Effects of soil compaction on soil physical and chemical properties in apple orchards

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Abstract

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Traffic-induced soil compaction is a widespread and detrimental process that substantially affects soil quality globally. This compaction often results in increased bulk density and penetration resistance, along with alterations in soil pore function and reduced soil fertility, all of which collectively degrades overall soil quality. Although assessments of soil compaction have primarily focused on structural changes, such as increased bulk density and reduced pore volume, the relationship between these structural alterations and key hydraulic properties have not been thoroughly explored. Consequently, most research has concentrated on the structural impacts of compaction, with limited emphasis on how compaction influenced hydraulic properties or how intrinsic soil characteristics affected this response. Furthermore, there is a notable lack of comprehensive reviews or quantitative studies examining the effects of compaction on soil water retention and physical quality, as well as the role of soil properties in this context. Additionally, research on soil compaction in New Zealand apple orchards, particularly regarding traffic-induced compaction, is scarce. Therefore, this highlighted the need for studies investigating the effects of compaction on soil physical and chemical properties to address the existing knowledge gap regarding the causes and extent of compaction in orchard soils.

To date, the evaluation of soil compaction has mainly focused on structural changes like bulk density, with limited research on its impact on hydraulic properties. In New Zealand apple orchards, the effects of traffic-induced compaction on physical and chemical properties remain underexplored. This PhD study aims to address these gaps by investigating how orchard age and traffic patterns influence soil compaction, providing insights for better orchard management and long-term soil health. Three specific objectives were established:

(1) conduct a comprehensive meta-analysis to examine how soil water retention functions respond to compaction and the role of basic soil properties in this response; (2) assess the impact of soil compaction on physical properties (penetration resistance, bulk density, aggregate stability, soil gas diffusivity, soil water retention properties, saturated hydraulic conductivity, and soil porosities) across different planting ages and traffic positions; and (3) evaluate the effects of compaction on key soil chemical properties, including carbon, nitrogen, C/N ratio, mineralisable nitrogen, hot water extractable carbon and carbon stock.

The meta-analysis results indicated that while traffic and soil basic properties did not significantly impact field capacity, they led to a substantial reduction in macro-porosity and an overall increase in bulk density, which were influenced by factors such as traffic treatment, clay content, soil organic carbon, and soil moisture content at compaction. Furthermore, soil organic carbon and clay content significantly affected how soil responded to compaction, with variations in bulk density, macro-porosity, and available water capacity depending on soil moisture levels during compaction. The investigation into the impact of compaction on soil physical and chemical properties revealed that traffic positions significantly influenced most soil physical and chemical properties, except mean weight diameter and the C/N ratio in both orchards. In contrast, only mineralizable nitrogen was not significantly affected by the planting age across all soil properties in both orchards. Additionally, a strong interaction between traffic positions and planting ages on soil physical and chemical properties was observed in both orchards.

Keywords: Traffic-induced compaction, soil carbon, nitrogen, penetration resistance, soil water retention, saturated hydraulic conductivity, macro-porosity, soil physical properties, soil chemical properties, hot water extracble carbon, mineralisable nitrogen, aggregate stability, soil quality index, meta-analysis

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To my grandfather, in loving memory.

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Chapter 1

Introduction

1.1 Background

Soil compaction is one of the most common and harmful processes threatening soil quality worldwide. Peth et al. (2010) reported that compaction-induced soil degradation affected approximately 33 million hectares of arable land in Europe and a staggering 68 million hectares globally. In natural ecosystems, compaction can result from processes such as freezing and thawing, soil swelling and shrinking, and certain chemical precipitation events (Défossez & Richard, 2002; Pagliai et al., 2003). In agriculture, soil compaction is primarily caused by farming activities, especially the movement of heavy machinery and the trampling of animals (Hamza & Anderson, 2005; Hu et al., 2021). Due to the increasing demand for higher food production and the escalating weight of agricultural machinery, modern soils are subjected to significantly greater pressure compared to historical conditions (Hu et al., 2021). This intensified traffic-induced soil structural degradation (compaction) adversely impacts soil structure (Hu et al., 2018), leads to the loss of soil organic matter (Beare et al., 1994) and stands out as one of the foremost challenges in modern agriculture (Wei et al., 2021). Soil compaction typically has detrimental effects on various soil physical and chemical properties. It can alter essential soil functions, including soil water retention, gas exchange capacity, and nutrient mobility (Chan et al., 2006). As a result, these changes can have profound implications for plant growth and agricultural production (Wei et al., 2021).

As a type of soil structural issue, it is important to introduce the concept of soil structural vulnerability or susceptibility. Soil structural vulnerability refers to the soil's ability to resist stress (Kay et al., 1994) When soil is structurally vulnerable, it tends to undergo more significant changes in its physical properties when exposed to cultivation or compaction pressures (Hu et al., 2021). Many methods have been proposed to assess soil compaction susceptibility. For instance, compactibility (Gupta & Allmaras, 1987), compressibility (Gupta & Allmaras, 1987), and soil strength for compaction (Horn & Fleige, 2009). However, these methods focus solely on soil structural changes, like bulk density or volume alteration. Strain or total volume/bulk density changes were not assessed in combination with key hydraulic properties that influence soil functions critical to ecosystem services.

The severity of soil compaction is influenced by fundamental soil properties such as clay content and soil organic matter concentration, as well as traffic-induced treatments and the moisture content during compaction. The tire pressure exerted by machinery on the soil surface can vary depending on soil texture. For example, machines apply vertical pressure on coarse-textured soils but exert multidirectional pressure on heavier soils (Ellies et al., 2000). Deeper soil compaction tends to occur in areas subjected to a higher frequency of traffic passes compared to areas with fewer passes (Glab, 2014; Gomez-Rodriguez et al., 2013; Voorhees et al., 1979). In cases of compaction, soil structural changes are strongly correlated with the shifting and rearrangement of soil particles (aggregates) under varying moisture conditions as the applied force compresses the soil (Dexter, 1988). Soil organic matter also plays a significant role when soil is subjected to compression forces. Organic matter within the soil profile, which adheres to clay particles and binds to micro and macro aggregates, has the potential to mitigate soil compaction caused by heavy machinery (Shah et al., 2017). To date, studies on soil compaction have primarily focused on structural changes rather than examining how compaction affects soil hydraulic properties and the role of fundamental soil properties in influencing this response.

In horticultural systems, soil compaction is a common issue due to orchard management practices. Approximately 46% of orchard and vineyard sites in New Zealand are affected by soil compaction, which results in macro-porosity levels falling below the target range set by MPI(Ministry for the Environment & Stats NZ, 2021). According to the Pipfruit (2017), around 12% of the area of apple orchard in New Zealand is compacted. The primary cause of compaction in orchards is the use of machinery for spraying pesticides and fungicides (Paltineanu et al., 2016). For instance, Goh et al. (2001) found significantly lower bulk density and higher infiltration rates around the tree line compared to vehicle tracks, and compaction also reduced the total number of earthworms. Penetration resistance (PR) was found to be significantly higher in traffic areas compared to non-traffic areas, both in topsoil and subsoil (Vogeler et al., 2006), which limited the root growth of plants (Zou et al., 2001). The second reason for compaction in apple orchards is the cumulative effect of traffic over the years, combined with the natural hardening of the soil as it ages, both of which can adversely affect soil properties (Moraes et al., 2019; Ramos et al., 2022). To date, only a limited number of studies have been conducted to determine the effects of soil compaction on physical and chemical properties in apple orchards worldwide ((Paltineanu et al., 2016; Swarts et al., 2016;

Wei et al., 2021) and New Zealand (Deurer et al., 2012; Goh et al., 2001; Vogeler et al., 2006), and the relationship between traffic track and planting ages on soil functions remains unclear.

1.2 Research objectives

This PhD project aims to explore the effects of traffic-induced compaction on orchard's soil properties by using a comprehensive literature review (meta-analysis) to investigate how the soil water retention function response to compaction and how the soil basic properties affect this response, field and laboratory studies to explore the impact of soil compaction on soil physical and chemical properties in New Zealand apple orchards as listed below:

1. A comprehensive literature review to identify how soil properties (e.g. clay content, soil moisture content, and organic matter) affect the responses of soil hydraulic properties to compaction.
2. Investigate impacts of compaction on soil physical properties under different planting ages and traffic positions in New Zealand apple orchards.
3. Determine the effects of compaction on soil chemical properties under different planting ages and traffic positions in New Zealand apple orchards.

1.3 Thesis structure

Chapter 1: This chapter describes the thesis background, and the main objectives of this research performed.

Chapter 2: Literature review of the mechanisms and factors involved in the soil compaction formation and how the consequence due to the compaction on properties, identified research gap and detailed research objectives.

Chapter 3: Meta-analysis of how soil water retention function response to compaction and how the soil basic properties affect this response.

Chapter 4: Field and lab experiment to determine the traffic induced-compaction effects on soil physical properties under different planting ages in New Zealand apple orchards.

Chapter 5: Field and lab experiment to Investigate of traffic induced-compaction impact of compaction on soil chemical properties and health under different planting ages in New Zealand apple orchards.

Chapter 6-7: Collective discussion and summary of the results from chapters 3 to 5 and the recommendations for future research.

Chapter 2

literature Review

2.1 introduction

Soil compaction is one of the most widespread and damaging processes affecting soil quality globally (Hamza & Anderson, 2005; Hu et al., 2021; Peth et al., 2010; Shah et al., 2017). It occurs when soil particles are rearranged, reducing the void spaces between them and bringing them into closer contact, which leads to an increase in bulk density (Hamza & Anderson, 2005). Peth et al. (2010) reported that compaction-induced soil degradation affected approximately 33 million hectares of arable land in Europe and a staggering 68 million hectares worldwide. In natural ecosystems, compaction can result from various processes such as freezing and thawing, soil swelling and shrinking, and certain chemical precipitation events (Défossez & Richard, 2002; Pagliai et al., 2003). However, in agricultural contexts, soil compaction is most commonly attributed to farming practices, particularly machinery traffic and animal trampling (Hamza & Anderson, 2005; Hu et al., 2021). Owing to the growing demand for increased food production and the escalating weight of agricultural machinery, contemporary soils experience significantly higher levels of pressure compared to historical conditions (Hu et al., 2021). This intensified traffic-induced soil structural degradation (compaction) adversely impacts soil structure (Hu et al., 2018), leads to the loss of soil organic matter (Beare et al., 1994) and stands out as one of the foremost challenges in modern agriculture (Wei et al., 2021). Soil compaction typically has detrimental effects on various soil physical and chemical properties. It can alter essential soil functions, including soil water retention, gas exchange capacity, and nutrient mobility (Chan et al., 2006). As a result, these changes can have profound implications for plant growth and agricultural production (Wei et al., 2021). As a form of soil structural issue, it is important to introduce the concept of soil structural vulnerability or susceptibility. Soil structural vulnerability (susceptibility) refers to the soil`s structural capacity to withstand stress (Kay et al., 1994) When soil is structurally vulnerable, it tends to exhibit more pronounced changes in its physical properties when subjected to cultivation or compaction pressures (Hu et al., 2021).

This PhD study aims to investigate how soil compaction affects soil properties and health. The purpose of this chapter is to provide insight into understanding the mechanisms and factors involved in soil compaction and the effects that compaction has on soil physical, chemical, and hydraulic properties. This chapter will provide the necessary context for analysing how these effects contribute to changes in soil health, supporting the broader objectives of the study.

2.2 Causes and influencing factors of soil compaction

Soil compaction can occur through both natural and anthropogenic processes within contemporary agricultural practices. It can occur naturally due to processes like freezing and thawing, swelling and shrinking of the soil, or internal forces caused by clay movement, organic acids, or glacial activity (Défossez & Richard, 2002; Horton et al., 2016; Pagliai et al., 2003). Soil compaction caused by anthropogenic processes, such as mechanised equipment and the trampling of animals, is recognised as a prominent factor contributing to soil. The continuous intensification of agriculture demands more operations such as tillage, irrigation, and fertiliser application, often employing ever-larger and heavier machines; this has raised the risk of soil compaction (Shah et al., 2017) and it is recognised as the most common cause of soil compaction (Hamza & Anderson, 2005; Nawaz et al., 2012; Shah et al., 2017). Traffic-induced soil compaction is usually influenced by loading (the weight of the machine) (Nawaz et al., 2012) and soil strength (the capacity of soil to resist deformation or failure under applied stress) (Alakukku et al., 2003). The loading of machinery is contingent upon various factors, including axle load, tyre characteristics, and the interaction between tyres and the soil (Nawaz et al., 2012). Soil strength, in turn, is influenced by a combination of soil chemical and physical attributes, such as soil structure, organic matter content, and moisture levels during the compaction process (Nawaz et al., 2012).

2.2.1 Soil internal factors effects on the compactions

The degree of soil compaction is governed by factors linked to soil properties, such as initial bulk density, soil texture, soil organic matter, initial water content, and structural characteristics (aggregates). Soils with higher initial bulk density generally experience a lower degree of compaction when subjected to further compressive forces (Hu et al., 2023; Keller et al., 2011; Schjonning & Larnandé, 2018). However, an increase in bulk density is also an indication of soil compaction, especially in fine-textured soils (Hu et al., 2023). Compared to coarser-textured soils, clayey and silty soils are more sensitive to soil compaction at a given bulk density (Hillel, 2003). Soils predominantly composed of 1:1 type clay minerals, such as kaolinite, exhibit lower compaction susceptibility compared to soils primarily consisting of 2:1 type clay minerals, such as smectite and vermiculite (Hamza & Anderson, 2005; Warrick, 2001). The texture effect is also closely related to the soil water content when compaction occurs, with maximum compaction usually found when soil wetness is at a medium level (Adekalu & Osunbitan, 2001; Hu et al., 2023; Luciano et al., 2012). Additionally, the higher valency of adsorbed cations (ranging from monovalent to divalent to trivalent) and increased ionic strength result in less risk of compaction under the same compressive force (Warrick, 2001). Soil texture also affects soil aggregate stability, which influences soil compactibility (Borůvka et al., 2002; Hu et al., 2023). Soil particles, especially clay particles, bind micro- and macro-soil aggregates, helping to prevent soil compaction (Shah et al., 2017). The higher the soil aggregate stability, the lower the risk of soil becoming compacted (Shah et al., 2017).

Soil organic carbon usually plays a significant role in soil aggregate stability and, hence, in reducing soil compactibility. Studies have shown that increasing soil organic carbon (SOC) content enhances the formation and stability of soil aggregates by facilitating organic binding agents (Hamza & Anderson, 2005; Nawaz et al., 2012; Shah et al., 2017). It also improves aggregate strength by modifying the cohesiveness of inter- and intra-aggregate structures and increasing particle friction within the aggregates (Shah et al., 2017). At lower SOC contents, aggregate stability is reduced, which is linked to higher degrees of soil compaction (Hu et al., 2023). Furthermore, other factors that affect the severity of compaction are also related to soil organic matter. For example, higher SOC contents have the potential to diminish maximum soil compactibility by augmenting rebounding forces and enhancing the soil's elastic properties (Hamza & Anderson, 2005; Warrick, 2001).

Soil moisture content at the time of compaction is another important factor affecting the severity of soil compaction. In general, lower initial water content results in reduced soil deformability (Richard et al., 1999). Increasing initial soil water content raises the susceptibility of soil to compaction (Hu et al., 2023). If the soil becomes too wet, compaction becomes less severe, but the risk of plastic deformation increases (Hamza & Anderson, 2005; van Asselen et al., 2009). The principles behind this non-linear behaviour were described by Dexter (1988), who defined three types of structural changes when a given force compresses aggregates under different moisture conditions. Under dry conditions, a minimal degree of aggregate reconfiguration and breakage takes place primarily at contact points between soil particles. In moderately moist conditions, some aggregates fracture, and materials flow with water into the spaces between the remaining intact aggregates. In highly wet conditions, compression predominantly occurs through plastic deformation, resulting in the formation of flat contact areas where the aggregates are pressed against each other (Dexter, 1988). Therefore, it is suggested that when the soil is wetter than the field capacity, the traffic of heavy machinery should be avoided (Batey, 2009; Tim Chamen et al., 2015)). Alternatively, low-ground-pressure tyres could be used during the wetter season to reduce or prevent soil compaction (Tim Chamen et al., 2015).

2.2.2 Soil external factors for causing compaction

Traffic-induced compaction has been commonly reported by many authors in cropping and horticultural systems, as well as in forestry (Deurer et al., 2012; Jourgholami et al., 2019; Nazari et al., 2023; Paltineanu et al., 2016; Petry et al., 2016; Schäffer et al., 2007; Tuzzin de Moraes et al., 2016; Wei et al., 2021). The degree of compaction caused by traffic wheels depends on several factors, including axle load, which is the weight transmitted to the ground through a single axle of a vehicle, tyre dimensions (size), which determine the area affected by the tyre, velocity, which is the speed of the vehicle moving across the soil, tyre inflation pressure, and the number of traffic passes (Hamza & Anderson, 2005).

When the applied load surpasses the soil's internal strength, plastic deformation occurs, resulting in structural changes (Dexter & Horn, 1988). Plastic deformation refers to the permanent alteration in the shape or structure of soil when subjected to a compressive force that surpasses its elastic limit—the maximum stress the soil can withstand without permanent damage (Haas et al., 2016). This deformation involves the rearrangement and displacement of soil particles as the soil is subjected to a compressive force that exceeds its elastic limit (Dexter, 1988). The changes in soil structure caused by compaction have significant effects on soil water transport processes(Dexter, 1988).

A higher axle load usually results in a stronger effect of soil compaction by applying greater ground contact pressure (Hamza & Anderson, 2005; Nawaz et al., 2012; Shah et al., 2017). Ground contact pressure, which is calculated by dividing the axle load by the area of contact between the machine and the soil, represents the force driving soil compaction (Hamza & Anderson, 2005). With the same contact surface area, an increase in load weight (contact pressure) leads to a greater level of compaction (Gysi et al., 1999; Nawaz et al., 2012). Moreover, the compaction effect in deeper soil layers is influenced by the total axle load, as greater pressure applied to the soil results in a deeper impact on its structure (Botta G et al., 1999; Hamza & Anderson, 2005). For example, Hamza and Anderson (2005) reported that when the axle load exceeds 9 Mg, bulk density and penetration resistance increase in the subsoil below 30 cm.

Tyre size and inflation pressure also influence the degree of soil compaction, as they control the contact area between machinery and the ground. Smaller or single-tyre farm machines have been found to result in more severe compaction compared to multi-tyre machines due to the higher ground pressure exerted per unit area (Shah et al., 2017). Under the same machine weight, lower inflation pressure can reduce ground contact pressure and therefore significantly decrease the level of compaction (Hamza & Anderson, 2005).

The speed of track wheeling also strongly affects the degree of traffic-induced compaction. Faster traffic speeds reduce the duration of loading and the magnitude of stress, resulting in less compaction (Alakukku et al., 2003; Zhai & Horn, 2019b). For example, under the same axle load, shorter loading durations result in smaller compaction effects on the soil (Ghezzehei & Or, 2001; Keller et al., 2013). Moreover, the frequency of traffic highly affects the degree of compaction, the more passes, the greater the soil deformation. As reported by many authors, the first pass of traffic generally results in the most severe compaction (Ampoorter et al., 2010; Hamza & Anderson, 2005; Nawaz et al., 2012; Shah et al., 2017). Subsequent traffic passes continue to affect soil properties in deeper layers, but to a decreasing extent (Hamza & Anderson, 2005; Horn & Fleige, 2003). According to an extensive review by Hamza and Anderson (2005), when the number of passes exceeds 10, compacted soil layers can be found down to a depth of 50 cm.

2.3 Compaction effects on soil properties

Various soil physical parameters, such as bulk density, penetration resistance, aggregate stability, soil pore-related functions, and soil hydraulic properties, have been used to characterise the extent of traffic-induced soil compaction (Nawaz et al., 2012). A brief review of the changes in soil properties when subjected to compaction is provided below to enhance the understanding of how soil properties respond to compaction.

2.3.1 Compaction effects on soil bulk density and porosity

Soil bulk density and total porosity are commonly used parameters to characterise the extent of compaction and its implications for soil physical properties (Assouline, 2006). When soil strength, which refers to the ability of soil to resist deformation and rupture under applied forces, is exceeded, its capacity to resist external loading diminishes. This results in increased contact between soil particles, leading to a denser soil structure (Dexter, 1988). As compaction increases, soil particles are rearranged closer together, which leads to an increase in dry bulk density and a corresponding decrease in total soil porosity. Properties such as soil penetration resistance and saturated hydraulic conductivity are strongly associated with bulk density (da Silva et al., 1997; Lipiec & Hatano, 2003; Unger & Jones, 1998). Since compaction primarily affects soil physical properties through changes in bulk density and total porosity, these factors are easier to measure compared to indirect effects like soil aeration and water movement (Batey & McKenzie, 2006).

Soil pores are usually classified into three types: macro-pores, meso-pores, and micro-pores. Macro-pores play an important role in gas and water flow, supplying oxygen to the soil microbiota (Shah et al., 2017; Zhai & Horn, 2019a). Compared to other soil pores, macro-pores are more sensitive to compaction, and their proportion can easily be reduced during the compaction process (Alakukku, 1996; Shah et al., 2017). The volume of meso- and micro-pores is usually not affected or only slightly impacted by soil compaction (Etana et al., 2013; Ma et al., 2022). This is because the homogenisation of the soil pore system typically increases with more traffic wheeling (Horn et al., 2003).

However, measuring the extent of compaction using bulk density or total porosity does not provide direct insights into pore-related functions, such as water storage, movement, and soil aeration. This is because soil pore connectivity and continuity, which are important for fluid flow, cannot be represented by total porosity or bulk density alone (Zhai & Horn, 2019a). Under a given bulk density for the same soil, pore geometry and continuity can vary greatly due to differences in soil type and management. Therefore, for assessing the effects of soil compaction on the soil water regime, pore-related functions are a more useful indicator(Hu et al., 2023).

2.3.2 Compaction effects on gas diffusivity

Soil structural degradation due to compaction generally leads to reduced gas diffusion. This occurs because gas diffusivity in the soil is regulated by structural properties such as pore continuity, connectivity, and air-filled porosity (Talukder et al., 2022). Since the intensity of compaction increases, there is a decrease in soil porosity, primarily due to the reduction of large pores, which leads to a reduction in air-filled porosity as well as alterations in pore continuity and connectivity (Ball & Ritchie, 1999; Zhai & Horn, 2019a). According to Papendick and Runkles (1965), changes in pore continuity and connectivity (increased pore tortuosity) and a reduction in air-filled pore space restrict gas diffusion when the soil becomes wet. Thus, gas diffusivity is a more accurate metric for explaining soil gas movement and representing the average continuity of air-filled pores in soil affected by compaction (Moldrup et al., 2001). Numerous studies have documented the effects of compaction on gas diffusivity (Deepagoda et al., 2011; Moldrup et al., 2013; Moldrup et al., 2001; Papendick & Runkles, 1965; Rousset et al., 2022; Talukder et al., 2022; Zhai & Horn, 2019a). These studies show that when soil aeration and gas exchange are reduced, there are likely reductions in crop production and increases in N_2O emissions (Glab, 2014; Hamza & Anderson, 2005; Zhai & Horn, 2019a).

2.3.3 Compaction effects on penetration resistance

Soil penetration resistance has been widely used to identify soil compaction in the field. Generally, soil penetration resistance increases with the degree of soil compaction, although this also varies with soil wetness (Nawaz et al., 2012; Shah et al., 2017). The higher the intensity of mechanical forces (traffic weight and passes) applied, the greater the extent of compaction, resulting in soil particles being packed closer together and thus increasing the soil's penetration resistance (Shah et al., 2017). For example, Pagliai et al. (2003) found that penetration resistance increased by 12.5% and 49.6% after one and four passes of wheeled tractor traffic, respectively. Lower soil water content results in higher penetration resistance (Batey, 2009; Hu et al., 2023; Lipiec et al., 2002; Shah et al., 2017), whereas higher soil moisture content leads to lower penetration resistance due to reduced soil cohesion and strength, making the soil structure more flexible (Hamza & Anderson, 2005; Horn et al., 1995; Nawaz et al., 2012). Root penetration in the soil is highly influenced by soil penetration resistance (Keller et al., 2019). For instance, Sinnett et al. (2008) reported that in their experiment in forest soil (anthropic regosol) affected by sand and gravel extraction, almost 90.7% of roots were present in soil with penetration resistance lower than 3 MPa, while a smaller proportion of roots (70.2%) was found in soil with PR less than 2 MPa. In most cases, roots can penetrate the soil with PR greater than 2 MPa only by using bio-channels and through temporal changes in soil properties, such as those caused by varying moisture content or driven by land-use management (Martino & Shaykewich, 1994).

2.3.4 Compaction effects on hydraulic properties

Alteration of the soil pore system due to compaction directly affects soil water retention and transport processes in the vadose zone (Alaoui et al., 2011; Assouline, 2006). Soil water retention, typically expressed as the soil water retention curve (as shown in Figure 1), is used by many authors to determine the dynamics of soil pore size distribution under varying soil management practices (Holthusen et al., 2018; van Dijck & van Asch, 2002; Wu et al., 1997; Yadav et al., 2020). By altering the soil pore size distribution, compaction results in a flattened water retention curve, characterized by lower total porosity and a reduction in the slope at the inflection points (Alaoui et al., 2011; Dexter, 2004). This flattening occurs due to changes in the volume of macro-pores and an increase in micro-porosity. The loss of macro-pores from compaction markedly decreases soil water retention at higher matric potentials, thereby flattening the slope of the soil water retention curve (de Moraes et al., 2019; Startsev & McNabb, 2001). For example, Berisso et al. (2012) found that the volumetric water content at -6, -10, and -30 hPa was significantly reduced in compacted soil; similar results were also reported by Startsev and McNabb (2001) and Glab (2014). Conversely, water retention at lower suctions was either unaffected or increased after compaction due to an increase in micro-pore volume (Anlauf & Rehrmann, 2012; Ngo-Cong et al., 2021; Startsev & McNabb, 2001). The point where these two processes converge is known as the inflection point, as shown in Figure 1 (Dexter, 2004). Above this point, the curve represents pores formed due to soil structure, which are primarily air-filled, while below the inflection point, the pores are mostly a result of texture and hold water more tightly (Dexter, 2004).

