EFFECTS OF FULL INVERSION TILLAGE DURING PASTURE RENEWAL ON SELECTED SOIL FERTILITY INDICES

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DEDICATION

This thesis is dedicated to my parents, Mr. Jebril Amanor and Mrs. Adiza Maku.

ABSTRACT

The impacts of using a one-off Full Inversion Tillage (FIT) method at pasture renewal on soil carbon (C) stocks and other agronomic aspects is currently being researched in New Zealand (NZ) pastoral systems, following establishment of multiple field trials in the North and South Island. However, there is currently minimal available research information on the subsequent effects of FIT on soil fertility. Therefore, the first objective of this study was to assess the impact of tillage method (No Tillage, Shallow Tillage and FIT), performed at pasture renewal, on the soil fertility of two contrasting soil types under grazed pasture. The second objective was to estimate the amounts of fertiliser nutrients required to replace the nutrients removed from the 0-7.5 cm soil sampling depth, as a result of FIT.

The study involved soil sampling of three trial sites, in the North Island of New Zealand, which were used to assess tillage treatment effects on soil total C and N, pH, Olsen extractable P, exchangeable cations and CEC. The soil sampling was approximately 18, 13 and 8 months following the tillage treatments at Field trials 1, 2 and 3, respectively, and was based on a two-factor factorial design, consisting of three tillage treatments (Field trial 1 or 2: No Tillage (NT), FIT and Shallow Tillage (ST); Field trial 3: NT, FIT and Permanent Pasture (PP)) and four soil depths (0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm). The soil at Field trial 1 and 3 is a Pallic soil and at Field trial 2 is an Allophanic soil.

Across the three sites 8-13 months after tillage treatments, the FIT treatment transferred 16-46% more total C and 24-41% more total N from the 0-7.5 cm soil depth to deeper depths, compared to the NT treatment, but did not change the total C and N stocks in the entire 0-30 cm soil depth. The effect of FIT on soil fertility parameters was only significant for Olsen extractable P, exchangeable K and exchangeable Mg. The FIT treatment reduced soil (0-7.5 cm) Olsen P, exchangeable K and Mg levels by approximately 11-21 mg Olsen P/ha, 0-10.1 MAF QT K and 7-14 MAF QT Mg across the three sites, corresponding to additional P, K and Mg requirements that ranged from 60-120 kg P/ha, 0-1010 kg K/ha and 72-160 kg Mg/ha, respectively. These additional nutrient requirements equate to estimated fertiliser costs that ranged from $210-420/ha, $0-707/ha, and $94-208/ha (excluding transport and spreading costs) for Olsen P, exchangeable Mg and exchangeable K, respectively, across the three field trials. The study found that the total estimated cost of replacing nutrients removed from the topsoil depth (0-7.5 cm) ranged across the sites from $362 - 1,293/ha. The range in cost is influenced by initial soil fertility levels and the depth and degree of soil inversion implemented. If the initial soil fertility is higher than optimum, then the amount of nutrients required to increase the soil tests to just within the optimum range will be lower than the cost replacement of available nutrients removed from the 0-7.5 cm soil depth.

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1. CHAPTER ONE: Introduction

High soil organic matter levels, supported by fertiliser inputs, play a significant role in enhancing soil quality and maintaining the long-term sustainability of New Zealand pastoral systems (Karlen et al., 1997; Haynes, 2000; Percival et al., 2000). In pastoral farms, fertiliser ranks among the three largest expenses incurred during production (Monaghan et al., 2007; Destremau & Siddharth, 2018), and its importance in the farm production chain has been the focus of much research over the past 50 years (Monaghan et al., 2007). Many of these studies have focused on improving our understanding of the movement and transformation of fertiliser nutrients entering pastoral soils, and on quantifying the loss of nutrients from soils, which is also used to determine maintenance fertiliser requirements and inform nutrient budgeting software (Wheeler et al., 2003). These studies have also focused on establishing the relationships between soil tests, for key plant growth limiting nutrients, and pasture production responses (Haynes & Williams, 1993; Morton & Roberts, 1999; Edmeades et al., 2006; Edmeades et al., 2010).

Improvements in nutrient management have contributed to higher levels of pasture production, which have helped support increases in dairy farm production over the last three decades. This increased production has been brought about by both the intensification of dairy farms as well as the expansion of dairying through the conversion and development of dairy stock, sheep and beef farms. From 1990 to 2018, total cow numbers in the country increased from about 2.40 million to 4.99 million; this was associated with a rise in total dairy land from about 1.02 million ha to 1.76 million ha (Dairy New Zealand, 2018). Monaghan et al. (2005) highlighted two main characteristics of this land use change, which are i) a focus on low lying areas where landscape characteristics such as climate, soils, and topography permit feeding of cows all year round and ii) an improvement in pasture management through intensive fertiliser use and use of high performing grass species.

On pastoral dairy farms the majority of added plant nutrients come in the form of nutrient fertilisers purchased outside the farm, or recycled in livestock excreta and/or farm diary effluent (Monaghan et al., 2007; Hanly et al., 2017). Nutrients in pasture soils are usually stratified, with the greatest proportion occurring in the topsoil where roots are most active (Cayley et al., 2002; Dougherty et al., 2006), due to it being the main zone of accumulation and recycling of soil organic matter, and due to the surface application of fertilisers and livestock excreta (Karlen et al., 1997; Chan et al., 2002).

Soil organic matter in agricultural farms represent a large store of carbon (C) and there is rising demand to store more soil C in New Zealand pastoral farms in order to reduce the concentration of greenhouse gas (GHG) emissions into the atmosphere. New Zealand’s gross GHG emissions as at 2017 were 81 million tonnes of carbon dioxide equivalent, 49% of which were from the agriculture sector, and over half of agricultural emissions were from methane and nitrous oxide released from dairy pastoral farms (Ministry for the Environment, 2018). At the same time, because of higher inputs of organic materials in the 0-7.5 cm layer typically under New Zealand long-term grazed pastures, there is a subsequent decline in soil C saturation particularly in the top 0-7.5 cm depth (Whitehead et al., 2018), which has typically limited the potential of increasing soil C stocks (Six et al., 2002; Stewart et al., 2007; Beare et al., 2014). Also, pastures need relatively frequent renewal (every 7 to 10 years), and that can be done using tillage, either shallow till (to approximately 5 cm depth) or standard till (to approximately 10-20 cm depth), thus causing additional losses of C (Rutledge et al., 2014).

This loss of C may be only short-term because carbon inputs from pasture litter, pasture root and dung will soon replenish the C lost (Hedley et al., 2009; Curtin et al., 2010). However, there is a limit to C storage in topsoil, and the soil eventually returns to a near steady state of C addition and losses being equal.

Recent researches about increasing grassland carbon storage are now focusing on using Full Inversion Tillage (FIT) performed once, as a substitute tillage method during pasture renewal (Lawrence-Smith et al., 2015; Alcántara et al., 2016; Schiedung et al., 2019). Under the FIT method, a disc and skimmer fitted mouldboard plough cuts to a soil depth >20 cm, transfers the topsoil into the bottom of the next furrow and exposes the subsoil in turn, so that the new topsoil mixed with subsoil is expected to be able to sequester larger amounts of C, due to its lower soil C level (Chung et al., 2010).

In New Zealand, multiple field trials have been established both in the North Island (Calvelo Pereira et al., 2019) and in the South Island (McNally et al., 2019) to test the effect of Full Inversion Tillage (FIT) on C storage. A one-off FIT event during pasture renewal (FIT-renewal) provides an opportunity to increase the stock of soil C by altering the vertical distribution of the organic matter. However, the use of FIT could cause unintended changes in topsoil fertility (0-7.5 cm depth), particularly because of the redistribution of plant nutrients along with the organic matter transferred into the new subsoil. For instance, Zhang et al. (2009) recorded a decline in soil Olsen P extractable phosphorus concentrations in the surface soil (0-7.5 cm), 18 months following a conventional tillage operation to a depth of approximately 20 cm, due to redistribution of phosphorus caused by tillage. Therefore, the current study was conducted as part of the on-going North Island field trials to investigate the effect of FIT-renewal on the fertility status of two contrasting pasture soils in New Zealand. Knowledge on the overall effect of Full Inversion Tillage on soil fertility will provide useful insight into possible subsequent fertiliser requirements that may arise following the tillage activity and the economic consequences for pastoral farmers in New Zealand.

1.1. Research objectives

The specific objectives of this study were:

1. To assess the impact of tillage method (No Tillage, Shallow Tillage, Full Inversion Tillage), performed during pasture renewal, on the soil pH, Olsen P, exchangeable basic cations, CEC and total carbon and nitrogen contents of a Pallic and an Allophanic soil under grazed pasture.
2. To estimate the amounts of fertiliser nutrients required to replace soil fertility removed from the 0-7.5 cm soil sampling depth, as a result of Full Inversion Tillage.

2. CHAPTER TWO: Literature review

2.1. Soil fertility and soil testing in dairy grazed pasture farm systems

2.1.1. Components of soil fertility in long term grazed pastures

The productivity of New Zealand (NZ) pasture soils has strong dependence on organic matter stocks because, organic matter-

1. helps to improve soil structure through the formation of soil aggregates, allowing for greater soil aeration and drainage (Cornforth, 1998).
2. serves as a reserve for key growth limiting nutrients, such as nitrogen (N), sulphur (S), and phosphorus (P), which generally contribute to pasture soil fertility (Perrott & Sarathchandra, 1987).
3. provides organic colloids that, in addition to the soil mineral constituents, retain and exchange inorganic forms of nutrient cations (e.g. Ca, K, Mg and Na) between the soil solution phase (Parfitt et al., 1995), allowing for timely nutrient availability and uptake.

In pastures, the build-up of soil organic matter is pronounced in the top 7.5 cm depth and declines with increasing soil depth (Kelliher et al., 2012; Beare et al., 2014), as a result of higher inputs of pasture litter and root stocks, and deposition of higher amounts of dung and effluent from farm animals in the 0-7.5 cm layer (Hedley et al., 2009). This pattern of organic matter distribution is consistent with that of the level of many of the major pasture nutrients and pH, which show distinct stratification with soil depth, thus, ensuring higher fertility in the top 0-7.5 cm layer, where pasture roots are most active (Cowie et al., 1996). The high nutrient supply is explained by the generally large fertility demand of the high-yielding clover based pastures commonly used in New Zealand pasture systems (Williams & Haynes, 1990) and the limited ability of the clover species to compete for nutrients (Haynes, 2000). The application of pasture nutrients, occur mostly through external fertilisers in the case of P, K, S and Ca, but to a lesser extent, N and Mg. The majority of new N inputs usually occur through biological N_2 fixation from the clover species, following establishment (Williams & Haynes, 1990). However, with intensification of dairying over the past few decades, there has been an increase in use of manufactured N fertilisers (Clark et al., 2007), which is typically applied in autumn, late-winter and spring at rates of 23-50 kg/ha/application, or 100-150 kg N/ha/year (Dairy New Zealand, 2012).

Naturally, New Zealand mineral soils have acidic pH (5.8-6.0) (Roberts & Morton, 2012), and because pasture farm management activities and associated farm processes (e.g. fertiliser applications, nitrate leaching) usually lead to a further increase in soil acidity (Bolan et al., 1991; Hedley & Bolan, 2003), frequent pH monitoring has become an important aspect of proper pasture management. Very acidic pH if not ameliorated through lime additions, can greatly influence nutrient availability and reduce pasture performance.

In the case of P, the inorganic forms are inherently low, which means that achievement of optimum pasture yield requires top dressing with fertiliser P. Phosphorus addition to soils is most commonly achieved through the addition of single superphosphate, which also supplies S. This leads to a build-up of organic and inorganic forms of the nutrients in the soil, with most of the inorganic forms held in solution, on soil exchange sites or strongly absorbed on specific anion sorption sites, and the organic fractions being tied up in organic matter. Historically, single superphosphate has been the main fertiliser used in NZ agriculture. In 1980, single superphosphate made up about 90% of fertiliser sold in NZ and urea fertiliser was only 1%.

By 2014 single superphosphate share was about 50% and urea had increased to about 23% of fertiliser used (Norton & Drew N, 2016).

Another important component of grazed diary pasture is the contribution of grazing animals to the nutrient recycling, through dung and urine excreta return (Luo et al., 2017). But because nutrients from these sources vary in terms of the pathway of entry into the pasture system, nutrient from grazing animals are often spatially separated, with K and N applied mostly through urine and P and Ca through dung (During, 1984). In addition, these nutrients are often supplied in higher amounts to small areas of the paddock, which may on average represent less than 5% of the total surface area of the paddock per grazing (Saunders, 1984). Therefore, this results in a high degree of spatial variability in soil fertility, but also contributes to nutrient losses (Monaghan et al., 2007).

2.1.2. Common soil tests as influenced by pasture soil fertility requirements

The amount of fertiliser nutrients applied to soils vary depending on whether they are added to the pasture system as capital or as maintenance fertilisers (Cornforth, 1998). Capital fertiliser applications are aimed at raising the plant-available nutrient levels of undeveloped pastures or pastures that have below optimal soil fertility status. The amount of capital fertiliser needed to raise the available nutrient levels in the pasture sampling depth (0-7.5 cm) to near optimum may vary depending on the type of soil, present stocking rate, the size of the soil test change required and the type of nutrient to be applied (Cornforth, 1998). On the other hand, maintenance fertilisers are aimed at replenishing any of the nutrients lost through pasture uptake or through losses, such as leaching and surface run-off, in order to maintain soil tests at current levels (During, 1984; Haynes & Williams, 1993), as discussed in more detail in the next section.

Total soil C stocks under New Zealand's high producing pasture systems generally are higher than those of arable systems, and in the 0-30 cm depth, would usually reach or exceed ~100 t C/ha, compared to about ~85 t C/ha for arable systems (Beare et al., 2013). For a given pasture system, the amount of C stored in the soil (i.e. the C stock) is a balance between C deposited through plant roots, animal excreta and above-ground plant litter and the amount of C lost in decomposition (Lal, 2018) and through direct harvest (Kirschbaum et al., 2017). The amount of soil C (0-15 cm) generally varies depending on landscape features such as soil type and slope angle, as well as farm management practices (Whitehead et al., 2018). Allophanic soils have the largest C stocks whereas that of Recent soils are at the lower end of the list (Shen et al., 2018). The nature of farm management factors influencing soil C Changes determine whether a particular soil is accumulating soil C, undergoing C loss or is maintaining a steady C state. For example, studies involving pasture renovation or pasture renewal have reported short- term losses of carbon, which can be rapidly replaced following establishment of new grass (Schipper et al., 2017). Also, some studies have indicated the possibility of increasing soil C stabilization through farm practices that increase soil fauna population, but this comes with a possible negative implication of increasing nitrous oxide emissions (Whitehead et al., 2018). Under newly established pasture where the initial soil C stock is low, soil C is expected to accumulate rapidly with time, and at that stage, the amount of soil C relative to soil N is often greater. However, as the pasture continuous to age under sustained production, the C to N ratio begins to decline (Jackman, 1964), so that under long term grazed pastures where organic matter would be accumulating at a slow rate following stabilization (Beare et al., 2014), the relationship between soil C and N tend to be influenced greatly by soil N. For instance, the C/N ratio of undeveloped scrub reportedly decreased from 33 to 11 under pasture management following build-up of soil N (Walker et al., 1959). This increase in soil N stock can be associated with changes that occur under pasture management, being mainly the intensive supply of major nutrients through the use of fertilisers, aimed at increasing cow numbers by improving pasture productivity (Clark et al., 2007). For example, adequate P and S fertiliser inputs generally allow for increased pasture production by enhancing atmospheric N_2 fixation by the legume component of the pasture, up to rates of 300 kg N/ha/year (Hoglund & Brock, 1987), leading to a reduction in the C/N ratio of organic matter to values typically as low as 10 (Schipper & Sparling, 2011). The reduction in C/N ratio occurs from immobilization of the N component into soil organic matter as the N content increases, coupled with a rather slow rate of C accumulation (Jackman, 1964; Schipper & Sparling, 2011). Therefore, under long term grazed pastures, there is the development of organic matter sink typically enriched with N, primarily from biological fixation, which additionally serves as source of available N for pasture uptake and production. By incorporating C and N loss components, because of the effect different farm management practices have on C and N dynamics (Schipper et al., 2010), periodic losses of soil C and N can implicate variations in the nature and rate of C and N accumulation, and subsequently cause differences in the soil C/N ratio across different pasture systems; so that for the same number of production years under different pasture systems, C and N accumulation would expectedly be at a lower rate under pasture systems where management induced losses of C and N were greatest.

