-draining and high-quality soils, which is reflected in the results of this study. Aggregate stability was significantly higher in the Horotiu silt loam under a NT system (1.07 mm), and significantly lower in the Bruntwood silt loam under a FC system (0.55 mm) (Table 4.1). This is due to a combination of the least intensive cultivation (NT) and the highest quality soil (Horotiu silt loam), and vice versa for the most intensive cultivation (FC) and the lower quality soil (Bruntwood silt loam). The increased presence of SOM in NT also contributes to the strength, binding, and stability of soil aggregates and the higher allophane content in the Horotiu silt loam contributes to a higher aggregate stability (WRC, 2011b; WRC, 2011a; Lowe, 2020). All values are still below 1.5 mm, however, the Horotiu silt loam under NT is significantly more stable than the remaining soil types within each cultivation intensity and these soils more resistant to intensive land use (Haynes & Knight, 1989).

Penetration resistance was significantly higher in the Horotiu silt loam under a NT system (2.00 MPa), and significantly lower in the Bruntwood silt loam under a FC system (1.63 MPa) (Table 4.1). NT systems typically have a higher penetration resistance due to a lack of aeration created by cultivation (FAR, 2019b), and FC or ST typically have a reduced penetration resistance as they are aerated through cultivation (Burgess *et al.*, 2000). It is inconsistent that the Horotiu silt loam has a higher penetration resistance than the Bruntwood silt loam as penetration resistance is correlated to bulk density and porosity, both of which are higher in the Horotiu silt loam.

4.5.4 Soil quality in cropping systems

Many of the soil quality values measured in this study fall below or above target ranges created by expert panels (LMF, 2009; LCRS-MW, 2020). For target ranges, a single cropping and horticultural class was created as it was unfeasible to accurately classify the large number of horticultural and cropping land uses. However, this was a significant generalization giving very broad targets and for this reason cropping and horticulture target ranges are “poorly defined” (LMF, 2009; Sparling *et al.,* 2008).

Lower SOM, weaker aggregate stability, and compact soils are typical for cropping systems regardless of the cultivation system or soil order as the harvesting process removes a large proportion of organic matter (McLaren & Cameron, 1996; Haddaway *et al.*, 2016). It may be more important in cropping systems to track how soil quality changes over time in terms of improving or declining soil quality variables, rather than if it falls into suggested broad guidelines. The variables of largest concern under cropping systems are declines in SOM (TC & TN) and aggregate stability, which are both of risk to long term cropping productivity and profitability. In this study, although TC, TN, and aggregate stability are below recommended target values, they are still significantly higher under a NT system and there are no differences in maize yields between cultivation intensities. This indicates that a NT system may be most beneficial for a maize cropping system in terms of sufficient maize yields while increasing SOM and aggregate stability. Although there were no significant differences in macroporosity and bulk density, literature suggests that NT initially becomes more compact than higher intensity cultivation systems, however, after several years will equilibrate. Whereas a FC system may initially decrease in bulk density however increase after several years (Cotching *et al.,* 1979).

Results from this study indicate a combination of a NT system and the inherent properties of the Horotiu silt loam are most beneficial for soil quality in a maize cropping system, and of the three cultivation intensities examined, the Bruntwood silt loam shows greatest improvements when under a NT system. It may be impractical for growers to treat soil types differently as they are often unevenly distributed, such as seen in this study area (Figure 4.2).

4.5.5 Changes in soil quality over time

It is important to consider that the study area was under long term cropping and largely FC systems prior to the beginning of this trial and hence soil quality may have already been considerably degraded when the trial started in 2014. It is also important to note that it is typical for cropping systems (regardless of the cultivation system) to have poorer soil quality for particular variables such as low SOM and aggregate stability as the harvesting process removes a large proportion of organic matter and will disrupt aggregates (McLaren & Cameron, 1996; Haddaway *et al.*, 2016). Therefore, the improved soil quality seen in NT compared to the greater intensity cultivations may be

reflective of either the soil recovering from previous depletion or that the soil quality in FC and ST is actively declining while NT is remaining at an equilibrium. It is difficult to determine which of these explanations may be accurate as the majority of soil quality variables have only been measured in the study area from 2017. Additionally, this 2019 study had a much higher sampling density and intensity than previous years, consequently it is difficult to identify trends over time.

These results highlight the importance of careful identification of soil types within the cropping area, and if practicable (i.e. if different soil types occur and can be differentiated across a large enough area), there may be opportunity to cultivate soil types differently to minimise soil quality degradation. Furthermore, when monitoring soil quality, knowledge of the distribution of soil type in the cropping area is critical as uneven distribution is likely and low-density random sampling will likely skew soil quality data, interpretation, and the ability to analyse trends. The high number of significant differences in soil quality indicators recognizes the need for soil types to be identified and monitored in this study area. It remains unknown if other significant differences or trends would have been identified previously if the trial area were differentiated by soil type (such as if maize yields differ between soil type).

This research highlights the importance of sustained and intensive soil quality monitoring over time in this study area. Arshad (1999) and Francis and Knight (1993) note that over time (> 5 years) the crop yields under NT increase substantially from FC, and the long term (15 year) FAR Chertsey trial shows significant differences in C and N from 0 – 15 cm and maize yields between treatments which indicates the need for long term intensive monitoring of this and other cultivation trials. Based on this, it is recommended that basic annual monitoring is undertaken at the study area, and more intensive sampling (such as in this study) is undertaken every several years until a minimum 10-year sampling period has been achieved so to properly identify trends in soil quality.

4.6 Conclusions

This study revealed that cultivation intensity has a significant effect on soil quality in Allophanic soils. When considering the most important soil quality indicators in cropping systems, NT was shown to be most beneficial as indicated by significantly greater TC and TN at the soil surface and aggregate stability than higher intensity cultivation systems.

Soil pH was significantly different between cultivation treatments; however, the ranges were still optimal for maize cropping. The measured higher SOM and aggregate stability at the soil surface of NT systems is consistent with findings from a number of previous studies including previous FAR trials in New Zealand (FAR, 2019), and internationally (Crittenden *et al.*, 2015; Arai *et al.*, 2018; Seitz *et al.*, 2019; Sithole & Magwaza, 2019). There was no evidence of a relationship between cultivation treatment and the remaining soil quality indicators (mineralisable N, Olsen P, bulk density, macroporosity, penetration resistance, VSA), however, it has been suggested that cultivation intensity may have a greater effect as length of time under cultivation increases (Cotching *et al.*, 1979; Francis & Knight, 1993; Arshad, 1999; FAR, 2019b).

Additionally, this study identified that soil quality is significantly influenced by intrinsic soil properties. The trial was dominated by two soil types, the Horotiu silt loam and Bruntwood silt loam, and although both are Allophanic soils, the Horotiu silt loam had superior soil quality than the Bruntwood silt loam, as indicated by significantly greater TC from 0 – 15 cm, aggregate stability, macroporosity and significantly lower bulk density. An interaction of cultivation intensity and soil type has a minimal influence on soil quality. However, the important cropping indicator aggregate stability was significantly higher in the Horotiu silt loam under the least intensive cultivation (NT).