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Figure 1. An example of a soil water retention curve showing the specific points related to water dynamics in the soil, the figure retrieved from Suazo et al. (2016).

Another important parameter widely used to evaluate the effect of soil compaction on hydraulic properties is saturated hydraulic conductivity (K_{sat}). Generally, K_{sat} values are highly associated with soil macro-pores and are significantly reduced by the compaction process (Ampoorter et al., 2010; Hu et al., 2021; Keller et al., 2019; Nawaz et al., 2012; Shah et al., 2017; Zhai & Horn, 2019b). This reduction in K_{sat} is attributed to the decreased volume and connectivity of macro-porosity during compaction. For example, Kuncoro et al. (2014) observed a strong positive linear relationship between soil pores larger than 30 µm and K_{sat} in their compaction experiments. Similarly, Kim et al. (2010) reported a 74% decrease in K_{sat} in silt loam soil at the first 10 cm in traffic positions compared to non-traffic positions, attributed to the loss of macro-pores.

2.3.5 Compaction effects on aggregate stability

Soil aggregate stability is a crucial factor in maintaining good soil structure and health, which affects productivity and sustainability (Shah et al., 2017). Soil particles cluster together to form aggregates due to cohesive forces and interactions with organic matter, cations, and anions. The stability of these aggregates is defined by their ability to resist dispersion and degradation (Shah et al., 2017). Higher aggregate stability is often associated with reduced effects of compaction on soil properties (Baumgartl & Horn, 1991; Hu et al., 2023; Shah et al., 2017). Compaction alters soil structure by breaking down aggregates or merging them into larger units, which increases bulk density and reduces the volume of larger pores (Batey, 2009; Horn et al., 1995; Richard et al., 1999). This process also decreases the connectivity of pore spaces (Défossez & Richard, 2002; Hamza & Anderson, 2005; Shah et al., 2017). The reduction in pore space and aggregate stability heightens the risk of surface runoff and soil erosion by decreasing infiltration rates and surface soil aggregation (Hamza & Anderson, 2005; Kosmas et al., 1997; Way et al., 2005).

Soil organic carbon is highly associated with the formation of soil aggregates, as it enhances binding between soil particles, stabilising the soil structure and increasing aggregate stability (Cao et al., 2021; Du et al., 2017; Six et al., 2000). In turn, stable aggregates help protect soil organic matter from microbial decomposition (Cao et al., 2021). Consequently, tillage, which often reduces aggregate stability by breaking larger aggregates, can lead to accelerated decomposition and loss of organic matter (Cao et al., 2021; Du et al., 2017; Six et al., 2000).

2.3.6 Compaction effects on soil chemical properties

As compaction alters soil physical properties such as water movement and gas exchange, it subsequently influences soil chemical properties. Compaction has been shown to affect the levels of carbon and nitrogen in the soil. For instance, De Neve and Hofman (2000) reported that carbon mineralisation was significantly reduced when the soil was compacted to a bulk density of 1.6 mg m^{-3}, resulting in a higher accumulation of organic carbon compared to uncompacted soil. Similarly, Tan and Chang (2007) observed a significant reduction in carbon mineralisation and net nitrification rates in incubation experiments with artificially compacted silt loam soil. These reduced rates of carbon and nitrogen mineralisation indicate lower microbial activity, as evidenced by decreased CO_2 emissions, which are directly linked to microbial processes (Beare et al., 2009; Silveira et al., 2010).

Regarding nitrogen cycling, the anaerobic conditions more prevalent in compacted soils can increase denitrification, consequently elevating N_2O emissions (Nawaz et al., 2012). Denitrification rates and N_2O emissions in compacted soils have been found to be 2 to 7 times higher than those in uncompacted soils, depending on the degree of compaction (Abbasi & Adams, 1998; Li et al., 2014; Soane & Van Ouwerkerk, 1995). This increase in denitrification due to compaction reduces nitrogen availability for plants (Tan et al., 2007) and may lead to increased fertiliser requirements or reduced crop production(Nawaz et al., 2012). Additionally, soil compaction affects the redox potential of the soil solution by reducing oxygen availability, which shifts microbial processes from aerobic to anaerobic pathways. This shift can further reduce the availability of phosphorus (P) and potassium (K) to plants (Frene et al., 2024).

2.3.7 Compaction effects on soil microbial communities and fauna

Soil microbial communities play a significant role in nutrient cycling, carbon sequestration, and the formation of soil aggregates (Frene et al., 2024). Compaction influences the composition and function of these microbial communities by limiting habitat space between aggregates and reducing the availability of water, oxygen, and nutrients (Bach et al., 2018; Frene et al., 2024). For example, Li et al. (2004) found that in soils with high bulk density, the abundance of soil bacteria and fungi decreased by 26 to 40%. Similar findings have been reported by other researchers (Frey et al., 2011; Hartmann et al., 2014; Longepierre et al., 2021). However, some studies suggest that soil compaction does not significantly affect total microbial biomass, depending on environmental conditions and microbial species(Jordan et al., 2003; Ponder Jr & Tadros, 2002; Tan & Chang, 2007). In compacted soil, less oxygen is available for microbial communities due to the reduction in macro-pore volume, which leads to anaerobic conditions and reduces overall microbial activity (Pupin et al., 2009). These conditions can also alter the populations of microbes responsible for nutrient transformation, resulting in reduced nutrient availability for plants (Pupin et al., 2009). For instance, Smeltzer et al. (1986) reported that the populations of bacteria, fungi, nematodes, and arthropods were all significantly smaller in compacted soils. Soil compaction may not affect the overall population of soil fauna but can influence their distribution (Nawaz et al., 2012). For example, nematodes, which play an important role in the soil food web through the decomposition of organic matter, nutrient cycling, and herbivory (Bouwman & Arts, 2000), are affected by compaction. According to Bouwman and Arts (2000), in heavily compacted soil, herbivore nematodes predominated over bacterivore and omnivore nematodes. Additionally, the population of earthworms is also reported to decrease with increased soil compaction, as they are not able to move through soil with penetration resistance above 3 MPa (Chan & Barchia, 2007; Dexter, 1978; Radford et al., 2001). Furthermore, the activities of enzymes such as phosphatase, urease, amidase, and dehydrogenase were found to be reduced in compacted soil (Jordan et al., 2003; Nawaz et al., 2012; Pupin et al., 2009; Tan & Chang, 2007).

2.4 Current soil compaction studies in New Zealand

On a global scale, increasing attention has been paid to soil compaction problems (Wei et al., 2021). Many researchers have conducted studies on the effects of compaction on agricultural and forestry systems (e.g., (Awe et al., 2020; de Moraes et al., 2019; Fashi et al., 2017; Holthusen et al., 2018; Rossetti & Centurion, 2018; Yadav et al., 2020)). In New Zealand, soil compaction issues are frequently encountered because of soil management practices(Haynes & Tregurtha, 1999; Hu et al., 2021; Shepherd et al., 2001). According to the Ministry for the Environment & Stats NZ (2018), approximately 65% of dairy sites, 39% of horticultural and cropping sites, and 41% of dry stock sites were found to have soil compaction issues between 2014 and 2017. Many studies have explored the effects of soil compaction on productivity and environmental outcomes in cropland and dairy farming at a national scale (e.g., (Balaine et al., 2013; Chamindu Deepagoda et al., 2020; Hu et al., 2021; Jayarathne et al., 2021; McQueen & Shepherd, 2002).

However, there are limited studies conducted on horticultural systems that investigate the effects of compaction on soil properties and health in New Zealand. Macro-porosity in approximately 48% of orchard sites was below the target range between 2014 and 2018, indicating an increase in soil compaction in orchards compared to the period between 2014 and 2017 (Ministry for the Environment & Stats NZ, 2021). As a significant export horticultural product for New Zealand, fresh apple production generated a value of nearly $900 million in 2020 (MPI, 2020). According to Pipfruit (2017a), around 12% of the area of apple orchards in New Zealand was compacted. The primary cause of compaction in orchards can be attributed to the repeated traffic of machinery used for spraying pesticides and fungicides (Paltineanu et al., 2016). For instance, Goh et al. (2001) found significantly lower bulk density and higher infiltration rates around the tree line than on vehicle tracks, and soil compaction caused by traffic vehicles also reduced the total number of earthworms. Penetration resistance (PR) was also found to be significantly higher in traffic areas compared to non-traffic areas in both topsoil and subsoil (Vogeler et al., 2006), which can limit root growth. Additionally, the adverse impacts from the stresses exerted by machinery are cumulative over the years (Ramos et al., 2022). To date, only a limited number of studies have been conducted to determine the effects of soil compaction on physical and chemical properties in apple orchards in worldwide ((Paltineanu et al., 2016; Swarts et al., 2016; Wei et al., 2021) and New Zealand (Deurer et al., 2012; Goh et al., 2001; Vogeler et al., 2006), and the relationship between traffic track and planting ages on soil functions remains unclear.

2.5 Identified research gap and objectives of this PhD study

2.5.1 Identified research gaps

This review of literature has revealed several gaps in our current knowledge As discussed in this review, the evaluation of soil compaction has predominantly focused on changes in soil structure, such as bulk density or alterations in pore volume. However, the relationship between these structural changes and key hydraulic properties, which are crucial for soil functions and ecosystem services, has not been adequately explored. Most existing studies concentrate on the structural aspects of compaction, with limited attention given to how compaction affects soil hydraulic properties or how basic soil characteristics influence this response. To date, there has been a lack of comprehensive reviews or quantitative studies on the impact of compaction on soil water retention and physical quality, including the role of inherent soil properties in this process.

Given the limited research on soil compaction in New Zealand apple orchards, particularly regarding traffic-induced compaction, a study is needed to examine its effects on soil properties, including chemical, physical, and hydraulic characteristics. While compaction issues are known to occur, there is a significant gap in understanding their specific causes and extent in orchard soils. By investigating the influence of orchard age and traffic patterns on soil properties, we hypothesise that older orchards, with longer exposure to traffic, may exhibit greater levels of compaction. This research is critical not only for improving orchard management practices by identifying compaction risks but also for understanding the long-term impacts of orchard practices on soil health.

2.5.2 Research objectives

Given these knowledge gaps identified here, this PhD project aims to explore the traffic-induced compaction effects on the soil properties, including chemical and physical properties. To achieve this objective, three specific aims were devised. By conducting a comprehensive literature review (meta-analysis) to investigate how the soil water retention-related function responds to compaction and how the soil's basic properties affect this response. Data collected from field and laboratory studies were gathered to explore the impact of soil compaction on soil physical, chemical and hydraulic properties in New Zealand apple orchards:

1) Conduct a comprehensive literature review and meta-analysis to investigate how soil properties, such as clay content, soil moisture content, and organic matter, influence the response of soil water retention-based properties to compaction. This review will identify the key factors that mediate the relationship between compaction and soil water retention-based properties, addressing the current lack of understanding in this area.

2) Investigate the impact of soil compaction on soil physical properties (e.g., bulk density, porosity), hydraulic properties (e.g., infiltration rate, water retention), and overall soil physical health in New Zealand apple orchards. This objective will include examining how these impacts vary with different planting ages and traffic positions, filling the gap in knowledge about the long-term effects of compaction on orchard soils.

3) Assess the effects of soil compaction on soil chemical properties (e.g., carbon, nitrogen, hot water extractable carbon and mineralisable nitrogen) and overall soil health under varying planting ages and traffic positions in New Zealand apple orchards. This study

will provide insights into the chemical changes induced by compaction under varying planting ages and traffic positions, contributing to a better understanding of how compaction influences soil fertility and sustainability in orchard systems.

Chapter 3

Meta-Analysis of soil water retention-based properties in response to traffic-induced compaction

3.1 Abstract

Traffic-induced soil compaction is a significant factor contributing to soil structural degradation in modern agriculture, affecting soil water storage properties and overall soil physical quality. To enhance our understanding of how these properties respond to traffic-induced compaction and to investigate the influence of soil basic properties soil organic carbon, clay content, and soil water content at compaction), a meta-analysis was conducted to assess the effects of traffic passes, axle-load, and tyre inflation pressure on soil water retention based properties (field capacity, available water capacity, and macro-porosity, bulk density and S index). Overall, the traffic and soil basic properties did not significantly affect field capacity, but they led to a substantial reduction in macro-porosity of approximately 26%. Less intensity of traffic tended to result in an increase, or less reduction, in available water capacity (AWC) and soil quality index (S index). Bulk density (BD) exhibited an overall increase of 5.1%, with significant influences from traffic treatment, clay content, soil organic carbon, and soil water content at compaction. The soil organic carbon content strongly influenced the response of available water capacity ($p < 0.05$), bulk density ($p = 0.009$), and S index ($p = 0.0008$) to compaction. High clay content corresponded to a substantial increase in BD ($p<0.05$), a decrease in macro-porosity ($p<0.05$), and a reduction in the soil's available water capacity (AWC, $p<0.05$). When soil water content during compaction is low (0-75% of field capacity), compaction resulted in the most significant increase in bulk density ($p<0.05$) and a decrease in field capacity as calculated by dynamic criteria used to define field capacity (FC_{AO}, $p<0.05$) Medium moisture content at compaction (75-100% of field capacity) corresponded to the lowest increase in BD, highest increase in field capacity at -10 kPa (FC_{10}) and highest decrease in AWC_{10}, AWC_{AO} and S index.

3.2 Introduction

Soil deformation, such as traffic-induced compaction is recognised as a global issue due to its adverse effects on agricultural production and the environment (Nawaz et al., 2012; Shaheb et al., 2021; Sonderegger & Pfister, 2021). The escalation in wheel loads imposed by agricultural machinery during farming operations is a major cause for heightened levels of soil compaction observed over recent decades (Keller et al., 2019). Soil compaction can cause the reduction of soil total porosity, increase bulk density, and alter the soil pore structure that governs water movement and storage, solute transport, nutrient availability, and root growth (Alaoui et al., 2011). These alterations in soil structure subsequently have adverse impacts on food production, the habitat for soil organisms, and various other ecosystem functions (Obour & Ugarte, 2021). For instance, the increase in soil bulk density (BD) and penetration resistance can delay plant emergence, impede root growth, and limit water and nutrient uptake (Bengough et al., 2011; Nawaz et al., 2012). Moreover, key soil functions that are related to soil water retention or storage properties can be significantly affected by traffic-induced compaction (Alaoui et al., 2011; Anlauf & Rehrmann, 2012; Fu et al., 2019).

The extent of compaction caused by field traffic has been linked to several factors, including the number of traffic passes, tyre inflation, the size of tyres, and axle load (Défossez & Richard, 2002; Hamza & Anderson, 2005; Shah et al., 2017). For example, tractors with different track tyres will generate less soil compaction if their tracks have a larger surface area in comparison to wheels on tractors with equivalent power ratings (Brown et al., 1992). Défossez and Richard (2002) reported that high axle load caused compaction and damaged the soil structure and subsoil. In terms of traffic passes, the first pass commonly had a more pronounced impact on inducing soil compaction compared to the further passes (Bakker & Davis, 1995; Fu et al., 2019; Hamza & Anderson, 2005; Nawaz et al., 2012) Likewise, Voorhees et al. (1979) observed that substantial soil compaction in a clay soil occurred at a depth of 75mm after traffic, and this compaction effect extended to deeper soil profiles, ranging from 150 to 300 mm, after three passes.

The magnitude of soil compaction is not only dependent on traffic factors but is also influenced by basic soil properties (such as soil texture and organic carbon (SOC) content) along with the soil moisture status during the compaction (Ampoorter et al., 2010; Défossez & Richard, 2002; Hamza & Anderson, 2005; Hu et al., 2021; Shah et al., 2017). Lower soil compactibility is usually found in soils containing higher SOC content (Nawaz et al., 2012). In contrast, higher compactibility is commonly associated with soils containing less clay content and organic matter (Hu et al., 2023). The extent of soil compaction is also closely related to moisture content at compaction (Hamza & Anderson, 2005; Hu et al., 2023). For example, Smith et al. (1997) pointed out that under a given soil moisture content and compaction force, the degree of compaction depended on the clay content. Similar findings have been reported by many authors (Horn & Fleige, 2003; Hu et al., 2023; Lamandé et al., 2018; Schjønning & Lamandé, 2018), indicating that the relationship between compactibility and soil moisture content may be non-linear and influenced by soil texture. Many studies have investigated the effects of soil compaction on soil water retention-based properties and physical quality (e.g., (Glab, 2014; Ramezani et al., 2017; Schaffer et al., 2008; Tarawally et al., 2004; Wu et al., 1997). In most cases, these studies focused solely on the impact of individual attributes of wheel traffic, such as either axle-load or traffic pass frequency. They examined changes in soil water retention-based properties and physical characteristics without accounting for levels in wheel traffic attributes, including levels of inflation pressure, weight associated with axle-load, and frequency of traffic. Additionally, it is important to consider factors such as soil organic carbon (SOC), clay content, and moisture content at compaction when examining their influence on the degree of soil compaction and its impact on water retention-based and physical quality. Furthermore, no studies have conducted a quantitative or comprehensive review of the impact of compaction on soil water retention-based properties and physical quality, including how soil basic properties influence the compaction effect on these soil characteristics.

In this study, a meta-analysis (MA) approach was employed to analyse data from previously published peer-reviewed articles and quantify the impact of traffic-induced compaction on soil water storage properties (field capacity, available water capacity, and macro-porosity) and soil physical quality (bulk density and S index). This meta-analysis aims to address the following specific objectives: to understand how soil water retention-based properties and soil physical quality respond to varying levels of traffic-induced compaction; and to explore the influence of soil basic properties, such as soil organic carbon (SOC) and clay content, as well as moisture content at the time of compaction, on this response.

3.3 Materials and Methods

3.3.1 Data collection

A comprehensive search was conducted for peer-reviewed journal articles related to soil compaction and soil water retention curve parameters using the Web of Science and Google Scholar search engines. The search spanned the period from 1979 to 2020 due to the data availability and the resolution of the result graph. Publications that contained key components related to soil compaction, soil physical properties, and soil hydraulic properties were selected for further screening. Specific keywords and phrases, including 'soil compaction', 'compaction and bulk density', 'compaction and soil pore functions', 'compaction and soil water retention curve', 'soil water release curve', 'soil moisture characteristic curve', and 'compaction and hydraulic properties', were utilised to identify relevant papers. The articles obtained at the end of the search were screened based on the availability of full texts or the inclusion of pertinent information within our research scope. To ensure a comprehensive search, we also examined the references cited in individual articles and key peer-reviewed publications authored by researchers specialising in soil compaction.

The search considered only articles related to machinery traffic compaction and a stringent selection criterion identified 40 relevant studies for analysis. These criteria included the availability of full-text articles, the inclusion of pertinent information on soil physical properties of interest, and a comparison between non-compacted (control) and alternative treatment groups. Data from these studies were organised into a table, and graphical data were digitised using the GetData Graph Digitize (GetData Graph Digitizer, 2013). Within each study, we conducted multiple paired comparisons by comparing the control group with one or more compaction-treated groups. Through this comprehensive process, we obtained a total of 405 paired comparisons at a consistent depth of 0-30 cm. The specific depth depended on data availability within the 40 selected articles for our research.

3.3.2 Database management

The extracted data from the selected articles were standardised by converting them into consistent units, and the soil water retention curves were re-fitted using a standardised approach. This standardization was necessary due to variations in the methods used across most studies. For example, field capacity (FC) was originally calculated at different tension levels such as -10 kPa and -33 kPa. The calculation method was harmonised by adopting a uniform -10 kPa tension level. The Van Genuchten (Van Genuchten, 1980) model was used to fit the soil water retention curve (SWRC) as Equation 1 below:

$$\frac{\theta(\psi) - \theta r}{\theta s - \theta r} = [1 + (\alpha|\psi|^{n})^{-m} \qquad (1)$$

where $\theta(\psi)$ is the volumetric water content at a certain suction, $\theta s\ and\ \theta r$ are the saturated and residue water content on a volume basis, α is the air-entry value, and n is the pore size distribution index. Additionally, an alternative method for calculating field capacity was applied, this was based on the maximum extent of hydraulic connected pathways that facilitate unsaturated capillary flow (Assouline & Or, 2014). The field capacity value was then computed using fitted α and n from the Van Genuchten model as shown in Equation 2:

$$\psi_{FC} = -\frac{1}{\alpha}[\frac{n-1}{n}]^{(1-2n)/n} \qquad (2)$$

Available water capacity (AWC) was calculated as the difference from FC to -1500 kPa in both methods (-10 kPa and dynamic criteria used to define field capacity introduced by (Assouline & Or, 2014)). The macro-porosity (volume of pores with diameter greater than 30 µm and the soil physical quality index S which were derived from SWRC were also selected as the parameters for this meta-analysis. The S index was calculated by the following Equation 3:

$$S = \left| -n(\theta_{sg} - \theta_{rg}) \left(\frac{2n-1}{n-1}\right)^{\frac{1}{n-2}} \right| \qquad (3)$$

where θ_{rg} and θ_{sg} are residual and saturated soil water content on a mass basis. According to Dexter (2004), soil physical quality (S index) could be categorised into different classes, including very poor ($S < 0.02$), poor ($0.02 < S < 0.035$), good ($0.035 < S < 0.05$), and very good ($S > 0.05$). The information on soil properties variables and compaction treatment were grouped and categorised as in Table 1.

Table 1. The grouped and categorised information for soil variables, control, and treatment for this meta-analysis study.

Control to treatment Variables	Category	Soil properties variables	Category
Control	Control (No experimental traffic)	SOC content	Low (0-1%)
Traffic passes	Minor (1-2 passes)		Medium (1-3%)
	Moderate (3-5 passes)		High (>3%)
	Severely (>5 passes)	Clay content	Low (0-20%)
Axle load	Light (1-6 Mg)		Medium (20-40%)
	Moderate (7-14 Mg)		High (>40%)
	Severely (>14 Mg)	Soil moisture content at compaction	Low (0-75% field capacity)
Tire Inflation pressure	Low (0- 140 kPa)		Medium (75-100% field capacity)
	High (>140 kPa)		High (>100% field capacity)

For studies where only soil organic matter (SOM) information was available, the value of soil organic carbon (SOC) was obtained by converting SOM using Equation 4 below (Obour & Ugarte, 2021):

$$\mathrm{SOM} = 1.72 \times \mathrm{SOC} \qquad (4)$$

The selected soil physical and hydraulic properties for conducting this meta-analysis were field capacity (FC at -10 kPa and calculated by dynamic criteria used to define field capacity, Assouline & Or, 2014), available water capacity (AWC calculated from -10 to -1500 kPa and dynamic criteria used to define field capacity), bulk density (BD), macro-porosity (pore size> 30 µm), and S index. The initial value (measured soil physical and hydraulic properties value before compaction) of these soil physical and hydraulic properties was also categorised in Table 2.

Table 2. The categorised information for initial values (prior to compaction) of selected soil physical and hydraulic properties for this meta-analysis study.

Initial soil physical and hydraulic properties	Category	Description
Initial available water capacity (AWC)	Low	0-15%
	Medium	15%-20%
	High	>20%
Initial field capacity (FC)	Low	0-30%
	Medium	30%-40%
	High	>40%
Initial bulk density (BD)	Low	0-1.25 (g cm^{-1})
	Medium	1.25-1.35 (g cm^{-1})
	High	>1.35 (g cm^{-1})
Initial macro−porosity	Low	0-10%
	Medium	10%-15%
	High	>15%
Initial S index	Low	0-0.035
	Medium	0.035-0.05
	High	>0.05

3.3.3 Statistical analysis

The whole statistical analysis was conducted in RStudio. The R package “metafor” was employed to perform most of the analyses below (Viechtbauer, 2010). The natural log-transformed response ratio (LnRR) was used to calculate the effect size (Hedges et al., 1999) as shown in Equation 5:

$$LnRR = Ln(\frac{X_{trea}}{X_{ctrl}}) \qquad (5)$$

where X_{trea} is the mean treatment value and X_{ctrl} is the mean value in the control group. Equation 6 below was used to calculate the variance of each effect size:

$$v = \frac{S_t^2}{\overline{x}_t^2 n_t} + \frac{S_c^2}{\overline{x}_c^2 n_c} \qquad (6)$$

where n_t is the sample size of the treatment group, n_c is the sample size of the control group, St and Sc are the standard deviations of the treatment and control group. The effect size was calculated by the “escalc” function in the R package “metafor” (Viechtbauer, 2010). When the variance-weighted mixed-model produced a mean effect size value with 95% confidence intervals (Cis) that did not overlap 0, it indicated that a significant difference occurred. To enhance interpretation, the weighted effect size was transformed back into a percentage change from the control treatment using the equation provided below (Equation 7):

$$Change\ (\%) = (e^{LnRR} - 1) \times 100 \qquad (7)$$

The analyses initially employed random-effects models to evaluate the overall responses. Subsequently, mixed-effects meta-regressions were conducted, incorporating several fixed factors (SOC, clay content, three types of traffic treatment - passes, axle-load, and pressure - and moisture content at compaction) as moderators for each response soil physical and hydraulic property. In meta-regressions, the total heterogeneity can be partitioned into two components: the variance explained by the moderators, represented by the Qm-statistic (a Wald-type test of model coefficients, assessing whether the moderator accounts for any significant variability in the data), and the residual error variance, denoted as Qe (Cochran, 1954). A significant Qm-statistic serves as an indicator of the moderators' contribution to the observed heterogeneity in effect sizes (Viechtbauer, 2010).