However, unlike some of the other major nutrients, routine soil testing for available N is not considered useful for pastoral farms, not only because inputs of N mostly come from N fixation from the atmosphere through legumes (Peoples et al., 1998) but also because of the high spatial variability in soil mineral N caused by the return of N in urine patches.

Soil pH is another soil parameter that has an important influence on soil nutrient availability. It is useful for defining the status of other physicochemical and biological properties of the soil, from which useful correlations can be established (Davies, 1992; Pietri & Brookes, 2008). For example, a high pH of 6.0 and above are known to increase P desorption of allophanic soils, thus, increasing available P levels to plants. Conversely, very low pH (< 5) results in the increased solubility of exchangeable Al which can affect pasture root performance and phosphorus availability. New Zealand pasture soils perform best within a pH range of 5.8 to 6.0, except for peat soils, where optimum values range between 5.0-5.5 (Roberts & Morton, 2012). Measurement of soil pH are used mainly to estimate lime requirements of soils (Lynch & During, 1978). But because soil pH has strong relationships with soil texture and soil organic matter levels, some researchers have estimated lime requirement of soils based on soil properties such as cation exchange capacity, which in turn is influenced by soil texture and organic matter contents (Bolt et al., 1976; Curtin & Trolove, 2013; Curtin et al., 2015). There is a greater potential for pH to decrease under improved pastures. Major contributions to this pH decrease occur through the release of excess H^+ ions in pasture rooting zones due to N_2-fixing by clover and ammonium nitrification, followed by nitrate leaching (Thomas & Hargrove, 1984; Bolan et al., 1991; Hedley & Bolan, 2003). Thus, lime application is typically practiced 2-4 years to maintain pH at the optimum ranges for pasture production (During, 1984).

The common soil test used in New Zealand as an indicator of plant available phosphorus is the Olsen P test, selected following a number of trials (Saunders, 1965; Grigg, 1968; Sherrell, 1970; Grigg, 1972, 1977), as most suitable for New Zealand conditions since it was found to provide a more comprehensive correlation with P uptake and plant yield. The Olsen P test

(Olsen, 1954) was originally developed for alkaline conditions but was modified to suit New Zealand soils which are acidic, mostly having pH less than 6.0. The method involves extracting a volume rather than a weight of air dried and sieved soil by supplying sufficiently high concentration of anion (0.5M $NaHCO_3$) that can cause desorption of the P element into solution (Olsen, 1954). The target Olsen P range for pasture soils (0-7.5 cm soil depth) is between 20 to 30 mg P/L and Ash and Sedimentary soils, and between 35-45 mg P/L for Peat and Pumice soils (Roberts & Morton, 2012). The amount of P fertiliser required to raise the Olsen P level of a soil varies with the Anion Storage Capacity (ASC, i.e. P retention) of the soil, from 4 to 18 kg P/ha (additional to maintenance requirements) for every 1 mg P/kg increase in Olsen P values. Allophanic soils with high ASC levels (>75%) are at the upper part of this range and Sedimentary soils with low ASC (<25%) are the lower part of this range (Roberts & Morton, 2012). The ASC of a soil influences the proportion of the P added in fertilisers that is lost through adsorption and fixation mechanisms following contact with positively charged soil surfaces (Saunders, 1965; Parfitt, 1990). The ASC of a soil is closely influenced by the chemical constituents (variable charge clays: e.g. sesquioxides, anhydrous Al and Fe oxides and hydroxides) of the soil parent material, organic matter contents and the extent to which the parent materials have gone through pedogenesis (Saunders, 1965). Other external soil properties which significantly affect a soil’s ASC include pH; very low pH conditions contribute to protonation of the variable charged clays providing positive clay surfaces onto which phosphate-P is adsorbed and fixed (Gunjigake & Wada, 1981).

The Cation Exchange Capacity (CEC) of soils is usually defined as the capacity of soils to adsorb and exchange cations (Chapman, 1965; Bache, 1976; Carter & Gregorich, 2008). The range of CEC values for NZ soils typically vary between 0-50 $cmol_c$/kg depending on the soil order

(Searle, 1986), and are related to the surface area and surface charge of the clay minerals and organic matter constituents (Carter & Gregorich, 2008). Allophanic soils with high organic matter contents have CECs above 15 $cmol_c/kg$, whereas the Recent soils and Pallic soils with lower organic matter levels typically have CECs between 5 and 15 $cmol_c/kg$ (Curtin & Trolove, 2013). The exchangeable cations can be grouped into exchangeable bases (Ca, Mg, Na and K), acidic cations (Al and H), and other cations such as Fe, and NH_4^+ (Blakemore et al., 1987). The basic cations measured in CEC determination are the water soluble and rapidly exchangeable fractions which are essential for plant growth (Simard et al., 1990). A more important way of describing the basic cations is by expressing them as a percentage of the CEC- Percent Base Saturation, which generally gives an indication of pasture soil fertility status. Generally, soils with high Percent Base Saturation are characterized by high pH which enables buffering against acidic cations released from acidifying process such as nitrification. In addition, soils which are highly saturated with bases tend to be more fertile than soils which are not because of the higher levels of basic cations available for pasture uptake. Soil pH is important in predicting what proportion of the CEC is saturated with bases; base saturation would generally equal CEC at pH of 7 or higher but base saturation would be below CEC when pH is below 7 (Sparling & Schipper, 2002). Even though a soil may appear to have high base saturation, differences in soil cation exchange properties such as the high selectivity of soils for certain cations than others results in differences in the availability of the respective basic cations, so that under New Zealand pasture systems, Ca tends to dominate the exchange site, followed by Mg, then K (Edmeades, 1980).

The concentrations of exchangeable K required to achieve optimum pasture production varies between soil types. The range is between 0.49-0.7 $cmol_c/kg$ (7-10 MAF QT K) for Allophanic soils, 0.35-0.57 $cmol_c$/kg (5-8 MAF QT K) for Pallic soils and 0.35-0.49 $cmol_c$/kg (5-7 MAF QT K) for Peat soils (Roberts & Morton, 2012). Achieving these targets depends on how much of the cation is applied in fertiliser, the affinity of the soil exchange sites for the cation and the concentrations of other cations, particularly the divalent cations present in soil. Addition of large amounts of Ca either through lime application or in superphosphate fertilisers can contribute to K leaching because of the selective adsorption of Ca cations by the clay exchange sites (Edmeades, 1982). According to Parfitt (1992), the concentration of K retained on soil exchange site vary between 0 and 20% depending on how much Ca is added to the soil. The concentration of K on the exchange sites influences the amounts of the cation released into solution for pasture uptake. This solution K which depends on buffering capacity of the soil colloids is usually lower in allophanic soils, compared to Sedimentary soils because, unlike Sedimentary soils which have higher K reserves in the clay mineral that weather to provide solution K (Jackson & During, 1979), the clay constituents of allophanic soils are weakly buffered (Parfitt (1992).

The ranges of exchangeable Mg concentrations of the different soil groups reported to be optimum for pasture production and for dairy animal health are 0.38-0.48 $cmol_c$/kg (8-10 MAF QT) and 1.2-1.4 $cmol_c$/kg (25 to 30 MAF QT), respectively (Roberts & Morton, 2012). Except for the Pumice and Allophanic soils, the high Mg reserve of New Zealand soils tend to ensure that these concentrations are maintained fairly well under most pasture systems (Metson, 1974). Consequently, fertiliser nutrient management for Mg are limited to the Pumice and Allophanic soils. But because of competitive inhibition, Mg concentrations can be limited following application of high amounts of other cations (e.g. Ca, Na and K) to soils, or under low pH conditions. In the livestock industry, Mg deficiency is a major problem as it results in hypomagnesaemia, a disorder associated with low blood Mg in ruminants (Grace, 1983).

Competitive inhibition manifests when Mg is displaced into solution from the soil exchange complex following increased concentrations of the other cations through fertiliser additions, dung and effluents from farm animals, with an associated decline in exchangeable Mg concentrations as leaching proceeds thereafter. This same phenomenon is repeated when high amounts of Ca are supplied to the soil through lime application.

2.2. Nutrient recycling on grazed dairy pastures, and the implications for pasture soil fertility and the environment

2.2.1. Nutrient management option for maintaining pasture soil fertility

The way that nutrients are cycled under grazed pastures is captured in how these nutrients are added to the system, transformed within the system and removed from the system. Nutrient losses may occur through grass ingestion and transfer by livestock, production removal, leaching and run-off losses, and gaseous losses (i.e. volatilization and denitrification in the case of N). Several researches have revealed that the majority of N losses are related to the amount of the nutrient returned to pastures in dung and urine, with N fertiliser being a minor direct contributor to losses (Ledgard, 2001; Di & Cameron, 2002; Cameron et al., 2013). The explanation for this is the high pasture N content, particularly in spring, compared to the N requirement of the average livestock, and the resultant high N (equivalent rate of 400-800 kg N/ha) excreted in small urine patches. So, in a typical long-term grazed pasture system, where the supply of N is mostly based on N fixed from the atmosphere by the legumes and that of the nutrient supplied through organic matter decomposition, grazing management practices (e.g. standing cows off pasture), rather than fertiliser management, will have more influence reducing N losses. Along with the nutrients removed from the production system, which would not be recovered, N losses through leaching creates additional problems of cation losses (Rajendram et al., 1998) and increased acidification (Hedley & Bolan, 2003).

The main source of pasture soil P is fertiliser, and the majority of the nutrient is removed from the plant available pool by transfer by livestock, product removal, soil absorption and through run-off losses (Cornforth, 1998). As the soil P status increases then the risk of P run-off losses also increases. The balance between optimum pasture soil test P and reduced P losses can be achieved by employing best practices; these practices may include applying P fertilisers more than two weeks before irrigation and avoiding applications close to periods with high rainfall and wet soil moisture conditions. Generally, the concentration of P lost through run-off has been shown to be exponentially related to amount of P fertiliser applied, however, where overland flow occurs, the amount of P lost tends to decrease 30-60 days after the application (Dougherty et al., 2011). A large proportion of the P ingested by grazing livestock in pasture is returned to the pasture through excreta, which is mostly in dung (During, 1984). This dung P is added in small discrete patches, spread over the pasture land, which can contribute to runoff losses, depending on a range of factors such as, coincidence of rainfall and grazing, grazing intensity and duration, rainfall intensity and duration, soil drainage class and topography (Djodjic et al., 2018). Maintenance of pasture production requires replenishing these losses through fertiliser application or other means, such as farm dairy effluent (FDE), to maintain optimum soil test P concentrations. As previously highlighted, the amount of P required to raise the concentration to the optimum range varies between soils, depending on the ASC of the soil.

Changes in the concentrations of soil exchangeable cations can vary depending on factors such as the amount and form (whether as mineral fertiliser, animal excreta or FDE) of cation added to the soil (Sakadevan et al., 1993; Bolan et al., 2004), pasture uptake of cations (Mundy, 1983; Edmeades & Perrott, 2004), the soil's cation exchange capacity (influenced by soil organic matter and mineral contents) (Curtin et al., 2015), climatic conditions and the behaviour of other ions in the soil (Said, 1959). Under grazed pasture systems, the addition of animal excreta, in the form of dung and urine, represent an important means by which cations are recycled, as also is the case for N and P. The amount of the cations retained in the grazing animal is usually a small fraction of the total amount of the cations ingested in pasture, so that substantial amounts of the cations are returned to the system through dung and urine (During, 1984). The percentage Mg, K and Ca excreted, in dung and urine combined, by lactating dairy cows were 92, 90 and 80%, respectively (Hutton et al. (1965). Excess cation uptake has also been shown in field experiments following FDE applications to pasture soils, where K, but not Ca and Mg, uptake by pasture increased with increasing FDE application creating Ca and Mg deficiencies for grazing dairy cows (Bolan et al., 2004). This is consistent with the notion that high concentration of a particular cation increases its capacity to exchange other cations from exchange sites into solution making them prone to loss (Edmeades, 1980; Parfitt, 1992), so that an increase in the K levels through FDE application, decreased Ca and Mg availability for pasture.

An important source of fertility decline related to cation removal appear to occur through leaching. Usually, these cations are leached as accompanying anions, such as nitrate, chloride and sulphate. Saunders and Metson (1959) reported from a study which measured high Mg leaching under increased K applications to an Allophanic soil and chloride was the main anion leached in association with the cations. Similarly, a two-year study conducted on a mole and pipe drained Pallic soil showed that chloride was the most leached anion, and the amount of cations on a charge basis leaving the field through drainage roughly equalled those of the anions removed (Heng et al., 1991). The cation exchange characteristics of soils are important considerations when investigating cation leaching. The variation in leaching losses can occur because of differences in cation exchange capacity, so that soils with high cation exchange properties would be expected to leach lesser amounts of cations (Coleman et al., 1959; Curtin et al., 2015). For example, Allophanic soils with high organic matter and high variable charge clay contents have high CEC, which increases as soil pH approaches neutral. Under the high producing systems high organic matter stocks are, therefore, important for reducing cation leaching losses because of their significant contribution to CEC of soils.

2.2.2. Proposed management strategies for reducing environmental impacts of nutrient losses under intensively grazed dairy pasture systems

The implications of these nutrient losses are that in order to continually sustain pasture production, maintenance fertilisers and lime applications are required to correct the nutrient deficits and the acidification created. Generally, on an annual basis, the amount of maintenance fertiliser required to replace these losses in a typical long term Permanent Pasture system is expected to be lower compared to what would be needed for building fertility (i.e. capital fertiliser) of undeveloped land (Cornforth, 1998; Morton & Roberts, 1999; Roberts & Morton, 2012). The amount of replacement fertiliser, may among other factors, depend on how much nutrient is required to raise the soil test value to the target range and the type of soil under production.

In addition to the economic implications of these losses are the environmental aspects, which include mainly N and P enrichment of water bodies and the loss of GHGs, methane, carbon dioxide and nitrous oxide emissions (Ledgard et al., 1999; Monaghan et al., 2005; Pinares-Patiño et al., 2009). In view of these environmental problems, research efforts backed by central government, regional councils and industry have, over the past 10 years, centred on ways of reducing these losses from agricultural systems. The research efforts have contributed to the development of novel nutrient management procedures, which are based on achieving both optimum pasture production and environmental safety (Morton & Roberts, 1999; Monaghan et al., 2007). For example, suggested options to reducing P losses from farm and catchment scales have included ensuring Olsen P concentration do not exceed the optimum ranges using nutrient budgeting tools (Wheeler et al., 2006; Dougherty et al., 2011), redistributing of the highly saturated P in the topsoil through ploughing (Sharpley, 2003), using P fertilisers that are less soluble compared to superphosphate fertilisers (McDowell et al., 2003), and applying irrigation a week after P fertiliser application or applying P fertiliser under minimal rainfall conditions (Bargh, 1978).

Because of the greater mobility associated with N, strategies for reducing N losses have varied depending on the processes influencing the loss and how the nutrient is removed from the system. Some of these strategies are described comprehensively by Monaghan et al. (2007). Gaseous losses from dairy pastoral farms are also receiving worldwide attention because of the subsequent implication on global warming and climate change (Karl & Trenberth, 2003). The increase in the average global temperatures beyond 0.7 ^{o}C (Wirth, 1989) has informed environmentalist, scientists and general stakeholders on the need to increase the carbon sink of pasture soils to offset the increasing levels of these gases in the atmosphere. Current developments in this area is the possibility of exploiting the cultivation phase of pasture renewal as a strategy to store more carbon in pasture soils.

2.3. Changes in soil fertility at the time of pasture renewal when including tillage of contrasted intensity

2.3.1. Periodic pasture renewal and its importance to pasture productivity

While maintaining optimum nutrient levels in pasture systems favour high pasture productivity (Williams & Haynes, 1990), it is often the case that long-term grazed pastures would revert to less productive forms. A usual practice of pasture systems is occasional renewal of less productive pasture, as a consequence of environmental and management factors such as disease, pest infestations, gaps in pasture, invasion of pasture by weeds, drought and treading damage (Tozer et al., 2015) in order to improve yield. Similarly, in the New Zealand, there is transformation from the stage where pasture systems are developed from native vegetations to the stage where pasture undergoes periodic renewal, typically after every 10 years.