This study suggests that a NT system and the inherent properties of the Horotiu silt loam is the most favourable combination for improved soil quality in a maize cropping system, although the Bruntwood silt loam also shows greatest soil quality results when under a NT system. It is however likely impractical for growers to treat soil types differently as soils are often unevenly distributed in an area. As there were no differences in maize yields with cultivation intensities, the improvements in soil quality under NT indicates that NT may be a more suitable cultivation system without decreasing productivity or profitability.

Many of the soil quality variables fall below or exceed target ranges (LMF, 2009; LCRS-MW, 2020). Therefore, the overall soil quality in this study area is considered to be poor regardless of cultivation treatment or soil type. However, it is recognized that cropping target ranges are “poorly defined” and lower SOM, poorer aggregate stability, and compact soils are typical of cropping systems regardless of the cultivation system or soil

order. Prior to the beginning of this trial in 2014, the study area was under long term cropping, hence soil quality may have been degraded at the initiation of the trial and any improvements observed under NT may either be attributed to the soil recovering from this previous SOM depletion and physical degradation or that the soil quality in FC and ST is actively declining while NT remains at an equilibrium. Trends in soil quality are difficult to determine as previous soil quality variables were measured in the study area at a much lower sampling density and intensity. Similarly, there has been no previous sampling of individual soil types in this study area so trends in soil quality indicators nor differences in yield dominated with soil type cannot be identified at this stage.

This study identifies the need for further research and sustained monitoring to track long term changes in soil quality under various cultivation treatments, as well as taking soil type into account, where practical, when monitoring these changes. It is recommended that basic annual monitoring is undertaken at the study area, and more intensive sampling (such as in this study) is undertaken every several years until a minimum 10-year sampling period has been achieved so to accurately identify trends. Further research into the resilience or vulnerability of a range of soil orders and soil types to varying cultivation intensity is required to understand whether certain inherent soil properties of an order or type is better suited to a particular cultivation intensity, and whether yields can be improved or maintained. The results from this study into the effect of cultivation intensity on soil quality will contribute to encouraging more sustainable growing practices in New Zealand so to reduce common issues in arable systems such as SOM decline and physical degradation.

Chapter 5

Conclusions

5.1 Introduction

Soil quality is essential to the overall productivity and health of land as it supports a range of ecosystem services that primary production relies on (Mackay *et al.*, 2013). Where soil quality is degraded, so is the capability to support these essential services and its fitness for use is reduced, which can reduce soil productivity, crop production and profitability, and can impact other aspects of the environment such as water quality (MfE & StatsNZ, 2018). A nationally consistent set of soil quality indicators are used to monitor soil quality in New Zealand, comprised of total C (TC), total N (TN), mineralisable N, soil pH, Olsen P, bulk density, and macroporosity, along with optional indicators of aggregate stability, penetration resistance, and VSA. These variables can monitor in soil quality in response to land use (Lilburne *et al.*, 2004; Sparling & Schipper, 2004; Sparling *et al.*, 2004).

Maize is the primary crop grown on arable land in the Waikato region, predominantly on the Allophanic soils of the region such as the Horotiu and Bruntwood soil series due to their well-drained and resilient properties (FAR, 2008; Nicholls *et al.*, 2009; Reid & Morton, 2019). Loss of SOM and physical degradation such as low aggregate stability are of large concern under intensive cultivation and are major limitations to continuous maize production (Sparling *et al.,* 1992; FAR, 2018).

A number of studies in New Zealand have investigated the effect of cultivation intensity on soil quality (FAR, 2019; Haynes & Knight, 1989; Francis & Knight, 1993). These studies consistently found that NT systems have greater C levels and higher aggregate stability at the soil surface than higher intensity cultivation systems (ST or FC). It was also found that regardless of differences in soil quality between cultivation intensities, there were typically no differences in maize yield. The FAR cultivation trial in Chertsey, New Zealand demonstrated that greater differences in soil quality and maize yields may be observed between cultivation intensities with increasing time under continuous maize (> 5 years) (FAR, 2019); also supported by a number of other international studies (Cotching *et al.*,

1979; Francis & Knight, 1993; Arshad, 1999). International studies also consistently report higher SOM or soil C in the topsoil and higher aggregate stability under NT systems, compared to FC or ST systems.

The main aim of this thesis was to determine whether there were significant differences in soil quality between varying intensity cultivation systems (FC, ST, NT) on Allophanic soils in the Hamilton Basin. Further aims were to determine whether the inherent soil properties of the Horotiu silt loam and Bruntwood silt loam would dominate the soil quality within the study area, and to identify whether soil quality was influenced by an interaction of both cultivation intensity and soil type. To achieve these aims, 12 plots with four replicates of each treatment were sampled using standard soil quality laboratory methods, and results analysed using ANOVA and compared to recommended target ranges (LMF, 2009; LCRS-MW, 2020).

The following sections will summarise the key findings of this study as presented in chapter four. Recommendations for future research are provided in Section 5.5.

5.2 Influence of cultivation intensity on soil quality

Cultivation intensity had a significant influence on TC and TN in the top 10 cm, aggregate stability, and soil pH ($p < 0.05$). NT had significantly higher TC (3.98 %), TN (0.41 %), and aggregate stability (0.97 mm, MWD) than ST (3.77 %, 0.39 %, 0.73 mm, MWD) and FC (3.56 %, 0.37 %, 0.62 mm, MWD). Significantly higher SOM and aggregate stability at the soil surface in NT is due to soil aggregates not being destroyed by cultivation practices, therefore SOM remains protected from accelerated decomposition within soil and accumulates (Doran & Zeiss, 2000; Zuber *et al.*, 2018). The rate of organic matter input versus output (maize harvest) is more balanced in the NT treatment as crop residues are not broken up and incorporated into the soil, instead remaining on the surface providing a significant SOM source in the topsoil (Hart *et al.*, 1988; Haynes & Knight, 1989; Diekow *et al.*, 2005). Soil pH is significantly lower under NT (6.1) compared to ST (6.2) and FC (6.5), however this is still within optimum ranges for maize (5 – 7). Although both SOM content and aggregate stability are higher under NT, all treatment values fall below or above target ranges (LMF, 2009; LCRS-MW, 2020).

Cropping and horticulture target ranges are "poorly defined" (Sparling *et al.,* 2008; LMF, 2009), and lower SOM and aggregate stability are typical for cropping systems regardless of the cultivation system or soil order as the harvesting process removes a large proportion of organic matter (McLaren & Cameron, 1996; Haddaway *et al.*, 2016). SOM (TC & TN) decline and decreased aggregate stability are considered the largest risk to long term cropping productivity and profitability (Schipper & Sparling, 2000; Cavanagh *et al.*, 2017). Although TC, TN, and aggregate stability are below recommended target values, they are still significantly higher under a NT system and as there are no differences in maize yields between cultivation intensities at this point in the trial, a NT system may be most beneficial for a maize cropping system in terms of sufficient maize yields while improving SOM and aggregate stability.