To assess the impact of various factors on selected soil physical and hydraulic properties, the R package 'glmulti' was used to perform multi-model inference, which was guided by Akaike's information criterion (AIC) (Akaike, 1998). This method involves model selection by fitting all conceivable combinations of factors while considering AIC values. The significance of a specific factor was quantified by the summation of weights assigned to models in which the candidate factor was incorporated.

The publication bias in each soil physical and hydraulic property was analysed by Egger’s regression (Figure A 4-10), which regressed the effect size against their standard errors weighted by their inverse variance (Egger et al., 1997). In the absence of publication bias, we expect the weighted regression slope to be zero. The trim-and-fill method (Duval & Tweedie, 2000) was applied to detect and address funnel plot asymmetry resulting from potential publication bias.

3.4 Results

3.4.1 Effects of soil compaction on bulk density and macro-porosity

Overall, the bulk density (BD) significantly increased by 5.1% (ES 0.05) and all soil factors (initial BD, MC at compaction, clay content and SOC) had an influence on the effect size of BD ($p<0.05$, Figure 2, appendix Figure A 1e, Figure A 2e). With low initial BD, dry and wet MC at compaction, high clay content and high SOC (>3%) having the highest increase in BD (from 4.8%, ES 0.05 to 11.9%, ES 0.11) upon compaction. All traffic categories elicited a rise in bulk density (BD), with the increment ranging from a minimum of 0.8% (effect size, ES 0.01, high load weight) to the most substantial increase of 7.3% (ES 0.07, high pass number). High SOC content led to the most significant BD increase of 11.9% (ES 0.11), while the BD increased by 7.4% under high clay content. The importance level analysis revealed that SOC plays a more key role in affecting the effect size of bulk density under compacted conditions (Appendix Figure A 3e).

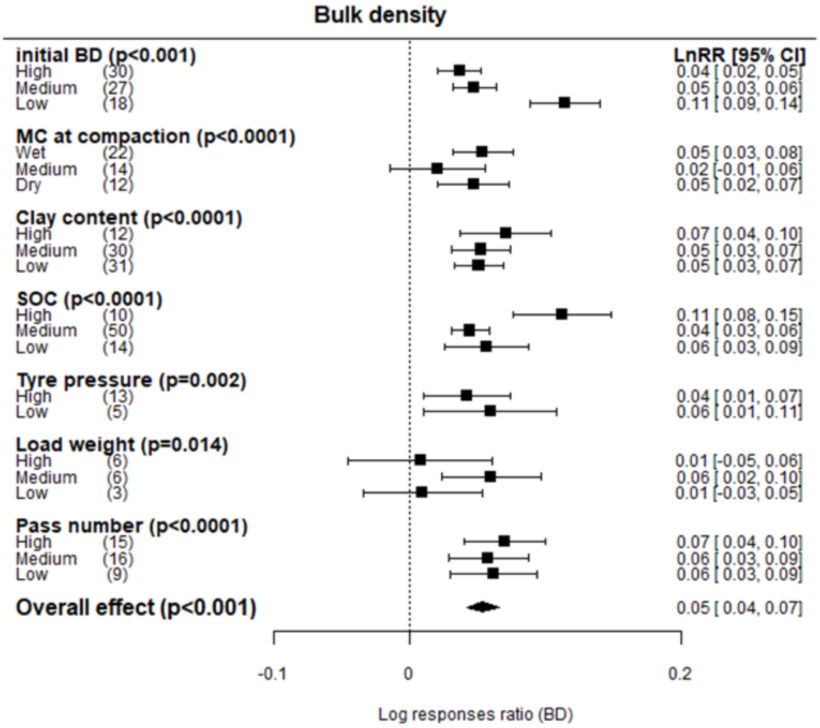


Figure 2. Log response ratio for the effect of soil compaction on bulk density (BD), bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, and $p<0.05$ indicates the factor significantly influences the BD response to compaction.

The overall results also showed a notable reduction of 25.9% (ES -0.30) in macro-porosity. The SOC content ($p<0.05$, Figure 3, appendix Figure A 1f), clay content ($p<0.05$, Figure 3, appendix Figure A 2f) and MC at compaction affected the effect size on macro-porosity significantly ($p<0.05$, Figure 3), With higher initial macro-porosity (medium/high), dry MC at compaction, high clay content, and medium SOC (1-3%) having the highest decrease in macro-porosity (30.9% to 68.9%) upon compaction. Increases in the traffic factor level resulted in a decrease in macro-porosity. A low number of passes already reduced macro-porosity by 14.5%

(ES -0.16). This reduction doubled when the pass number changed to medium (ES -0.32) and was approximately 4 times higher when the pass number increased to high (ES -0.63). Medium levels of load weight caused a 49.6% (ES -0.69) reduction in macro-porosity which was approximately 4 times higher than the low level of load weight. Moreover, the high level of tyre pressure led to the greatest reduction in macro-porosity by 25.1 % (ES -0.29), which was over 3 times higher compared to the low level of tyre pressure. Medium level of SOC resulted in the highest reduction in macro-porosity with 32.4% (ES -0.39). The macro-porosity reduction was most pronounced in soils with high clay content, showing a substantial decrease of -68.9% (ES -1.17). Regarding moisture content at compaction (MC at compaction), there was a notable decrease in macro-porosity when the soil was dry, with a reduction of 56.8% (ES -0.84). According to the importance level analysis, the clay, study treatment (traffic treatment), and MC at compaction were the key factors influencing the effect size of macro-porosity (importance level > 0.8, appendix Figure A 3f).

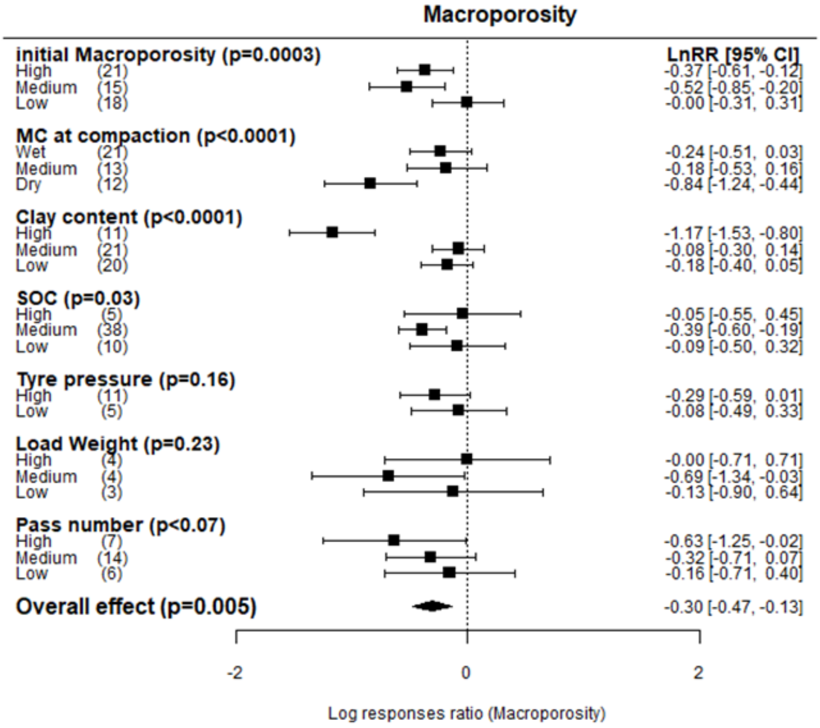


Figure 3. Log response ratio for the effect of soil compaction on macro-porosity, bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, and p<0.05 indicates the factor significantly influences the macro-porosity response to compaction.

3.4.2 Effects of soil compaction on field capacity and available water capacity

Overall, the changes in field capacity at -10 kPa (FC_{10}) as a response to compaction were not significant ($p=0.08$). For FC_{10}, there was an overall increase of 2 % (ES 0.02), as shown in Figure 4. The changes due to traffic factors ranged from -1% (medium tyre pressure, ES -0.01) to 6.5% (high pass number, ES 0.06). Factors such as high SOC and medium MC at compaction produced the highest increase in FC_{10} by 8.8% (ES 0.09) and 7.4% (ES 0.07), respectively. A 5.1% increase in FC_{10} (ES 0.05) was observed in the case of low initial FC_{10}, while a 1% increase (ES 0.01) was recorded for medium initial FC_{10}. High initial FC_{10}, on the other hand, exhibited an 3.1% increase. MC at compaction substantially affected the response of field capacity at -10 kPa to compaction, with medium MC at compaction (75-100% of FC) having the highest increase (7.4%) upon compaction (Figure 4, appendix Figure A 1a and Figure A 2a).

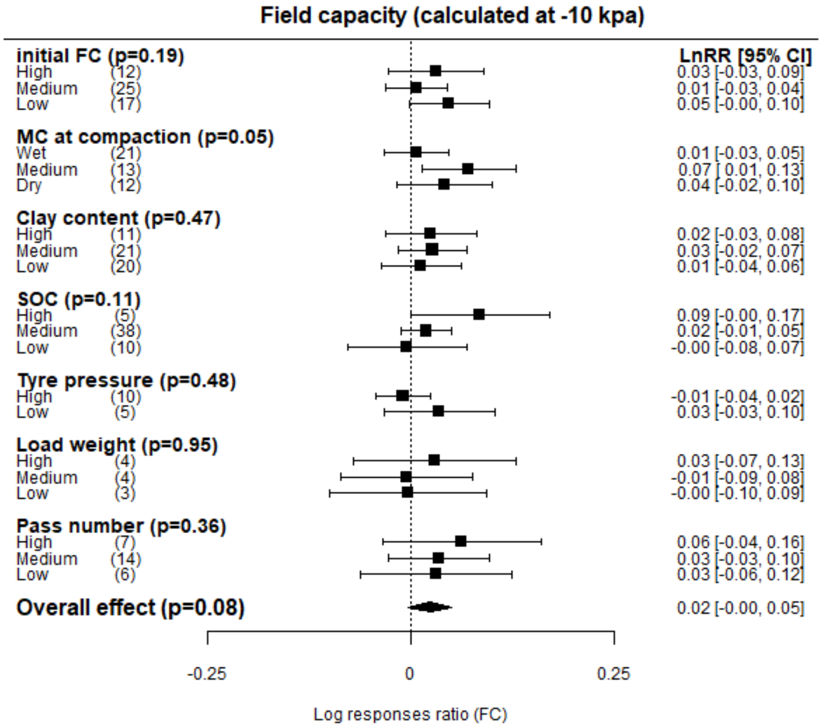


Figure 4. Log response ratio for the effect of soil compaction on available water capacity calculated from -10 kPa (FC_{10}), bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, $p<0.05$ indicates the factor significantly influences the FC_{10} response to compaction.

In contrast, FC_{AO} slightly decreased by 3.9% (ES -0.04) as shown in Figure 5. Initial FC_{AO}, MC at compaction, and SOC significantly affected the response of FC_{AO} to compaction, with high initial FC_{AO}, dry MC at compaction (<75% of FC), high SOC having the highest decrease (-

8.82 to 14.8%) upon compaction. The high level of SOC content resulted in a -11.2% (ES 0.12) reduction in FC_{AO} and the medium level of MC at compaction increased FC_{10} by 2.3% (ES 0.02). The medium level of traffic factor led to the smallest changes in FC_{AO} with -2.7% (ES -0.03), 0.8% (ES 0.01) and -3.4% (ES -0.03) in pass number, load weight, and tyre pressure, respectively. The result of meta-regression revealed that the soil basic properties and moisture content at compaction effect on the response of FC_{AO} to compaction were significant with p<0.0001 (SOC content), p<0.0001 (clay content) and importance level > 0.8 (moisture content at compaction (appendix Figure A 1b, Figure A 2b and Figure A 3b).

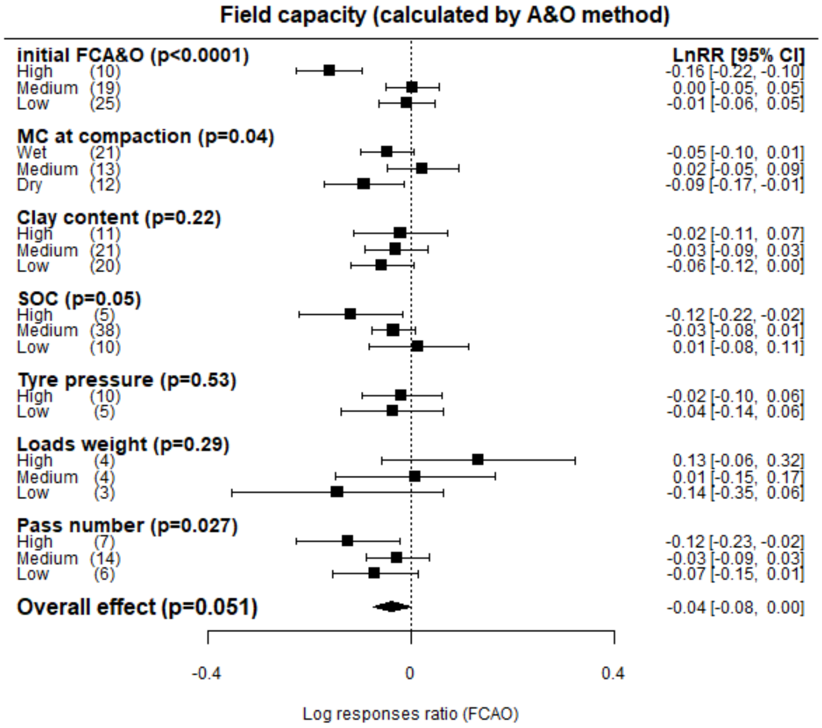


Figure 5. Log response ratio for the effect of soil compaction on field capacity calculated by dynamic criteria used to define field capacity (FC_{AO}), bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, and p<0.05 indicates the factor significantly influences the FC_{AO} response to compaction.

Overall, compaction did not significantly affect the available water capacity computed from -10 to -1500 kPa (AWC_{10}), which decreased by 3.9% (ES -0.04) on average (Figure 6). SOC significantly affected the response of AWC_{10} to compaction, with high SOC (>3%) having the highest increase by 56.7% (ES 0.45), and low SOC (<1%) having the highest decrease by 18.1% upon compaction. High initial AWC_{10} and medium SOC tend to have higher decreases in AWC_{10}, although these effects were not significant when compared with other conditions. Clay content had no substantial influence on effect size in AWC_{10} (p=0.83). The low level of clay content resulted in -2.3% (ES -0.02), and this decrease tripled at the high clay level with 6.8%

(ES -0.07) in AWC_{10}. An increase in the traffic factor level led to AWC_{10} generally decreasing. However, there was a trend that low traffic factor led to an increase or less reduction in AWC_{10} by 12.8% (pass number, ES 0.12), -5.7% (load weight, ES -0.06) and 4.5% (tyre pressure, ES 0.05). Although this increase or reduction was not significant.

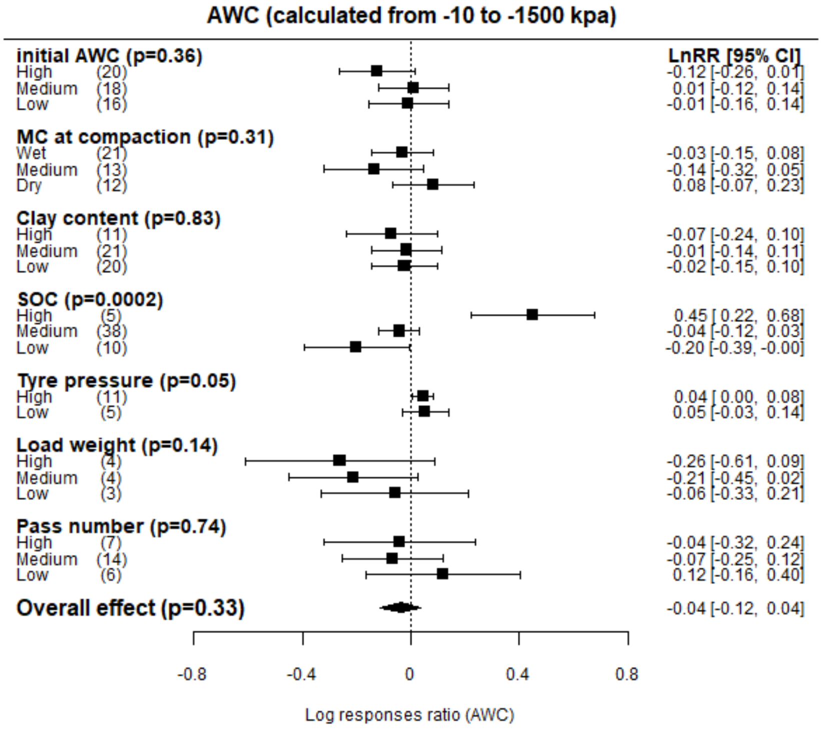


Figure 6. Log response ratio for the effect of soil compaction on available water capacity calculated from -10 to -1500 kPa (AWC), bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, and p<0.05 indicates the factor significantly influences the AWC_{10} response to compaction.

On the contrary, the overall reduction in AWC_{AO} was significant at -16.5% (ES -0.18, Figure 7). MC at compaction, clay content and SOC strongly affected the response of AWC_{AO} to compaction, with medium MC at compaction, high clay content and high SOC (>3%) having the highest decrease from 26.4% (ES -0.31) to 33.6% (ES -0.41) upon compaction. Initial AWC_{AO} also strongly influenced the response of AWC_{AO} to compaction, with medium AWC_{AO} showing the highest decrease by -19.75% (ES -0.22) upon compaction. High pass number, medium load weight and low tyre pressure all resulted in a substantial decrease in AWC_{AO}, with 36% (ES -0.44), 25% (ES -0.29) and -9.44% (ES -0.10), respectively. An increase in the pass number resulted in a further decrease in AWC_{AO}. The importance level analysis suggested that the SOC (importance level > 0.8, appendix Figure A 3c) and moisture content at compaction (MC at compaction, importance level > 0.8, appendix Figure A 3d) were key factors for affecting the effect size of AWC_{AO}. Only MC at compaction was considered a crucial factor in affecting the effect size of AWC_{AO} (Appendix Figure A 3d).

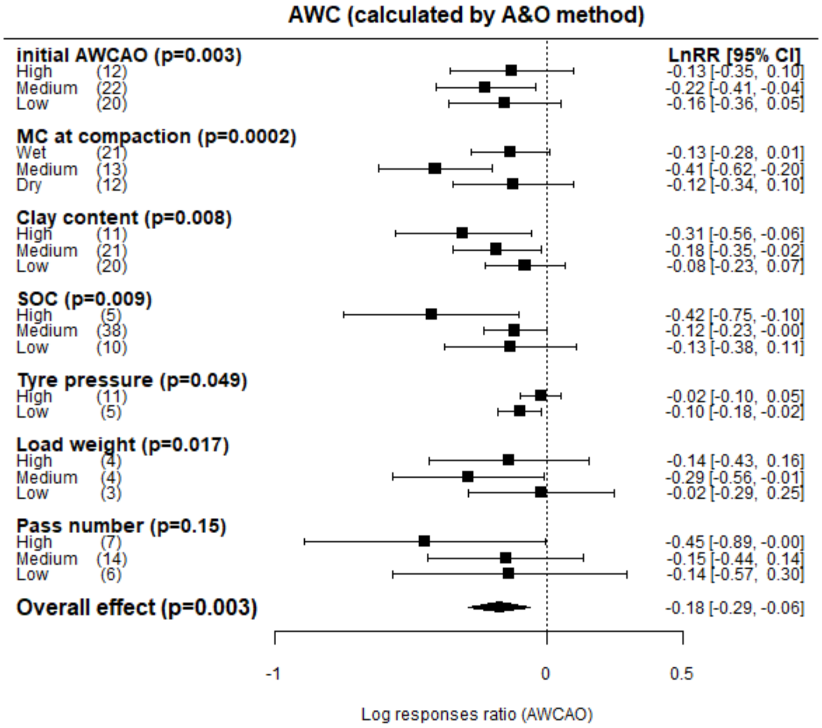


Figure 7. Log response ratio for the effect of soil compaction on available water capacity calculated by dynamic criteria used to define field capacity (AWC_{AO}), bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, and p<0.05 indicates the factor significantly influences the AWC_{Ao} response to compaction.

3.4.3 Effects of soil compaction on S index

The S index was reduced by 16.5% (ES -0.18), and the effect size of the S index was highly affected by the SOC content ($p<0.05$, Figure 8, appendix Figure A 1g), clay content ($p<0.05$, Figure 8, appendix Figure A 2g) and MC at compaction ($p< 0.05$, Figure 8). The traffic factors showed no significant influence on the S index at all levels. The greatest reduction in the effect size of the S index was found in medium pass number, high tyre pressure and high load weight by 12.1% (ES -0.12), 15.3% (ES -0.17) and 23.7% (ES -0.27), respectively. Low and medium SOC resulted in a substantial decrease in the S index with 34.1% (ES -0.42) and 16.5% (ES -0.18), respectively. An increase in clay content did not cause further changes in effect size from -0.17 (low and high, -15.6%) to -0.19 (medium, -17.3%). The moisture content at compaction showed the most significant reduction by 32.3% (ES -0.39) under medium conditions and the second highest reduction by 17.5% (ES -0.19) under wet conditions. The result of the importance level analysis suggested that the SOC, study treatment (traffic treatment) and MC at compaction were the key factors for affecting the effect size of the S index (importance level > 0.8, appendix Figure A 3g)

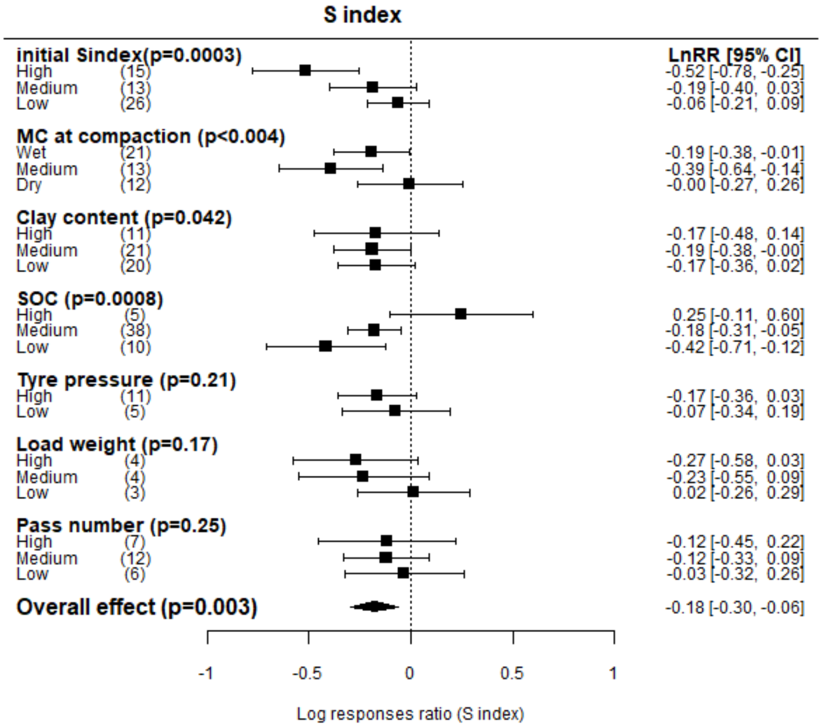


Figure 8. Log response ratio for the effect of soil compaction on the S index, bars represent the 95% confidence intervals, numbers in brackets indicate the number of paired comparisons from the dataset, and p<0.05 indicates the factor significantly influences the S index response to compaction.

3.5 Discussion

3.5.1 The response of soil water retention-based properties to traffic-induced compaction

Traffic-induced soil compaction has strong effects on soil physical properties. These include increases in BD and FC_{10}, while significantly decreasing macro-porosity, FC_{AO}, AWC_{AO} and the S index. The extent of these effects can be influenced by different traffic factors, such as pass number, load weight and tyre pressure. The meta-analysis performed here sheds some light on these effects.

A higher number of traffic passes tended to result in a greater decrease in macro-porosity, FC_{AO}, AWC_{AO} and S index (Figures 3, 5, 7 and 8). Traffic commonly caused the majority of the effects of compaction on soil properties at the first pass (Bakker & Davis, 1995) and further traffic passes were likely to affect the subsoil and lead to a prolonged duration of compaction effects (Alaoui et al., 2011). Medium load weight was associated with the highest increase in bulk density and the most substantial decrease in macro-porosity, AWC_{AO} and S index (Figures 7 and 8). In contrast, low loads were associated with the lowest effects in FC_{AO} (Figure 5). High tyre pressure led to greater reductions in macro-porosity and the S index (Figures 3 and 8), while low pressure more significantly impacted AWC_{AO} (Figure 7). Similar findings by Obour and Ugarte (2021) demonstrated that medium load weight (7-14 Mg), tyre pressure (140-300 kPa) and pass numbers (4-8 passes) most effectively increased soil bulk density and significantly decreased saturated hydraulic conductivity. These changes also affected soil pore size distribution, including soil connectivity and tortuosity (Vervoort & Cattle, 2003).