Pasture renewal in New Zealand is normally characterised by spraying off the old pasture with herbicide in either spring, late summer or early autumn, followed by land cultivation involving either no or shallow tillage (to approximately 5 cm depth) or standard tillage (to approximately 10-20 cm depth) methods to directly establish a new pasture (i.e., pasture to pasture renewal) (Trolove et al., 2019), or to establish firstly a summer forage crop, such as turnips, followed by autumn re-grassing with a more productive ryegrass and clover cultivars (i.e., pasture to crop to pasture renewal) (Hanly et al., 2017). Pasture renewal generally improves pasture quality (species composition and vigour), in addition, where *pasture to crop to pasture renewal* is practiced, the turnip crop allows the accumulation of a high amount of dry matter, which can be fed to livestock in summer when pasture growth is typically low. For instance, dry matter yield of rye-grass and white clover increased to about 2-folds with an associated reduction in pest incidence following pasture renewal (Tozer et al., 2015). Similarly, it was found that, sword persistency and herbage utilization of rye-grass improved, with a subsequent contribution to higher milk production after pasture renewal (Shalloo et al., 2011).

Aside the above listed benefits of pasture renewal are the short to medium-term environmental consequences, which can reduce the economic viability of the renewal campaign (Bell et al., 2009). The ratio of costs to benefits associated with pasture renewal for diary systems is provided in the New Zealand grassland literature (See Bryant et al., 2010; McLean, 2011). It is known that, large amounts of available nitrogen forms can be released following decomposition of litter materials from cleared pasture; on the onset of the winter rains, the released N forms can be leached into water bodies in the form of nitrate resulting in contamination of these water bodies (Di & Cameron, 2002; Smit & Velthof, 2010). Again, winter grazing especially at high stocking rates can increase the risk of P loss in run-off as large amounts of dung and urine are deposited in small concentrated areas during feeding, consequently leading to major environmental problems (Dougherty et al., 2004).

One of the major trade-offs in the literature associated with pasture renewal, which has informed this review is the loss of soil C in the soil surface layer (0-7.5 cm) that proceed the cultivation phase of pasture renewal (Shepherd et al., 2001). Even though it has been shown that this soil C loss is only short to medium-termed because of the rapid accumulation of organic matter from the newly established grass, the short term C loss is a challenge to the growing demand to increase soil C stocks, aimed at reducing atmospheric greenhouse gas emissions, as pertaining to the Sustainable Development Goals for zero hunger, climate action, and life on land by 2030 (FAO, 2018). This set-back is reflected in the minimal to negligible increase in the original soil C stocks following establishment of the new pasture as the surface soil C is reverted to near saturation again in a short duration (Curtin et al., 2010). Consequently, researchers are now considering the use of one-off Full Inversion Tillage (FIT) method (FIT-renewal) as a substitute tillage method during pasture renewal to not only offset the short term losses of surface soil C, but increase the potential for more soil C storage (Lawrence-Smith et al., 2015; Alcántara et al., 2016; Schiedung et al., 2019).

2.3.2. Full Inversion Tillage at pasture renewal to increase C storage and the potential impacts on the fertility of pasture soils

The use of one-off FIT method (FIT-renewal) as a substitute for shallow tillage (to approximately 5 cm depth) or standard till methods (to approximately 10-20 cm depth) at pasture renewal has been proposed as an alternative strategy for increasing pasture soil C storage to reduce atmospheric CO_2 levels (Lawrence-Smith et al., 2015; Alcántara et al., 2016; Schiedung et al., 2019). Under the FIT method, a disc and skimmer fitted mouldboard plough cuts to a soil depth >20 cm, transfers the topsoil into the bottom of the next furrow and exposes the subsoil in turn, thus ensuring: 1) stabilisation of soil C in the buried C-rich surface soil following exposure to conditions that limit decomposition (Curtin et al., 2010; Alcántara et al., 2017), and 2) introduction of sub-surface soils to litter from newly established pasture, and animal excreta that decompose to build up C more quickly than was occurring in the buried C-saturated surface soil (Hedley et al., 2009). In this case, the new topsoil mixed with subsoil is expected to be able to store larger amounts of C due to its lower soil C concentration (Chung et al., 2010) and high content of unsaturated mineral surfaces (Baldock & Skjemstad, 2000; Rasse et al., 2005).

Multiple field trials have been established both in the North Island (Calvelo Pereira et al 2019) and in the South Island (McNally et al., 2019) of New Zealand to assess the effects of pasture renewal using a one-off FIT method on the vertical redistribution of organic matter in pastoral soils. Whereas this one-off FIT-renewal is expected to increase pasture soil C stock, the consequent implication on pasture soil fertility, particularly in the surface layer (0-7.5 cm) following transfer of the surface soil nutrients along with soil organic matter to the deeper soil depths is not known.

Information available in the literature about the effect of pasture renewal on pasture soil fertility are limited to changes following shallow tillage (to approximately 5 cm depth) or standard tillage methods (to approximately 10-20 cm depth). For instant reduction in pasture Olsen extractable P concentrations in the top 0-7.5 cm depth 18 months after a standard tillage method to a depth of 20 cm during pasture renewal was reported by Zhang et al. (2009). There are other studies under cropping systems such as those by Curtin and Trolove (2013); Curtin et al. (2015) which noted that 8-12 years of cropping with intensive tillage (mouldboard plough to 20 cm), minimum tillage (harrowing to 10 cm depth) and no tillage methods, after conversion from a permanent pasture, soil organic matter contents significantly declined under the cropping systems, with a subsequent reduction in pH, CEC and of exchangeable cation concentration under the cropping systems. Research is therefore required in other to quantify the changes in pasture soil fertility as a result of soil inversion and the transference of surface soil (0-7.5 cm) materials along with organic matter to deeper soil depths post FIT-renewal.

2.4. Conclusions, research gap and research hypotheses

The use of one-off FIT method at pasture renewal (FIT-renewal) to sequester more soil carbon is currently being researched in New Zealand pastoral systems, following establishment of multiple field trials in the North and South Island. But there is limited available research information on the subsequent effects of this one-off FIT renewal on pasture soil fertility. Thus, research is needed to investigate fertility changes that may arise as a result of renewing pastures under long term grazed pastures, using a one-off FIT method. From the research gap identified in the literature, the hypothesis based upon which this thesis is focused is that, in less than 2 years following pasture renewal-

- *there will be a loss of soil fertility in the standard pasture soil sampling depth (0-7.5 cm) under FIT compared to the less tilled or untilled soils because of the transfer of key pasture nutrients to deeper soil depths.*

3. CHAPTER THREE: Materials and methods

On-going research in New Zealand is studying the wider impact of FIT-renewal on soil C stocks and other agronomic aspects, (Calvelo Pereira et al., 2018; Calvelo Pereira et al., 2019; McNally et al., 2019). As part of this research, a new sampling campaign was designed to specifically assess short-term changes of selected fertility parameters (pH, Olsen extractable P, K, Mg, Ca, Na and CEC) following pasture renewal using contrasted tillage treatments in several field trials under development in the North Island. A detailed description of each of the field trials can be found elsewhere (Calvelo Pereira et al., 2018; Calvelo Pereira et al., 2019). Following is a brief description of each study site and field trial design.

3.1. Description of study sites

3.1.1. Field trial 1

Field trial 1 was established on Paddock 35 of Massey University's No.4 dairy farm, located in the Manawatu Region, about 5 km away from the Palmerston North city (40^{o} 23‘ 46.79” S; 175^{o} 36’ 35.77’’ E) on a Tokomaru silt loam [Pallic soil (Hewitt, 2010)]. The trial site was originally under cultivation with a mixture of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), which was grazed by dairy cows. The soils of the area (Tokomaru silt loams) are low to moderately fertile clay loams developed in loess and having their surface soils underlain by a highly compacted grey silt loam fragipan that impedes drainage of water through the soil (Scotter et al., 1979). The productivity of the soils, therefore, depends very much on top dressing with fertiliser and the use of suitable drainage system. Drainage on the trial site was managed using mole and pipe drains, a system of furrows formed by dragging a mole plough through the soil; with excess water expelled from the soil through a perforated pipe connected to the system of furrows by mole channels fixed perpendicular to the perforated pipes (Houlbrooke & Monaghan, 2009; Pearson, 2015). Before the renewal practice, the trial site was sampled at the 0-7.5 and 7-15 cm depth to ascertain the initial, pre-renewal fertility status for the site (Table 3.1). In the 0-7.5 cm depth, all the fertility parameters were within the optimum ranges that turnip (Nicholls et al., 2009), and ryegrass and clover-based pasture (Roberts & Morton, 2012) require under this soil type, whereas, in the 7.5-15 cm depth, only pH was within the optimum range that both turnip (Nicholls et al., 2009) and ryegrass and clover-based pasture (Roberts & Morton, 2012) require under this soil type.

Table 3.1. Soil chemical properties determined for the respective field trial sites prior to the tillage treatments. The soil properties presented are for samples collected from the 0-7.5 and 7.5-15 cm depths for the Field trials 1 and 3; and 0-5, 5-10 and 10-15 cm depths for Field trial 2. Methods of analysis were based on those described by (Blakemore et al., 1987).

		Parameters								
Trial/Soil type	Depth (cm)	pH	Olsen P (mg/kg)	P-Retention (%)	Sulphate-S (mg/kg)	Exchangeable bases (cmol_c/kg)				CEC (cmol_c/kg)
						K	Ca	Mg	Na	
Field trial 1 Pallic soil	0-7.5	6.15	32.7	-	10.6	0.6	9.0	2.0	0.1	15.9
	7.5-15	5.81	13.9	-	5.9	0.3	6.0	1.0	0.1	12.1
Field trial 2 Allophanic soil	0-5	5.70	53.7	77.8	23.5	1.2	11.9	1.4	-	26.9
	5-10	5.70	28.7	84.6	16.3	0.7	9.3	0.7	-	24.4
	10-15	5.70	13.9	87.7	26.0	1.7	4.3	0.3	-	18.9
Field trial 3 Pallic soil	0-7.5	5.74	31.3	-	11.7	0.7	6.6	2.1	0.2	15.0
	7.5-15	5.59	22.7	-	13.7	0.3	5.4	1.4	0.1	12.5

3.1.2. Field trial 2

Field trial 2 was established on a commercial sheep and beef farm near Maxwell in the Taranaki/Whanganui region (39° 47' 46.50"S; 174° 54' 1.62" E) on Allophanic soils (Hewitt, 2010). The trial site was originally under cultivation with a mixture of perennial ryegrass and clover-based pasture, browsed by sheep and beef cattle. The Allophanic soils of the trial site are an intergrade of Egmont, Westere and Parakino soils, with the former two being the more dominant (Wilde, 1976). As noted by Wilde (1976), even though all three soils developed from volcanic parent materials, the Egmont and Westere soils show properties closely similar to their parent materials than do the Parakino soils, partly because their formation is influenced by Pleistocene sand underlying their volcanic parent materials. Despite the differences, the soils are generally moderate in fertility, deep, friable, well drained, making them suitable for pastoral farming (Wilde, 1976). Phosphate management is however a problem because, the soils are dominated by allophane, giving them high phosphorus retaining ability (Cornforth, 1998; Nanzyo, 2002). The Field trial 2 site was sampled at the 0-5, 5-10 and 10-15 cm depths prior to the renewal practice to ascertain the pre-renewal fertility status for the site (Table 3.1). In all the soil depths sampled, pH was below the optimum range that turnip require (Nicholls et al., 2009), but within the optimum range that ryegrass and clover-based pasture (Morton & Roberts, 1999) require under this soil type. The other fertility parameters measured at all the soil depths sampled, but for Olsen P and exchangeable Mg at the 10-15 cm depth, were in the optimum range for that required by both turnip (Nicholls et al., 2009), and ryegrass and clover-based pasture (Morton & Roberts, 1999) for this soil type.

3.1.3. Field trial 3

Field trial 3 was set up on paddock 50 at the same farm, and on the same soil type as Field trial 1. Prior to trial set up, the site was under cultivation with mixed perennial ryegrass and clover-based pasture, which was grazed by dairy cows. The site was sampled at the 0-7.5 and 7-15 cm depth prior to the renewal practice to ascertain the initial, pre-renewal fertility status for the site (Table 3.1). In both the 0-7.5 and 7.5-15 cm depths, all the measured fertility parameters, but for K in the 7.5-15 cm depth were within the optimum ranges that ryegrass and clover-based pasture require for this soil type (Roberts & Morton, 2012).

3.2. Relevant details on experimental design, establishment and monitoring of field research sites prior to fertility assessment

3.2.1. Field trial 1

At the Field trial 1, pasture renewal involving a *spring grass to summer crop to autumn grass rotation* was carried out between early October 2016 and early April 2017; Figure 3.1, on 14 experimental plots, each measuring approximately 0.09 ha in size (Figure 3.2). A calendar of the main management activities carried out during the design of the field trials is provided in Figure 3.1. The renewal was differentiated using three contrasting tillage treatments performed once, on late November 2016 after the original pasture on all plots were spray killed with glyphosate in early October 2016. The tillage treatments used were described as follows: No Tillage (NT), characterised by direct drilling of seeds; Shallow Tillage (ST), characterised by rotary hoeing to a depth of approximately 5 cm; and Full Inversion Tillage (FIT), characterised by deep ploughing using a mouldboard plough fitted with a disc and skimmer capable of ploughing to approximately 25-30 cm depth, which transfers the topsoil into the bottom of the next furrow and lifts the subsoil over the topsoil. Treatments were assigned to each plot following a completely randomized design; NT and FIT treatments were replicated 5 times, whereas, ST treatment was replicated 4 times (Figure 3.2). Each of the tillage treatments (i.e., NT, ST and FIT) were used at the time of sowing a summer fodder crop (leafy turnip: *camprestris spp rapa*, var Hunter) on late November 2016.

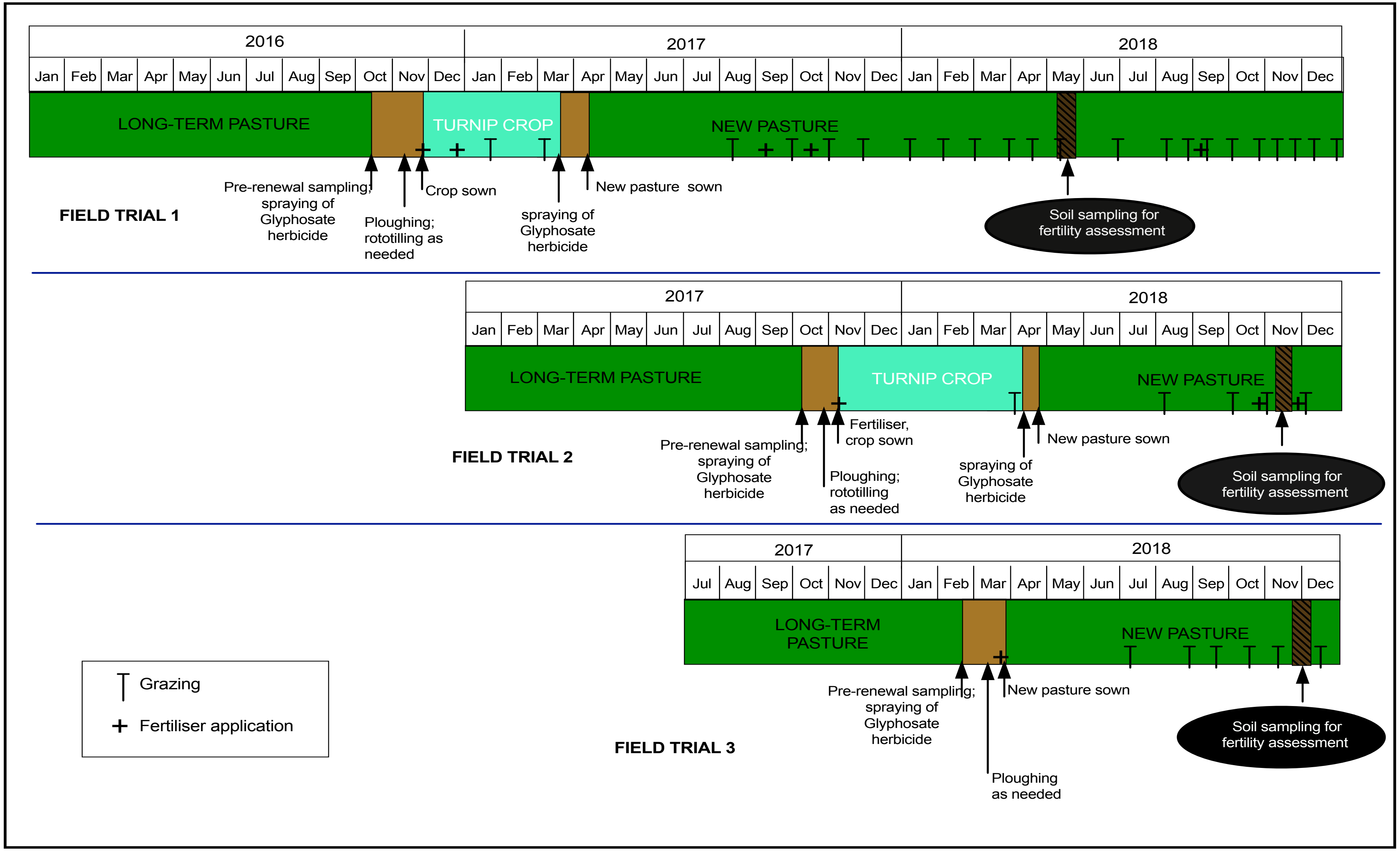

Figure 3.1. Management calendar describing main activities for each field trial. Fertility sampling performed for this study occurred at the indicated dates, at the new pasture phase, approximately 18, 13 and 8 months following tillage treatments for Field trial 1, 2 and 3, respectively.