5.3 Influence of soil type on soil quality

Soil type had a significant influence on soil quality, indicated by differences in TC and TN from 0 – 15 cm and the cumulative depth of 0 – 30 cm, aggregate stability, bulk density, macroporosity, penetration resistance, and Olsen P ($p < 0.05$). The Horotiu silt loam had significantly higher TC (For 0 – 10 cm = 4.02 %) and TN (For 0 – 10 cm = 0.42 %) compared to the Bruntwood silt loam (For 0 – 10 cm; TC = 3.52 %. TN = 0.36 %). This difference was observed for the majority of depths including 0 – 10 cm, 0 – 7.5 cm, 7.5 – 15 cm, and cumulative depth of 0 – 30 cm. The Horotiu silt loam also had higher MWD aggregate stability (0.82 mm) in comparison to the Bruntwood silt loam (0.73 mm). The higher allophane content in the Horotiu silt loam is thought to inhibit organic matter breakdown and stabilize the C portion, in turn improving bindings and stability of aggregates (Yuan, 2010). The lower bulk density (0.96 t m^{-3}) and inversely higher macroporosity (14.93 %) in the Horotiu silt loam is reflective of its naturally versatile, porous, and permeable properties (WRC, 2011b). Both soils have compacted topsoil (> 0.9 t m^{-3}) due to being in a cropping system, however the Horotiu silt loam appears to be more resilient to these impacts than the Bruntwood silt loam (1.05 t m^{-3} & 12 %). The Horotiu silt loam had significantly higher penetration resistance (1.94 MPa) than the Bruntwood silt loam (1.79 MPa), however contradicting previous studies where a more aerated soil (Horotiu) has a reduced penetration resistance (Burgess *et al.*, 2000). The Bruntwood silt loam had significantly higher Olsen P (105.5 µg g^{-1}) compared to the

Horotiu silt loam (82.9 μg g^{-1}) due to the Horotiu silt loam having significantly higher P retention (up to 98 %) due to the higher clay and allophane content of the topsoil than the Bruntwood silt loam with a lower P retention (average of 88 %) (LCRS-MW, 1978). The optimum Olsen P range for Allophanic soils is noted to be between 20 – 30 μg g^{-1} therefore both soils have high or excessive levels of Olsen P and are risking P leaching and runoff (Morton & Roberts, 2018). The significant number of differences identified between soil types indicates that soil quality in the study area is strongly influenced by intrinsic soil properties.

5.4 Influence of cultivation intensity and soil type on soil quality

An interaction between cultivation intensity and soil type had a significant influence on penetration resistance and aggregate stability ($p < 0.05$). Penetration resistance was significantly higher in the Horotiu silt loam under a NT system (2.00 MPa), and significantly lower in the Bruntwood silt loam under a FC system (1.63 MPa). NT systems typically have a higher penetration resistance due to a lack of aeration through mechanical break up of clods and aggregates (FAR, 2019b), and FC or ST typically have a reduced penetration resistance as they are aerated through cultivation (Burgess *et al.*, 2000), however the results from this study were inconsistent with previous studies as the Horotiu silt loam had a higher penetration resistance than the Bruntwood silt loam. Aggregate stability MWD was significantly higher in the Horotiu silt loam under a NT system (1.07 mm), and significantly lower in the Bruntwood silt loam under a FC system (0.55 mm). This is due to a combination of the least intensive cultivation (NT) and the highest quality soil (Horotiu silt loam), and vice versa for the most intensive cultivation (FC) and the lower quality soil (Bruntwood silt loam). All values are below the recommended lower limit of 1.5 mm. However, whilst a soil with an aggregate stability below 1 mm, MWD is considered to be “very poorly stable”, the Horotiu silt loam under NT is significantly more stable than the remaining soil types and cultivation intensity combinations, and therefore more resistant to intensive land use (Haynes & Knight, 1989).

5.6 Future research

Prior to the beginning of this trial in 2014, the study area was under long term cropping and largely FC systems, hence SOM and physical quality may have been considerably depleted at the start of the trial. The superior soil quality observed in NT (greater SOM and aggregate stability – both deemed critical for cropping systems) may be reflective of either the soil recovering from this previous SOM depletion (e.g. slowly rebuilding OM reserves) and physical degradation or that the soil quality in FC and ST is actively declining while NT remains at an equilibrium. It is difficult to determine which of these explanations may be accurate as soil quality has only been measured in the study area from 2017 and this study had much higher sampling density and intensity than previous years; consequently, it is difficult to identify trends over time.

This study identifies the need for further research and sustained monitoring to track changes in soil quality under various cultivation treatments over longer periods of time, as well as considering soil type, where practical, when monitoring these changes. This is important as the trial is relatively young (5 years old) and a number of studies indicate that there may be more significant differences between cultivation intensities with increasing time under continuous maize. It is recommended that basic annual monitoring is undertaken at the study area, and more intensive sampling (such as in this study) is undertaken every several years until a minimum 10-year sampling period has been achieved so to accurately identify trends under long term continuous maize. More sustained sampling over a longer period may also reveal differences in maize yield under various cultivation systems.

This study highlighted the importance of careful identification of soil types within the cropping area. Insufficient data from previous soil quality sampling and no differentiation of soil types means any significant differences or trends in soil quality or maize yield with soil type are currently unable to be identified. Knowledge of the distribution of soil type in the cropping area is critical as uneven distribution is likely and low-density random sampling will likely skew soil quality data, interpretation, and the ability to analyse trends. Further research into the resistance and vulnerability of a range of soil orders and soil types under varying cultivation intensity is required to understand whether a certain soil order or particular inherent soil properties are better suited to a

particular method of cultivation, and if yields are improved or maintained. This could identify whether there may be the option to cultivate soil types differently to minimise soil quality degradation.

Further research on the effect of cultivation intensity on soil quality could include additional influences on soil quality and how these changes under varying cultivation intensities. This may include varying annual crops, varying winter cover crops and the effect of not using cover crops. Further analysis of SOM contents further down the soil profile may also be valuable to investigate the distribution of C and N below 30 cm and whether there are any differences between FC, ST and NT. For further research, sediment runoff as a measure of soil erosion may be another useful indicator to show how a NT or reduced cultivation system may reduce soil erosion and therefore reduce the potential for contaminating waterways.