The influences of compaction on soil properties could be largely linked to changes in soil structure complexity, which modified the heterogeneity of soil pore space to a more uniform distribution (Obour & Ugarte, 2021). Compaction tended to reduce the proportion of macropores (greater than 30 µm) while increasing the volume of meso- and micropores, counteracting gravitational forces (Alakukku, 1996; Obour & Ugarte, 2021). This increase in the volume of meso- and micro-pores would cause an increase in the water content that is held at lower matrix potential (Assouline et al., 1997; Fu et al., 2019), especially for matric potentials from -250 to -1550 kPa (Alaoui et al., 2011). Hence, the available water capacity (calculated from -10 to -1500 kPa, Figure 6) showed an increase or less decrease, the trend in the low traffic treatment levels. It has been reported that with increasing compaction, the number of micropores that retain moisture content at -1500 kPa increases (Anlauf & Rehrmann, 2012; Ngo-Cong et al., 2021). And as the macro-porosity decreased with compaction, this led to a reduction in available water capacity. Results depicted in Figure 3 supported this, indicating a decrease in macro-porosity with increasing traffic treatment levels. Compaction tended to increase the continuity of soil pores by expanding the contact surface area between soil aggregates (Gupta et al., 1989; Richard et al., 2001). This could reduce the soil matric potential at which ψ_{FC} was defined by Assouline and Or (2014), hence leading to a lower moisture content retained at field capacity and also resulting in less available water capacity (Fu et al., 2021). This could be seen in contrast to the results presented in Figures 5 and 4, where the increase in the traffic treatment level corresponded to a smaller reduction in the effect size of FC_{AO} compared to FC_{10}. A similar pattern was also noted for AWC calculated by dynamic criteria used to define field capacity (AWC_{AO}, in Figure 7).

Regardless of the degree of compaction, soil bulk density was substantially increased while the value of the S index decreased. The increase in bulk density after applying a compressive force resulted from the conversion of macro-aggregates into micro-aggregates, a reduction in pore space, and the rearrangement of micro-aggregates and primary soil particles (Barik et al., 2014; Dörner et al., 2010; Matthews et al., 2010). The soil physical quality index (S index) was not only strongly influenced by bulk density but also reflects the quality of the soil microstructure. Dexter (2004) pointed out that the value of the S index is sensitive and tends to decrease as bulk density increases. The results of this meta-analysis, shown in Figure 8, supported this view, indicating a consistent downward trend in the S index with increasing compaction intensity. The S index corresponded to the slope of the soil water retention curve at its inflection point. Since compaction altered soil pore size distribution, as discussed in the previous paragraph, the S index tended to decrease as the soil water retention curve flattened (Alaoui et al., 2011; Assouline et al., 1997; Dexter, 2004). Therefore, changes in the S index also reflected shifts in soil bulk density and soil water retention properties. As suggested by Dexter (2004), soils with an S index value below 0.035 could be considered to have poor quality, which could limit nutrient and water movement, hinder root penetration, and increase the risk of soil structural degradation.

3.5.2 The influence of soil properties on the response of soil water retention-based properties to traffic-induced compaction

The initial value of a soil property before compaction strongly influenced the effect size of compaction. The meta-analysis performed on literature data revealed that lower initial values of BD and FC_{10} resulted in greater changes (increases) in these properties when the soil was compacted (Figures 2 and 4). Conversely, soils with medium or high initial levels for these properties tended to experience substantially smaller decreases under the same pressure. Other studies also found that soils with lower initial bulk density are more likely to become compacted after encountering compressive force (Hu et al., 2023; Keller et al., 2011).

In the aspect of soil pore system-related properties, high SOC content increased considerably field capacity at -10 kPa ($FC_{10,}$ Figure 4) and available water capacity from-10 kPa to -1500 kPa ($AWC_{10,}$ Figure 6), while high SOC level corresponded to the most notable decreases in field capacity and available water capacity measured using the dynamic criteria used to define field capacity (FC_{AO} and AWC_{AO}, Figure 5 and 7). This is not surprising as the formation of aggregates, water retention capacity, and soil bulk density are highly affected by the SOC content in soil (Blanco-Canqui et al., 2013). Dexter et al. (2008) also observed a positive correlation between soil organic carbon (SOC) content and soil matrix porosity.

Likewise, Fukumasu et al. (2022) suggested that the proportion of pores with a diameter > 0.2 µm was positively correlated with SOC. Additionally, an observed pronounced increase in macropores within the range of 480-720 µm was associated with an increase in SOC content (Fukumasu et al., 2022). Besides, SOC was also found to increase water storage capacity in the soil matrix. For example, Blanco-Canqui et al. (2013) reported that an increase of 1% in SOC increased available water content by an average of 12.5 mm in medium-textured soil. A similar relationship between SOC and available water capacity was observed in this study, as shown in Figure 6. The effect size on AWC_{10} significantly increased with SOC content, with the most substantial increase in AWC_{10} associated with high SOC content (>3%). However, higher levels of soil organic carbon (SOC) corresponded to a reduction in available water capacity calculated dynamic criteria used to define field capacity (AWC_{AO}, Figure 7). This was likely aligned with the amplified matrix porosity and decreases the soil matric potential at which ψ_{FC} is defined by dynamic criteria used to define field capacity, as discussed in the previous section.

Soils with high soil organic carbon (SOC) levels exhibited the greatest increases in bulk density (BD, Figure 2). It is widely acknowledged that the incorporation of SOC plays a protective role in shielding soil from deformation stresses, including compaction (Défossez et al., 2014). However, higher SOC content in soil could imply that the initial values for bulk density are much smaller (Blanco-Canqui et al., 2013; Blanco-Canqui et al., 2009; Fukumasu et al., 2022), matrix porosity and water retention capacity are greater (Blanco-Canqui et al., 2013; Dexter et al., 2008; Fukumasu et al., 2022) when compared with soils that had low SOC levels originally. Therefore, these soils' physical properties would be at levels most susceptible to compaction (Défossez et al., 2014). The largest increase in the effect size of bulk density happened when the SOC level was categorised as high (> 3%) in Figure 2, this may indicate that the high level of SOC does not help the soil to maintain good soil bulk density after traffic. Noticeably, under the classification of medium SOC content (1% to 3%), the effect size of bulk density exhibited the smallest increase, indicating that the concentration of SOC could be advantageous for resisting compaction. The S index (soil physical quality index) was also closely associated with SOC. Dexter (2004) mentioned that a reduction in organic matter content was associated with a decline in soil physical condition, resulting in a smaller S index value, this is corroborated by the results from the meta-analyses, as shown in Figure 8. On the other hand, most of the data for quantifying the effects of SOC was within the medium range (1% to 3%). The limited data available for high and low SOC levels may compromise the interpretation of results by reducing representability. Soils with medium levels of soil organic carbon (SOC) tended to experience the most significant reductions in macro-porosity under compaction (Figure 3), and a similar pattern was observed with initial macro-porosity (Figure 3). The possible explanation was that the relationship between SOC and macro-porosity may be indirect. Firstly, higher SOC levels were commonly associated with greater macro-porosity in general (Fukumasu et al., 2022; Koop et al., 2023). Secondly, soils enriched with SOC tended to be more resilient to compaction, partially mitigating the effects of soil compaction from traffic (Shah et al., 2017). Thirdly, traffic-induced compaction was found to be more likely to reduce the volume of macropores that actively contribute to water flow (connected macropores) rather than all macropores (>30 µm) (Lipiec & Hatano, 2003). Consequently, soils with higher organic carbon content were expected to be less likely to experience a significant reduction in macro-porosity. Müller et al. (2018) reported that the macro-porosity tended to decrease with the reduction in soil organic carbon content. However, the highest increase in bulk density was observed in soils with high SOC, likely due to their initially lower bulk density before compaction (as shown in Figure 2). Soils with low initial macro-porosity exhibited the smallest changes under traffic compaction, suggesting that those with lower SOC had less macro-porosity available for further reduction. In contrast, soils with medium SOC levels were less resilient to compaction than those with high or low SOC, leading to the greatest reductions in macro-porosity. This observation was further supported by changes seen in soils with medium initial macro-porosity.

High clay content was associated with the most substantial increase in BD (Figure 2), and a decrease in macro-porosity, AWC_{10} and AWC_{AO} (Figures 3, 6, and 7). The effect of clay content on the water retention-based properties and soil physical quality in response to traffic-induced compaction was relatively weaker compared to the profound impact of soil organic carbon (SOC). The most obvious effect of clay content was on macro-porosity (Figure 3 and Figure A 3f), the high level of clay content resulted in a decrease in macro-porosity which was strongly determined by particle size distribution and soil organic carbon (Koop et al., 2023). Increasing clay content was likely to increase micropores and reduce macropores, this was especially the case when the clay content is above 30% when micropores became predominant (Elkady et al., 2015). However, when considering the impact of clay content on compaction, the effect was often confounded by soil wetness or moisture content at the time of compaction (Hu et al., 2023; Schjonning & Larnandé, 2018). Generally, the compaction effect would be greater with the increase in moisture content at compaction (Elkady et al., 2015; Nawaz et al., 2012). Most of the outcomes derived from this meta-analysis exhibited a consistent trend. Specifically, when the moisture content at compaction was categorised as dry, it was associated with the smallest decrease in effect sizes across various parameters. These parameters encompass available water capacity calculated using both methods and the S index (Figures 6, 7 and 8). This finding highlighted those soils in dry moisture conditions exhibited smaller susceptibility to compaction. However, the dry MC at compaction resulted in the most profound decrease in macro-porosity (Figure 3). This was attributed to the rearrangement of soil aggregates and alterations in the inter-aggregate structure, ultimately leading to an increase in bulk density and a decrease in soil porosity (Alaoui et al., 2011; Dexter, 1988). Since total porosity was typically derived from soil bulk density (Flint & Flint, 2002), bulk density also reflected changes in soil total porosity. Compared to total porosity, macro-porosity was more sensitive to compaction (Alaoui et al., 2011) and this helped to explain the most significant decrease of macro-porosity in Figure 3 under dry moisture conditions (compared to BD result in Figure 2). Furthermore, from perspective of mechanical properties, the reduction in moisture content increased the soil's effective stress, which referred to the stress that contributed to soil strength and deformation behaviour. This increased resistance against compressive forces, thus mitigating the effects of compaction on the soil (McNabb et al., 2001). When soil moisture content at compaction was classified as wet, the effect of compaction on the water storage properties and soil physical quality was close to or slightly higher than in dry conditions, as shown in the results for available water capacity (Figures 6 and 7), field capacity (Figure 4 and 5) and the S index (Figure 8). When soil pores were filled with water, the soil became less compressible due to the smaller volume of air and the direct contact between soil particles decreases as the film of water around clay particles becomes thicker (McNabb et al., 2001). Moreover, an increase in the clay content tended to enhance the moisture content at certain soil matric potential compared to coarser textured soil (Elkady et al., 2015), hence reducing the compaction effect on soil water storage properties in clay-rich soils. Besides, the SOC enrichment may also contribute to mitigating the compaction effect on soil at high moisture content and fine-textured soil (clay and silty clay soils) during the compaction (Smith et al., 1997).

When the MC at compaction was at a medium level, it resulted in the lowest increase in BD, the highest increase in FC_{10} (Figure 4), and the greatest decrease in AWC_{10}, AWC_{AO}, and the S index (Figure 6, 7 and 8). Moreover, the macro-porosity also showed the smallest reduction when the MC at compaction at a medium level (Figure 3). There was an increase in field capacity calculated using both methods (Figure 4 and Figure 5), indicating a potential increase in meso- and microporosity under this soil moisture content condition. Nevertheless, even with the increase in field capacity, the available water capacity calculated by both methods (Figures 6 and 7) and the S index (Figure 8), all experienced a notable decrease compared to the wet and dry levels. This indicated that medium levels of moisture content at compaction contributed to a potential increase in micropores, those that hold water beyond a soil matrix potential of -1500 kPa. Additionally, it was found that soil compaction had the most substantial impact on water retention properties when the soil had a medium level of moisture content during compaction. A similar conclusion was also drawn by Adekalu and Osunbitan (2001), Luciano et al. (2012) and (Ishaq et al., 2001), and supported that the relationship between moisture content and compaction effect on soil storage properties might be non-linear (Hu et al., 2023).

Additionally, Figure 2 showed minimal changes in bulk density under medium soil moisture conditions, reflecting a lesser reduction in porosity after soil compaction compared to both dry and wet moisture content levels. This suggested that changes in BD may not always correlate with changes in other soil properties, such as AWC (Figures 6 and 7) and the S index (Figure 8). Yavuzcan et al. (2005) proposed that medium levels of soil moisture content during compaction tended to result in better soil physical conditions following traffic-induced compaction. Conversely, in dry soil conditions, compaction resulted in the highest increase in BD and the greatest decreases in macro-porosity but the smallest reduction in AWC (Figures 6 and 7) and the S index (Figure 8). This may be because initial pore geometry and continuity in soil can vary under the given bulk density (Zhai & Horn, 2019b). Therefore, bulk density may not accurately reflect pore geometry dynamics under different soil management practices, especially for soil water and gas transport properties, as it was not always a sensitive indicator of compaction effects (Horn & Fleige, 2003; Hu et al., 2021; Lipiec et al., 2003; Zhai & Horn, 2019b).

While this meta-analysis provided valuable insights into the impact of machinery-induced soil compaction on soil water retention-based properties and physical quality, a limitation should be considered. With the limited number of publications focusing on soil water retention properties in the context of traffic-induced compaction, the available dataset was insufficient for isolating the impact of individual factors or minimising the effects of other variables. For future research, additional data collection is needed to provide deeper insights into the response of water retention-based properties to compaction.

3.6 Conclusions

This study employed a meta-analysis approach to synthesising findings from the literature on the impact of compaction induced by machinery traffic, encompassing factors such as pass number, load weight, and tyre pressure, on soil water retention-based properties and soil physical quality. Overall, soil compaction increases bulk density (BD) and field capacity at -10 kPa (FC_{10}), while reducing the macro-porosity, field capacity calculated by dynamic criteria used to define field capacity method (FC_{AO}), available water capacity (AWC_{10} and AWC_{AO}) and the soil physical quality index (S index). High tyre pressure results in greater reductions in macro-porosity and the S index, while low pressure is associated with more substantial decreases in AWC_{AO}. A medium level of load weight tends to cause the highest increase in bulk density and the most substantial decreases in macro-porosity, AWC_{AO}, and the S index. In contrast, a low load weight corresponds to the greatest reduction in FC_{AO}. The high level of traffic pass number leads to the most significant decreases in macro-porosity, FC_{AO}, AWC_{AO}, and the S index.

The initial status of soil properties significantly influences the effect size of soil properties upon compaction. Generally, soils with low BD and FC_{10} experience more considerable increases upon compaction, while high and medium levels of other properties tend to decrease the most. When the moisture content at compaction (MC at compaction) is at a medium level, the increase in BD is the lowest, the increase in FC_{10} is the highest, and the most profound decreases in AWC_{10}, AWC_{AO}, and the S index occur. This observation suggests that changes in bulk density do not always align with changes in other properties, such as AWC and the S index. Dry soil conditions correspond to the highest increase in BD and the greatest decrease in macro-porosity and FC_{AO}.

Soils with high clay content show the greatest increase in BD, and marked reduction in macro-porosity, AWC_{10}, and AWC_{AO}. Soils with high soil organic carbon (SOC) content experience the highest increases in BD, FC_{10}, AWC_{10}, and the S index, while also showing the most significant reductions in FC_{AO} and AWC_{AO}. Additionally, soils with a medium level of SOC exhibit the greatest reduction in macro-porosity.

Overall, this meta-analysis suggests that managing machinery traffic is crucial for mitigating soil compaction and protecting soil health, particularly in soils with specific characteristics or under certain moisture conditions. To enhance understanding of how soil water retention properties respond to compaction, future research should explore more and a broader range of data that would allow more detailed analyses.

Chapter 4

Investigation of the impacts of compaction on soil physical properties under different planting ages in New Zealand apple orchards

4.1 Abstract

To evaluate the impact of compaction on soil physical and hydraulic properties in New Zealand apple orchards, I conducted measurements of the penetration resistance (PR), bulk density (BD), mean weight diameter (MWD) and soil gas diffusivity (D_p/D_o), soil water retention properties, and saturated hydraulic conductivity across two apple orchards varying in planting ages and levels of compaction, which were influenced by traffic positions.

In general, significantly higher penetration resistance (PR) and bulk density (BD) were found in the track positions compared to non-track positions in both orchards. At the Belfast site, PR and BD values were 2.8 MPa and 1.3 g/cm^3, respectively, while at the Richmond site, they were 2.7 MPa and 1.3 g/cm^3, respectively. These measurements were taken at a depth of 0-30cm. In comparison, near tree positions showed lower PR and BD values, with PR of 2 MPa and BD of 1.3 g/cm^3 at the Belfast site, and PR of 2 MPa and BD of 1.2 g/cm^3 at the Richmond site. The highest MWD values were observed in track positions, with values of 1.9 mm at the Belfast site, and 2.2 mm at the Richmond site, respectively. Conversely, the lowest MWD values were found in the near tree position with 1.2 mm in the Belfast site and 2.2 mm in between the track position in the Richmond site. The PR and BD increased with planting age in both orchards. Gas diffusivity (D_p/D_o) was not significantly affected by the planting ages and traffic positions at -1.5 kPa matric potential ($p>0.05$) in 0-10 cm. While overall, both PR and BD increased with planting age, orchards with intermediate planting ages (12 to 17 years) demonstrated relatively superior soil physical quality. This was characterised by higher mean weight diameter (MWD) and S index values, along with comparatively BD and better soil water retention properties, particularly when compared to the youngest and oldest orchards in both sites. These results suggest that soil physical quality may temporarily improve during certain stages of orchard development before further compaction occurs with continued ageing.

This study identified significant effects of planting ages and traffic positions on soil PR, BD, FC_{10}, and micro-porosity. Longer planting ages resulted in higher traffic passes in track positions, which increased PR in both orchards. Conversely, reduced traffic intensity and increased vegetation coverage led to a less pronounced compaction effect on PR. For bulk density, traffic had a greater impact in orchards with shorter planting ages, while the effect of planting age became more significant in orchards with longer planting ages. Extended planting durations increased FC10 due to traffic-induced compaction converting larger pores into smaller ones. Micro-porosity was predominantly influenced by planting age rather than traffic.

4.2 Introduction

The increasing demand for food production has led to the intensive use of wheel traffic in agricultural systems, resulting in severe soil compaction worldwide (Nawaz et al., 2012). Traffic-induced compaction has led to many adverse impacts on soil physical properties and influences environmental health by regulating the hydrological process (Fu et al., 2021). For example, Alaoui et al. (2011) pointed out that soil compaction typically modifies the soil pore system, which governs water movement, storage, and solute transport. Likewise, Obour and Ugarte (2021) suggested that these changes within the soil pore system, in turn, affect nutrient availability, soil organism habitats, and food production (Obour & Ugarte, 2021). Thus, soil compaction can significantly alter soil's physical, chemical, and biological properties (Hamza & Anderson, 2005; Nawaz et al., 2012; Shah et al., 2017), with its negative impact on physical properties being extensively documented by numerous researchers in many agricultural, horticultural and forestry fields (Blumfield et al., 2005; Deurer et al., 2012; Fukumasu et al., 2022; Glab, 2014; Goh et al., 2001; Hamza & Anderson, 2005).

Soil compaction is commonly found in the orchards due to the machinery traffic for applying pesticides or fungicides against diseases and pests (Paltineanu et al., 2016). The external stress induced by the trafficking machinery negatively impacts the yield, the energy requirements for cultivation, and soil water storage, and amplifies the need for fertilisers, among other adverse consequences (Tim Chamen et al., 2015). Petry et al. (2016) observed that within compacted soil areas of a peach orchard, the frequency of thick roots diminished with increasing soil depth, attributed to the rise in soil mechanical resistance. Besides, diminishing soil porosity due to soil compaction impacts water and gas flow, as well as nutrient pools within the soil, leading to a consequential reduction in yield (Ramos et al., 2022). As a significant export horticultural product for New Zealand, fresh apple production generated a value of nearly $900 million in 2020 (MPI, 2020). Pipfruit (2017b) noted that approximately 12% of apple orchard areas were influenced by soil compaction, these phenomena were also reported in studies focusing on the Canterbury and Hawke's Bay regions (Deurer et al., 2012; Deurer et al., 2008; Goh et al., 2001; Vogeler et al., 2006). However, these publications primarily concentrated on single factor or properties. For example, Deurer et al. (2012) only focused on the relationship between carbon and traffic effects. Vogeler et al. (2006) only measured the soil's physical and hydraulic properties under traffic-induced compaction. However, soils may endure cumulative adverse impacts from the stresses exerted by machinery over the years (Ramos et al., 2022). Moreover, the various traffic positions within an orchard system can result in differing levels of soil compaction. For example, Goh et al. (2001) observed a significantly lower bulk density and a higher infiltration rate around the tree line compared to areas on vehicle tracks. Therefore, the understanding of how planting ages and traffic positions affect soil physical properties, hydraulic properties and health in apple orchards remains inadequate. Additionally, there has been a scarcity of research dedicated to examining the impact of compaction on soil properties specifically within apple orchards globally (e.g.(Deurer et al., 2012; Deurer et al., 2008; Goh et al., 2001; Paltineanu et al., 2016; Vogeler et al., 2006; Wei et al., 2021) and even less research have been conducted in New Zealand in apple orchards (Deurer et al., 2012; Deurer et al., 2008; Goh et al., 2001; Vogeler et al., 2006). Thus, the investigation of planting ages and traffic position influences is also advantageous for horticultural practices.

This study aims to investigate the impact of soil compaction on soil physical and hydraulic properties within two New Zealand apple orchards with differing planting ages. This study hypothesises that longer exposure to traffic may exhibit greater levels of compaction effect on soil physical properties. Specifically, this research focuses on examining penetration resistance, bulk density, aggregate stability, soil gas diffusivity, soil water retention properties, saturated hydraulic conductivity, and soil porosities. This study addresses three primary research questions:

(1) How do varying planting ages influence the soil's physical properties within the apple orchards?

(2) How do different traffic positions affect the soil's physical properties within the apple orchards?

(3) How does the interaction between planting ages, traffic positions, and soil depth impact soil physical and hydraulic properties within the apple orchards?

4.3 Material and method

4.3.1 Site description

Two distinct apple orchards were selected in Belfast in Christchurch (Canterbury) and Richmond (Tasman district), New Zealand. Belfast experiences an average annual temperature of approximately 11 °C, while Richmond's average annual temperature is around 12.1 °C. The mean annual rainfall in Belfast is 648 mm, whereas Richmond receives a higher mean annual rainfall of 1396 mm. The soil in Belfast and Richmond orchards are silt loam soils classified as Recent and Brown under New Zealand's classification system (Hewitt, 2010) and as Entisols and Dystrudepts in the USDA system, respectively (Soil Survey Staff, 2022). Pest and fungal disease control followed New Zealand's Integrated Fruit Production (IFP) protocols in both orchards. The soil composition in Belfast is characterised as silt texture, averagely comprising of silt, at 66.3%, with 5.5% sand and 28.2% clay within the 0 to 90 cm depth range for the whole orchard. The Belfast orchard has a history of apple tree cultivation spanning over 40 years. We selected blocks representing different tree ages, including 3, 12, and 40 years. The 12- and 40-year-old blocks had a prior land use as a dairy farm, while the 3-year-old block transformed a swamp into a vegetable and berry farm before transitioning into an orchard. Fertiliser applications are absent in all blocks, and irrigation is limited to in late spring and summer via drip lines (3- and 12 years orchard) or sprinkler (40-years orchard) when soil become dry. The orchard practices approximately 35 times of chemical spray per year, primarily using fungicides with 2-5 tone vehicle (4WD). Calcium was supplied as a foliar spray of $CaCl_2$ at approximately 8 kg Ca ha^{-1}, and lime was applied at 200 kg ha^{-1}.

In Richmond, the soil texture is classified as loam, with a composition of 21% sand, 56% silt, and 23% clay within the 0 to 90 cm depth range for the whole orchard. The orchard was previously a dairy farm. Before the land use switch to apple planting, the soils were subsoil in the whole area. Blocks representing apple trees ages 12, 17, and 28 years were selected. The traffic frequency in this orchard involves approximately 25 applications per year with 2-5 tone vehicle (4WD). Applications included lime at a rate of 1 tonne per hectare, potassium at 200 kg per hectare, and the nutrient-rich foliar spray "Finish It" at 40 kg per hectare. The composition of "Finish It" is as follows: 6.4% nitrogen, 6.2% phosphorus, 30.8% potassium, 2.7%

sulphur, along with trace elements such as magnesium, iron, manganese, zinc, copper, boron, molybdenum, and iodine. Additionally, drip irrigation was carried out 2–3 times a week during the summer period. Additionally, there was no cover vegetation observed in the track position while the vegetation was fully covered in between track positions in both orchards.

4.3.2 Soil sampling

Intact soil cores were systematically collected from both sites to assess soil hydraulic properties. The soil cores from the Belfast site were obtained in July 2022, with dimensions of 7.3 cm in diameter and 7.5 cm in height. For the Richmond site, 10 cm in diameter and 7.5 cm in height intact cores were collected in June 2023. The reason for using 7.3 cm diameter cores for Belfast was specific to testing the gas diffusivity of compacted samples. The sampling locations were strategically chosen between two trees (no traffic, no vegetation cover), on the traffic track (no vegetation cover), and between the tracks (potentially trafficked, covered by vegetation), as illustrated in Figure 9. At each sampling point, intact soil cores were collected from three different depths: 0.01 to 0.085 m to represent the soil layer from 0 to 0.1 m, 0.11 to 0.185 m to represent the soil layer from 0.1 to 0.2 m, and 0.21 to 0.285 m to represent the soil layer from 0.2 to 0.3 m. For each age block, four replicates were taken for each sampling position, resulting in a total of 108 samples. Besides, 36 undisturbed samples were also collected next to intact cores for analysis of water sieving aggregates stability for the top 0.01 to 0.085 m, representing the soil layer from 0 to 0.1 m. For analysing soil chemical properties, 216 disturbed soil cores were also collected at 0–0.1 m, 0.1-0.2 m, 0.2-0.3 m, 0.3-0.5 m, 0.5-0.7 m and 0.7-0.9 m for the measurement of soil texture, and soil chemical properties as presented in the next chapter.