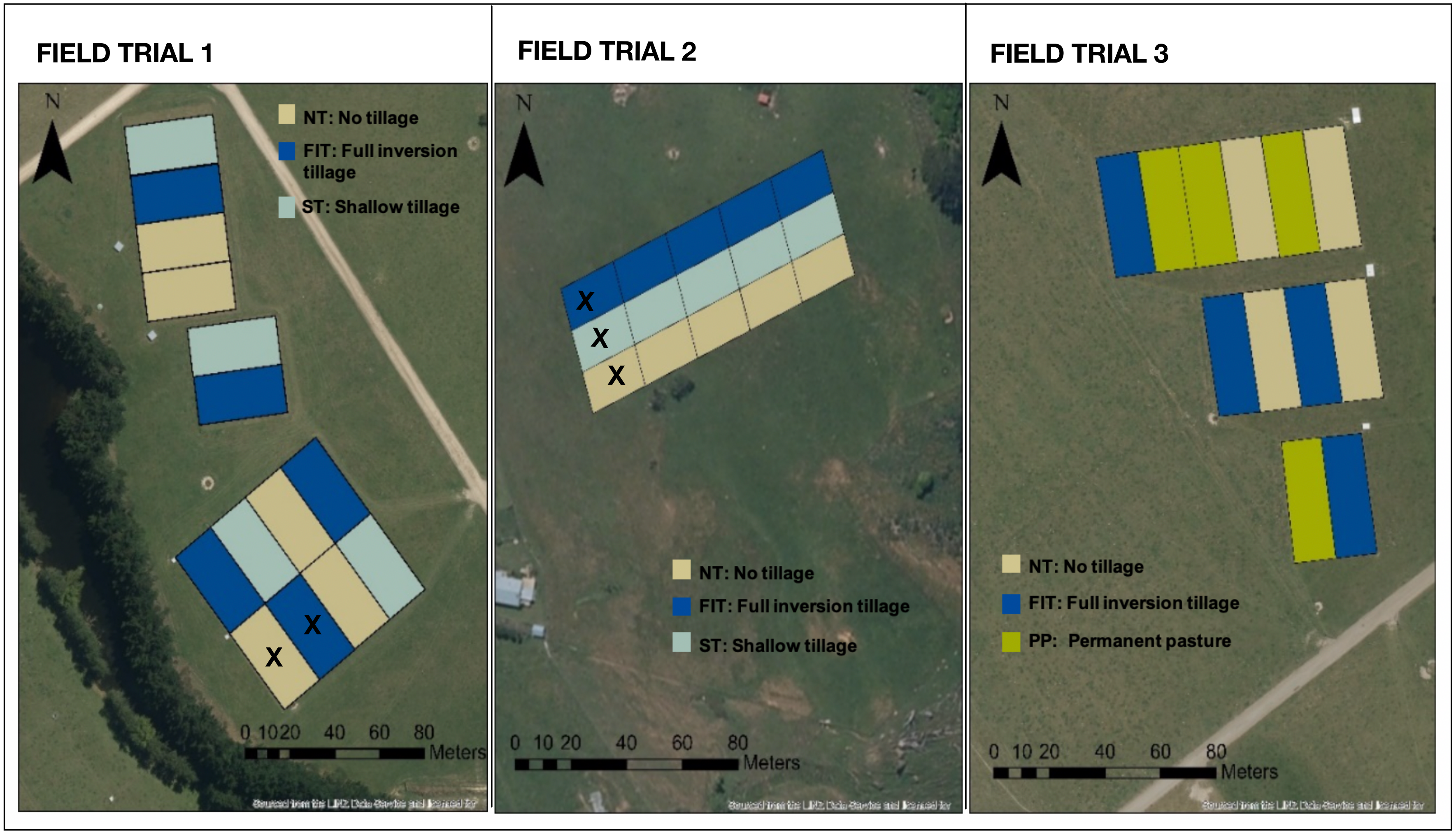

Figure 3.2. Layout of each of field trials as originally established, with plots showing representative tillage treatments and Permanent Pasture assigned (per colour codes). Layout of Field trials 1 and 3 were done by means of the completely randomized design (CRD) and Field trials 3 by means of the random complete block design (RCBD). Plots marked in "X" were not included in this study.

All plots were fertilised prior to sowing, during growth of summer crop and following autumn pasture re-sowing, with FIT plots receiving additional doses of basal P and K fertilisers than did NT and ST plots (Calvelo Pereira et al 2019). NT and ST treatment plots received 30 kg P/ha, 52 kg N/ha, 60 kg S/ha, 60 kg K/ha and 6 kg B/ha applied in the form of kynofos 21 (21% P), ammonium sulphate (21% N:24% S), potassium chloride (50% K) and sodium borate (15% B) in late November 2016 (basal application); 148 kg N/ha, applied in the form of urea (46% N) in late December 2016; 30 kg P/ha, and 30 kg N/ha, 34 kg S/ha, 50 kg K/ha applied in early September 2017 as per the fertiliser forms used in late November 2016; and 30 kg N/ha and 14 kg S/ha applied in mid-October 2017 in the form of Ammo. FIT treatment plots received exactly the same amounts and types of fertilisers always; additionally, during basal fertilisation in November 2016, 30 kg P/ha and 60 kg K/ha were applied as Kynophos 21 and KCl, respectively (Calvelo Pereira et al., 2019).

Turnip growth during summer was monitored regularly and cows grazed the plots following the usual farm rotation, in late January 2017 and in early March 2017. Following the second grazing, all the plots were sprayed with glyphosate (16 March 2017) to prepare them for sowing new pasture. On 10 April 2017, a mixture of perennial ryegrass and white clover was sown by direct drilling into crop stubble to establish a new permanent pasture. Yield of the new grass was assessed periodically using a rising plate-meter, followed by analysing for total N content of herbage collected prior to each grazing rotation (Calvelo Pereira et al., 2019). The new pasture was grazed by dairy cattle according to the usual farm grazing rotation.

3.2.2. Field trial 2

At the Field trial 2, a pasture renewal involving a *spring grass to summer crop to autumn grass rotation,* was carried out between early October 2017 and 17 April 2018; Figure 3.1, on 15 experimental plots along a slope gradient, each measuring 0.03 ha in size (Figure 3.2). A calendar of the main management activities carried out during the field trial design is provided in Figure 3.1. The renewal was differentiated using the same three contrasting tillage treatments (NT, ST and FIT) described for the Field trial 1 in Section 3.3.1 above. All plots were firstly sprayed of the original pasture with glyphosate in early October 2017, before the tillage treatments were assigned in 25 October 2017. Each tillage treatment was allocated to 5 experimental plots (5 replicates) following a randomized complete block design (Figure 3.2). Finally, on 2 November 2017, a summer fodder crop was sown into the prepared seed bed at each plot. All the treatment plots were fertilised prior to sowing and during growth of summer crop. The same amounts of fertiliser were added to all treatments (i.e. NT, ST and FIT) as follows: 48 kg N/ha, 53 kg P/ha and 1.5 kg B/ha applied in the form of Diammonium phosphate and sodium borate in early November 2017 (basal application); following usual practice in this farm, 3209 kg lime/ha were applied in mid-March 2018. Finally, 54 and 47 kg N/ha were applied in the form of urea in early August and late October 2018, respectively.

Turnip growth during summer was monitored regularly and cows grazed the plots following the usual farm rotation, in early January 2018. Following the grazing rotation, the plots were sprayed again on 17 April 2018, and a mixture of perennial ryegrass and white clover sown by direct drilling into the crop stubble to establish a new permanent pasture. Yield of the new grass was assessed periodically using a rising plate-meter (Calvelo Pereira et al., 2018). The new pasture was grazed by sheep and beef according to the usual farm grazing rotation.

3.2.3. Field trial 3

At the Field trial 3, a pasture renewal involving *an autumn grass to grass rotation* was carried out between 23 February 2018 and 27 March 2019 (Figure 3.1). A calendar of the main management activities carried out during the field trial design is provided in Figure 3.1. The trial was designed using 12 experimental plots, 8 of which were renewed of the original permanent pasture, and the remaining 4 maintained in the original permanent pasture (Figure 3.2). All plots measured approximately 0.06 ha in size.

The renewal was differentiated using the same NT and FIT treatments, which were performed once between 12 March 2018 and 19 March 2019. The renewed plots were firstly sprayed of the original pasture with glyphosate in 23 February 2018, before the two tillage treatments (NT and FIT) were assigned as per what is described under Field trial 1 in Section 3.2.1. The two tillage treatments (NT and FIT) were allocated to the 8 plots (4 replicates per tillage treatment) following a completely randomized design (Figure 3.2). In this field trial, the FIT treatment was characterised by deep ploughing using a new mouldboard plough fitted with a disc and skimmer capable of ploughing to approximately 30-35 cm depth, which transfers the topsoil into the bottom of the next furrow and lifts the subsoil over the topsoil. The Permanent Pasture on the remaining 4 plots (4 replicates) constituted a third treatment, referred thereafter as PP treatment (Figure 3.2). All plots were fertilised in late March 2018 prior to sowing of new grass as follows: a) 31 kg P/ha, 28 kg N/ha, 15 kg S/ha, 28 kg K/ha applied as diammonium phosphate and potassium sulphate.

On 27 March 2019, a mixture of perennial ryegrass and white clover was sown by direct drilling into the newly prepared seed bed to establish a new pasture which was grazed by dairy cattle according to the normal farm grazing rotation. Yield assessment of new grass was done periodically using a rising plate-meter (Calvelo Pereira et al., 2019).

3.3. Assessment of short-term changes in soil C and N, and in selected soil fertility parameters

In order to assess short-term changes in C and N, as well as the impact of each treatment considered (either No Tillage, Shallow Tillage, Full Inversion Tillage, or Permanent Pasture) on selected fertility parameters (soil pH, Olsen P, exchangeable basic cations and CEC), a soil sampling campaign targeting the on-going field trials described was developed during the period May to November 2018, which corresponds approximately with 18, 13 and 8 months following the tillage treatments for Field trial 1, 2 and 3, respectively (Figure 3.1).

The short-term assessment of soil C and N, and the fertility parameters was based on combination of treatments per field trial and specific common soil depths to establish a two-factor factorial design, comprising three levels of treatments (Field trial 1 or 2: NT, FIT and ST; Field trial 3: NT, FIT and PP) and four levels of soil depths (0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm).

3.3.1. Soil sample collection and processing

A common number of 12 plots in total, i.e., 4 replicate plots per treatment were selected for the soil C and N, and fertility sampling at each field trial (Figure 3.2). At each field trial, soil cores were collected with a percussion corer to a depth below 30 cm (see Figure 3.3). Two diagonal transects were used when sampling each experimental plot, with between 4 to 6 representative soil samples collected along each transect to give a total of 8 to 12 soil samples per plot. The cores taken at each experimental plot were then cut into 7.5 cm depth increments (0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm) and placed in labelled plastic bags (one composite sample per depth increment). The composite samples were air-dried, gently crushed, passed through a 2-mm sieve and thoroughly homogenized prior to all laboratory measurements.

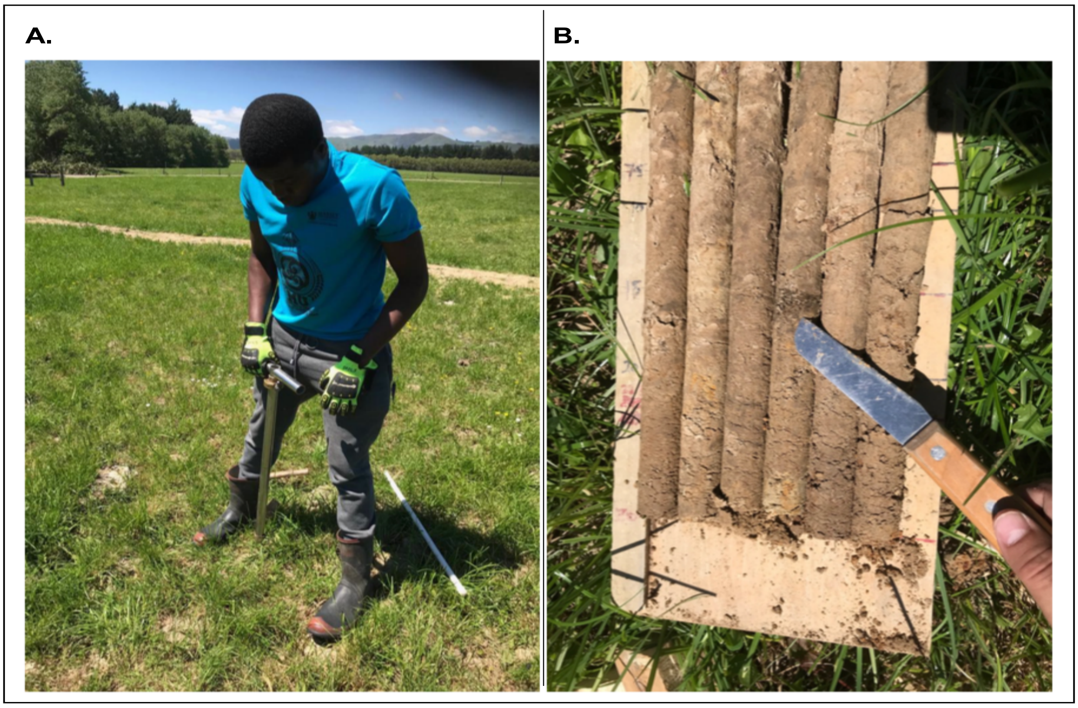

Figure 3.3. Sampling activity at Field trial 3 (Massey University's No.4 dairy farm-paddock 50) on 14 November 2018, about 8 months after the new grass was established. A) soil coring to 30 cm depth using a percussion corer B) soil core columns arranged for slicing into representative depth intervals of 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm.

3.4. Soil analyses: C, N and fertility parameters

3.4.1. Total soil C and N

All air dried, < 2mm samples stored were prepared for elemental analysis by gently grinding (< 0.5 mm) a representative subsample; total C and N concentrations were determined by using a Vario MACRO cube elemental system (Elementar Analysensysteme GmbH, Hanau, Germany).

The total C and N concentrations were further converted into C and N stocks by using bulk density data available from an independent assessment of soil bulk density done for each plot and site at similar times than current fertiliser assessment. The total soil C and N stock were initially determined at a fixed depth (i.e. 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm depth) and then stocks were calculated using the equivalent soil mass method as described by (Ellert &

Bettany, 1995). By using the equivalent soil mass approach, differences in C and N stocks caused by contrasted bulk density values following tillage treatments are taken into consideration. At each site and for each individual depth, the average soil mass among the different tillage treatments was used as the standard reference or equivalent soil mass (Mg/ha). Each equivalent soil mass was then used to recalculate C and N stocks (Ellert & Bettany, 1995; Calvelo Pereira et al., 2018).

3.4.2. Soil pH

The pH of the soils were measured in water using the method described by (Blakemore et al., 1987). Soil: solution ratio of 1:2.5 involving 10 g of air dried, <2 mm soil and de-ionised water was prepared, stirred vigorously and left overnight to a enable the solution to attain the temperature of the room. The pH readings were then taken using a pH meter.

3.4.3. Olsen extractable P

Soil Olsen extractable P concentrations were determined using the phosphate by phosphomolybdate method described in (Blakemore et al., 1969), which is based on that of Olsen et al. (1954). 1 g of air-dried, < 2mm samples were weighed into centrifuge tubes and shaken in 20 mL sodium hydrogen carbonate (with pH adjusted to 8.45-8.50) for about 30 minutes using an end over end shaker. The contents of the centrifuge tubes were centrifuged at 9000 rpm for 3 min and filtered through Whatman no. 6 filter paper into empty plastic tubes. Four millilitres of the filtrates were transferred into 50 mL volumetric flasks and diluted with about 30 mL deionised water. 10 mL Murphy and Riley reagent was added to the content of each flask, the flasks shaken gently, topped up with deionised water to the mark and then allowed to stand for approximately 30 minutes for colour (blue) development. The intensity (absorbance) of the colour formed was measured in a spectrophotometer at a wavelength of 712 nm.