Soil degradation and declines in soil quality through cultivation and harvesting of crops and poor matching of land use to soil capability have been identified as major issues in New Zealand (MPI, 2015; MfE & StatsNZ, 2018). This research provides evidence of the current level of soil degradation in the study area across a range of cultivation regimes, and in particular how intensive cultivation methods are degrading important aspects of soil quality in cropping systems. This research shows by adopting more sustainable growing practices in New Zealand, we can prevent further degradation and aid in replenishing essential SOM stocks and building up soil strength. In turn, minimising soil degradation and improving soil fertility and physical quality may improve yields and productivity, and therefore profitability. The ability to show that soil quality can directly relate to profitability (increased yields, decreased machinery costs) requires long term and sufficiently sampled trials, and may result in wider adoption of NT planting and more sustainable cropping regimes throughout NZ and internationally.

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Appendix A

Visual Soil Assessment Sheet

Cropping farm soil quality - visual soil assessment score sheet

Date:

Paddock name:

Current crop:

X crop:

Soil type:

Soil texture:

Soil moisture and seasonal conditions:

	Site one	Site two
General comments *Draw a map of where in the paddock you dig the holes*		
1. Structure and porosity score		
2. Turbidity score		
3. Earthworm score		
Total score per site (add 1, 2 and 3)		
Average score for paddock (Site one plus Site two total score divided by 2)		
Earthworms/m^2	Multiply the number of earthworms found in the soil sampled using the 'farmer spade method' by 16. Site one: Site two:	

Figure 1. VSA field sheet used for study (FAR, 2020).

Cropping farm soil quality - mini visual soil assessment (miniVSA) method

There are many functional benefits of maintaining or building soil quality. These include improvements in root development, drainage, and water holding capacity and reduced runoff risk. Soil quality is positively correlated with yield.

Equipment

Spade, tarpaulin, 2 x clear containers (1-2 L), 2 L water, score sheet, camera (photos are an important tool to compare differences over time).

When to sample

Be consistent with the time of year that you carry out the assessment. The best time is early spring when there is enough moisture for earthworms to be active. Don't carry out the assessment within 4-6 weeks cultivation.

Where to sample

Select the paddock/s that you want to monitor. Identify two areas in the paddock (avoiding wheel tracks) to carry out the VSA.

Note on the form

- Where in the paddock you have dug the hole.
- How easy it was to dig, were there any hard layers (pans) or any visible surface crusting?
- If there are roots, how far do they go down? If there is a compacted layer you might see roots grow out at a right angle or just clean stop. Do they have a rhizosheath (a layer of soil and microbes stuck to the root) or are the roots bare?
- Are there any mottles in the top soil (a bad sign indicating compaction and water logging).

1. Dig a hole using the farmer spade method (Figure 1)

Place the soil on a tarp. Record the soil's texture if you know it. Texture refers to the proportion of sand, silt and clay in the soil. Clay soils tend to store more organic matter, drain slower and have greater stability than sandy soils.

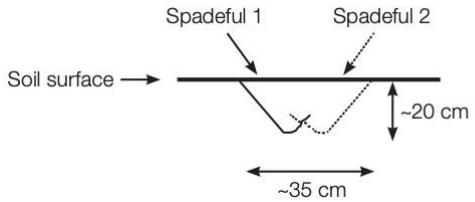

Figure 1. The farmer spade method.

2. Score structure and porosity

Part clods by hand and look for signs of nutty aggregates as opposed to clean compacted faces. Use clods from the top 5-7 cm when scoring.

Score based on the descriptions in the structure and porosity score table.
Refer to Figures 2 and 3 for examples of a high and low score.

Condition	Description	Score
Good condition	Good distribution of nutty aggregates with no significant clodding.	2
Moderate condition	Soil contains some nutty aggregates but also a significant proportion of coarse firm clods and/or fine non-aggregated soil.	1
Poor condition	Very few nutty aggregates. Soil dominated by coarse compacted, very firm clods and/or fine non-aggregated soil.	0

Figure 2. A high score (2) may look like the samples above.

Figure 3. A low score (0) may look like the sample above.

3. Score turbidity

Dig a hole in an undisturbed area near the paddock i.e. a grass verge. Look at the structure as this can be a helpful point of reference when scoring paddock structure and porosity as the undisturbed soil is indicative of what the soil can look like. Partially fill the clear containers with water and submerge a clod of the top 5-7 cm of soil from the undisturbed verge in one container and from the hole dug in the paddock in the other container. Let the soil sit and observe. If the behaviour of the paddock soil is very similar to the undisturbed soil this is a good sign (the undisturbed soil is in the container to the right in Figure 4). The cloudier the water becomes with suspended soil (i.e. becomes turbid), the lower the score. Take a photo and save for future reference.

Score based on the descriptions in the turbidity table.

Condition	Description	Score
Good condition	Low turbidity. Water remains clear or has a similar turbidity to the undisturbed soil.	2
Moderate condition	Medium turbidity. Water becomes cloudy but it does not happen immediately (within 1 minute).	1
Poor condition	High turbidity. Water immediately becomes cloudy with suspended matter compared to the undisturbed soil.	0

High score **Low score**

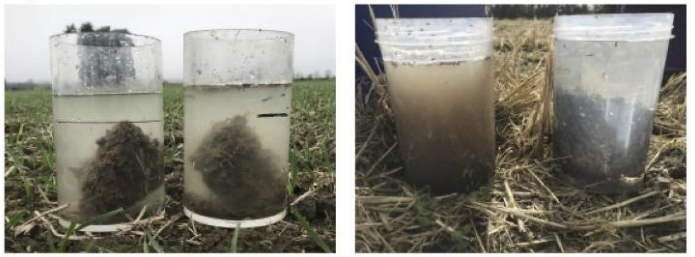

Figure 4. Samples showing the difference between a high and low turbidity score.

4. Score earthworms

Sort through the soil sample taken using the farmer spade method (Figure 1) and count the number of earthworms. Look around the roots since earthworms often reside amongst the roots just below the shoot. Score based on the below table and record. To convert to earthworms per m^2 multiply the number of earthworms found in the soil sampled using the 'farmer spade method' (Figure 1) by 16.

Earthworm score table.

Total earthworm count	Score
>8	2
4-8	1
2-4	0.5
<2	0

5. Total your scores

On the score sheet add up 1, 2 and 3 for Site one and Site two.

Calculate the average score for the paddock (add Site one and Site two total scores and divide by 2).

How are you tracking?