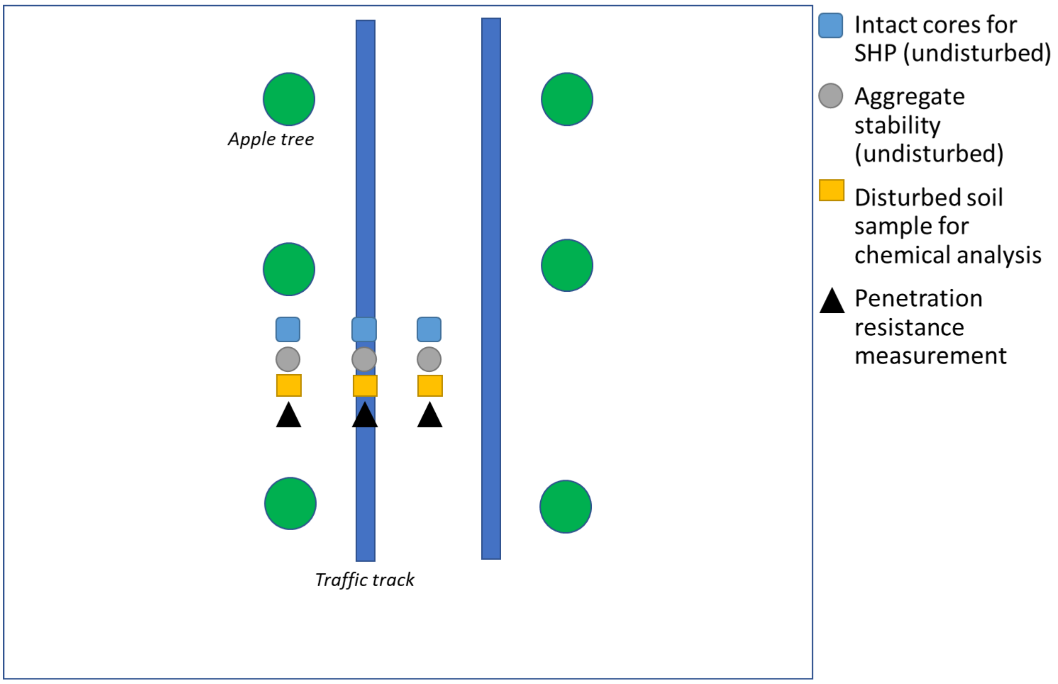


Figure 9. Sampling positions for intact cores, disturbed samples for soil chemical properties, Penetration resistance, and undisturbed samples for water-sieving aggregate stability.

4.3.3 Soil physical properties measurement and calculation

Soil physical properties measurement

Soil bulk density (BD, g/cm3) was calculated as the ratio of dry soil mass (dried for 24 hr at 105 °C) to the volume of the soil intact cores. The soil penetration resistance test was conducted in the field while collecting disturbed and undisturbed soil samples in both orchards measured within a depth of 0 to 0.4 m (with 0.1m testing interval) with 4 replicates by using a field cone penetrometer (hand penetrometer Eijkelkamp, cone surface area 1 cm^2, Royal Eijkelkamp, the Netherlands)., the measured field data of PR were corrected by at 20% moisture content to minimise the soil moisture effects on PR as Equation 8 below:

$$PR_{0.2} = PR_{measured} * (0.2/\theta_{g-measrued})^{b} \qquad (8)$$

Where $PR_{0.2}$ is penetration resistance corrected at 20% moisture content, $PR_{measured}$ is the measured field data of PR, $\theta_{g\text{-measured}}$ is the measured soil moisture content while the penetration resistance measurement. b is the correction coefficient by depth(Hu, 2024).

The method for measuring water-stable aggregates was adapted from Beare and Bruce (1993). In this slaking procedure, 75 grams of air-dried soil were subjected to wet sieving for 20 minutes at a frequency of 120 cycles per minute with a 2 cm stroke length. This method facilitated the recovery of water-stable soil aggregates in six size categories: 2–5 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, 0.053–0.25 mm, and less than 0.053 mm. Subsequently, these aggregates were oven-dried at 50°C for a minimum of 6 hours until they reached a constant weight. The mean weight diameter (MWD) of these aggregates was then calculated using an adapted equation from Kemper and Rosenau (1986) as Equation 9 below:

$$MWD = exp(\frac{\sum Wi \times InXi}{\sum Wi}) \qquad (9)$$

Where Wi is the weight of aggregates in each size fraction, Xi is the mean size of each aggregate size class (mm).

Soil water retention-based properties

Soil water retention curves were established by measuring the soil water content at various pressures, including 0, −6, −10, −40, -80, −100, and −500 cm. This was achieved using a tension table and vacuum plate. The chosen pressure ranges are significant as previous studies have indicated that the impact of tillage and compaction on pore space is more noticeable within these pressure ranges (Kargas et al., 2016). The Van Genuchten (1980) model was employed to fit the data and describe soil water retention curve (SWRC) as Equation 10 below:

$$\frac{\theta(\psi) - \theta r}{\theta s - \theta r} = [1 + (\alpha|\psi|^{n})^{-m} \qquad (10)$$

Where $\theta s \text{ and } \theta r$ are the saturated and residue water content on a volume basis. α is the air-entry value, and n is the pore size distribution index. In this study, residual water content (θr) was the measured air-dried gravimetric water content times the bulk density (g cm^{-1}). θs is the saturated water content at 0 kPa, θ(ψ) is the volumetric water content (cm^{3} cm^{-3}) at suction ψ.

Soil water content at field capacity is commonly determined at -10 kPa in New Zealand. According to Assouline and Or (2014), water content at field capacity could be related to the suction at the maximum extent of hydraulically connected pathways that supported unsaturated capillary flow and calculated by α and n from Van Genuchten (1980) model as below Equation 11 below:

$$\psi_{FC} = -\frac{1}{\alpha}[\frac{n-1}{n}]^{(1-2n)/n} \qquad (11)$$

By replacing ψ with ψ_{FC}, the water content at field capacity could be obtained. The available water capacity (AWC) could be calculated as the difference between water content at field capacity (θ_{fc}) and permanent wilting point (PWP) which is defined as the water content at -1500 kPa fitted from Equation 10.

Through the soil water retention curve (SWRC), three pore diameter classes could be classified: macro-porosity, meso-porosity, and micro-porosity, corresponding to diameters of >30 µm, 30-5 µm and <5 µm, respectively. Moreover, Reynolds et al. (2009) suggested that the relative field capacity (RFC) could be used as an indicator of the ability of soil to store water and air. RFC could be calculated by Equation 12:

$$RFC = \frac{\theta_{fc}}{\theta_s} \qquad (12)$$

Where $\theta_{fc}$and θ_s are the water content at field capacity and saturation, respectively. The optimum range for RFC value was suggested at 0.6 to 0.7 which maximised the microbial production of nitrate (Reynolds et al., 2009). RFC value below 0.6 suggested the reduced microbial production of nitrate due to insufficient water(Reynolds et al., 2009). In contrast, an RFC value above 0.7 suggested there was insufficient air for microbials to produce nitrate (Reynolds et al., 2009).

S index, an essential physical parameter, serves as an indicator of soil physical quality, aligning with observations related to soil compaction and organic matter content (Dexter, 2004). To determine the soil physical quality of both orchards under the various planting ages and traffic positions, the soil quality index (S index) could be calculated by Equation 13 retrieved from Dexter (2004) as below:

$$S = \left| -n(\theta_{sg} - \theta_{rg}) \left(\frac{2n-1}{n-1} \right)^{\frac{1}{n-2}} \right| \qquad (13)$$

Where θrg and θsg are residual and saturated soil water content on a mass basis as described in chapter 4. According to Dexter (2004), soil physical quality (S index) could be categorised into different classes, including very poor ($S < 0.02$), poor ($0.02 < S < 0.035$), good ($0.035 < S < 0.05$), and very good ($S > 0.05$).

Gas diffusivity and Ksat

Measurements of Gas diffusivity (D_p/D_o) were performed after SWRC measurement using a method adapted from Rolston and Moldrup (2002) at -1.5, -4 and -8 kPa. Briefly, soil cores were carefully positioned and isolated above a chamber that was continuously flushed with an oxygen-free gas (90% Ar and 10% N_2) until the chamber was oxygen-free. After ensuring the chamber was O_2-free, the base of the soil core was connected to the chamber. This setup allowed ambient air to diffuse through the soil core into the chamber. The gas composition within the chamber was monitored using a recalibrated sensor (model KE-12, Figaro Inc.), Calibration of the O_2 sensors was conducted using gas mixtures with O_2 concentrations of 0%, 30%, and 99.9%. In order to calculate the $D_p/D_{o,}$ the natural logarithm of the relative concentration of oxygen in the chamber ($\text{In}C_r$) was calculated and $C_{r\ \text{was}}$ calculated as Equation 14 follows:

$$C_r = \frac{C_g - C_s}{C_0 - C_s} \qquad (14)$$

Where C_g is the oxygen concentration in the chamber at a time, C_0 is the initial oxygen concentration at the beginning of measurement, C_s is the oxygen concentration above soil cores (20.9%), The linear slope of the plot of $\text{In}C_r$ vs time is measured and equal to Equation 15:

$$-\frac{D_p \alpha_1^2}{\varepsilon} \qquad (15)$$

Then the D_p was determined using the calculated value of ε (air-filled porosity) and the value of α_1 from table 4.3-1 of Rolston and Moldrup (2002). The equation for calculating D_o (soil gas diffusion coefficient in air) was adapted from Currie (1960) as Equation 16 follows:

$$D_o = D_{T,p}\left(\frac{273}{T}\right)^n \qquad (16)$$

Where $D_{T,p}$ is the value coefficient of diffusion at a given temperature and pressure, n is a constant value near 1.75 for gases. Due to time constraints, soil gas diffusivity measurements were conducted exclusively on samples from the Belfast site.

The saturated hydraulic conductivity (Ksat) was measured by the constant head method (Klute, 1965). In order to minimise the temperature effects on the Ksat result, the obtained raw Ksat value were corrected for 20 °C as Equation 17 below:

$$K_{S20} = K_{sat}\frac{\eta_t}{\eta_{20}} \qquad (17)$$

Where η_t and η_{20} are the viscosity at given temperatures t and 20 °C, respectively. K_{sat} and K_{s20} are the saturated hydraulic conductivity at temperature t and 20 °C, respectively.

4.3.4 Statistic analysis

The statistical analysis was carried out using RStudio. The "predictmeans" package was utilised to perform multivariate analysis of variance (MNOVA) within the general linear model, assessing the impact of various factors such as age, position, and depth, along with their interactions, on soil physical and hydraulic properties. For multiple comparisons, the Least Significant Difference (LSD) of means was employed. To address skewed data, a logarithmic transformation (log10) was applied to achieve variance before conducting the statistical analyses.

4.4 Results

4.4.1 Soil physical properties

Bulk density

As expected, the traffic positions significantly affected the soil BD in both orchards. The track position showed the highest mean BD value in both orchards with 1.31 g/cm3 (Belfast site, Table 3) and 1.34 g/cm3 (Richmond site, Table 4). The lowest BD were found in near tree position with 1.25 g/cm3 (Belfast site, Table 3), and 1.20 g/cm3 (Richmond site, Table 4). There were significant differences detected between each traffic position in both sites.

The soil bulk density was significantly affected by the planting ages in both orchards (Table 3 and Table 4). In the Belfast site (Table 3), the highest mean BD value was measured in 3-year planting ages with 1.36 g/cm3 while the lowest mean BD value appeared in 12 years planting age with 1.17 g/cm3. 40 years of planting age recorded the second highest BD value with 1.28 g/cm3. In the Richmond site (Table 4), the highest mean BD value was shown in 12-year planting age (1.29 g/cm3) while the lowest value was observed in 17-year planting age

(1.26 g/cm3). There was no significant difference in bulk density (BD) between the 12- and 28-year planting ages, but the 17-year planting age differed significantly from the others.

Significant interactions between planting age, traffic positions and depth were observed on BD in both orchards. In the Belfast site, bulk density (BD) was consistently higher in track positions in the 3-year, and 12-year planting ages compared to other positions (Figure 10). No significant interactions were found between traffic positions and the 40-year planting age in terms of BD. Bulk density (BD) was found to be significantly lower at the 0-10 cm soil depth in the 12-year and 40-year planting ages compared to other depths (Figure 11). In the 3-year planting age, BD was only significantly lower at the 0-10 cm depth compared to the 20-30 cm depth (Figure 11). Regarding the interactions between traffic position and soil depth, the track position had the highest BD compared to other traffic positions, and this difference was significant in the 0-10 cm depth range compared to other depths (Figure 12).

In terms of BD in the Richmond site, there was no significant interaction between planting ages and traffic positions. However, significant interactions were observed between planting ages and soil depth, as well as between traffic positions and soil depth (Table 4). In 0 to 10 cm, the soil BD was significantly lower than in other soil depths at all planting ages, while there was no significant difference between 10-20 cm and 20-30 cm (Figure 14). Regarding the interactions between traffic positions and soil depth, higher bulk density (BD) was observed below 10 cm compared to the 0-10 cm depth across all positions. No significant difference in BD was detected between the 10-20 cm and 20-30 cm depths (Figure 15).

Table 3. Effect of age of planting (3, 12 and 40 years), traffic position (near tree, track, and between track), soil depth and their interactions on soil physical properties in Belfast site. Values are means with different letters showing significant differences within the group except where LSD and significance levels are noted. LSD: least significant difference calculated at a significant level of p< 0.05. Symbols "*", "**", "*" and "ns" indicate the main or interaction effect was significant at P<0.001,0.01, 0.05 and p >0.05, respectively.**

Variables		Penetration Resistance (MPa)	Bulk density (g/ cm^{3})	Mean weight diameter (mm)	S index	RFC	Gas diffusivity		
							Dp/Do at -1.5kPa	Dp/Do at -4kPa	Dp/Do at -8kPa
Age	3	2.19^{a}	1.36^{a}	0.57^{a}	0.052^{a}	0.87^{a}	0.0017^{a}	0.0098^{a}	0.0108^{a}
	12	2.57^{b}	1.17^{b}	1.9^{b}	0.057^{a}	0.89^{a}	0.0042^{a}	0.0115^{a}	0.0126^{a}
	40	2.69^{c}	1.28^{c}	1.53^{c}	0.041^{b}	0.83^{b}	0.0052^{a}	0.0092^{a}	0.0092^{a}
Positions	Near tree	2.21^{a}	1.25^{a}	1.20^{a}	0.042^{a}	0.83^{a}	0.0021^{a}	0.0046^{a}	0.005^{a}
	Track	2.88^{b}	1.31^{b}	1.30^{a}	0.052^{b}	0.9^{b}	0.0069^{a}	0.0168^{a}	0.0184^{a}
	Between track	2.36^{a}	1.25^{a}	1.51^{a}	0.055^{b}	0.86^{c}	0.0021^{a}	0.0084^{a}	0.0092^{a}
Depth (cm)	0-10	2.23^{a}	1.18^{a}		0.062^{a}	0.88^{a}			
	10-20	2.48^{b}	1.3^{b}		0.052^{a}	0.87^{a}			
	20-30	2.71^{c}	1.33^{c}		0.036^{a}	0.84^{b}			
.	30-40	2.53^{b}							
LSD and Significant level	Age	0.12***	0.03***	0.35***	0.01^{ns}	0.02***	0.005^{ns}	0.006^{ns}	0.007^{ns}
	Position	0.12***	0.03***	0.35^{ns}	0.01^{ns}	0.02***	0.005^{ns}	0.006**	0.007**
	Depth	0.14***	0.03***		0.01^{ns}	0.02**			
	Age × Position	0.21***	0.05*	0.61^{ns}	0.02^{ns}	0.04^{ns}	0.009^{ns}	0.0011^{ns}	0.0012^{ns}
	Age × Depth	0.24***	0.05***		0.02**	0.04**			
	Position × Depth	0.24***	0.05**		0.02^{ns}	0.04^{ns}			
	Age × Position × Depth	0.42^{ns}	0.08*		0.03^{ns}	0.07*			

Table 4. Effect of age of planting (12, 17 and 28 years), traffic position (near the tree, track, and between track), soil depth and their interactions on soil physical properties in Richmond site. Values are means with different letters showing significant differences within the group except where LSD and significance levels are noted. LSD: least significant difference calculated at a significant level of $p < 0.05$. Symbols “*”, “**”, “*” and "ns” indicate the main or interaction effect was significant at $P<0.001$,0.01, 0.05 and $p > 0.05$, respectively.**

Variables		Penetration Resistance (MPa)	Bulk density (g/cm^{3})	Mean weight diameter (mm)	S index	RFC
Age	12	2.45^{a}	1.29^{a}	2.39^{a}	0.024^{a}	0.74^{a}
	17	2.54^{ab}	1.26^{b}	2.18^{b}	0.028^{b}	0.70^{b}
	28	2.62^{b}	1.29^{a}	1.92^{c}	0.026^{ab}	0.78^{c}
Positions	Near tree	1.31^{a}	1.20^{a}	2.16^{a}	0.027^{a}	0.69^{a}
	Track	2.76^{b}	1.34^{b}	2.19^{a}	0.028^{b}	0.8^{b}
	Between track	2.55^{c}	1.29^{c}	2.15^{a}	0.023^{c}	0.74^{c}
Depth (cm)	0-10	2.59^{ab}	1.14^{a}		0.031^{a}	0.76^{a}
	10-20	2.58^{a}	1.33^{b}		0.023^{b}	0.75^{a}
	20-30	2.58^{a}	1.36^{c}		0.024^{b}	0.71^{b}
	30-40	2.40^{b}				
LSD and Significant level	Age	0.10^{**}	0.025^{*}	0.19^{***}	0.002^{**}	0.02^{***}
	Position	0.10^{***}	0.025^{***}	0.19^{ns}	0.002^{***}	0.02^{***}
	Depth	0.12^{***}	0.025^{***}		0.002^{***}	0.02^{***}
	Age × Position	0.178^{**}	0.043^{ns}	0.33^{ns}	0.003^{ns}	0.04^{ns}
	Age × Depth	0.21^{ns}	0.043^{***}		0.003^{ns}	0.04^{ns}
	Position × Depth	0.21^{***}	0.043^{*}		0.003^{ns}	0.04^{**}
	Age × Position × Depth	0.36^{ns}	0.07^{ns}		0.005^{*}	0.06^{ns}

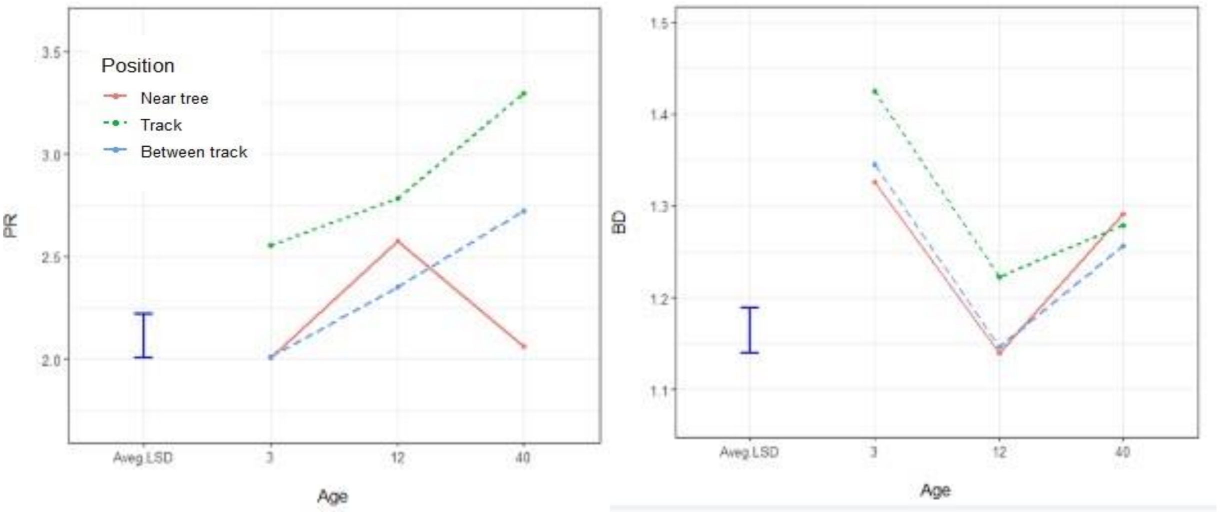


Figure 10. The interaction effect of traffic position and planting ages on soil physical properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$). PR: penetration resistance (MPa), bulk density (BD).

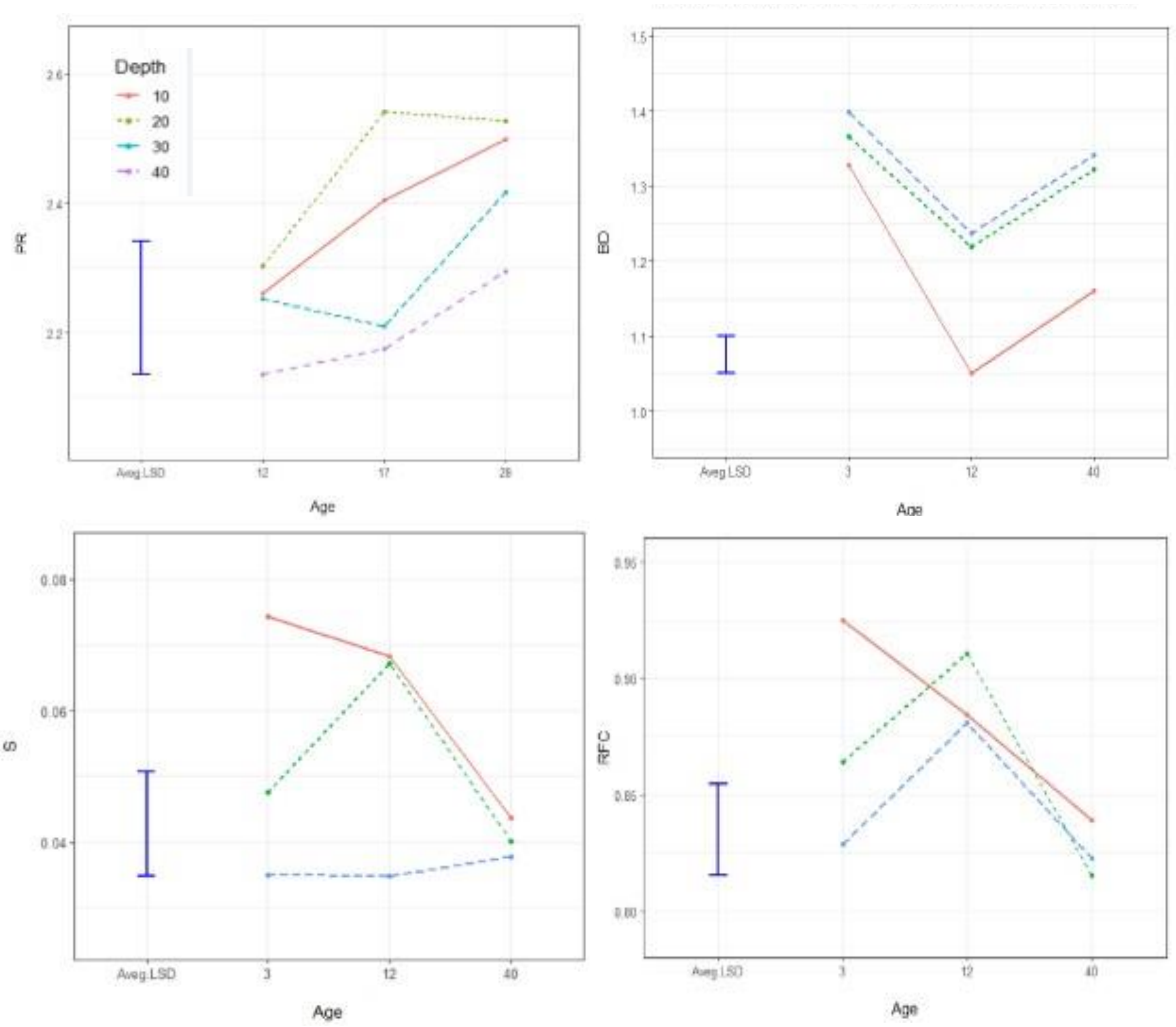


Figure 11. The interaction effect of planting ages and soil depth on soil physical properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$). BD: bulk density. S: soil quality index, RFC relative field capacity.

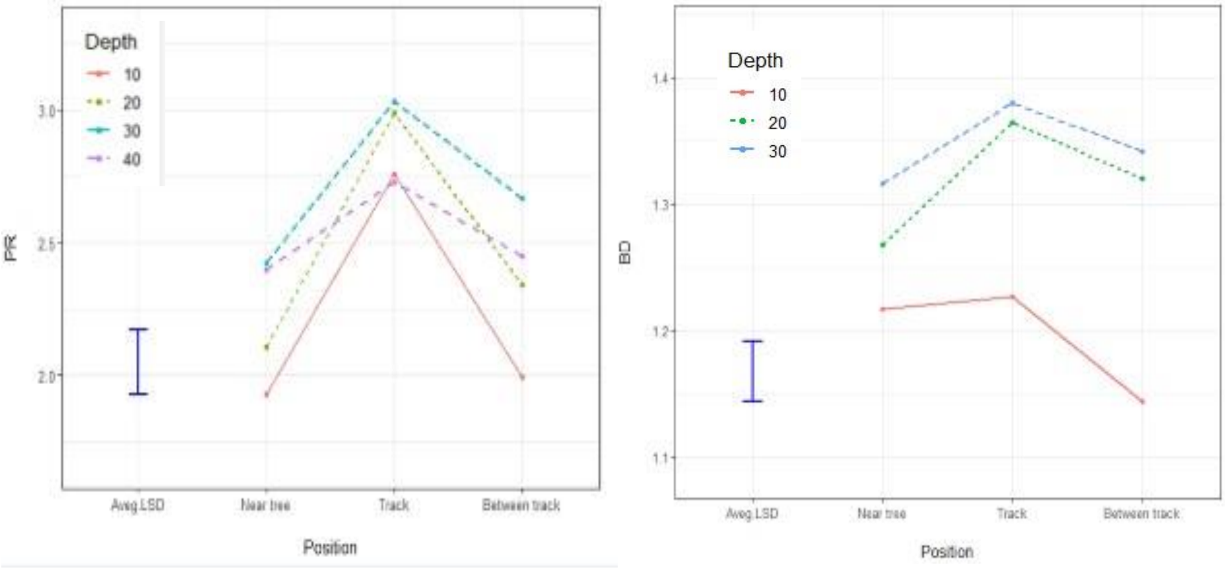


Figure 12. The interaction effect of traffic positions and soil depth on soil physical properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$).PR: penetration resistance, BD: bulk density.