A standard curve based on the soil Olsen extractable P range for New Zealand soils was also generated from a 5 µg P/mL standard stock solution. Exactly 0, 1, 2, 4, 5, 6 and 8 mL of the 5 µg P/mL standard stock solution were transferred into separate 50 mL volumetric flasks to give seven different solutions of known concentrations. The procedure for colour development described above was repeated and the absorbance of the solutions measured in a spectrophotometer at 712 nm. A linear graph of the absorbances measured and the known solution concentrations was developed and used to estimate the Olsen extractable P concentrations of the soil samples from the absorbances measured.

3.4.4. CEC and exchangeable cations

The cation exchange properties of the soils were measured by extracting the basic cations (Ca, Mg, K and Na) in 1M ammonium acetate solution (pH 7), using the semi-micro leaching technique (Blakemore et al., 1987). The leaching procedure involved passing 50 mL of the 1M ammonium acetate solution (pH 7) through a mixture of 1g air-dried, <2mm soil sample and acid-washed silica sand packed in semi-micro leaching tubes with moist filter paper plug. Leachates were collected into 50 mL flasks and analysed for changes in pH (pH drop) to ascertain the concentration of H^+ ions. The flasks were then made up to the 50 mL mark with ammonium acetate solution (pH 7) and 2 mL of 2600 ppm strontium and caesium solution before analysing for the cations using microwave-plasma atomic emission spectroscopy (4200 MP-AES, Agilent Technologies, Singapore). Using the summation approach (Blakemore et al., 1987), the cation exchange capacity (CEC) of the soils were then calculated from the amount of basic cations (in $cmol_c/kg$) and H^+ ions determined.

In order to establish the effect of the tillage treatments on the soil test values and the subsequent implications on basic cation fertiliser requirements, the basic cation concentrations in the 0-7.5 and 7.5-15 cm depths were recalculated to MAF QT values based on the relationship between cmol$_c$/kg and the MAF QT (Hills Laboratories Limited). The calculations were based on the relationships below.

- Potassium: K(cmol$_c$/kg) x 20.8 x VW = K (MAF QT)
- Calcium: Ca(cmol$_c$/kg) x 1.29 x VW = Ca (MAF QT)
- Magnesium: Mg(cmol$_c$/kg) x 23.3 x VW = Mg (MAF QT)
- Sodium: Na(cmol$_c$/kg) x 53 x VW = Na (MAF QT)

Where VW is the volume weight or Laboratory Bulk Density (BD) in mg/L.

The laboratory bulk density was estimated by weighing 10 mL of air-dried and sieved (<2mm) soil sample collected following the soil fertility assessment. The ratio of soil mass recorded to the 10 mL volume gave the laboratory bulk density. Due to expected differences in soil particle sizes in the 0-7.5 and 7.5-15 cm depths following the different tillage treatments, and between the different soil types used; for each field trial, the laboratory bulk densities were estimated separately for the different tillage treatments, by using averages of three replicate laboratory bulk density measurements made at each of the soil depths for a given tillage treatment. Data on exchangeable cation in MAF QT values are shown in Appendix E.

3.5. Statistical analyses

The Minitab 18 statistical software (Minitab LLC, State College, Pennsylvania, United States) was used to run all statistical analyses. The total C and N concentrations and the soil fertility variables were analysed using a two-way ANOVA test involving treatment (i.e., either NT, ST and FIT treatments for Field trials 1 and 2 or PP, NT and FIT treatments for Field trial 3) and soil depth (i.e., either four soil depth levels: 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm as per the analyses of total C and N concentrations, pH, Olsen extractable P concentrations and the exchangeable basic cation concentrations or two soil depth levels 0-7.5 and 7.5-15 as per analyses of the MAF QT data). To test differences in total C and N stocks to equivalent soil mass (0-30 cm nominal depth), a one-way ANOVA was used, comparing the effect of tillage treatments as per Field trials 1 and 2 or tillage treatments plus Permanent Pasture as per Field trial 3. All Analyses were based on the randomized complete block design in the case of Field trial 2 and the completely randomized design in the case of Field trials 1 and 3, at a 5% significance level. Where the interaction was statistically significant ($p<0.05$), the Tukey's least significant difference (LSD) was used to separate means. All graphs were drawn using GraphPad prism Version 7 (GraphPad Software 2365 Northside Dr., Suite 560, San Diego, CA 92108).

4. CHAPTER FOUR: Results and Discussion

4.1. Overall effect of FIT on soil mixing

The current study focuses particularly on the effects of a Full Inversion Tillage method for renewing pastures, in comparison with No Tillage or Shallow Tillage methods, on pasture soil fertility. Except otherwise stated, differences in soil fertility from the FIT treatment are discussed with reference to the NT treatment. Generally, following Full Inversion Tillage with a mouldboard plough, the results from all the trials, are suggestive of soil transference into deeper depths and subsequent redistributing total soil C and N, as well as Olsen extractable P and exchangeable cations (Ca, Mg, K, Na) across the 0-30 cm soil depth sampled. As discussed below, overall, this soil inversion reflects mixing of the highly stratified nutrient-rich topsoil layers with the deeper layers that are relatively nutrient-poor, rather than quantitative changes in the total levels of nutrients. It is worth noting that two different mouldboard ploughs were used in this study; one fitted to reach a depth of approximately 25-30 cm (Field trial 1 and 2) and the other fitted to reach a depth of approximately 30-35 cm (Field trail 3). This is likely to have influenced the actual effect of FIT treatment, relative to other treatments, on observed changes soil test values with soil depth that are discussed in the following sections.

4.2. Changes in Total soil C and N

At Field trial 1, the vertical distribution of both total C and N concentrations followed a consistent trend, with the concentrations of both elements being significantly ($p<0.05$) affected by the tillage treatments (Figure 4.1). The concentrations of total C and N under the FIT treatments were more uniform with soil depth, whereas, both elements were distinctly stratified with depth for the NT and ST treatments (Figure 4.1). In the 0-7.5 cm depth, the average total C and N concentrations for the FIT treatment were significantly ($p<0.05$) lower, being 27.4 g C/kg and 2.9 g N/kg, respectively, compared to 39.7 g C/kg and 4.2 g N/kg, respectively for the NT treatment. Conversely, in the deeper soil depths the total C and N concentrations were not different ($p>0.05$) between the NT and FIT treatments, despite being higher for the FIT treatment. The average total C and N stocks in the 0-7.5 cm nominal depth (equivalent to 941 Mg soil/ha) were 25.7 Mg C/ha and 2.8 Mg N/ha for the FIT treatment, being 24% lower compared to 37.3 Mg C/ha and 3.9 Mg N/ha, respectively for the NT treatment (Table 4.1). However, tillage did not change the soil C and N stocks for the accumulated 0-30 cm nominal depth, equivalent to 4054 Mg soil/ha, as values were variable but similar (at $p>0.05$) among tillage treatments (on average, 96.8, 98.3 and 93.9 Mg C/ha for NT, FIT and ST treatments, respectively and 10.8, 10.9 and 10.6 Mg N/ha for NT, FIT and ST treatments, respectively; Table 4.1).

At Field trial 2, the vertical distribution of both total C and N concentrations were significantly ($p<0.05$) affected by the tillage treatments, as was observed at Field trial 1 (Figure 4.1). The concentrations of total C and N under the FIT treatment were more uniform with soil depth, whereas, both elements were distinctly stratified with soil depth under the NT and ST treatments (Figure 4.1). In the 0-7.5 cm depth, the average total C concentration, but not total N, was significantly ($p<0.05$) lower under the FIT treatment. The concentration measured was 58.8 g C/kg compared to 70 g C/kg for the NT treatment. Whereas in the 15-22.5 cm depth, both the average total C and N concentrations under the FIT treatment were significantly ($p<0.05$) higher, being 53.9 g C/kg and 5.8 g N/kg, respectively, compared to 35.5 g C/kg and 3.8 g N/kg, respectively, for the NT treatment. The average total C stocks in the 0-7.5 cm nominal depth (equivalent to 528 Mg soil/ha) was 31.0 Mg C/ha for the FIT treatment, being 16% lower compared to 36.9 Mg C/ha for the NT treatment (Table 4.1). However, tillage did not significantly change the soil C stocks for the accumulated 0-30 cm nominal depth, equivalent to 2702 Mg soil/ha, because although the NT treatment had the lowest total soil C, the difference from the other two treatments was not large enough to be statistically ($p>0.05$) significant (on average, 114.1, 133.6 and 131.2 Mg C/ha for NT, FIT and ST treatments, respectively; Table 4.1).

At Field trial 3, the vertical distribution of both total C and N concentrations were also significantly ($p<0.05$) affected by the tillage treatments (Figure 4.1). The concentrations of total C and N under the FIT treatment were more uniform with soil depth, whereas, both elements were distinctly stratified with soil depth under the NT and PP treatments (Figure 4.1). In the 0-7.5 cm depth, the average total C and N concentrations under the FIT treatment were significantly ($p<0.05$) lower, being 21.2 g C/kg and 2.4 g N/kg, respectively, compared to 38.8 g C/kg and 4.1 N g/kg, respectively, under the NT treatment. Whereas the concentrations in the 15-22.5 cm depths under the FIT treatment were significantly ($p<0.05$) higher, being 27.3 g C/kg and 3.1 g N/kg, respectively, compared to 17.8 g C/kg and 2.1 g N/kg, respectively for the NT treatment. The average total C and N stocks in the 0-7.5 cm nominal depth (equivalent to 832 Mg soil/ha) were 17.0 Mg C/ha and 2.0 Mg N/ha for the FIT treatment, being 46% and 41% lower compared to 32.3 Mg C/ha and 3.4 Mg N/ha, respectively for the NT treatment (Table 4.1). However, tillage did not change the soil C and N stocks for the accumulated 0-30 cm nominal depth, equivalent to 3798 Mg soil/ha, as values were variable but similar (at $p>0.05$) among tillage treatments (on average, 83.5, 88.7, 81.5 Mg C/ha for NT, FIT and PP treatments, respectively and 9.5, 10.0 and 9.5 Mg N/ha for NT, FIT and PP treatments, respectively; Table 4.1).

The total C and N contents of the Allophanic soil (Field trial 2) were higher than those measured for the Pallic soils (Field trials 1 and 3), which is expected due to Allophanic soils having a greater capacity to store organic matter. Soil inversion under the FIT treatment resulted in less stratification of soil C and N, compared to the other tillage treatments and permanent pasture, but did not cause any significant change in the total C and N stocks in the soil profile (at a 0-30 cm nominal depth), compared to the other treatments.

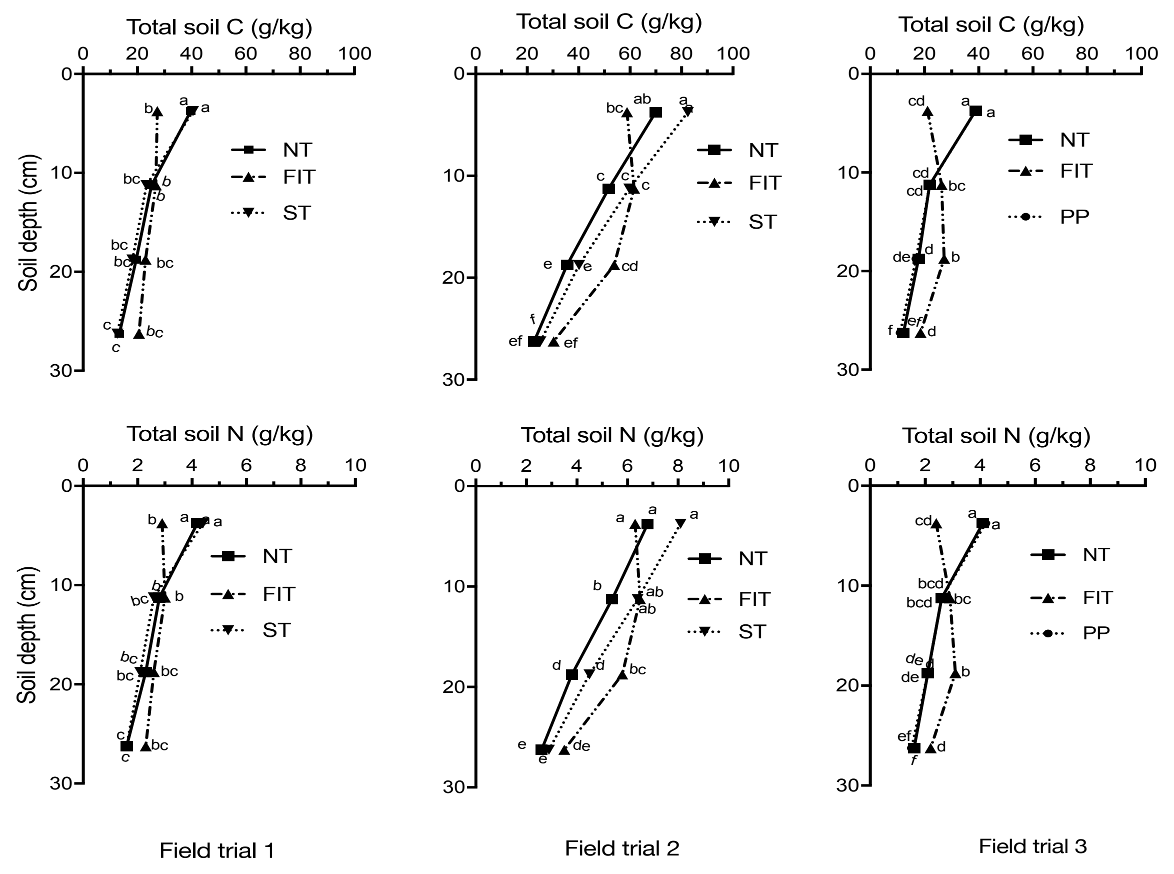

Figure 4.1. Distribution of total C and N concentrations with soil depth under the tillage treatments and Permanent Pasture at the Field trials. The Total C and N concentrations at Field trials 1, 2 and 3 were determined approximately 18, 13 and 8 months, respectively following the tillage treatments. Comparisons between means were based on an interactive effect ($p<0.05$) of tillage treatments and soil depth. Under each Field trial, plotted points (means) with the same letter(s) are not significantly ($p>0.05$) different.

Table 4.1. Average C and N stocks (Mg/ha soil) calculated at an equivalent soil mass for each nominal depth studied for the Field trials 1, 2 and 3. Results from a one-way analysis of variance comparing the effect of tillage treatments and Permanent Pasture on C and N stocks at an equivalent soil mass are included. For a given field trial and variable, means with the same letter(s) are not significantly (p>0.05) different and means without letters were not affected (p>0.05) by the tillage treatments or tillage treatments plus Permanent pasture.

Tillage treatments	Mg C/ha soil					Mg N/ ha soil				
	0-7.5 cm	7.5-15 cm	15-22.5 cm	22.5-30 cm	0-30 cm	0-7.5 cm	7.5-15 cm	15-22.5 cm	22.5-30 cm	0-30 cm
						Field trial 1				
NT	37.3ab	24.6c	19.9c	15.0c	96.8	3.9ab	2.7bc	2.3c	1.8c	10.8
FIT	25.7bc	26.1bc	23.4c	23.1c	98.3	2.8bc	2.9abc	2.6c	2.6c	10.9
ST	38.1a	22.7c	18.5c	14.6c	93.9	4.1a	2.6c	2.2c	1.8c	10.6
						Field trial 2				
NT	36.9ab	34.7ab	24.5c	17.9d	114.1	3.6	3.6	2.6	2.1	11.9
FIT	31.0ab	41.4a	37.2ab	23.9c	133.6	3.3	4.4	4.0	2.7	14.4
ST	43.5a	40.1a	27.8c	19.8d	131.3	4.3	4.3	3.1	2.3	14.0
						Field trial 3				
NT	32.3a	21.5bc	17.0e	12.7f	83.5	3.4ab	2.5cd	2.0e	1.6f	9.5
FIT	17.6e	25.9b	26.1b	19.1c	88.7	2.0e	2.9bc	2.9bc	2.2de	10.0
PP	32.3a	21.6bc	16.1e	11.5f	81.5	3.5a	2.5cd	2.0e	1.5f	9.5

This observation is consistent with the findings of other researchers (Curtin et al., 2015; Calvelo Pereira et al., 2019), who reported vertical redistribution of soil organic matter following soil inversion and a significant decline in organic matter contents in the top 7.5 cm depth, but with no significant differences in average total pooled organic matter stocks for the whole soil profile under the tilled compared to untilled soils. At Field trial 3 there was a greater percentage (46%) reduction in C stock in the 0-7.5 cm depth from FIT, compared to Field trials 1 and 2. As mentioned in the Methods section (Section 3.2), this could possibly be explained by the use of a different mouldboard plough for the FIT treatment at Field trial 3, which achieved cultivation to a greater soil depth (approximately 30 cm).