5-6	
3-4	
1-2	

Appendix B

Statistical Analysis

Analysis of variance (**Aggregate stability 0 – 10 cm)**

Variate: AggStabmm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.043130	0.014377	0.57	
Block.Plot stratum					
Trt	2	0.491651	0.245826	9.71	0.013
NT - Others	1	0.442223	0.442223	17.47	0.006
Residual	6	0.151859	0.025310	3.04	
Block.Plot.Soil stratum					
Soil	1	0.046212	0.046212	5.54	0.043
Soil.Trt	2	0.112905	0.056452	6.77	0.016
Soil.NT - Others	1	0.044917	0.044917	5.39	0.045
Residual	9	0.075007	0.008334		
Total	23	0.920764			

Tables of means

Variate: AggStabmm

Grand mean 0.775

Soil	B	H
	0.731	0.819

Trt	NT	ST	FC
	0.967	0.734	0.623

Soil	Trt	NT	ST	FC
B		0.862	0.786	0.545
H		1.072	0.682	0.702

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	0.0373	0.0795	0.0917
d.f.	9	6	9.89
Except when comparing means with the same level(s) of			
Trt			0.0646
d.f.	9		

Analysis of variance **(Air-filled porosity (Macroporosity @ - 10 kPa 0 – 5 cm)**

Variate: MnAFP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	34.988	11.663	1.04	
Block.Plot stratum					
Trt	2	37.801	18.900	1.69	0.262
NT - Others	1	33.770	33.770	3.02	0.133
Residual	6	67.077	11.179	2.91	
Block.Plot.Soil stratum					
Soil	1	49.923	49.923	13.00	0.006
Soil.Trt	2	3.753	1.877	0.49	0.629
Soil.NT - Others	1	0.413	0.413	0.11	0.750
Residual	9	34.573	3.841		
Total	23	228.114			

Tables of means

Variate: MnAFP

Grand mean 13.48

Soil	B	H
	12.04	14.93

Trt	NT	ST	FC
	11.81	13.82	14.83

Soil	Trt	NT	ST	FC
B		10.18	12.93	13.02
H		13.44	14.71	16.63

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	0.800	1.672	1.938
d.f.	9	6	10.04
Except when comparing means with the same level(s) of			
Trt			1.386
d.f.			9

Analysis of variance **(Bulk density 0 – 5 cm)**

Variate: MnBD

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.015716	0.005239	2.73	
Block.Plot stratum					
Trt	2	0.007610	0.003805	1.98	0.219
NT - Others	1	0.007482	0.007482	3.89	0.096
Residual	6	0.011532	0.001922	1.37	
Block.Plot.Soil stratum					
Soil	1	0.045098	0.045098	32.26	<.001
Soil.Trt	2	0.001377	0.000689	0.49	0.627
Soil.NT - Others	1	0.000006	0.000006	0.00	0.949
Residual	9	0.012582	0.001398		
Total	23	0.093916			

Tables of means

Variate: MnBD

Grand mean 1.0039

Soil	B	H
	1.0472	0.9605

Trt	NT	ST	FC
	1.0288	0.9942	0.9885

Soil	Trt	NT	ST	FC
B		1.0715	1.0287	1.0415
H		0.9862	0.9598	0.9356

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	0.01526	0.02192	0.02881
d.f.	9	6	13.23
Except when comparing means with the same level(s) of Trt			0.02644
d.f.			9

Analysis of variance **(Mineralisable N 0 – 10 cm)**

Variate: MnMinN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	7389.99	2463.33	7.63	
Block.Plot stratum					
Trt	2	1468.41	734.21	2.27	0.184
NT - Others	1	1460.01	1460.01	4.52	0.078
Residual	6	1937.66	322.94	28.23	
Block.Plot.Soil stratum					
Soil	1	18.94	18.94	1.66	0.230
Soil.Trt	2	9.29	4.65	0.41	0.678
Soil.NT - Others	1	6.45	6.45	0.56	0.472
Residual	9	102.95	11.44		
Total	23	10927.25			

Tables of means

Variate: MnMinN

Grand mean 22.48

Soil	B	H
	23.37	21.59

Trt	NT	ST	FC
	33.51	17.69	16.24

Soil	Trt	NT	ST	FC
B		33.67	18.53	17.92
H		33.36	16.86	14.57

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	1.381	8.985	9.143
d.f.	9	6	6.43
Except when comparing means with the same level(s) of Trt			2.392
d.f.			9

Analysis of variance **(Olsen P 0 – 10 cm)**

Variate: MnP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	930.53	310.18	1.13	
Block.Plot stratum					
Trt	2	2710.35	1355.18	4.93	0.054
NT - Others	1	2708.68	2708.68	9.85	0.020
Residual	6	1649.56	274.93	11.13	
Block.Plot.Soil stratum					
Soil	1	3059.78	3059.78	123.91	<.001
Soil.Trt	2	18.34	9.17	0.37	0.700
Soil.NT - Others	1	17.44	17.44	0.71	0.422
Residual	9	222.24	24.69		
Total	23	8590.79			

Tables of means

Variate: MnP

Grand mean 94.2

Soil	B	H
	105.5	82.9

Trt	NT	ST	FC
	109.2	86.4	87.0

Soil	Trt	NT	ST	FC
B		121.7	97.3	97.5
H		96.8	75.5	76.6

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	2.03	8.29	8.65
d.f.	9	6	7.09
Except when comparing means with the same level(s) of			
Trt			3.51
d.f.			9

Analysis of variance **(Penetration Resistance)**

Variate: MnPen

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.272999	0.091000	1.40	
Block.Plot stratum					
Trt	2	0.150500	0.075250	1.15	0.377
NT - Others	1	0.098247	0.098247	1.51	0.266
Residual	6	0.391143	0.065190	40.05	
Block.Plot.Soil stratum					
Soil	1	0.130769	0.130769	80.33	<.001
Soil.Trt	2	0.033293	0.016647	10.23	0.005
Soil.NT - Others	1	0.011498	0.011498	7.06	0.026
Residual	9	0.014651	0.001628		
Total	23	0.993354			

Tables of means

Variate: MnPen

Grand mean 1.8621

Soil	B	H
	1.7882	1.9359

Trt	NT	ST	FC
	1.9525	1.8740	1.7597

Soil	Trt	NT	ST	FC
B		1.9097	1.8216	1.6335
H		1.9954	1.9263	1.8859

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	0.01647	0.12766	0.12925
d.f.	9	6	6.30
Except when comparing means with the same level(s) of Trt			0.02853
d.f.	9		

Analysis of variance **(Soil pH 0 – 10 cm)**

Variate: MnpH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.06999	0.02333	0.72	
Block.Plot stratum					
Trt	2	0.74460	0.37230	11.47	0.009
NT - Others	1	0.37377	0.37377	11.52	0.015
Residual	6	0.19474	0.03246	2.21	
Block.Plot.Soil stratum					
Soil	1	0.00895	0.00895	0.61	0.455
Soil.Trt	2	0.04437	0.02218	1.51	0.271
Soil.NT - Others	1	0.03914	0.03914	2.67	0.137
Residual	9	0.13196	0.01466		
Total	23	1.19461			

Tables of means

Variate: MnpH

Grand mean 6.277

Soil	B	H
	6.258	6.296

Trt	NT	ST	FC
	6.101	6.213	6.518

Soil	Trt	NT	ST	FC
B		6.138	6.147	6.488
H		6.063	6.279	6.547

Standard errors of differences of means

Table	Soil	Trt	Soil Trt
rep.	12	8	4
s.e.d.	0.0494	0.0901	0.1085
d.f.	9	6	11.13
Except when comparing means with the same level(s) of Trt			0.0856
d.f.			9