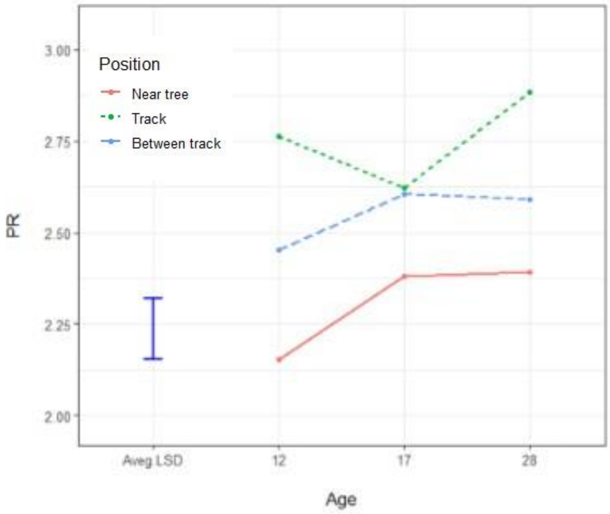


Figure 13. The interaction effect of planting ages and traffic positions on soil physical properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$).PR: penetration resistance.

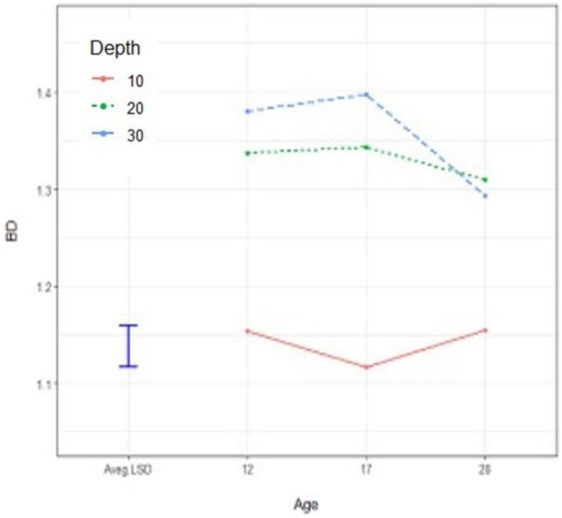


Figure 14. The interaction effect of planting ages and soil depth on soil physical properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$). BD: bulk density.

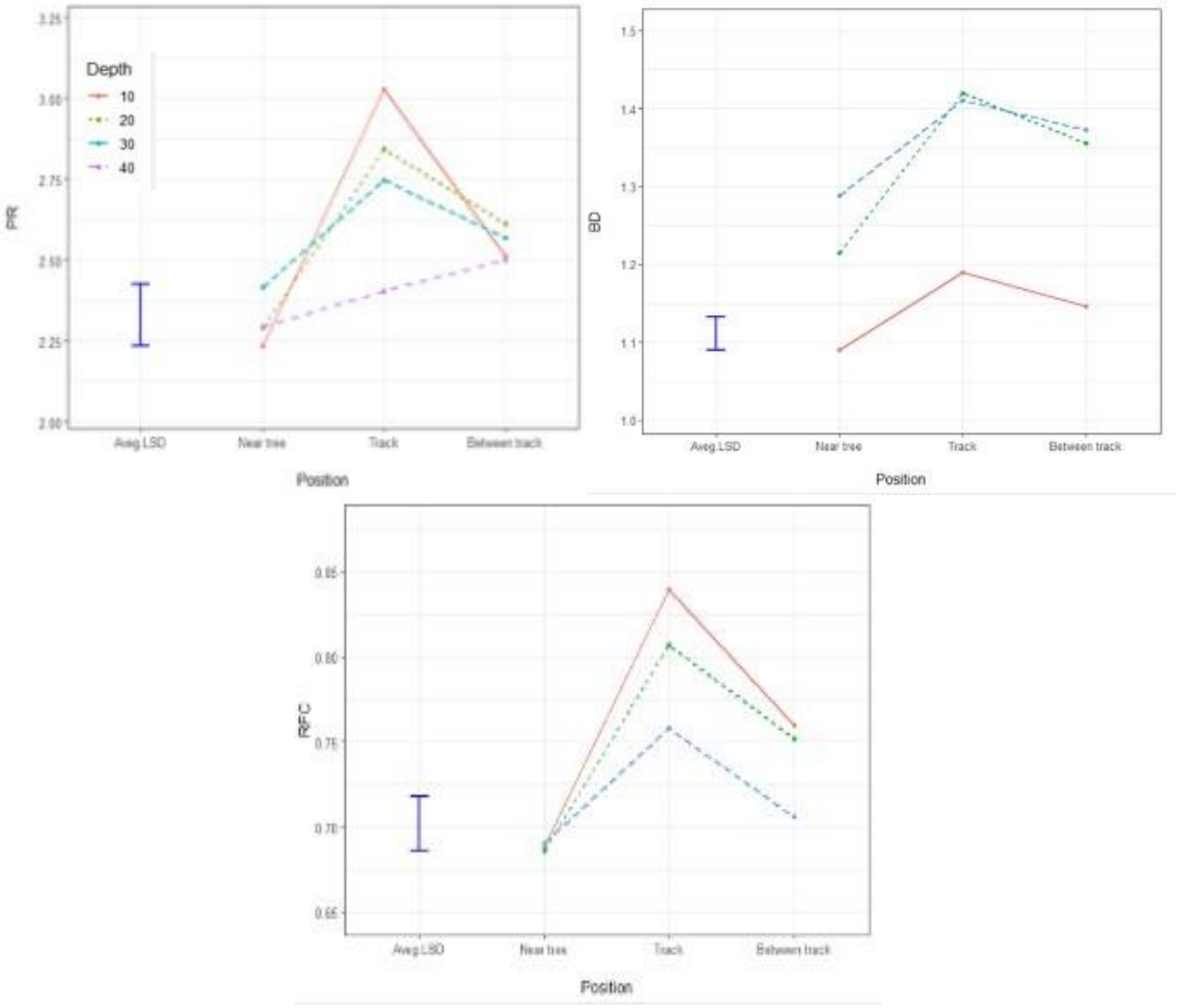


Figure 15. The interaction effect of traffic position and soil depth on soil physical properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$). PR: penetration resistance, BD: bulk density, RFC: relative field capacity.

Penetration resistance

Traffic positions resulted in significant differences in penetration resistance (PR) and exhibited a consistent trend across both orchards. As expected, the highest PR value was found on the track positions with 2.9 MPa in the Belfast site and 2.8 MPa in the Richmond site. The lowest PR value was examined on the near tree position with 2.2 MPa in the Belfast site and 2.3 MPa in the Richmond site. There was no statistically significant difference detected between near tree and between track positions in the Belfast site but in the Richmond site. The track position significantly differed from other positions.

Penetration resistance (PR) generally increased with the age of planting in both orchards (Table 3 and Table 4). The highest PR values were recorded in orchards aged 28 years and 40 years, with measurements of 2.7 MPa in the Belfast site and 2.6 MPa in the Richmond site, respectively. The lowest PR values were found in orchards aged 3 with measurements of 2.2 MPa in the Belfast site and aged 12 with 2.5 MPa in the Richmond site, respectively.

There were significant interactions found between traffic positions, soil depth and planting ages in the Belfast site. In Figure 10, the track position consistently showed the highest penetration resistance (PR) across all planting ages at the Belfast site. Notably, PR was significantly higher in the 3-year and 40-year planting ages compared to other positions. In the 40-year planting age, the PR near the tree position was significantly lower than in other positions. At the Richmond site, PR was consistently lower at near tree position across all planting ages (Figure 13). However, the track position showed the highest PR values across all planting ages, except for the 17-year planting age, where no significant difference in PR was observed (Figure 13). The profound interactions between planting ages and soil depth were observed in the Belfast site, with the increase in the soil depth the PR generally increased across all planting ages (Figure 11). Notable interactions between traffic positions and soil depth were found in both orchards. At the Belfast site, PR values increased with soil depth across all positions, with the highest PR recorded at 20 to 30 cm across all sampling positions. In contrast, at the Richmond site, the highest PR was found at 0 to 10 cm in the track position, while no significant differences were detected in the near tree and between track positions at any soil depth (Figure 15).

Aggregates stability

There was no significant traffic position effect detected on the mean weight diameter of water-stable aggregates (MWD) in both orchards, while the MWD was significantly influenced by planting age in both orchards (Tables 3 and 4). The highest MWD values were observed at the 12-year planting age, which was the middle age at the Belfast site (1.9 mm, Table 3), and at the Richmond site (2.4mm, Table 4), where it represented the youngest planting age. The lowest MWD values were recorded at the 3-year planting age in the Belfast site (0.6 mm) and the 28-year planting age in the Richmond site (1.9 mm).

S index and Relative field capacity

The S index was significantly influenced by planting ages and traffic positions in both orchards (Tables 3 and 4). The highest S index was recorded at the 12-year planting age in Belfast (0.057) and the 17-year planting age in Richmond (0.027). Conversely, the lowest S index was observed at the 40-year planting age in Belfast (0.041) and the 12-year planting age in Richmond (0.023). In terms of traffic positions, the lowest S index in Belfast was found near the tree position (0.042), whereas, in Richmond, the lowest value was recorded at the track position (0.02).

A significant interaction between planting ages and soil depth was observed only at the Belfast site (Figure 11). In the 3-year and 12-year planting ages, the S index was consistently higher in the 0 to 10 cm soil depth, showing a significant difference compared to the 20 to 30 cm depth. However, at the 40-year planting age, there were no significant differences in the S index across all soil depths.

Traffic positions and planting age significantly affected the relative field capacity (RFC) in both orchards. The RFC was notably higher in the track position, with values of 0.9 at the Belfast site and 0.8 at the Richmond site. RFC values differed significantly across positions, following a consistent pattern in both orchards: the lowest RFC was observed in the near tree position, followed by the second highest in the between track position. Regarding planting age, RFC was significantly lower at 40 years (0.83) in Belfast and at 17 years (0.70) in Richmond.

Significant interactions between planting ages and soil depth were observed at the Belfast site, while interactions between traffic positions and depth notably influenced RFC in Richmond. At the Belfast site, RFC decreased consistently with increasing planting age from 3 to 40 years at the 0-10 cm depth, with a marked difference between 3 and 40 years. In

Richmond, the RFC followed a similar trend across all soil depths, with the track position consistently exhibiting the highest RFC values and near tree position constant showing the lowest RFC values. Significant differences were found between the 0-10 cm and 20-30 cm depths within the track and between track positions.

Soil water storage properties (SWSP)

Overall, traffic position significantly affected all soil water storage properties at the Belfast site, except for micro-porosity ($p < 0.05$, Table 5). On average, FC_{AO} values were slightly higher in the near tree position (0.38 cm^3/cm^3) and between the track position (0.35 cm^3/cm^3) compared to the track position (0.33 cm^3/cm^3). A similar pattern was observed for AWC_{AO}, with values of 0.15 cm^3/cm^3 in the near tree position, 0.16 cm^3/cm^3 in the between track position, and 0.14 cm^3/cm^3 in the track position. For FC_{10}, the highest mean value was recorded in the between track position (0.46 cm^3/cm^3), while the lowest was in the near tree position (0.44 cm^3/cm^3). AWC_{10} followed a similar trend, with the between track position showing the highest value (0.26 cm^3/cm^3) and the near tree position having the lowest (0.20 cm^3/cm^3). Macro-porosity was highest in the near tree position (9%) and lowest in the track position (5.3%). Meso-porosity reached its peak in the between track position (11%) and was at its lowest in the near tree position (9%). Micro-porosity was most pronounced in the track position (35.3%) and the smallest in the between track position (34.6%). No significant differences were detected in most soil water storage properties between the near tree and between track positions. However, significant differences were observed in FC_{10}, AWC_{10}, macro-porosity, and meso-porosity, with the track position differing notably from the near tree position. In general, soil water storage properties generally decreased with increasing soil depth.

Traffic position significantly affected all soil water storage properties at the Richmond site, except for meso-porosity ($p < 0.05$, Table 6). The highest FC_{AO} value was observed in the near tree position (0.44 cm^3/cm^3), while the lowest values were recorded in both the track and between track positions (0.41 cm^3/cm^3). The highest AWC_{AO} value was also found in the near tree position (0.18 cm^3/cm^3), with the track position showing the lowest (0.12 cm^3/cm^3). FC_{10} values peaked at the track position (0.40 cm^3/cm^3) and were identical in both the near tree and between track positions (0.38 cm^3/cm^3). AWC_{10} was highest in the between track position (0.13 cm^3/cm^3) and lowest in the track position (0.11 cm^3/cm^3). Additionally, macro-porosity reached its highest average in the near tree position (17.1%) and its lowest in the track position (9.8%). For micro-porosity, the highest value was recorded in the track position (34.9%) and the lowest in the between track position (32.7%). Significant differences were detected between the track position and other positions, except for AWC_{10} and meso-porosity. Similar to the Belfast site, soil water storage properties generally decreased with soil depth.

At the Belfast site, planting ages significantly affected most soil water storage and hydraulic properties except for AWC_{AO}, as indicated with a significance level of $p < 0.05$ (Table 5). Specifically, the 12-year planting age group demonstrated the highest average values for FC_{AO} (0.38 cm^3/cm^3), FC_{10} (0.50 cm^3/cm^3), AWC_{10} (0.26 cm^3/cm^3), and micro-porosity (39.6%), while exhibiting the lowest value for macro-porosity (6.2%). In contrast, the 3-year planting age group exhibited the lowest values for FC_{AO} (0.31 cm^3/cm^3), FC_{10} (0.42 cm^3/cm^3), AWC_{AO} (0.14 cm^3/cm^3), and micro-porosity (31.6%). Soil samples from the 40-year planting age group showed the highest value for macro-porosity (9%) and the lowest values for AWC_{10} (0.21 cm^3/cm^3), and meso-porosity (9.3%). Significant differences were detected only in micro-porosity across all planting ages at the Belfast site, while no significant differences were found in FC_{AO} and meso-porosity between the 12- and 40-year planting ages. The 3-year planting age showed no substantial differences in AWC_{10}, macro-porosity, and meso-porosity compared to the 12-year planting age. These findings may suggest that the 12-year planting age significantly enhances specific soil water retention and hydraulic properties, highlighting the importance of planting age in soil management practices.

In the Richmond site, planting ages significantly influenced most soil water storage and hydraulic properties, excluding FC_{AO} ($p < 0.05$, Table 6). For FC_{AO} and FC_{10}, all planting ages exhibited similar values for FC_{AO} (0.40 cm^3/cm^3), while the 28-year planting age displayed the highest FC_{10} (0.40 cm^3/cm^3). The values for AWC_{AO} and AWC_{10} peaked at 17 years, registering at 0.14 cm^3/cm^3 for AWC_{AO}, with AWC_{10} reaching a shared peak at both 17 and 28 years (0.12 cm^3/cm^3). In terms of porosity, macro-porosity was highest at 17 years (15.32%) and lowest at 28 years (11.32%). Meso-porosity increased with age, with the lowest at 12 years (6.61%) and the highest at 28 years (7.14%). Conversely, micro-porosity rose from 33.79% at 12 years to 35.51% at 28 years, marking the highest value. Significant differences were detected in AWC_{AO}, macro-porosity, and micro-porosity across all planting ages. However, no significant differences were found in AWC_{10} and meso-porosity between the 17- and 28-year planting ages. The 12-year planting age showed no substantial differences in FC_{10} when compared to the 17-year planting age.

There were significant two-way interaction effects were observed on soil water storage properties in the Belfast site (Table 5), while three-way interaction effects only demonstrate significance in FC_{AO}. Figure 16 illustrates the interactions between traffic positions and planting ages on field capacity at -10 kPa (FC_{10}, $p<0.001$) and micro-porosity ($p<0.01$). At a planting age of 3 years, the highest FC_{10} and micro-porosity were found near tree positions, with no significant difference compared to other traffic positions. When planting age reached 12 years, the highest FC_{10} and micro-porosity were observed between track areas, while the lowest was at near tree positions. For the 40-year planting age, the highest FC_{10} and micro-porosity were recorded in track positions, with the lowest values in near tree positions. Compared to other planting ages, the FC_{10} and micro-porosity was substantially higher in 12 years compared to other planting ages at all traffic positions.

Significant interactions between planting ages and soil depth were detected for FC_{AO}, AWC_{10}, meso-porosity, and micro-porosity (Figure 18). FC_{AO} values increased with planting age in the 0-10 cm and 10-20 cm depths. However, in the 20-30 cm depth, FC_{AO} values rose from 3 to 12 years before declining from 12 to 40 years. AWC_{10} decreased with planting age in the 0-10 cm depth, with significantly higher values observed at 3 years compared to other depths. At 12 years, AWC_{10} in the 0-10 cm and 10-20 cm depths did not show significant differences but differed considerably from the 20-30 cm depth. No significant variation was found in AWC_{10} across all depths at 40 years. Meso-porosity decreased with increasing planting age in the 0-20 cm depths and was significantly higher in the 0-20 cm depths compared to the 20-30 cm depth at 3 and 12 years. At 40 years, meso-porosity showed no significant differences across depths. Micro-porosity peaked at all soil depths at the 12-year planting age, with no significant differences between the 3- and 12-year planting ages. In the 40-year planting age, micro-porosity was significantly higher in the 0-10 cm depth compared to other depths.

Interactions between traffic position and soil depth had notable effects on FC_{10}, AWC_{AO}, macro-porosity, meso-porosity, and micro-porosity at the Belfast site, as depicted in Figure 19. FC_{10} values decreased with soil depth and were consistently higher in the 0-10 cm depth across all traffic positions, with the near tree position showing markedly lower values compared to other positions at this depth. AWC_{AO} was notably lower in the track position at both the 0-10 cm and 10-20 cm depths compared to other positions, while the near tree position exhibited considerable differences at the 20-30 cm depth. Macro-porosity was lowest in the track position at each depth and significantly lower than in the near tree position. Meso-porosity was elevated in the between track position compared to other positions at the same depth and showed considerably higher values in the near tree and between track positions at the 0-10 cm depth compared to the 20-30 cm depth. Additionally, micro-porosity was substantially higher in the 0-10 cm depth in both the track and between track positions relative to other soil depths.

At the Richmond site, no significant two-way interactions were observed between planting ages and traffic positions (Table 6). However, significant interactions were found between planting ages and soil depth, as well as between traffic positions and soil depth (Table 6). As shown in Figure 17, significant interactions were identified in FC_{10} regarding planting ages and traffic positions. FC_{10} was found to be substantially lower in 17 years compared to other planting ages in 0 to 10 cm and it reached the highest value in 28 years of planting age. This pattern was also applied to other soil depths.

Moreover, notable interactions between traffic positions and soil depth were identified for FC_{10}, FC_{AO}, AWC_{AO}, macro-porosity, and micro-porosity (Figure 20, $p < 0.05$). The track position consistently exhibited the highest FC_{10} values at all soil depths, with FC_{10} being markedly higher in the 0-10 cm depth across all positions compared to deeper layers. A similar depth effect was observed for FC_{AO}, where the near tree position consistently had the highest values compared to other positions, while the lowest FC_{AO} values appeared at the 0-10 cm and 10-20 cm depths. For AWC_{AO}, the track position consistently showed the lowest values at all soil depths, while the near tree position exhibited the highest AWC_{AO} values across all depths. Interestingly, AWCAO was elevated in the 20-30 cm depth in the track position compared to other depths, suggesting that subsoil compaction may extend to 20 cm at the Richmond site. Macro-porosity followed a similar trend, with notably lower values in the track position at the 0-10 cm and 10-20 cm depths compared to the 20-30 cm depth, and lower than other positions across all soil depths. Consistent with observations from the Belfast site, micro-porosity was higher in the track position at all soil depths compared to other positions and was markedly greater in the 0-10 cm depth than in the deeper layer.

In terms of gas diffusivity, the gas diffusivity (D_p/D_o) tended to be significantly affected by the track position while the planting ages not significantly affected the D_p/D_o (Table 3). The higher D_p/D_o value was only found in the track position and the difference was significant at -4 and -8 kpa.

Saturated hydraulic conductivity

The results for saturated hydraulic conductivity (LogKs) revealed no significant effect of traffic position at the Belfast site; however, notable effects were observed at the Richmond site. At the Belfast site, LogKs was consistently lower in the track position (1.66), while in Richmond, it was 2.42 in the track position (Tables 5 and 6). The highest LogKs values were found in the near tree position, with 1.70 at the Belfast site and a substantially higher 3.26 at the Richmond site, compared to the track and between track positions.

Planting age significantly influenced LogKs at the Belfast site but had no marked effect at the Richmond site. In Belfast, LogKs were significantly lower in the 3-year planting age (1.04) compared to the 12- and 40-year planting ages, which showed no significant difference between them, with values of 2.10 and 2.08, respectively. Although planting age did not significantly affect LogKs at the Richmond site, there was a slight increase from 2.83 at 12 years to 2.96 at 17 years before decreasing to 2.61 at 28 years.

Regarding interactions between traffic position, planting age, and soil depth, significant effects were observed between planting age and soil depth at the Belfast site (Figure 18). LogKs were considerably higher in the 12- and 40-year planting ages at the 0-10 cm depth, while no differences were noted in the deeper soil layers across all planting ages. Besides, significant interactions between traffic positions and soil depth were also detected at Belfast site (Figure 19), with a greater Logks in 0-10 cm in track and between track positions compared to other soil depth. No statistically difference was detected in near tree position across all soil depth on Logks.