4.3. Soil pH

At Field trial 1, the distribution of soil pH with soil depth was not significantly (p>0.05) affected by the tillage treatments (Figure 4.2). There was a general trend of soil pH increasing with soil depth for the FIT treatment and decreasing with soil depth for the other two tillage treatments up to 22.5 cm, however, differences were relatively small. The pH measured in the standard pasture soil sampling depths (0-7.5 cm) were 5.73, 5.71 and 5.65 for the NT, ST and FIT treatments, respectively, which were lower compared to the pH of 6.14 measured prior to the establishment of the trials (Table 3.1); and only slightly below the target range required for optimum performance of ryegrass and clover based pasture of 5.80-6.00 (Roberts & Morton, 2012). The lower soil pH values for all treatments, 18 months following when the tillage treatments were imposed, is likely the result from acidification processes, such as nitrification, following cultivation, and also subsequently from urine return and N fertiliser use on the newly established grazed pastures (Bolan et al., 1991; Hedley & Bolan, 2003). The pH values measured in the 15-22.5 cm soil depth were 5.52, 5.53 and 5.73 for the NT, ST and FIT treatments, respectively. The slightly higher pH in the deeper soil depth under the FIT treatment, compared to the other tillage treatments, may have resulted from the soil inversion mechanism when the pH in the top 7.5 cm depth was 6.14.

At Field trial 2, the distribution of soil pH with soil depth was not significantly (p>0.05) affected by the tillage treatments, with all three tillage treatments showing decreasing pH with soil depth (Figure 4.2). However, pH under the FIT treatment was higher than the other tillage treatments at all four soil depths. The pH in the standard pasture rooting depth (0-7.5 cm), were 6.10, 6.05 and 6.32 for the NT, ST and FIT treatments, respectively, with all being within the target range for optimum performance of ryegrass and clover based pasture (Morton & Roberts, 1999). The stratification of pH with soil depth under all three tillage treatments was

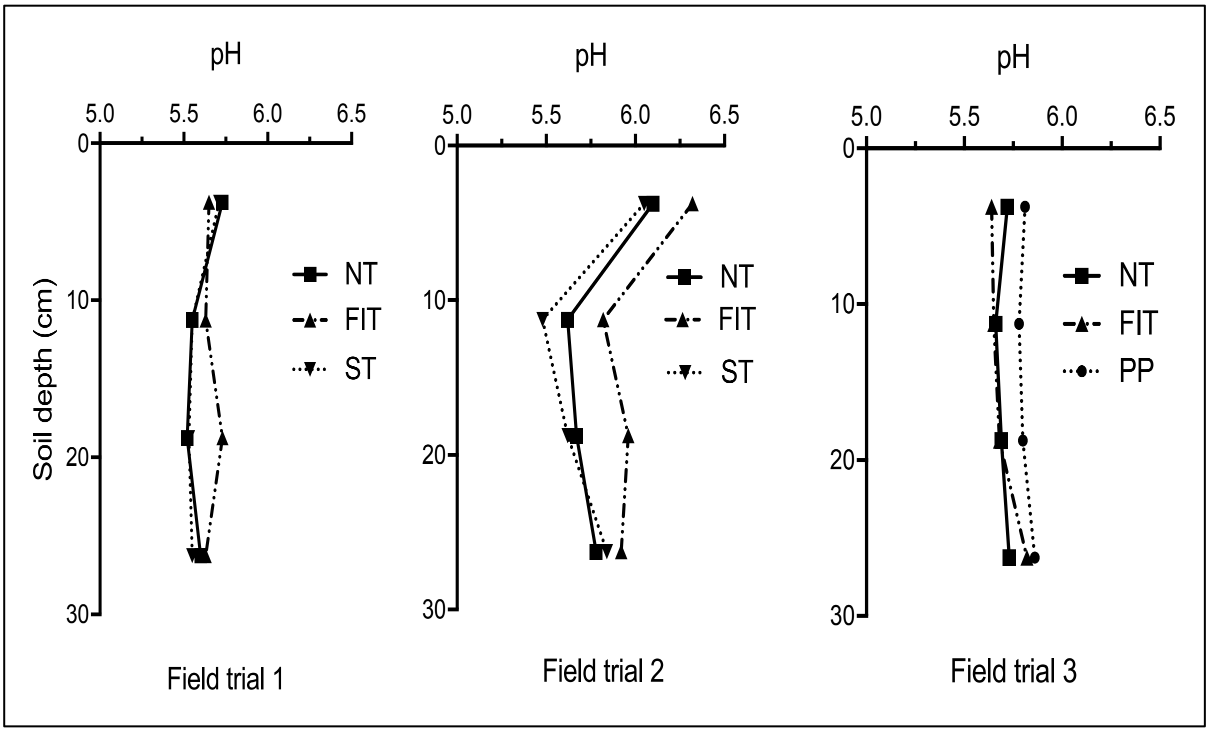

Figure 4.2. Distribution of pH with soil depth under the different tillage treatments and Permanent Pasture at the Field trials. Soil pH at Field trials 1, 2 and 3 were determined approximately 18, 13 and 8 months, respectively following the tillage treatments. Comparisons between means were based on an interactive effect (p<0.05) of tillage treatments and soil depth.

likely due to the influence of the 3056 kg lime/ha applied after the tillage treatments were implemented (Cornforth, 1998; Roberts & Morton, 2012). This agrees with the generally higher pH (0-7.5 cm) for all three tillage treatments, compared to the pH of 5.70 measured prior to the commencement of this trial; Table 3.1. Other researchers (Wang et al., 1999), noted a distinct vertical stratification of pH in an Allophanic soil after the application of 5000 kg lime /ha, with an increase in pH in the surface layer from 4.80 to 6.40. In the current study, below the 7.5 cm depth, pH under all three tillage treatments were nearer the pH of 5.70 measured (0-15 cm) prior to trial commencement. This is consistent with the general observation that the effect of lime application on soil pH is mainly restricted to the top 0-7.5 cm depth, where the lime is applied (Wang et al., 1999), and indication that pH barely changed in the deeper soil depths under the FIT treatment. In addition, the higher pH in the 0-7.5 cm depth for the FIT treatment, compared to the other two tillage treatments, is likely to have resulted from a decrease in pH buffering due to lower soil C (Curtin & Trolove, 2013), which would mean that the capacity of the soils under the FIT treatment to resist any increase in pH immediately following lime addition is lower. Thus, for soils with stratified soil pH (i.e. a trend of decreasing with soil depth), FIT has the potential to increase subsoil pH, and while this may be at the expense of initially reducing surface soil pH, the lower surface soil carbon for the FIT treatment means that less lime is required to increase the pH compared with NT.

Similar to the other two trials, at Field trial 3, the distribution of soil pH with soil depth was not significantly (p>0.05) affected by the tillage treatments (Figure 4.2). There was a general trend of a relatively uniform soil pH values with soil depth under both tillage treatments and the Permanent Pasture treatment. Soil pH in the 0-7.5 cm depth under the NT, PP and FIT treatments were 5.74, 5.82 and 5.64, respectively, which were close to the pH of 5.71 measured prior to the establishment of the trials (Table 3.1), possibly due to less time (8 months) for soil acidification to occur and because the initial pH was lower, therefore, closer to pH where the soil would naturally be buffered to. For the NT and FIT treatments, these pH values were only slightly below the optimum range required for optimum performance of ryegrass and clover based pasture (Roberts & Morton, 2012). Whereas the pH of 5.82 under the PP treatment was within the target range (Roberts & Morton, 2012). Unlike at the other two field trail sites, there was no increase in soil pH for the FIT treatment at deeper soil depths, compared to the NT treatment. The PP treatment shows that soil pH is uniform with soil depth at this site, therefore, there is limited potential for the inversion of soil, from using FIT, to redistribute higher pH soil from the surface to deeper depths.

In general, the results support that the sites with higher stratification of pH with soil depth (i.e. soil pH is highest in the surface soil) prior to trial establishment, which will be sites that have had recent lime application, then there is greater potential for FIT to increase soil pH at deeper soil depths. Therefore, liming before FIT has potential to reduce subsoil acidity. In these situations, FIT may also result in decreasing pH in the surface soil, by bringing lower pH soil further up the soil profile, but having lower C content, this soil is likely to require less lime to correct soil pH compared to non-tilled surface soil. Where soil pH is more uniform with soil depth prior to FIT, then the effect of FIT on change soil pH with soil depth is expected to be negligible.

4.4. Olsen extractable P

At Field trial 1, all three tillage treatments showed a general trend of decreasing Olsen extractable P concentrations with soil depth (i.e. a high degree of stratification), which is typically expected under long-term pastures (Zhang et al., 2009) (Figure 4.3). The FIT treatment showed slightly less stratification, compared to the other tillage treatments, however, differences between treatments were small, and not significant at all soil depths. At Field trial 1, the Olsen P concentrations (0-7.5 cm) were 46.8, 41.3 and 45.7 mg Olsen P/kg, for the NT, FIT and ST treatments, respectively, which were all above the target range required for optimum performance of ryegrass and clover based pasture (Roberts & Morton, 2012). A possible reason why the difference in Olsen P between the FIT and other tillage treatments was not greater at this site, may be due to the FIT treatment receiving an additional dose of P fertiliser (30 kg P/ha) following the tillage event. On this soil type (assuming 5 kg P/ha per 1 mg P/kg Olsen P unit change for Sedimentary soil on average) this quantity of fertiliser P could have contributed to about a 6 mg P/kg increase for the FIT treatment, therefore, without this P addition the Olsen P (0-7.5 cm) could potentially have been closer to 12 mg P/kg.

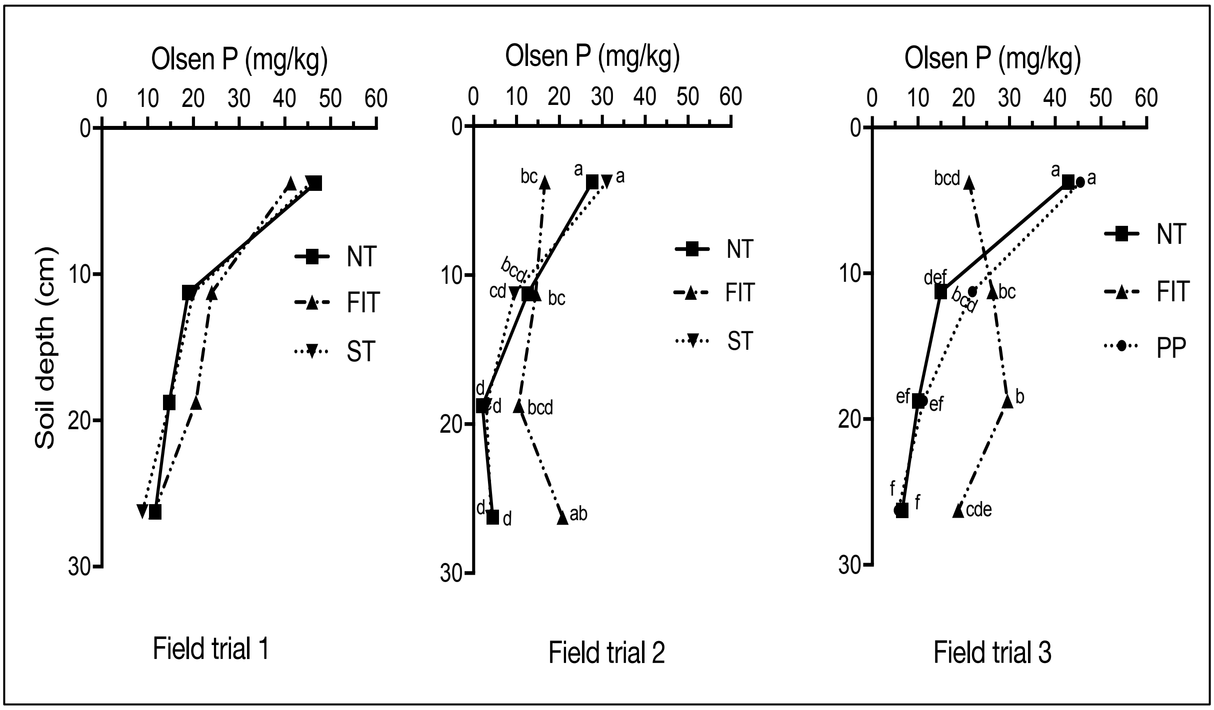

Figure 4.3. Distribution of Olsen extractable P concentrations with soil depth under the different tillage treatments at the Field trials. Olsen extractable P concentrations at Field trials 1, 2 and 3, were determined approximately 18, 13 and 8 months, respectively following the tillage treatments. Comparisons between means were based on an interactive effect ($p<0.05$) of tillage treatments and soil depth. Under each Field trial, plotted points (means) with the same letter(s) are not significantly ($p>0.05$) different, and plotted points (means) without letters show there was not an interaction ($p>0.05$) of tillage treatments or tillage treatment plus Permanent Pasture and soil depth.

At Field trial 2, the distribution of Olsen extractable P concentrations with soil depth was significantly ($p<0.05$) affected by the tillage treatments (Figure 4.3). Olsen extractable P concentrations were similar for the NT and ST treatments, with both treatments showing decreasing concentrations with soil depth. The concentrations of Olsen extractable P were more uniform with soil depth under FIT treatment, compared to the other two tillage treatments. In the 0-7.5 cm depth, the Olsen extractable P under FIT treatment was significantly ($p<0.05$) lower, being 16.6 mg Olsen P/kg compared to 27.7 mg Olsen P/kg for the NT treatment. Whereas, in the 22.5-30 cm depth, the Olsen extractable P concentration under FIT treatment was significantly ($p<0.05$) higher, being 20.8 mg Olsen P/kg compared to 4.5 mg Olsen P/kg for the NT treatment. The average Olsen extractable P concentration in the standard pasture sampling depth (0-7.5 cm) was 41%

lower for the FIT treatment, compared to the NT treatment, because of redistribution into the deeper soil depths, which is beyond the standard pasture sampling depth. The Olsen extractable P (0-7.5 cm) for the NT treatment was at the higher end of the target range of 20-30 mg/kg, with the value for the FIT treatment being below the target range (Morton & Roberts, 1999).

At Field trial 3, the distribution of Olsen extractable P concentrations with soil depth was also significantly ($p<0.05$) affected by the tillage treatments (Figure 4.3). Olsen extractable P concentrations were similar for the NT and PP treatments, with both treatments showing decreasing concentrations with soil depth. The concentrations of Olsen extractable P were more uniform with soil depth for the FIT treatment. In the 0-7.5 cm depth, the Olsen extractable P concentration under the FIT treatment was 51% lower ($p<0.05$), being 21.2 mg Olsen P/kg compared to 42.9 mg Olsen P/kg for the NT treatment. This represents transfer of substantial amount of potentially plant available P of about 21 mg P/kg from the standard soil sampling depth. In contrast, in the 15-22.5 and 22.5-30 cm depth, the Olsen extractable P concentration under FIT was significantly ($p<0.05$) higher, being 29.6 and 18.8 mg P/kg, respectively, compared to 10.1 and 6.6 mg P/kg, respectively for the NT treatment. For the FIT treatment, there was a substantial redistribution of Olsen extractable P from the surface soil to subsoil depths, beyond the standard pasture sampling depth. Like with the total C and N results, this is the result of the highly stratified nature of Olsen extraction P in long term pastures and the use of a plough that achieved a higher degree of soil inversion, compared to the other two trial sites. Zhang et al. (2009) also measured a reduction in Olsen P (0-7.5) using standard conventional tillage method to a plough depth of 20 cm, resulting in a reduction in concentration of 11 mg P/kg soil, from 37 to 26 mg P/kg soil. It is acknowledged that in the 7.5-15 cm depth, the Olsen extractable P concentration under the FIT treatment increased relative to the other two tillage treatments, and that this may be available for uptake by pasture roots (Drew & Saker, 1978). However, this would not be measured in standard pasture sampling depth and therefore, not accounted for when making fertiliser recommendations.