Analysis of variance **(Total N 0 – 10 cm)**

Variate: %_N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.038658	0.012886	4.59	
Block.Plot stratum					
Trt	2	0.038063	0.019031	6.78	0.029
Residual	6	0.016839	0.002806	0.33	
Block.Plot.Type stratum					
Soil Type	1	0.133843	0.133843	15.88	0.003
Type.Trt	2	0.016246	0.008123	0.96	0.418
Residual	9	0.075844	0.008427	6.04	
Block.Plot.Type.*Units* stratum					
	120	0.167516	0.001396		
Total	143	0.487008			

Tables of means

Variate: %_N

Grand mean 0.39

Type	B	H
	0.36	0.42

Trt	NT	ST	FC
	0.41	0.39	0.37

Type	Trt	NT	ST	FC
B		0.37	0.37	0.33
H		0.45	0.40	0.40

Standard errors of differences of means

Table	Type	Trt	Type Trt
rep.	72	48	24
s.e.d.	0.015	0.011	0.022
d.f.	9	6	13.71
Except when comparing means with the same level(s) of			
Trt			0.027
d.f.			9

Analysis of variance **(Total C 0 – 10 cm)**

Variate: %_C

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	3.0201	1.0067	3.71	
Block.Plot stratum					
Trt	2	4.3959	2.1980	8.11	0.020
Residual	6	1.6270	0.2712	0.48	
Block.Plot.Type stratum					
Type	1	9.0872	9.0872	16.04	0.003
Type.Trt	2	1.4519	0.7259	1.28	0.324
Residual	9	5.0980	0.5664	4.73	
Block.Plot.Type.*Units* stratum					
	120	14.3603	0.1197		
Total	143	39.0405			

Tables of means

Variate: %_C

Grand mean 3.77

Type	B	H
	3.52	4.02

Trt	NT	ST	FC
	3.98	3.77	3.56

Type	Trt	NT	ST	FC
B		3.66	3.66	3.24
H		4.31	3.88	3.87

Standard errors of differences of means

Table	Type	Trt	Type Trt
rep.	72	48	24
s.e.d.	0.125	0.106	0.187
d.f.	9	6	14.65
Except when comparing means with the same level(s) of			
Trt			0.217
d.f.			9

Analysis of variance **(Total N 0 – 30 cm cumulative)**

Variate: Mn%N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.003728	0.001243	6.47	
Block.Plot stratum					
Trt	2	0.000800	0.000400	2.08	0.205
FC-Others	1	0.000770	0.000770	4.01	0.092
Residual	6	0.001152	0.000192	0.12	
Block.Plot.*Units* stratum					
Soils	1	0.009944	0.009944	6.40	0.032
Trt.Soils	2	0.000241	0.000120	0.08	0.926
FC-Others.Soils	1	0.000226	0.000226	0.15	0.712
Residual	9	0.013989	0.001554		
Total	23	0.029853			

Tables of means

Variate: Mn%N

Grand mean 0.3027

Trt	NT	ST	FC
	0.3001	0.2974	0.3107

Soils	B	H
	0.2824	0.3231

Trt	Soils	B	H
NT		0.2809	0.3192
ST		0.2801	0.3146
FC		0.2860	0.3354

Standard errors of differences of means

Table	Trt	Soils	Trt Soils
rep.	8	12	4
s.e.d.	0.00693	0.01610	0.02089
d.f.	6	9	11.11
Except when comparing means with the same level(s) of			
Trt			0.02788
d.f.			9

Analysis of variance **(Total C 0 – 30 cm cumulative)**

Variate: Mn%C

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.3716	0.1239	8.49	
Block.Plot stratum					
Trt	2	0.0856	0.0428	2.93	0.129
FC-Others	1	0.0803	0.0803	5.50	0.057
Residual	6	0.0876	0.0146	0.12	
Block.Plot.*Units* stratum					
Soils	1	0.6707	0.6707	5.56	0.043
Trt.Soils	2	0.0588	0.0294	0.24	0.789
FC-Others.Soils	1	0.0333	0.0333	0.28	0.612
Residual	9	1.0849	0.1205		
Total	23	2.3592			

Tables of means

Variate: Mn%C

Grand mean 2.882

Trt	NT	ST	FC
	2.859	2.823	2.964

Soils	B	H
	2.715	3.049

Trt	Soils	B	H
NT		2.679	3.040
ST		2.722	2.924
FC		2.744	3.184

Standard errors of differences of means

Table	Trt	Soils	Trt Soils
rep.	8	12	4
s.e.d.	0.0604	0.1417	0.1838
d.f.	6	9	11.07
Except when comparing means with the same level(s) of			
Trt			0.2455
d.f.	9		

Analysis of variance **(Total N 0 – 7.5 cm)**

Variate: %_N

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block stratum	3		0.009227	0.003076	1.16	
Block.Plot stratum						
Treatment	2		0.009780	0.004890	1.84	0.238
Residual	6		0.015916	0.002653	0.53	
Block.Plot.Soil stratum						
Soil	1		0.082706	0.082706	16.57	0.003
Soil.Treatment	2		0.007171	0.003586	0.72	0.513
Residual	9		0.044915	0.004991	3.12	
Block.Plot.Soil.*Units* stratum						
	47	(1)	0.075085	0.001598		
Total	70	(1)	0.239583			

Tables of means

Variate: %_N

Grand mean 0.3846

Soil	B	H
	0.3507	0.4185

Treatment	None	Strip	Full
	0.3999	0.3825	0.3715

Soil	Treatment	None	Strip	Full
B		0.3624	0.3622	0.3276
H		0.4373	0.4028	0.4155

Standard errors of differences of means

Table	Soil	Treatment	Soil Treatment
rep.	36	24	12
s.e.d.	0.01665	0.01487	0.02524
d.f.	9	6	14.83
Except when comparing means with the same level(s) of Treatment			0.02884
d.f.			9

(Not adjusted for missing values)

Analysis of variance **(Total C 0 – 7.5 cm)**

Variate: %_C

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block stratum	3		0.7377	0.2459	0.87	
Block.Plot stratum						
Treatment	2		1.3886	0.6943	2.47	0.165
Residual	6		1.6887	0.2815	0.65	
Block.Plot.Soil stratum						
Soil	1		5.6382	5.6382	13.01	0.006
Soil.Treatment	2		0.9589	0.4794	1.11	0.372
Residual	9		3.9016	0.4335	3.17	
Block.Plot.Soil.*Units* stratum						
	47	(1)	6.4271	0.1367		
Total	70	(1)	20.2316			