Table 5. Effect of age of planting (3, 12 and 40 years), traffic position (near tree, track, and between track), soil depth and their interactions on soil hydraulic properties in Belfast site. Values are means with different letters showing significant differences within the group except where LSD and significance levels are noted. LSD: least significant difference calculated at a significant level of p< 0.05. Symbols "*", "**", "*" and "ns" indicate the main or interaction effect was significant at P<0.001,0.01, 0.05 and p >0.05, respectively. FC: field capacity, AWC: available water capacity, Logks20: log-transformed saturated hydraulic conductivity at 20 degrees, macro-porosity (>30 µm), meso-porosity (5-30 µm), micro-porosity (<5 µm), RFC: relative field capacity. Subscripts '10' and 'AO' represent the variables measured or calculated at soil matric potential of −10 kPa and ψ_{FC} referred to equation 11 (Assouline & Or, 2014), respectively.**

Variables		FC_{AO} (cm^3/cm^3)	FC_{10} (cm^3/cm^3)	AWC_{AO} (cm^3/cm^3)	AWC_{10} (cm^3/cm^3)	Macro-porosity (%)	Meso-porosity (%)	Micro-porosity (%)	LogKs (mm/hour)
Age	3	0.31^{a}	0.42^{a}	0.14^{a}	0.26^{a}	6.2^{a}	10.7^{a}	31.6^{a}	1.04^{a}
	12	0.38^{b}	0.50^{b}	0.15^{a}	0.26^{a}	6.2^{a}	10.2^{ab}	39.6^{b}	2.10^{b}
	40	0.37^{b}	0.43^{a}	0.15^{a}	0.21^{b}	9^{b}	9.3^{b}	33.5^{c}	2.08^{b}
Positions	Near tree	0.38^{a}	0.44^{a}	0.15^{a}	0.22^{a}	9^{a}	9^{a}	34.7^{a}	1.70^{a}
	Track	0.33^{b}	0.45^{b}	0.14^{b}	0.26^{b}	5.3^{b}	10^{b}	35.3^{a}	1.66^{a}
	Between track	0.35^{a}	0.46^{b}	0.16^{a}	0.26^{b}	7.2^{c}	11^{c}	34.6^{a}	1.86^{a}
Depth (cm)	0-10	0.43^{a}	0.49^{a}	0.16^{a}	0.28^{a}	6.6^{a}	11^{a}	37.4^{a}	2.10^{a}
	10-20	0.39^{a}	0.44^{b}	0.15^{a}	0.26^{a}	7^{a}	10^{b}	33.6^{b}	1.57^{b}
	20-30	0.37^{a}	0.42^{c}	0.14^{b}	0.20^{b}	7.8^{b}	8.4^{c}	33.7^{b}	1.55^{b}
LSD and Significance level	Age	0.02***	0.01***	0.01^{ns}	0.03***	1.3***	1*	1.4***	0.28***
	Position	0.02**	0.01**	0.01***	0.03**	1.3***	1**	1.4^{ns}	0.28^{ns}
	Depth	0.02*	0.01***	0.01***	0.03***	1.3^{ns}	1***	1.4***	0.28***
	Age × Position	0.04^{ns}	0.02***	0.02^{ns}	0.05^{ns}	2.2^{ns}	1.7^{ns}	2.4*	0.48^{ns}
	Age × Depth	0.04***	0.02^{ns}	0.02^{ns}	0.05***	2.2^{ns}	1.7***	2.4*	0.48***
	Position × Depth	0.04^{ns}	0.02**	0.02**	0.05^{ns}	2.2**	1.7*	2.4***	0.48*
	Age × Position × Depth	0.07*	0.04^{ns}	0.03^{ns}	0.09^{ns}	3.8*	2.9^{ns}	4.2^{ns}	0.83^{ns}

Table 6. Effect of age of planting (12, 17 and 28 years), traffic position (near tree, track, and between track), soil depth and their interactions on soil hydraulic properties in Richmond site. Values are means with different letters showing significant differences within the group except where LSD and significance levels are noted. LSD: least significant difference calculated at a significant level of $p < 0.05$. Symbols "*", "**", "*" and "ns" indicate the main or interaction effect was significant at $P<0.001$, 0.01, 0.05 and $p > 0.05$, respectively. FC: field capacity, AWC: available water capacity, Logks20: log-transformed saturated hydraulic conductivity at 20 degrees, macro-porosity (>30 µm), meso-porosity (5-30 µm), micro-porosity (<5 µm), RFC: relative field capacity. Subscripts '10' and 'AO' represent the variables measured or calculated at a soil matric potential of −10 kPa and ψFC referred to equation 11 (Assouline & Or, 2014), respectively.**

Variables		FC_{AO} (cm^3/cm^3)	FC_{10} (cm^3/cm^3)	AWC_{AO} (cm^3/cm^3)	AWC_{10} (cm^3/cm^3)	Macro-porosity (%)	Meso-porosity (%)	Micro-porosity (%)	LogKs (mm/hour)
Age	12	0.42^{a}	0.38^{a}	0.15^{a}	0.11^{a}	13.4^{a}	4.7^{a}	33.3^{a}	2.83^{a}
	17	0.42^{a}	0.37^{a}	0.17^{b}	0.12^{b}	15.5^{b}	5.1^{b}	32^{b}	2.96^{a}
	28	0.42^{a}	0.40^{b}	0.13^{c}	0.12^{b}	11.3^{c}	5.1^{b}	35^{c}	2.61^{a}
Positions	Near tree	0.44^{a}	0.38^{a}	0.18^{a}	0.12^{a}	17.1^{a}	4.9^{a}	32.8^{a}	3.26^{a}
	Track	0.41^{b}	0.40^{b}	0.12^{b}	0.11^{a}	9.8^{b}	4.8^{a}	34.9^{b}	2.42^{b}
	Between track	0.41^{b}	0.38^{a}	0.15^{c}	0.13^{ab}	13.3^{c}	5.2^{a}	32.7^{a}	2.73^{b}
Depth (cm)	0-10	0.46^{a}	0.43^{a}	0.16^{a}	0.13^{a}	13.6^{a}	5.3^{a}	37.9^{a}	3.35^{a}
	10-20	0.40^{b}	0.37^{b}	0.14^{b}	0.11^{b}	12.7^{a}	4.6^{b}	32.5^{b}	2.75^{b}
	20-30	0.39^{c}	0.35^{c}	0.15^{a}	0.11^{b}	13.9^{a}	4.9^{b}	30^{b}	2.31^{c}
LSD and Significance level	Age	0.01^{ns}	0.01^{***}	0.01^{***}	0.01^{*}	1.1^{***}	0.4^{**}	0.9^{***}	0.3^{ns}
	Position	0.01^{***}	0.01^{***}	0.01^{***}	0.01^{*}	1.1^{***}	0.4^{ns}	0.9^{***}	0.3^{**}
	Depth	0.01^{***}	0.01^{***}	0.01^{**}	0.01^{***}	1.1^{ns}	0.4^{***}	0.9^{***}	0.3^{***}
	Age × Position	0.02^{ns}	0.02^{ns}	0.01^{ns}	0.01^{ns}	1.9^{ns}	0.6^{ns}	1.6^{ns}	0.5^{ns}
	Age × Depth	0.02^{ns}	0.02^{*}	0.01^{ns}	0.01^{ns}	1.9^{ns}	0.6^{ns}	1.6^{ns}	0.5^{ns}
	Position × Depth	0.02^{*}	0.02^{***}	0.01^{*}	0.01^{ns}	1.9^{**}	0.6^{ns}	1.6^{***}	0.5^{ns}
	Age × Position × Depth	0.03^{ns}	0.03^{ns}	0.03^{ns}	0.02^{ns}	3.3^{ns}	1.1^{ns}	2.9^{ns}	0.9^{ns}

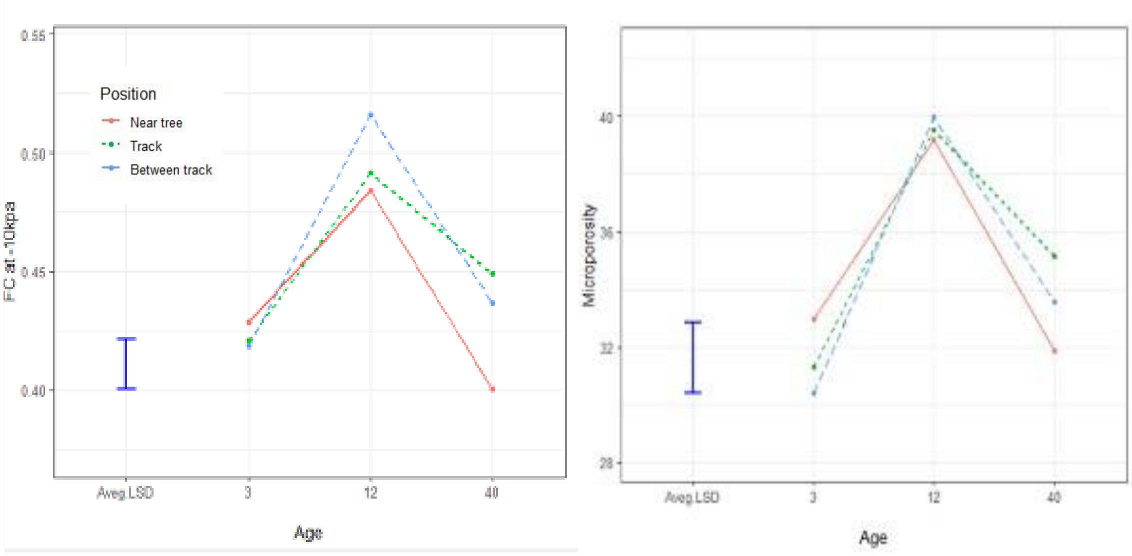


Figure 16. The interaction effect of traffic position and planting ages on hydraulic properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$). FC_{10}: field capacity calculated at soil matric potential of -10 kPa, micro-porosity (<5 µm).

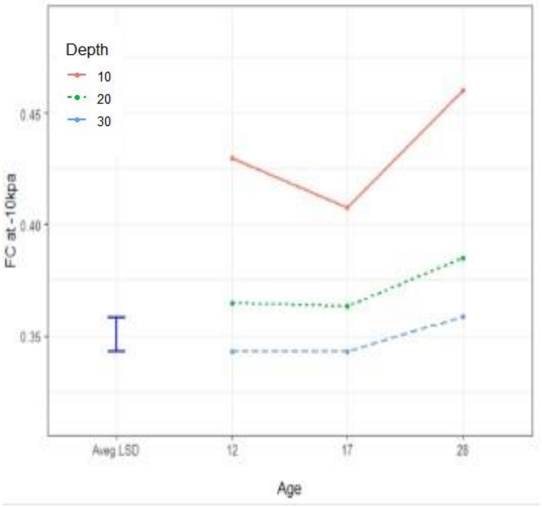


Figure 17. The interaction effect of planting ages and soil depth on soil hydraulic properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$). FC_{10}: calculated at soil matric potential of -10 kPa.

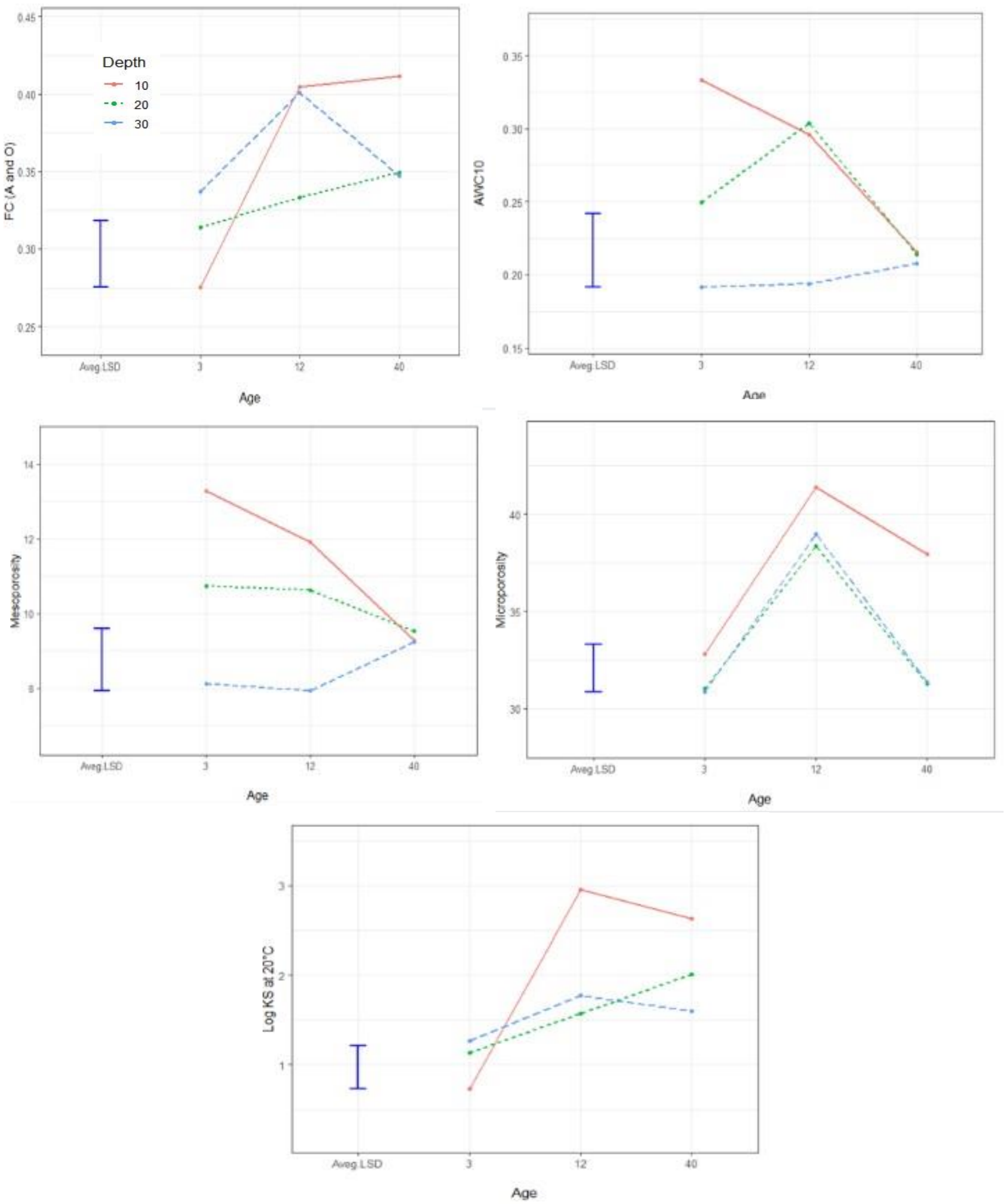


Figure 18. The interaction effect of planting ages and depth on soil hydraulic properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$). FCAO: field capacity calculated by dynamic criteria used to define field capacity (Assouline & Or, 2014), AWC10: available water capacity calculated from -10 kPa to -1500 kPa. Meso-porosity (5- 30 µm), Micro-porosity (<5 µm), Logks at 20 °C: log-transformed saturated hydraulic conductivity corrected at 20 °C.

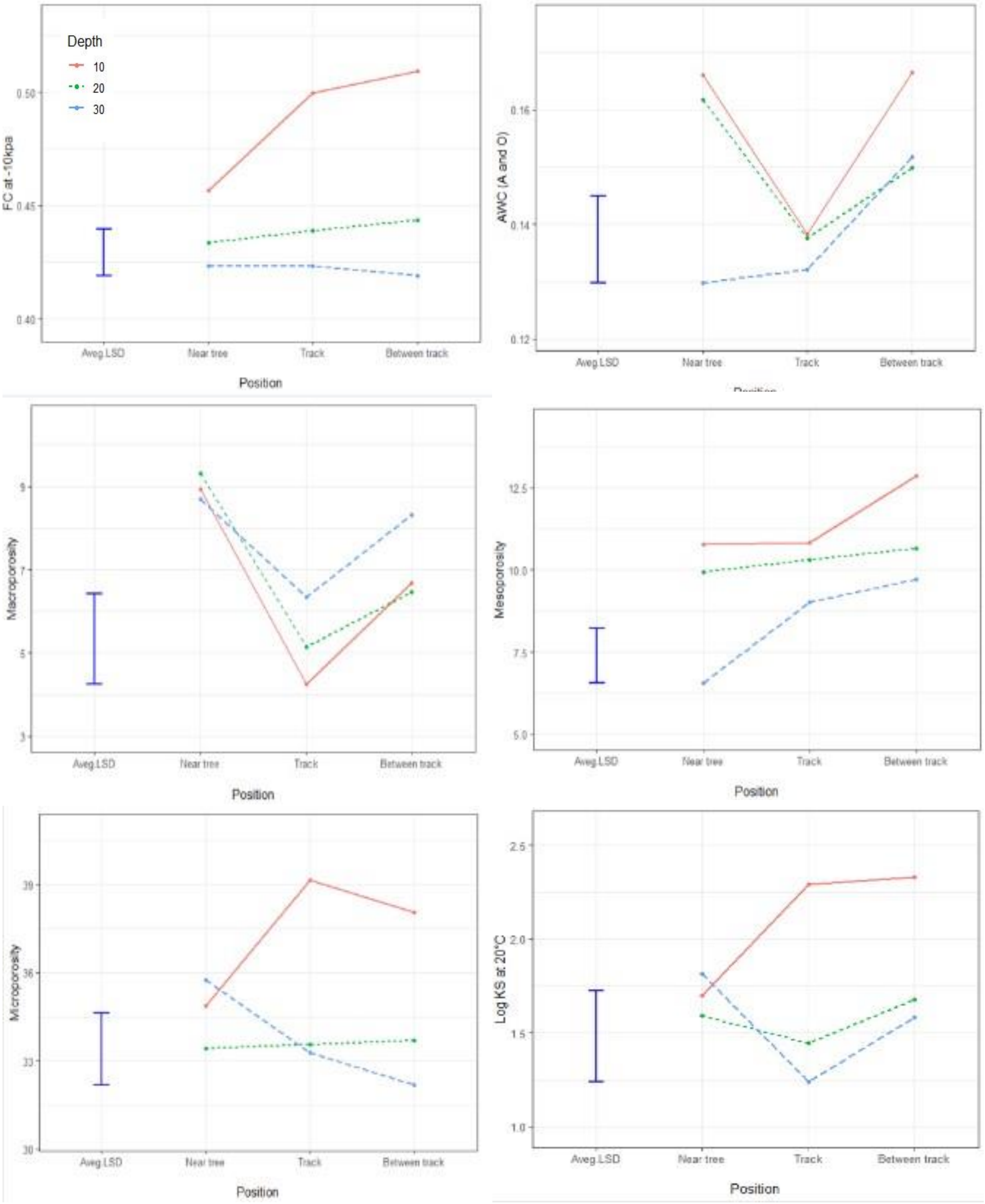


Figure 19. The interaction effect of traffic position and soil depth on soil hydraulic properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$). FC$_{10}$: field capacity calculated at soil matric potential of -10 kPa, AWC$_{AO}$: available water capacity calculated from FC$_{AO}$ to -1500 kPa, Macro-porosity (> 30 µm), Meso-porosity (5- 30 µm), Micro-porosity (<5 µm), Logks at 20 °C: log-transformed saturated hydraulic conductivity corrected at 20 °C.

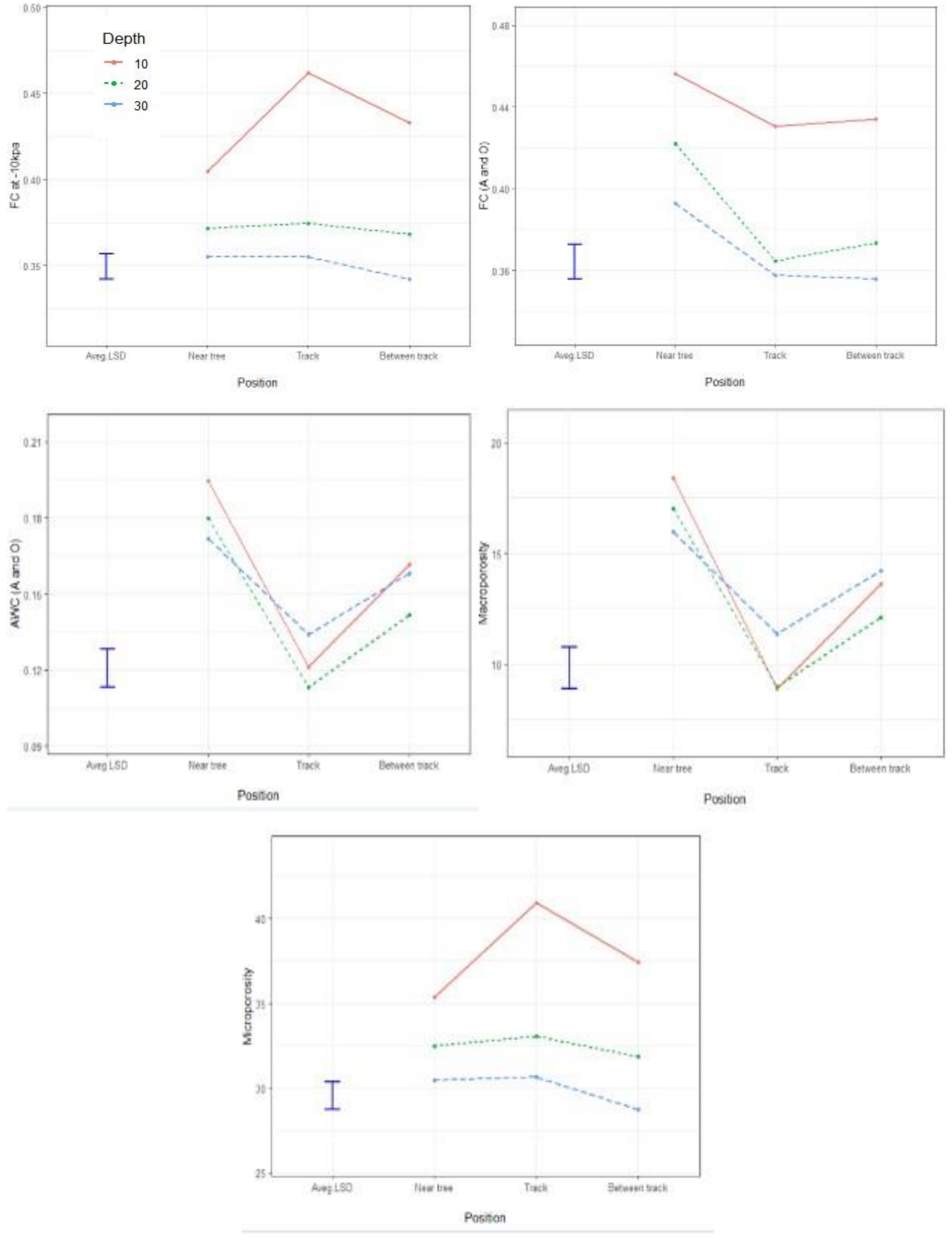
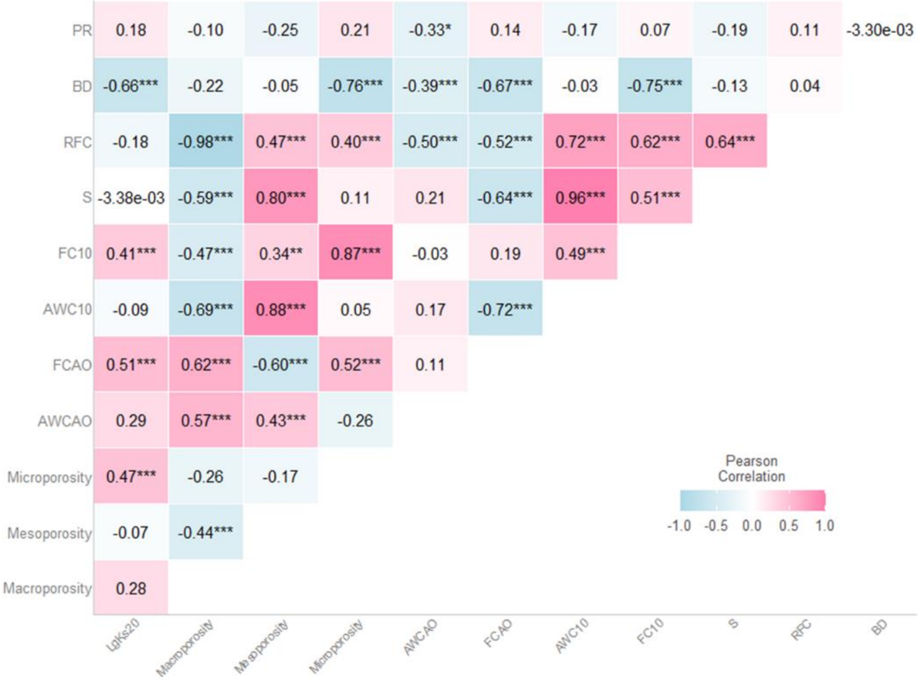


Figure 20. The interaction effect of traffic position and soil depth on hydraulic properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$).FC$_{10}$: field capacity calculated at soil matric potential of -10 kPa, FC$_{AO}$: field capacity calculated by dynamic criteria used to define field capacity (Assouline & Or, 2014), AWC$_{AO}$: available water capacity calculated from FC$_{AO}$ to -1500 kPa, Macro-porosity (>30 µm), Micro-porosity (<5 µm).

4.4.2 Correlation analysis of physical properties

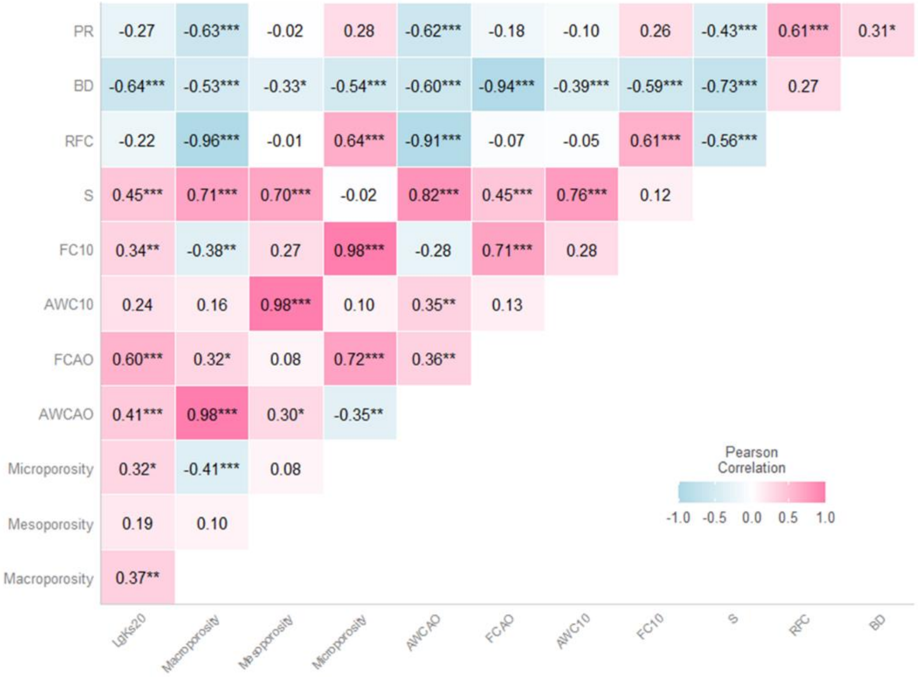
Figures 21 and 22 present the Pearson correlation matrices of physical properties in both orchards, highlighting several common correlations. In both orchards, bulk density (BD) exhibited a strong negative correlation with saturated hydraulic conductivity (LogKs), micro-porosity, AWC_{AO}, FC_{AO}, and FC_{10} ($p < 0.05$). The relative field capacity (RFC) showed a strong positive correlation with micro-porosity and FC_{10} while displaying a negative correlation with macro-porosity and AWC_{AO} ($p < 0.05$). The S index demonstrated a strong positive relationship with meso-porosity and AWC_{10} ($p < 0.05$). FC_{10} consistently had a strong negative correlation with macro-porosity, but a positive association with LogKs ($p < 0.05$). AWC_{AO} showed a strong positive correlation with meso-porosity in both orchards ($p < 0.05$). Similarly, FC_{AO} was strongly positively correlated with LogKs and micro-porosity ($p < 0.05$). Additionally, AWC_{AO} displayed a strong positive relationship with both macro-porosity and meso-porosity in both orchards ($p < 0.05$). These correlations reflected the consistent interrelationships among key soil physical properties across both orchard sites.