The observations at Field trials 2 and 3, but not at Field trials 1 are consistent with findings of other researchers (Schwab et al., 2006; Garcia et al., 2007; Zhang et al., 2009), who reported decreased surface soil P concentrations following tillage of long-term pasture soils. At the same time, the trend in the Olsen extractable P concentrations transferred from the 0-7.5 cm depth under the FIT treatments at the different field trials were consistent with the degree of soil inversion, which was greater at Field trial 3. In the 0-7.5 cm depth, the proportions of the Olsen extractable P concentrations not recovered under the FIT treatments relative to the NT treatments were 49% (11.1 mg/kg) and 51% (21.7 mg/kg) at Field trials 2 and 3, respectively. Field trial 2 was set up on an area dominated by Allophanic soils, which show higher phosphate retention (Anion Storage Capacity) compared to the Pallic soil type dominating the areas where Field trials 1 and 3 were set up (Wilde, 1976; Parfitt, 1990). As a consequence, higher amounts of fertiliser P would be required to raise the soil Olsen extractable P concentrations to near optimum values in the Allophanic soil. The Allophanic soil at Field site 2 has an average high phosphate retention values of about 80% (0-7.5 cm depth) (Calvelo Pereira et al., 2018), requiring at least 11 kg P/ha (i.e. average requirement for Ash soils) to raise the Olsen extractable P concentration by 1 mg P/kg. Consequently, the total amount of P required to raise the Olsen extractable P concentration from 16.6 mg Olsen P/kg, for the FIT treatment, to 21.7 mg Olsen P/kg for the NT treatment, would be approximately 121 kg P/ha. The Pallic soil (Tokomaru silt loam) at Site 3 has a phosphate retention of 24% (Schofield et al., 1981), which means that the amount of P required to raise the Olsen P concentration by 1 mg P/kg would be approximately 5 kg P/ha (i.e. average requirement for Sedimentary soils). Therefore, the total amount of P required to raise the Olsen extractable P concentration from 21.2 mg Olsen P/kg, under the FIT treatment, to 42.9 mg Olsen P/kg, under the NT treatment, would be approximately 105 kg/ha. In the case of Field trial 3, although the Olsen extractable P for the FIT treatment was still within the target range of 20-30 mg/kg, the 105 kg P/ha represents a potential reserve of plant available P that would have allowed fertiliser inputs to have reduced over time. This would be in the case for the NT treatment, which can receive no or sub-maintenance fertiliser P rates until the Olsen P has decreased to be within the optimum range. If the degree of soil inversion used at Field trial 3 was also used at Field trial 2, then it is conceivable that the amount of P fertiliser required to compensate for the greater redistribution of Olsen extractable P would have been higher.

4.5. Soil CEC and exchangeable cations

At Field trial 1, the effect of tillage treatments on CEC was not significant ($p>0.05$) at any of the soil depths (Table 4.2). There was a general trend of soil CEC decreasing with soil depth, however, CEC values for the FIT treatment were less stratified than the other two treatments. The FIT treatment had the lowest CEC value in the top 0-7.5 cm soil depth, but the highest values for the lower depths (7.5-30 cm). The CEC in the 0-7.5 cm soil depth was, 18.0, 15.4 and 15.5 cmol_c/kg for the NT, FIT and ST treatments, respectively, which are similar to the average CEC value (15.9 cmol_c/kg; Table 3.1) measured before the tillage treatments were assigned. For the exchangeable basic cations, there was also a general trend of the values being higher for the FIT treatment at the lower soil depths (7.5-30 cm), compared to the other tillage treatments. In the 0-7.5 cm soil depth, the FIT treatment showed lower values for Ca and Mg, whereas K and Na values were similar to the other treatments. For K, this will be due to the FIT treatment receiving a higher rate of K fertiliser (an additional 60 kg K/ha) relative to the other tillage treatments. Soil (0-7.5 cm) exchangeable Ca was 6.5, 8.6 and 8.0 cmol_c/kg and the exchangeable Mg was, 1.5, 1.1 and 1.5 cmol_c/kg for the NT, FIT and ST treatments, respectively. However, treatment differences were only statistically significant ($p<0.05$) in the case of Mg. The average MAF QT Mg values, in the 0-7.5 cm soil depth, for the NT treatment was 31.3, which was reduced by 23% to 23.9 for the FIT treatment. However, this lower exchangeable Mg concentration, in the 0-7.5 cm depth for the FIT treatment, was within the target range required for optimum ryegrass and clover-based pasture production for the type of soil used at this field trial. The significantly lower Mg levels and the slightly more uniform distribution of CEC and Ca with soil depth observed under the FIT treatment, relative to the other two tillage treatments, are indications that soil inversion reduced the levels of exchangeable cations and CEC in the top 7.5 cm soil depth.

At Field trial 2, there was also a general trend of soil CEC decreasing with soil depth, with CEC values for the FIT treatment being less stratified than the other two tillage treatments (Table 4.2). The CEC in the topsoil (0-7.5 cm) was lower for the FIT treatment (18.9 cmol_c/kg) compared the NT (28.5 cmol_c/kg) and ST (24 cmol_c/kg) treatments. However, the distribution of CEC with soil depth was not significantly ($p>0.05$) affected by the tillage treatments (Table 4.2). The soil concentration of the four exchangeable basic cations for the FIT treatment were either similar or lower in the topsoil (0-7.5 cm) and lower in the next soil depth (7.5-15 cm), compared to the other tillage treatments. However, there was insufficient evidence to support a statistically different effect of tillage treatment on the distribution of the basic cations (Table 4.2). Presumably, the application of lime following the tillage treatments increased the topsoil Ca concentrations for all treatments, however, the observation of higher Ca concentrations for FIT treatment at all of the lower soil depths (7.5-30 cm) is likely to have been influenced by soil redistribution from the tillage practice. Wang et al. (1999) showed that, the proportion of Ca on the cation exchange site of an Allophanic soil increased after the application of lime material, with an associated decline in Mg, K and Na levels.

Table 4.2. Analysis of variance for the interactive effect of tillage treatments or tillage treatments plus Permanent Pasture and soil depths on CEC and exchangeable cations (K, Ca, Mg, Na) at the Field trials. CEC and exchangeable cations data at Field trials 1, 2 and were determined approximately 18, 13 and 8 months, respectively following the tillage treatments. All comparisons between means were based on observing an interaction ($p<0.05$) of tillage treatments or tillage treatment plus and soil depth. For a given field trial and variable, means with the same letter(s) are not significantly ($p>0.05$) different, and means without letters show there was not an interactive effect ($p>0.05$) of tillage treatments or tillage treatment plus and soil depth.

Variables	Tillage treatments								
	Field trial 1			Field trial 2			Field trial 3		
	NT	FIT	ST	NT	FIT	ST	NT	FIT	PP
				CEC (cmol$_c$/kg)					
0-7.5 cm	18.0	15.4	15.5	28.5	18.9	24.9	20.5a	12.8b	17.5ab
7.5-15 cm	14.6	16.0	12.3	21.8	19.6	19.7	15.2ab	13.7b	12.5b
15-22.5 cm	8.2	14.2	9.8	21.0	18.6	14.7	10.6bc	16.8ab	11.3bc
22.5-30 cm	9.4	9.9	9.4	13.0	15.9	13.7	9.1c	14.9bc	10.8bc
				K (cmol$_c$/kg)					
0-7.5 cm	0.50	0.51	0.47	0.48	0.49	0.59	0.71ab	0.25c	0.75a
7.5-15 cm	0.26	0.33	0.24	0.26	0.43	0.33	0.28c	0.25c	0.44abc
15-22.5 cm	0.18	0.20	0.14	0.23	0.27	0.27	0.19c	0.37abc	0.35bc
22.5-30 cm	0.14	0.19	0.10	0.24	0.21	0.28	0.15c	0.31c	0.31c
				Ca (cmol$_c$/kg)					
0-7.5 cm	8.0a	6.5a	8.6a	9.5	8.0	9.8	4.8ab	4.2ab	6.0a
7.5-15 cm	6.4ab	8.3a	6.4ab	2.8	6.4	4.0	3.6b	5.1ab	4.7ab
15-22.5 cm	4.0cd	6.3abc	4.4bcd	2.9	4.1	2.4	4.8ab	5.3ab	4.5ab
22.5-30 cm	3.7d	4.7bcd	3.9cd	2.3	2.9	2.3	4.4ab	4.3ab	3.9ab
				Mg (cmol$_c$/kg)					
0-7.5 cm	1.5a	1.1bcd	1.5a	1.1	0.76	1.2	1.9a	1.1cde	2.2a
7.5-15 cm	0.98bcd	1.2b	0.95cde	0.54	0.74	0.55	1.2bcd	1.4bc	1.4bc
15-22.5 cm	0.67fg	1.1bc	0.73efg	0.63	0.55	0.37	0.85de	1.5b	0.97de
22.5-30 cm	0.60g	0.83edf	0.68fg	0.59	0.40	0.39	0.77e	1.2bcd	0.86de
				Na (cmol$_c$/kg)					
0-7.5 cm	0.12	0.15	0.17	0.20	0.21	0.24	0.15	0.08	0.12
7.5-15 cm	0.07	0.16	0.08	0.11	0.19	0.10	0.14	0.06	0.08
15-22.5 cm	0.04	0.14	0.07	0.11	0.21	0.13	0.12	0.06	0.08
22.5-30 cm	0.04	0.10	0.06	0.12	0.18	0.15	0.10	0.12	0.11

The excess Ca concentration following lime addition, coupled with the divalent charge of Ca may have increased its relative selectivity and adsorption to the exchange sites (Edmeades, 1982), so that the other cations were exchanged with relative ease into solution, where they were either utilised by plants and/or leached from the soil. However, both MAF QT K and Mg in the 0-7.5 cm depth were in the target range for optimum production of ryegrass/white clover based pasture (Morton & Roberts, 1999), with K being 8.0, 8.4 and 9.2 and Mg being 21.0, 14.7 and 20.4 for the NT, FIT and ST treatments, respectively (Table 4.2). This was presumably due to the originally high levels of K and Mg in the surface profile prior to the addition of lime.

At Field trial 3, the distribution of CEC was affected ($p<0.05$) by the tillage treatments, and there was a general trend of decreasing CEC with soil depth under the NT and PP treatments, whereas CEC values for the FIT treatment were less stratified with soil depth (Table 4.2). In the 0-7.5 cm depth, CEC was significantly ($p<0.05$) lower for the FIT treatment, being 12.8 $cmol_c/kg$ compared to 20.5 $cmol_c/kg$ for NT treatment. In contrast, in the 15-22.5 and 22.5-30 cm depths, the CEC values for the FIT treatment were higher, compared to the NT treatment, but differences were not significant. The CEC (0-7.5 cm depth) for the PP treatment was 17.5, which was close to the value of 15.0 $cmol_c/kg$ measured prior to trial establishment (Table 4.2; Table 3.1). For the exchangeable basic cations, there was also general trend of the values being higher for the FIT treatment at the deeper soil depths (7.5-30 cm), compared to the other tillage treatments. In the 0-7.5 cm soil depth, the FIT treatment showed significantly ($p<0.05$) lower values for K, and Mg, whereas for Ca and Na values were lower than or similar to the other treatments. Soil (0-7.5 cm) exchangeable K was 0.71, 0.25 and 0.75 $cmol_c/kg$ and the exchangeable Mg was 1.9, 1.1 and 2.2 $cmol_c/kg$ for the NT, FIT and PP treatments, respectively. The average MAF QT K values (0-7.5 cm depth), for the NT treatment was 15.2, which was reduced by 66% to 5.1 for the FIT treatment, which is a reduction of about 10 units. The value for the FIT treatment was at the lower end of the optimum range of 5-8. The average MAF QT Mg values (in the 0-7.5 cm depth) for the NT treatment was 37.9, which was reduced by 36% to 24.4 for the FIT treatment. However, the value for the FIT treatment was still above the target range required for optimum pasture production (8-10) and close to the ideal level of animal health (25-30).

Comparatively, regardless of tillage treatment, CEC measured at Field trial 2 were higher compared to CEC measured at the other two field trials; this was because of the higher soil organic matter and variable charged clay contents of the Allophanic soils (Cornforth, 1998). Overall, changes in CEC paralleled changes in soil C (Table 4.2; Table 4.1). The relationship between soil C and CEC of soils have been established by several researchers (Helling et al., 1964; Oades et al., 1989; Curtin et al., 2015), who noted that soil C and CEC were directly related, so that an increase in soil C expectedly increased CEC. Also, because the type of soils used in the current study show relatively equal proportions of clay constituents with increasing soil depth (Neall, 1982; Bruce, 1984), this direct effect of soil C on CEC was expected. At Field trial 3, where the FIT treatment involved a greater depth of cultivation, and possibly a greater degree of soil inversion than the other two sites, a significantly larger amount of soil C was transferred from the 0-7.5 cm to the deeper depths under this treatment, relative to the NT treatment, with CEC in turn reducing significantly ($p<0.05$) also.

For the exchangeable basic cations, the greater degree of soil inversion at Field trial 3 also resulted in higher losses of the cations from the top 7.5 cm depth to the deeper depths, compared to other two sites. However, among all four cations, only the soil test K values at Field trial 3 was significantly affected by FIT. The 66% (10.1 MAF QT) loss of K at Field trial 3 would require about 1000 kg K/ha to replenish, assuming that an average of 100 kg K/ha raises soil test K value by 1 unit on Pallic soils (Roberts & Morton, 2012). It is acknowledged that the Pallic soils have high K reserves (Jackson & During, 1979), therefore, the need for replacement K fertiliser to counteract the effect of FIT, is not as applicable as it is for Olsen P, as previously discussed. However, given that the 5.1 MAF QT K for the FIT treatment is at the bottom end of the optimum range (5-8), there may be an advantage of at least increasing the soil test closer to the middle of the optimum range, by increasing with about 1.5 units, which would equate to an additional requirement of about 150 kg K/ha.

4.6. Estimated fertiliser cost associated with soil inversion

This research has demonstrated that Full Inversion Tillage redistributes nutrients in the soil profile, which can have implications for fertiliser use. Therefore, it is useful to assess the potential cost of replacing soil fertility that has been removed from the standard soil sampling depth for pasture of 0-7.5 cm. The cost of liming was not including because the effect of tillage on pH change was not large between treatments and because lime is a relatively cheap soil amendment, so is unlikely to be an influential cost consideration when evaluating the use of Full Inversion Tillage.

At Field trial 1, the FIT treatment had about 6 Olsen P units lower than the NT treatment, but the FIT treatment also received 30 kg P/ha more P than the other treatments. Assuming an average of 5 kg P 1 unit (mg P/kg) in Olsen P (for Sedimentary soils), an additional 30 kg P/ha would be required for the FIT treatment Olsen P to be at the same level as the NT treatment. However, if the FIT treatment hadn't received that previous extra 30 kg P/ha, then the different between the treatments may have been closer to 12 Olsen P units. Therefore, total amount of P required for the FIT treatment to have the same Olsen P as the FIT treatment is estimated to be about 60 kg P/ha. At Field trial 2, the FIT treatment had an Olsen P about 11 Olsen P units lower than the NT treatment. Assuming an average of 11 kg P 1 unit in Olsen P (for Ash soils), an additional 121 kg P/ha would be required for the FIT treatment Olsen P to be at the same level as the NT treatment. At Field trial 3, the FIT treatment had an Olsen P about 21 Olsen P units lower than the NT treatment. Assuming an average of 5 kg P 1 unit in Olsen P (for Sedimentary soils), an additional 105 kg P/ha would be required to the FIT treatment Olsen P to be at the same level as the NT treatment.

Based on the above assumptions, the additional P requirements from FIT across the three sites ranged from 60-120 kg P/ha. Assuming fertiliser costs $3.50/kg P (based on assigning all of the single superphosphate (9% P) cost of $315/tonne to the P value), then this additional P requirement from the FIT treatment across the three sites would cost $210-420/ha (excluding transport and spreading costs). However, the amount of additional P required by the use of FIT will depend on the initial Olsen P level (and degree of soil stratification), the degree of soil inversion and the P retention of the soil.

The exchangeable K values (0-7.5 cm soil depth) for the FIT treatment were similar to the NT treatment at Field trial 1 and Field trial 2. At Field trial 1, the FIT treatment received an additional 60 kg K/ha, which may have contributed to its exchangeable K being similar to the other treatments. At Field trial 3, the FIT treatment resulted in an exchangeable K value 0.46 $cmol_c/kg$ (10.1 MAF QT K units) lower than the NT treatment. Therefore, the additional K required across the three sites to replace the K removed from the 0-7.5 cm soil sampling depth, would be 0-1010 kg K/ha (assuming about 100 kg K/ha per 1 MAF QT K unit change). Assuming that fertiliser costs $0.71/kg K (based on a potassium chloride (50% K) cost of

\$710/tonne), then this additional K from the FIT treatment costs \$0-717/ha (excluding transport and spreading costs).