Tables of means

Variate: %_C

Grand mean 3.712

Soil	B	H
	3.432	3.992

Treatment	None	Strip	Full
	3.890	3.694	3.551

Soil	Treatment	None	Strip	Full
B		3.565	3.573	3.158
H		4.215	3.816	3.944

Standard errors of differences of means

Table	Soil	Treatment	Soil Treatment
rep.	36	24	12
s.e.d.	0.1552	0.1531	0.2441
d.f.	9	6	15.00
Except when comparing means with the same level(s) of Treatment			0.2688
d.f.			9

Analysis of variance **(Total N 7.5 – 15 cm)**

Variate: %_N

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block stratum	3		0.002973	0.000991	0.95	
Block.Plot stratum						
Treatment	2		0.000135	0.000068	0.06	0.938
Residual	6		0.006251	0.001042	0.22	
Block.Plot.Soil stratum						
Soil	1		0.059791	0.059791	12.75	0.006
Soil.Treatment	2		0.002924	0.001462	0.31	0.740
Residual	9		0.042211	0.004690	1.87	
Block.Plot.Soil.*Units* stratum						
	47	(1)	0.118137	0.002514		
Total	70	(1)	0.232417			

Tables of means

Variate: %_N

Grand mean 0.3665

Soil	B	H
	0.3377	0.3953

Treatment	None	Strip	Full
	0.3679	0.3646	0.3669

Soil	Treatment	None	Strip	Full
B		0.3417	0.3420	0.3293
H		0.3941	0.3873	0.4045

Standard errors of differences of means

Table	Soil	Treatment	Soil Treatment
rep.	36	24	12
s.e.d.	0.01614	0.00932	0.02186
d.f.	9	6	12.52
Except when comparing means with the same level(s) of Treatment			0.02796
d.f.			9

(Not adjusted for missing values)

Analysis of variance **(Total C 7.5 – 15 cm)**

Variate: %_C

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block stratum	3		0.3560	0.1187	0.92	
Block.Plot stratum						
Treatment	2		0.0223	0.0111	0.09	0.919
Residual	6		0.7764	0.1294	0.37	
Block.Plot.Soil stratum						
Soil	1		3.5585	3.5585	10.10	0.011
Soil.Treatment	2		0.4339	0.2169	0.62	0.562
Residual	9		3.1716	0.3524	1.40	
Block.Plot.Soil.*Units* stratum						
	47	(1)	11.8343	0.2518		
Total	70	(1)	20.1530			

Tables of means

Variate: %_C

Grand mean 3.470

Soil	B	H
	3.248	3.692

Treatment	None	Strip	Full
	3.466	3.451	3.494

Soil	Treatment	None	Strip	Full
B		3.245	3.323	3.175
H		3.687	3.579	3.812

Standard errors of differences of means

Table	Soil	Treatment	Soil Treatment
rep.	36	24	12
s.e.d.	0.1399	0.1038	0.2004
d.f.	9	6	13.99
Except when comparing means with the same level(s) of Treatment			0.2423
d.f.			9

(Not adjusted for missing values)

Analysis of variance **(Total C 15 – 30 cm)**

Variate: %_C

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block stratum	3		3.2894	1.0965	3.90	
Block.Plot stratum						
Treatment	2		1.9542	0.9771	3.47	0.100
Residual	6		1.6886	0.2814	0.45	
Block.Plot.Soil stratum						
Soil	1		0.4992	0.4992	0.79	0.396
Soil.Treatment	2		0.0015	0.0008	0.00	0.999
Residual	9		5.6590	0.6288	1.47	
Block.Plot.Soil.*Units* stratum						
	47	(1)	20.0613	0.4268		
Total	70	(1)	33.0878			

Tables of means

Variate: %_C

Grand mean 2.173

Soil	B	H
	2.090	2.257

Treatment	None	Strip	Full
	2.041	2.073	2.406

Soil	Treatment	None	Strip	Full
B		1.953	1.996	2.321
H		2.130	2.151	2.490

Standard errors of differences of means

Table	Soil	Treatment	Soil Treatment
rep.	36	24	12
s.e.d.	0.1869	0.1531	0.2754
d.f.	9	6	14.50
Except when comparing means with the same level(s) of Treatment			0.3237
d.f.			9

(Not adjusted for missing values)

Analysis of variance **(Total N 15 – 30 cm)**

Variate: %_N

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Block stratum	3		0.033684	0.011228	3.01	
Block.Plot stratum						
Treatment	2		0.018241	0.009121	2.44	0.167
Residual	6		0.022396	0.003733	0.49	
Block.Plot.Soil stratum						
Soil	1		0.006303	0.006303	0.83	0.385
Soil.Treatment	2		0.000525	0.000262	0.03	0.966
Residual	9		0.068138	0.007571	1.57	
Block.Plot.Soil.*Units* stratum						
	47	(1)	0.226741	0.004824		
Total	70	(1)	0.374886			

Tables of means

Variate: %_N

Grand mean 0.2299

Soil	B	H
	0.2206	0.2393

Treatment	None	Strip	Full
	0.2163	0.2212	0.2522

Soil	Treatment	None	Strip	Full
B		0.2098	0.2082	0.2436
H		0.2228	0.2341	0.2608

Standard errors of differences of means

Table	Soil	Treatment	Soil Treatment
rep.	36	24	12
s.e.d.	0.02051	0.01764	0.03069
d.f.	9	6	14.70
Except when comparing means with the same level(s) of			
Treatment			0.03552
d.f.	9		

Analysis of variance **(VSA)**

Variate: Average_VSA_score

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.46538	0.15513	1.90	
Block.Plot stratum					
Treatment	2	0.48402	0.24201	2.97	0.127
NT-Others	1	0.45631	0.45631	5.60	0.056
FC-Strip	1	0.02772	0.02772	0.34	0.581
Residual	6	0.48885	0.08148	1.51	
Block.Plot.Soil_Type stratum					
Soil_Type	1	0.22705	0.22705	4.20	0.071
Soil_Type.Treatment	2	0.06473	0.03236	0.60	0.570
Soil_Type.NT-Others	1	0.00232	0.00232	0.04	0.841
Soil_Type.FC-Strip	1	0.06241	0.06241	1.16	0.310
Residual	9	0.48617	0.05402		
Total	23	2.21620			

Tables of means

Variate: Average_VSA_score

Grand mean 1.3

Soil_Type	Bruntwood	Horotiu
	1.2	1.4

Treatment	No Till	Strip Till	Full Cultivation
	1.5	1.2	1.1

Soil_Type	Treatment	No Till	Strip Till	Full Cultivation
Bruntwood		1.4	1.2	1.0
Horotiu		1.5	1.3	1.3

Standard errors of differences of means

Table	Soil_Type	Treatment	Soil_Type Treatment
rep.	12	8	4
s.e.d.	0.09	0.14	0.18
d.f.	9	6	12.83
Except when comparing means with the same level(s) of Treatment			0.16
d.f.	9		

Analysis of variance **(VSA turbidity score)**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tillage	2	2.0208	1.0104	8.82	0.002
Soil	1	0.0104	0.0104	0.09	0.766
Tillage.soil	2	0.1458	0.0729	0.64	0.541
Residual	18	2.0625	0.1146		
Total	23	4.2396			

c

Appendix C

FAR NCRS History

The following information is sourced from the Foundation of Arable Research, for further information on the trial visit:
https://www.far.org.nz/research/site/northern_crop_research_site

2007

Prior to 2007 the site was growing potatoes. In 2007 a three-hectare paddock was leased from the Chynoweth family trust which owns the entire 25 hectare block. Each season, various trials were established, including the evaluation of dairy shed effluent as a fertiliser for maize and comparison of drought tolerant hybrids. In October 2007 the Long-term Crop Establishment trial was first established comparing Full Cultivation, No-till planting and Strip-till established maize. The trial continued until 2016.