Across the three-trial sites, the reduction in exchangeable Mg for the FIT treatment ranged from about 0.36-0.80 $cmol_c/kg$ in the 0-7.5 cm soil depth, compared the NT treatment. A study by Hanly et al. (1999) showed a 0.50 $cmol_c/kg$ increase in exchangeable Mg from the addition of 100 kg Mg/ha, as a soluble Mg fertiliser, on the Tokomaru silt loam soil (Pallic soil). Loganathan et al. (2005) found a similar result on a Pumice soil, with a 0.60 $cmol_c/kg$ increase in exchangeable Mg from the addition of 100 kg Mg/ha. Based on these results it was assumed that about 20 kg Mg/ha would be required to increase exchangeable Mg by 0.10 $cmol_c/kg$. Therefore, the reduction in exchangeable Mg for the FIT treatment, compared to the NT treatment, would be equivalent to 72-160 kg Mg/ha. Assuming fertiliser costs \$1.30/kg Mg (based on a magnesium oxide (40% Mg) cost of \$520/tonne), then this additional Mg costs about \$94-208/ha (excluding transport and spreading costs).

Overall, the highest total cost of replacing nutrients removed from the 0-7.5 cm depth occurred at Field trial 3 site, which is for P, K and Mg combined would be about \$1,293/ha, while the lowest cost of \$362/ha was at Field trial 1. This was partly due to the high initial soil fertility and the greater degree of soil cultivation. However, it provides an example of the potential for the value of nutrients no longer measured in the soil sampling depth from FIT compared to NT.

5. CHAPTER FIVE: Conclusions

The current study showed that at all three field trials the FIT treatment affected the vertical distribution of soil C and N as well as some soil fertility parameters. There was a redistribution of soil C and N from the 0-7.5 cm nominal depth of 16-46% C and 24-41% N to deeper soil depths. However, tillage did not change the total C and N stocks for the accumulated 0-30 cm s depth.

For the soil fertility parameters, the effect of the FIT treatment was only significant on Olsen extractable P, exchangeable K and exchangeable Mg, and was greater overall at the Field trial 3 site where the degree of soil inversion was greatest. For soil pH, the FIT treatment has limited potential to decrease topsoil soil pH (0-7.5 cm) where pH is relatively uniform with depth before the treatment is implemented. Also, the use of liming at one site counteracted any differences between tillage treatments. Because liming is a relatively cheap soil amendment, the cost of adjusting any reduction in soil pH caused by the FIT treatment is expected to be inexpensive.

The FIT treatment reduced the Olsen P levels in the 0-7.5 cm depth by approximately 11-21 mg Olsen P/ha across the three sites, corresponding to additional P requirement of 60-120 kg P/ha. The exchangeable K levels in the 0-7.5 cm depth following the FIT treatment reduced by approximately 0-10.1 MAF QT K (0.00-0.46 cmol_c/kg) across the three sites, corresponding to additional K requirement that ranged from 0-1010 kg K/ha. The FIT treatment reduced the exchangeable Mg levels in the 0-7.5 cm depth also by approximately 7-14 MAF QT Mg (0.36-0.80 cmol_c/kg) across the three sites, corresponding to additional Mg requirement that ranged from 72-160 kg Mg/ha.

These additional nutrient requirements equate to costs that ranged from \$210-420/ha, \$0-717/ha, and \$94-208/ha (excluding transport and spreading costs) for Olsen P, exchangeable Mg and exchangeable K, respectively across the three field trials. The study found that the cumulative cost of replacing nutrients removed from the topsoil depth (0-7.5 cm) ranged across the sites from \$362-1,293/ha. The range in cost is influenced by the initial soil fertility levels and the depth and degree of soil inversion implemented. If the initial soil fertility is higher than optimum, then the amount of nutrients required to increase the soil tests to just within the optimum range will be lower than the cost of replacement of available nutrients removed from the 0-7.5 cm soil depth.

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APPENDICES

Appendix A. Raw data on soil C and N stocks measured at the field trials.

Table A.1. Soil C stocks in *Mg/ha* measured at the different depth intervals under the three tillage treatments at Field trial 1.

Tillage Treatments	Depth (cm)	Average C stock
FIT	0-7.5	25.8
FIT	7.5-15	26.1
FIT	15-22.5	23.4
FIT	22.5-30	23.1
NT	0-7.5	37.3
NT	7.5-15	24.6
NT	15-22.5	20.0
NT	22.5-30	15.0
ST	0-7.5	38.1
ST	7.5-15	22.7
ST	15-22.5	18.5
ST	22.5-30	14.6

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table A.2. Soil N stocks in *Mg/ha* measured at the different depth intervals under the three tillage treatments at Field trial 1.

Tillage Treatments	Depth (cm)	Average N stock
FIT	0-7.5	2.8
FIT	7.5-15	2.9
FIT	15-22.5	2.6
FIT	22.5-30	2.6
NT	0-7.5	3.9
NT	7.5-15	2.7
NT	15-22.5	2.4
NT	22.5-30	1.8
ST	0-7.5	4.1
ST	7.5-15	2.6
ST	15-22.5	2.2
ST	22.5-30	1.8

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table A.3. Soil C stocks in *Mg/ha* measured at the different depth intervals under the three tillage treatments at Field trial 2.

Tillage Treatments	Depth (cm)	Average C stock
FIT	0-7.5	31.1
FIT	7.5-15	41.7
FIT	15-22.5	37.5
FIT	22.5-30	24.3
NT	0-7.5	37.0
NT	7.5-15	35.0
NT	15-22.5	24.7
NT	22.5-30	18.2
ST	0-7.5	43.6
ST	7.5-15	40.4
ST	15-22.5	28.0
ST	22.5-30	20.1

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table A.4. Soil N stocks in *Mg/ha* measured at the different depth intervals under the three tillage treatments at Field trial 2.

Tillage Treatments	Depth (cm)	Average N stock
FIT	0-7.5	3.3
FIT	7.5-15	4.4
FIT	15-22.5	4.0
FIT	22.5-30	2.7
NT	0-7.5	3.7
NT	7.5-15	3.7
NT	15-22.5	2.7
NT	22.5-30	2.2
ST	0-7.5	4.3
ST	7.5-15	4.3
ST	15-22.5	3.1
ST	22.5-30	2.3

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table A.5. Soil C stocks in *Mg/ha* measured at the different depth intervals under the three tillage treatments at Field trial 3.

Tillage Treatments	Depth (cm)	Average C stock
FIT	0-7.5	17.6
FIT	7.5-15	25.9
FIT	15-22.5	26.1
FIT	22.5-30	19.2
NT	0-7.5	32.3
NT	7.5-15	21.5
NT	15-22.5	17.0
NT	22.5-30	12.7
PP	0-7.5	32.3
PP	7.5-15	21.6
PP	15-22.5	16.1
PP	22.5-30	11.5

FIT: Full Inversion Tillage NT: No Tillage PP: Permanent Pasture

Table A.6. Soil N stocks in *Mg/ha* measured at the different depth intervals under the three tillage treatments at Field trial 3.

Tillage Treatments	Depth (cm)	Average N stock
FIT	0-7.5	2.0
FIT	7.5-15	2.9
FIT	15-22.5	2.9
FIT	22.5-30	2.3
NT	0-7.5	3.4
NT	7.5-15	2.5
NT	15-22.5	2.0
NT	22.5-30	1.6
PP	0-7.5	3.5
PP	7.5-15	2.5
PP	15-22.5	2.0
PP	22.5-30	1.5

FIT: Full Inversion Tillage NT: No Tillage PP: Permanent Pasture

Appendix B. Raw data on soil pH measured at the field trials

Table B.1. Soil pH measured at the different depth intervals under the three tillage treatments at Field trial 1.

Tillage Treatments	Depth (cm)	Average pH
FIT	0-7.5	5.6
FIT	7.5-15	5.6
FIT	15-22.5	5.7
FIT	22.5-30	5.6
NT	0-7.5	5.7
NT	7.5-15	5.5
NT	15-22.5	5.5
NT	22.5-30	5.6
ST	0-7.5	5.7
ST	7.5-15	5.5
ST	15-22.5	5.5
ST	22.5-30	5.6

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table B.2. Soil pH measured at the different depth intervals under the three tillage treatments at Field trial 2.

Tillage Treatments	Depth (cm)	Average pH
FIT	0-7.5	6.3
FIT	7.5-15	5.8
FIT	15-22.5	6.0
FIT	22.5-30	5.9
NT	0-7.5	6.1
NT	7.5-15	5.6
NT	15-22.5	5.7
NT	22.5-30	5.8
ST	0-7.5	6.0
ST	7.5-15	5.5
ST	15-22.5	5.6
ST	22.5-30	5.8

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table B.3. Soil pH measured at the different depth intervals under the three tillage treatments at Field trial 3.

Tillage Treatments	Depth (cm)	Average pH
FIT	0-7.5	5.7
FIT	7.5-15	5.7
FIT	15-22.5	5.7
FIT	22.5-30	5.8
NT	0-7.5	5.7
NT	7.5-15	5.5
NT	15-22.5	5.7
NT	22.5-30	5.8
PP	0-7.5	5.7
PP	7.5-15	5.7
PP	15-22.5	5.7
PP	22.5-30	5.8

FIT: Full Inversion Tillage NT: No Tillage PP: Permanent Pasture

Appendix C. Raw data on Olsen extractable P measured at the field trials

Table C.1. Soil Olsen extractable P in *mg/kg* measured at the different depth intervals under the three tillage treatments at Field trial 1.

Tillage Treatments	Depth (cm)	Average Olsen extractable P
FIT	0-7.5	41.4
FIT	7.5-15	24.0
FIT	15-22.5	20.6
FIT	22.5-30	11.4
NT	0-7.5	45.7
NT	7.5-15	20.0
NT	15-22.5	14.9
NT	22.5-30	8.9
ST	0-7.5	46.8
ST	7.5-15	18.9
ST	15-22.5	14.8
ST	22.5-30	11.7

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table C.2. Soil Olsen extractable P in *mg/kg* measured at the different depth intervals under the three tillage treatments at Field trial 2.

Tillage Treatments	Depth (cm)	Average Olsen extractable P
FIT	0-7.5	16.6
FIT	7.5-15	14.5
FIT	15-22.5	10.5
FIT	22.5-30	20.8
NT	0-7.5	27.7
NT	7.5-15	12.6
NT	15-22.5	2.1
NT	22.5-30	4.5
ST	0-7.5	31.1
ST	7.5-15	9.5
ST	15-22.5	3.1
ST	22.5-30	4.1

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table C.3. Soil Olsen extractable P in *mg/kg* measured at the different depth intervals under the three tillage treatments at Field trial 3.

Tillage Treatments	Depth (cm)	Average Olsen extractable P
FIT	0-7.5	21.2
FIT	7.5-15	26.4
FIT	15-22.5	29.6
FIT	22.5-30	18.8
NT	0-7.5	43.0
NT	7.5-15	15.0
NT	15-22.5	10.1
NT	22.5-30	6.6
PP	0-7.5	45.5
PP	7.5-15	21.9
PP	15-22.5	11.2
PP	22.5-30	5.7

FIT: Full Inversion Tillage NT: No Tillage PP: Permanent Pasture

Appendix D. Raw data on CEC and exchangeable cations measured at the field trials

Table D.1. CEC and exchangeable basic cations in *cmol$_c$/kg* measured at the different depth intervals under the three tillage treatments at Field trial 1.

Tillage Treatments	Depth (cm)	Average CEC	Average basic cation concentration			
			K	Ca	Mg	Na
FIT	0-7.5	15.4	0.51	6.54	1.05	0.15
FIT	7.5-15	16.0	0.33	8.35	1.19	0.16
FIT	15-22.5	14.2	0.20	6.26	1.09	0.14
FIT	22.5-30	9.9	0.19	4.69	0.83	0.10
NT	0-7.5	14.4	0.48	8.56	1.47	0.17
NT	7.5-15	12.3	0.24	6.36	0.95	0.09
NT	15-22.5	9.8	0.14	4.44	0.74	0.07
NT	22.5-30	9.4	0.10	3.92	0.68	0.06
ST	0-7.5	17.9	0.50	8.05	1.48	0.12
ST	7.5-15	14.6	0.26	6.43	0.98	0.07
ST	15-22.5	8.2	0.18	3.98	0.68	0.05
ST	22.5-30	9.4	0.14	3.67	0.60	0.04

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table D.2. CEC and exchangeable basic cations *cmol$_c$/kg* measured at the different depth intervals under the three tillage treatments at Field trial 2.

Tillage Treatments	Depth (cm)	Average CEC	Average basic cation concentration			
			K	Ca	Mg	Na
FIT	0-7.5	18.9	0.49	8.04	0.76	0.21
FIT	7.5-15	19.6	0.43	6.35	0.74	0.19
FIT	15-22.5	18.5	0.27	4.08	0.55	0.21
FIT	22.5-30	15.9	0.21	2.90	0.40	0.18
NT	0-7.5	28.5	0.48	9.50	1.12	0.20
NT	7.5-15	21.8	0.26	2.78	0.54	0.11
NT	15-22.5	21.0	0.23	2.88	0.63	0.11
NT	22.5-30	13.0	0.24	2.34	0.59	0.12
ST	0-7.5	24.9	0.59	9.79	1.17	0.24
ST	7.5-15	19.6	0.33	3.98	0.55	0.10
ST	15-22.5	14.7	0.27	2.38	0.36	0.13
ST	22.5-30	13.7	0.28	2.28	0.39	0.15

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table D.3. CEC and exchangeable basic cations in *cmol$_c$/kg* measured at the different depth intervals under the three tillage treatments at Field trial 3.

			Average basic cation concentration			
Tillage Treatments	**Depth (cm)**	**Average CEC**	**K**	**Ca**	**Mg**	**Na**
FIT	0-7.5	12.8	0.25	4.17	1.09	0.08
FIT	7.5-15	13.7	0.25	5.11	1.37	0.06
FIT	15-22.5	16.8	0.38	5.29	1.46	0.07
FIT	22.5-30	15.0	0.31	4.30	1.16	0.12
NT	0-7.5	20.5	0.71	4.78	1.91	0.15
NT	7.5-15	15.2	0.28	3.61	1.19	0.14
NT	15-22.5	10.6	0.19	4.75	0.85	0.12
NT	22.5-30	9.1	0.15	4.36	0.77	0.10
PP	0-7.5	17.5	0.75	6.00	2.18	0.12
PP	7.5-15	12.5	0.44	4.72	1.35	0.08
PP	15-22.5	11.3	0.35	4.54	0.97	0.08
PP	22.5-30	10.8	0.31	3.89	0.86	0.12

FIT: Full Inversion Tillage NT: No Tillage PP: Permanent Pasture

Appendix E. Raw data on exchangeable K, Ca and Mg MAF QT values measured at the field trials

Table E.1. Exchangeable K, Ca and Mg in *MAF QT* measured at the different depth intervals under the three tillage treatments at Field trial 1.

Tillage Treatments	Depth (cm)	Average exchangeable K	Average exchangeable Ca	Average exchangeable Mg
FIT	0-7.5	10.4	8.2	23.9
FIT	7.5-15	6.6	10.3	26.5
NT	0-7.5	9.4	9.4	31.3
NT	7.5-15	5.2	7.9	21.7
ST	0-7.5	8.7	8.7	30.2
ST	7.5-15	5.0	8.2	22.0

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table E.2. Exchangeable K, Ca and Mg in *MAF QT* measured at the different depth intervals under the three tillage treatments at Field trial 2.

Tillage Treatments	Depth (cm)	Average exchangeable K	Average exchangeable Ca	Average exchangeable Mg
FIT	0-7.5	8.4	8.6	14.7
FIT	7.5-15	7.2	6.6	13.9
NT	0-7.5	8.0	9.9	21.0
NT	7.5-15	4.8	3.2	11.3
ST	0-7.5	9.2	9.5	21.0
ST	7.5-15	5.7	4.3	10.7

FIT: Full Inversion Tillage NT: No Tillage ST: Shallow Tillage

Table E.3. Exchangeable K, Ca and Mg in *MAF QT* measured at the different depth intervals under the three tillage treatments at Field trial 3.

Tillage Treatments	Depth (cm)	Average exchangeable K	Average exchangeable Ca	Average exchangeable Mg
FIT	0-7.5	5.1	5.2	24.4
FIT	7.5-15	4.6	6.0	28.9
NT	0-7.5	12.6	5.2	37.9
NT	7.5-15	5.6	4.4	26.2
PP	0-7.5	13.2	6.6	43.1
PP	7.5-15	8.7	5.8	30.1

FIT: Full Inversion Tillage NT: No Tillage PP: Permanent Pasture