Figure 1. Rain shelter constructed to investigate the drought tolerance of maize hybrids in 2011

2013

In 2013 the potato growers relinquished the rest of the property and FAR took over the lease of the entire 25 hectares, and then added another four hectares of trial area, for a total of seven hectares of trials. The remaining area was sub-leased to John Austin Limited for commercial production of maize grain.

Figure 2. Forages for Reduced Nitrate Leaching trial on block in 2013

2014

As a result of the development of State Highway 1 into the new expressway, the site lost approximately a hectare of land. Unfortunately, this included a whole replicate on the LTCE trial. We made the decision to abandon the trial in that block, and established the "new" LTCE trial in its current location. Also in 2014 a further 2 hectares of land was included the trial area, and the trial blocks were split up using permanent grass headlands to separate blocks with soils of different characteristics.

Figure 3. Crop rotation trial being harvested and baled while in the background the newly established Long Term Crop Establishment trial. December 2014

2015

In early 2015, all the trial areas were in maize or crop. We wanted to establish a cover crop trial in March and so a further 1.5 hectares of land adjacent to the entrance way was added.

2016

In 2016 an additional hectare was added and a long term crop rotation trial established using faba beans, gland clover and annual ryegrass followed by spring direct drilled maize.

Figure 4. Left to right: faba beans, gland clover and direct drilled maize sown into sprayed out annual ryegrass

2018

The final chapter in the expansion of the Northern Cropping Research Site is the winter of 2018 take-over of the entire 25-hectare property for FAR trials. The back ten hectares is being used for large scale replicated strip trials investigating crop systems, and also variable rate seed and fertiliser regimes.

Long- term maize crop establishment trial

Crop Details

Previous crop	Grain maize (*Zea mays*), annual ryegrass (*Lolium multiflorum*)	
Trial design	97m x 8 row plots, randomised, four replicates,	
Maize planted	17 October 2017	
Hybrid	P0021 Poncho®Plus	
Seeding rate	90,000 seeds/hectare	
Fertiliser	Planting	150kg/ha of Nitrophoska Extra
	Side-dress	30 November 2017 300kg/ha SustaiN
Herbicide	September 2017 2.5l/ha of Glyphosate 540	
	19 October 2017	Saflufenacil (Sharpen®@ 150 g/ha) and acetochlor (Roustabout®@ 3 l/ha) in 220 l/ha water
Slug bait	No-till 17 October and 31 October 2017 Metaldehyde (SlugOut®) 216 g ai/ha	
Harvested	19 May 2018	

Background

The benefits of reduced cultivation, such as reducing the risk of soil erosion and maintaining soil organic matter, are generally well accepted, however there has been limited uptake of no-till and strip-till by New Zealand maize growers. Cultivation practices can strongly influence important soil processes, which in turn can affect the short and long term profitability and sustainability of arable cropping systems. There are many reasons to decrease cultivation, including, retention of soil moisture, improved soil structure, less carbon loss, reduced soil erosion and the limiting of soil compaction. Establishment costs can also be reduced in some circumstances.

Objective

The aim of the long term crop establishment (LTCE) trial is to compare the effectiveness of full cultivation, strip-till and no-till crop establishment on the crop performance and profitability of maize each year, and their long- term effects on soil quality.

Method

The trial was planted in October 2017 with four replicates of three treatments:

- Full cultivation (FC) - disc ripped and just prior to planting power harrowed
- Strip-till (ST) - two passes of a SoilWarrior cultivator in mid-September 2017
- No-till planting (NT) – planted using John Deere MaxEmerge 2 no-till planter

Slug bait was applied twice to the no-till treatment. Days to emergence were recorded, as were plant numbers at the V5 stage.

Following grain black layer and plant dry down, the strips were harvested with a commercial John Deere combine, weighed into a weigh wagon, and a moisture sample taken and analysed using a Dickey John GAC 2100 Agri moisture meter.

Soil gravimetric water holding capacity was measured by inserting cylinders into the soil and filling with water over a period of 1–2 h until the soil within them was beyond saturation point. The cylinders were then covered and left to drain for 24 h before a soil sample from 0–7.5 cm depth was removed from within the cylinder and oven-dried to determine gravimetric soil moisture content.

Aggregate stability was measured by air drying the soil samples, then sieving underwater for 20 min on a nest of sieves (2.0, 1.0 and 0.5 mm in diameter). The aggregate stability is expressed as both % >1 mm and mean weight diameter (MWD).

The gross margin for the crop was calculated based on different establishment costs for the three treatments as shown in Table 1.

Figure 1. Trial site showing different crop establishment methods, and white nitrous oxide collection chambers

Results (2017/18)

There were no significant differences in the grain yield or gross margin between the three establishment treatments (Table 1). This result is consistent with other New Zealand research and on-farm trials.

Table 1 Results from long term crop establishment trial 2017/18 season

Treatment	Grain yield (t/ha @ 14% moisture)	Plant population	Crop establishment costs ($/ha)	Gross margin ($/ha)
Cultivated	14.1	92,500	$2,405	$2,646
Strip – till	14.1	91,500	$2,235	$2,788
No-till plant	13.1	89,000	$2,115	$2,567
LSD 5%	1.2			$411
CV	5.2%			9.6%

The LTCE has been undertaken for four seasons in the current location, and the mean results from the four seasons are given in Table 2. The four year results show the same trends as the 2017/18 season, with no significant difference in yield or gross margin between the three establishment treatments.

Table 2. Grain yield from different crop establishment treatments (t/ha @14% moisture) from previous and current seasons (4 years).

Treatment	Four harvests 2015-18	
	Yield (t/ha @ 14%)	GM ($/ha)
Cultivated	11.6	$1,755
Strip-till	11.7	$1,960
No-till plant	11.1	$1,801
LSD 5%	0.8	$430
CV	11.3%	36.0%

There was no significant difference between the three treatments in Gravimetric Water Content (average = 48.1%); or Aggregate Stability (average = 1.1mm mean weight diameter)