However, some strong correlations were distinct to each orchard and not shared between the two sites. In the Richmond site, PR showed strong negative correlations with macro-porosity, AWC_{AO}, S index, RFC, and BD ($p<0.05$). BD in Richmond also had strong negative correlations with macro-porosity, meso-porosity, AWC_{10}, and the S index ($p<0.05$). In Belfast, RFC exhibited strong negative correlations with FC_{AO} and positive correlations with meso-porosity, AWC_{10}, and the S index ($p<0.05$), whereas in Richmond, RFC was negatively correlated with the S index ($p<0.05$). FC_{10} displayed strong positive correlations with meso-porosity and AWC_{10} in Belfast but was positively associated with micro-porosity and FC_{AO} in Richmond ($p<0.05$). AWC_{10} was negatively correlated with macro-porosity and FC_{AO} in Belfast, while it showed a positive correlation with AWC_{AO} in Richmond. In Belfast, FC_{AO} was negatively associated with meso-porosity but positively related to macro-porosity, whereas in Richmond, it positively correlated with $AWC_{AO.}$ AWC_{AO} in Richmond also exhibited positive correlations with LogKs and negative correlations with micro-porosity. In Belfast, micro-porosity positively influenced LogKs, whereas in Richmond, it was negatively associated with macro-porosity. Lastly, meso-porosity in Belfast was negatively correlated with macro-porosity, while in Richmond, macro-porosity positively influenced LogKs.



	LgKs20	Macroporosity	Mesoporosity	Microporosity	AWCAO	FCAO	AWC10	FC10	S	RFC	BD
PR	0.18	-0.10	-0.25	0.21	-0.33*	0.14	-0.17	0.07	-0.19	0.11	-3.30e-03
BD	-0.66***	-0.22	-0.05	-0.76***	-0.39***	-0.67***	-0.03	-0.75***	-0.13	0.04	
RFC	-0.18	-0.98***	0.47***	0.40***	-0.50***	-0.52***	0.72***	0.62***	0.64***		
S	-3.38e-03	-0.59***	0.80***	0.11	0.21	-0.64***	0.96***	0.51***			
FC10	0.41***	-0.47***	0.34**	0.87***	-0.03	0.19	0.49***				
AWC10	-0.09	-0.69***	0.88***	0.05	0.17	-0.72***					
FCAO	0.51***	0.62***	-0.60***	0.52***	0.11						
AWCAO	0.29	0.57***	0.43***	-0.26							
Microporosity	0.47***	-0.26	-0.17								
Mesoporosity	-0.07	-0.44***									
Macroporosity	0.28										

Figure 21. Pearson correlation matrix showcasing the interrelationships of physical properties in Belfast site. The colour gradient represents the correlation strength, with red indicating a positive correlation and blue a negative correlation. Asterisks denote the significance levels of the correlations (* p<0.05, ** p<0.01, *** p<0.001).



	LgKs20	Macroporosity	Mesoporosity	Microporosity	AWCAO	FCAO	AWC10	FC10	S	RFC	BD
PR	-0.27	-0.63***	-0.02	0.28	-0.62***	-0.18	-0.10	0.26	-0.43***	0.61***	0.31*
BD	-0.64***	-0.53***	-0.33*	-0.54***	-0.60***	-0.94***	-0.39***	-0.59***	-0.73***	0.27	
RFC	-0.22	-0.96***	-0.01	0.64***	-0.91***	-0.07	-0.05	0.61***	-0.56***		
S	0.45***	0.71***	0.70***	-0.02	0.82***	0.45***	0.76***	0.12			
FC10	0.34**	-0.38**	0.27	0.98***	-0.28	0.71***	0.28				
AWC10	0.24	0.16	0.98***	0.10	0.35**	0.13					
FCAO	0.60***	0.32*	0.08	0.72***	0.36**						
AWCAO	0.41***	0.98***	0.30*	-0.35**							
Microporosity	0.32*	-0.41***	0.08								
Mesoporosity	0.19	0.10									
Macroporosity	0.37**										

Figure 22. Pearson correlation matrix showcasing the interrelationships of physical properties Richmond site. The colour gradient represents the correlation strength, with red indicating a positive correlation and blue a negative correlation. Asterisks denote the significance levels of the correlations (* p<0.05, ** p<0.01, *** p<0.001).

4.5 Discussion

4.5.1 Planting ages and traffic effect on soil physical properties

This study highlighted that the soil physical properties in both orchards were significantly affected by the planting ages and traffic-induced compaction. As a commonly used indicator for assessing soil compaction status, bulk density (BD) and penetration resistance (PR) were found to increase with the planting ages and traffic intensity in both orchards. The traffic track resulted in a considerably higher BD and PR than other positions. Similar conclusions were also drawn by many authors (de Moraes et al., 2019; Leij et al., 2002; McHugh et al., 2009; Ramezani et al., 2017; Startsev & McNabb, 2001; van Dijck & van Asch, 2002). Regardless of traffic disturbances, the increases in BD and PR with planting age may be attributed to the age-hardening process, where soil strength naturally increases over time due to stronger bonding and cementation among soil particles following initial disturbances(Moraes et al., 2019). A similar finding was also reported by Wei et al. (2021), their investigation of long-term plantation of apples showed that the BD and PR were increased by around 5.3 % and 29.3% in older orchards (>10 years) compared to younger orchards (< 10 years). Additionally, the higher PR and BD values observed in the subsoil (10 to 30 cm) indicate subsoil compaction in both orchards. For instance, at the Belfast site, PR values were significantly higher in the 10-20 cm (2.48 MPa) and 20-30 cm (2.71 MPa) depths compared to the 0-10 cm layer, highlighting the occurrence of subsoil compaction at these depths. In contrast, the PR did not change significantly in Richmond site in subsoil. This may be attributed to the slightly heavier soil texture and higher traffic passes (35 times vs 25 times) in Belfast orchard. As the PR value could affect the tree root penetration, Sinnett et al. (2008) noted that most forest tree roots were concentrated in areas where PR is below 3 MPa. Given this, the higher PR observed at the near tree positions in Belfast site is likely contributing to the slower growth rate of the 3-year-old apple trees in that orchard. Compared to traffic compaction, mean weight diameter was more affected by planting ages. MWD generally decreased with an increase in the planting ages in both orchards, indicating a deterioration in soil physical health and an increased risk of compaction in both orchards. Cao et al. (2021) reported that in their experiments, MWD decreased by 5.66% for orchard plantation ages ranging from 11 to 20 years and by 12.58% for ages ranging from 21 to 30 years compared to the 0 to 10 years range. On the other hand, higher MWD value was also found to be slightly higher in track position and between track positions in both orchards although there was no statistical significance detected between other positions. This phenomenon can be attributed to the influence of soil organic carbon and the physical protection of soil aggregates. As suggested by Deurer et al. (2012), the organic carbon loss through the water flow in the form of dissolved carbon under the traffic track was probably smaller, which may result in higher SOC accumulated in the soil profile. Hence, higher SOC content likely caused an increase in the stability of soil aggregation and its formation. Additionally, traffic-induced compaction altered soil pore structure, affecting soil microbial activities and preventing the decomposition of soil organic matter (Brevik et al., 2002; Deurer et al., 2012). Consequently, higher organic carbon is preserved in track positions, resulting in relatively higher aggregate stability compared to other positions.

The effect of traffic and planting ages on soil water retention properties, soil physical quality index (S index) and relative field capacity (RFC) was related to the alteration in the pore system in both orchards. As expected, the track position resulted in higher $FC_{10,}$ $AWC_{10,}$ micro-porosity, and lower Logks. The increase in FC_{10} was attributed to the conversion of macro-porosity to smaller pores such as meso-porosity and micro-porosity which response to water retention (Reichert et al., 2018; Thomas et al., 2019; Tuzzin de Moraes et al., 2016). The higher micro-porosity under track position also supported this explanation in this study (Tables 5 and 6). Therefore, increasing the volume of smaller pores (<30 µm) resulted in more water retained at -10 kPa and hence led to the higher RFC in track position as shown in Tables 3 and 4. Moreover, the correlation analysis also provided evidence that the FC_{10} and RFC had a strong negative correlation to macro-porosity and positively associated with meso-and macro-porosity. Furthermore, according to Reynolds et al. (2009), the RFC value was over 0.7 in track and between track positions in both orchards indicating a limited soil aeration capacity. This suggested that soil pore-related functions may be impaired not only in the areas directly impacted by tracks but also in the spaces between tracks—regions that were occasionally traversed by traffic. Moreover, the significantly lower macro-porosity was found in the track position as shown in Tables 3 and 4 which contributed to the lower saturated hydraulic conductivity in both orchards. However, the Logks in Belfast were more correlated to micro-porosity rather than macro-porosity due to the extremely low macro-porosity (half of the Richmond site) in the Belfast site (Figures 21 and 22). A similar result was also found by Hu et al. (2022), their study result showed the macro-porosity was not a strong determinant of water transport capability. Moreover, the track positions also resulted in the lower FC_{AO} and

AWC_{AO}. According to Assouline and Or (2014), the field capacity can be defined as a dynamic criterion related to the suction at the maximum extent of hydraulically connected pathways(ψ_{FC}). In other words, the greater pore continuity the lower water retained in the soil at $\psi_{FC,}$ due to a faster water flux within soil pores (Richard et al., 2001). Due to compaction, the reduction in pore space between aggregates and deformation at their contact points increased the contact surface area between the aggregates, consequently resulting in greater pore continuity (hydraulic continuity) in compacted soil compared to uncompacted soil (Fu et al., 2021; Gupta et al., 1989; Richard et al., 2001). Moreover, the soil water transport and aeration properties under the compaction condition were more related to the soil pore continuity rather than porosity dynamics (Horn et al., 2003; Lipiec et al., 2003). Therefore, the lower FC_{AO} and AWC_{AO} values observed under track positions were likely due to greater pore continuity, while higher relative gas diffusivity in track positions reflected greater average pore continuity of air-filled pores in the soil, as suggested by Moldrup et al. (2001). Additionally, pore continuity was also positively related to the organic matter content in the soil (Kuncoro et al., 2014), As the protection effect of compaction on SOC, the higher SOC content (as presented in next chapter) under track position also resulted in higher pore continuity that contributed to the lower FC_{AO} and AWC_{AO}, and higher relative gas diffusivity. Therefore, due to the adversely impacts such as lower macro-porosity and low infiltration capacity from soil compaction in both orchards, the risk of nutrient runoff, greenhouse gas emission and soil erosion would increase and potentially result in reduction in crop yield (Deurer et al., 2009; Hu et al., 2021).

Compared to the impact of traffic, soil water retention properties may be less sensitive to planting ages, particularly regarding soil pore system dynamics. As discussed, changes in soil water retention properties were related to pore dynamics, with differences in macro-porosity and micro-porosity affecting FC_{10} and AWC_{10}. In both orchards, FC_{AO} and AWC_{AO} did not show significant differences with longer planting ages, indicating that pore continuity was not significantly influenced by planting ages alone. The intermediate planting ages (12 years in Belfast, and 12 years and 17 years in Richmond site) showed relatively better soil water retention properties compared to younger and older planting ages (Tables 5 and 6) may indicate the ongoing soil recovery process under these planting ages. The dynamic equilibrium in soil structure recovery was reached from 5 to 18 years depending on the soil type, compactness and climate (da Silva et al., 2021; Nawaz et al., 2012). Moreover, without tillage distracting the soil structure, the accumulation of soil organic matter particularly in topsoil would like to result in the recovery of degraded soil (da Silva et al., 2021; Reichert et al., 2018). Thus, due to the natural recovery of soil structure over time, the soil water retention properties may not be strongly affected by the planting ages. For future studies, more emphasis should be placed on developing strategies to maintain better soil physical properties in long-term orchard plantations.

4.5.2 Interactions between planting ages and traffic on soil physical properties

In addition, at the Belfast site, bulk density (BD) was found to be higher in the 3-year planting age compared to the 12-year and 40-year planting ages. At the Richmond site, BD in the 12-year planting age was similar to that in the 28-year planting age. However, the pore size distribution differed significantly between these ages. For instance, despite similar BD values in the 12-year and 28-year planting ages at the Richmond site, meso-porosity and micro-porosity were significantly lower, and macro-porosity was significantly higher in the 12-year planting age compared to the 28-year planting age (Table 6). This outcome suggested that BD might not have been suitable for representing the compaction status, as the pore size distribution could differ even under the same bulk density, as suggested by Hu et al. (2021) and Zhai and Horn (2019b). This study also demonstrated that soil pore-related functions could be a useful indicator for assessing soil compaction conditions. Interactions between planting ages and traffic on soil physical properties

This section critically analysed the interactions between planting ages and traffic positions, which were found to have markedly influenced key soil properties, including bulk density (BD), penetration resistance (PR), field capacity at -10 kPa (FC_{10}), and micro-porosity in the Belfast site, and PR in the Richmond site. The discussion emphasised these interactions as they directly addressed the core hypothesis of this study. While the effects of soil depth on soil properties were well-recognised and extensively documented in the existing literature, this section prioritised the complex dynamics between planting ages and traffic positions due to their significant impact on soil physical properties.

The soil penetration resistance (PR) under the track position in both orchards increased with planting age (Figures 10 and 13). This trend was primarily due to the cumulative impact of prolonged traffic, as reported by several studies on the effects of repeated traffic passes on soil PR ((de Moraes et al., 2019; Hamza & Anderson, 2005; Nawaz et al., 2012; Wei et al., 2021). Additionally, high PR and repeated traffic passes in track positions prevented vegetation from establishing, further hindering the soil's ability to recover from compaction. Vegetation cover plays a crucial role in aiding soil recovery, as plant roots and residues in the soil profile help to alleviate existing compaction and reduce further compaction from traffic (Frene et al., 2024; Shah et al., 2017). In both orchards, PR in the near tree and between track positions showed evidence of this recovery. In the Belfast site, the PR in the between track position followed a similar pattern to the track position but was substantially lower, suggesting fewer traffic passes. Vegetation cover in these areas likely helped mitigate compaction effects, although some accumulation from potential traffic passes was still evident. In Richmond, the PR in the between track position displayed a similar trend to the near tree position but was notably higher, indicating that compaction effects might have accumulated even with natural recovery processes in place.

Traffic and planting age significantly influenced bulk density (BD) at the 3-year and 12-year planting ages, but this impact was not evident at 40 years. As expected, higher BD was recorded in track positions due to traffic-induced compaction. However, at 40 years, there were no significant differences in BD between traffic positions. This finding suggested that, in shorter planting durations, BD variations were mainly driven by traffic passes. Over time, BD tended to equalise across traffic positions, with a slightly higher BD observed in the near-tree position, as shown in Figure 10. This trend implied that, with longer planting durations, BD may be more strongly influenced by planting age rather than traffic impact.

The interactions between planting ages and traffic positions on FC_{10} and micro-porosity followed a similar underlying principle: lower micro-porosity corresponded to lower FC_{10}. Micro-porosity was primarily influenced by planting age rather than traffic, as evidenced by the lack of substantial differences between traffic positions across all planting ages, consistent with the findings presented in Tables 5 and 6. In contrast, FC_{10} was influenced by both planting age and traffic, as indicated by changes in FC_{10} within track positions; it shifted from being the second highest at 12 years to the highest at 40 years. This suggests that longer planting durations result in an accumulated effect of traffic-induced compaction on FC_{10}, likely due to the conversion of larger pores into smaller ones over time, as discussed in the previous section.

4.6 Conclusions

This study demonstrated that planting ages and traffic positions significantly affect soil physical properties in both orchards. As planting ages and traffic frequency increased, penetration resistance (PR) and bulk density (BD) also increased. Mean weight diameter (MWD) declined with increasing planting ages, but due to the physical protection of organic matter under compacted areas, MWD was higher in track positions. The S index was negatively correlated with increases in planting ages and traffic, indicating changes in pore structure dynamics in compacted soils. While planting age did not significantly affect relative gas diffusivity (D_p/D_o), The significantly higher D_p/D_o values may be attributed to higher pore continuity in track positions. The soil water retention properties were more sensitive to traffic rather than planting ages as the macro-porosity was strongly affected by the traffic and the conversion of larger pores to smaller pores such as meso-and micro-porosity during the compaction.

This study also revealed significant effects of planting ages and traffic positions on soil PR, BD, FC_{10} and micro-porosity. Longer planting ages resulted in higher traffic passes in track positions, which led to increased penetration resistance (PR) in both orchards. However, with less traffic intensity and more vegetation coverage, the compaction effect on PR was less pronounced in both orchards. The results regarding bulk density (BD) in response to interactions between traffic and planting ages indicated that, in orchards with shorter planting ages, BD was mainly affected by traffic. In contrast, in orchards with longer planting ages, the effect of planting age on BD was more pronounced than that of traffic. Longer planting durations led to increased field capacity at -10 kPa (FC_{10}) due to the cumulative effect of traffic-induced compaction, which converts larger pores into smaller ones. Micro-porosity, however, was primarily influenced by planting age rather than traffic.

Additionally, intermediate planting ages (12 years at the Belfast site and 12 to 17 years at the Richmond site) exhibited superior soil physical conditions, characterised by higher mean weight diameter (MWD) and soil physical quality index (S index) values, and better soil water retention properties and bulk density (BD). This suggested that these intermediate planting ages have better soil structure and health compared to other planting ages. Moreover, due to the inconsistency between BD and soil water retention properties in relation to soil pore dynamics, soil pore-related functions may be more suitable for assessing soil compaction status. Additionally, future studies should focus on developing strategies to maintain better soil physical properties in long-term orchard plantations, considering the dynamic changes in pore-related functions under the effects of traffic and planting ages.

Chapter 5

Determining the impact of compaction on soil chemical properties under different planting ages and traffic positions in New Zealand apple orchards

5.1 Abstract

The purpose of this study was to investigate the effects of soil compaction on several chemical properties across different planting ages and traffic positions in two New Zealand apple orchards. Soil cores were collected from near tree, under the wheel track, and between track positions at three depths (0–10, 10–20, and 20–30 cm) from orchards of three different planting ages at each site. The cores were analysed for total carbon (C) and nitrogen (N), C/N ratio, mineral nitrogen (Min-N), hot water extractable carbon (HWEC), and carbon stock.

In general, significantly higher C and N concentrations were found in track positions at both orchards, with values of 2.84% and 0.27% at the Belfast site, and 2.35% and 0.21% at the Richmond site, respectively. Similar trends were observed for carbon stock and HWEC in track positions, with values of 108.3 t/ha and 1330.9 mg kg-1 at the Belfast site, and 90.3 t/ha and 875 mg kg-1 at the Richmond site, respectively. C, N, and carbon stock increased with planting age at both orchards. Intermediate planting ages (12 to 17 years) exhibited relatively superior soil chemical quality, with the highest levels of C, N, Min-N, HWEC, and carbon stock, reflecting a more stable soil structure conducive to microbial activity and organic matter decomposition. Planting ages did not significantly influence Min-N or the C/N ratio.

The interactions between traffic positions and planting ages on soil carbon and nitrogen were significant, with compaction initially increasing soil organic carbon and nitrogen due to physical protection. However, this effect stabilised over time. Soil carbon stock, influenced by carbon content, soil depth, and bulk density, showed a greater increase at 40 years of planting, attributed to rising bulk density.

5.2 Introduction

As a form of hidden soil structural degradation (SSD), soil compaction is defined as the process where soil particles are rearranged to reduce the void space between them (Hamza & Anderson, 2005). Traffic-induced soil compaction is commonly observed in agriculture, horticulture, and forestry (Wei et al., 2021). Compaction can negatively impact key soil functions such as nutrient cycling, water flow, aeration, and habitat for soil organisms (Keller et al., 2019). In orchards, soil compaction frequently occurs due to machinery traffic for applying pesticides or fungicides to combat diseases and pests (Paltineanu et al., 2016). External stress from machinery traffic reduces soil water storage and root growth, leading to decreased crop yield and increased reliance on fertilisers, among other negative outcomes (Tim Chamen et al., 2015). Petry et al. (2016) observed that in areas with compacted soil in a peach orchard, the frequency of thick roots decreased with increasing soil depth when compared to un-compacted area, attributed to the rise in soil mechanical resistance. This is likely to result in a smaller capacity for plant to reach water and nutrients. Furthermore, reduced soil porosity due to compaction limited water and gas flow, leading to a disruption in the biochemical balance of soil and resulting in changes of chemical properties (Frene et al., 2024; Ramos et al., 2022).

Soil chemical properties are crucial indicators of soil health and are closely tied to soil productivity (Bogunovic et al., 2017). Numerous studies have documented the effects of soil compaction on chemical properties (eg,(Blumfield et al., 2005; De Neve & Hofman, 2000; Frene et al., 2024; Sainju et al., 2021)). For instance, compaction-induced anaerobic conditions can impact nitrogen availability due to the denitrification process and the release of gaseous nitrogen (Frene et al., 2024). Moreover, the reduced movement of soil solution in compacted soils can limit the availability of phosphorus and potassium to plants (Ferreira et al., 2021). Conversely, carbon mineralisation rate significantly decreases when soil bulk density exceeds 1.6 Mg m-3 (De Neve & Hofman, 2000). Cultivating compacted soils significantly increases net N-mineralisation (Blumfield et al., 2005; Silgram & Shepherd, 1999). Despite efforts of researchers to investigate the effects of compaction, existing studies have only addressed parts of the problem(Frene et al., 2024). further investigation into soil physical and chemical data can greatly aid in evaluating the impact of soil compaction and in developing models to predict soil compaction across a range of conditions(Hamza & Anderson, 2005; Nawaz et al., 2012). Thus, understanding the chemical properties under different compaction conditions is beneficial for assessing soil chemical health and provides valuable information for soil management.

As a significant export horticultural product for New Zealand, fresh apple production generated a value of nearly $900 million in 2020 (MPI, 2020). According to Pipfruit (2017b), approximately 12% of apple orchard areas were impacted by traffic-induced soil compaction. Moreover, little is known about traffic-induced compaction in apple orchards due to the lack of available soil information. Soil compaction is frequently observed in orchards due to machinery traffic, and the accumulation of stress caused by machinery over the years can result in detrimental effects on soil health (Petry et al., 2016; Ramos et al., 2022).Soil chemical properties may be influenced by the age of the orchard due to the cumulative effects of compaction. Despite this, few studies have been conducted in apple orchards focusing primarily on the effects of compaction induced by traffic (Deurer et al., 2012; Goh et al., 2001; Paltineanu et al., 2016; Vogeler et al., 2006; Wei et al., 2021). Therefore, the understanding of how planting ages and traffic positions affect soil chemical properties and health in apple orchards remains inadequate.

The primary objective of this study is to examine the impacts of soil compaction on various chemical properties (total carbon and nitrogen, mineral-N, hot water extractable carbon, and carbon stock) on soils across different planting ages and traffic positions in two New Zealand apple orchards. The hypothesis of this study is that with longer planting ages and traffic the greater compaction effect on soil chemical properties. Specifically, this research seeks to address three key questions: (1) how the varying planting ages would influence the soil chemical properties within the apple orchards; (2) how the different traffic positions would affect the soil chemical properties within apple orchards; (3) how the interaction between various factors such as planting ages, traffic positions, and soil depth affect soil chemical properties within apple orchards.

5.3 Material and method

5.3.1 Site description

Two apple orchards, located in Belfast (Canterbury) and Richmond (Tasman district), New Zealand, were chosen for this study as they had adjacent plots with similar soils but with different planting ages. Belfast has an average annual temperature of around 11°C, while Richmond's average annual temperature is approximately 12.1°C. Belfast receives an average annual rainfall of 648 mm, whereas Richmond has a higher average annual rainfall of 1396 mm. The soil in Belfast and Richmond orchards are silt loam soils classified as Recent and Brown under New Zealand's classification system (Hewitt, 2010) and as Entisols and Dystrudepts in the USDA system, respectively (Soil Survey Staff, 2022). Pest and fungal disease control followed New Zealand's Integrated Fruit Production (IFP) protocols in both orchards. The soil in Belfast is primarily composed of silt, at 66.3%, with 5.5% sand and 28.2% clay within the 0 to 90 cm depth range for the whole orchard. The orchard has been cultivating apple trees for over 40 years, with selected blocks representing tree ages of 3, 12, and 40 years. The 12- and 40-year-old blocks were previously used as a dairy farm, while the 3-year-old block was converted from a swamp to a vegetable and berry farm before becoming an orchard. None of the blocks used fertilisers, and irrigation was limited to late spring and summer. It was delivered via drip lines in the 3-year and 12-year orchards, or sprinklers in the 40-year orchard, and only when the soil dried out. The orchard carried out approximately 35 chemical sprays per year, primarily using fungicides applied with a 2–5 tonne 4WD vehicle. Calcium was supplied as a foliar spray of $CaCl_2$ at around 8 kg Ca per hectare, while lime was applied at a rate of 200 kg per hectare.

5.3.2 Soil sampling

In Richmond, the soil texture is classified as loam, with a composition of 21% sand, 56% silt, and 23% clay within the 0 to 90 cm depth range for the whole orchard. The orchard was previously a dairy farm. Blocks representing apple tree ages of 12, 17, and 28 years were selected. In this orchard, traffic frequency involves around 25 applications per year using 2–5 tonne 4WD vehicles. These applications include lime at 1 tonne per hectare, potassium at 200 kg per hectare, and the nutrient-rich foliar spray "Finish It" at 40 kg per hectare. The composition of "Finish It" is as follows: 6.4% nitrogen, 6.2% phosphorus, 30.8% potassium, 2.7% sulphur, and trace elements such as magnesium, iron, manganese, zinc, copper, boron, molybdenum, and iodine. Moreover, drip irrigation was conducted 2–3 times a week during the summer months.

Disturbed soil samples were systematically collected from both sites to assess soil chemical properties. The soil samples from the Belfast site were obtained in July 2022. For the Richmond site, soil samples were collected in June 2023. The sampling locations were strategically chosen between two trees (no traffic, no vegetation cover), on the traffic track (no vegetation cover), and between the tracks (potentially trafficked, covered by vegetations), as illustrated in Figure 23. For analysing soil chemical properties, 216 disturbed soil samples were collected at 0–0.1m, 0.1-0.2m, 0.2-0.3m, 0.3-0.5m, 0.5-0.7m and 0.7-0.9m for the measurement of soil texture, soil carbon, and nitrogen.

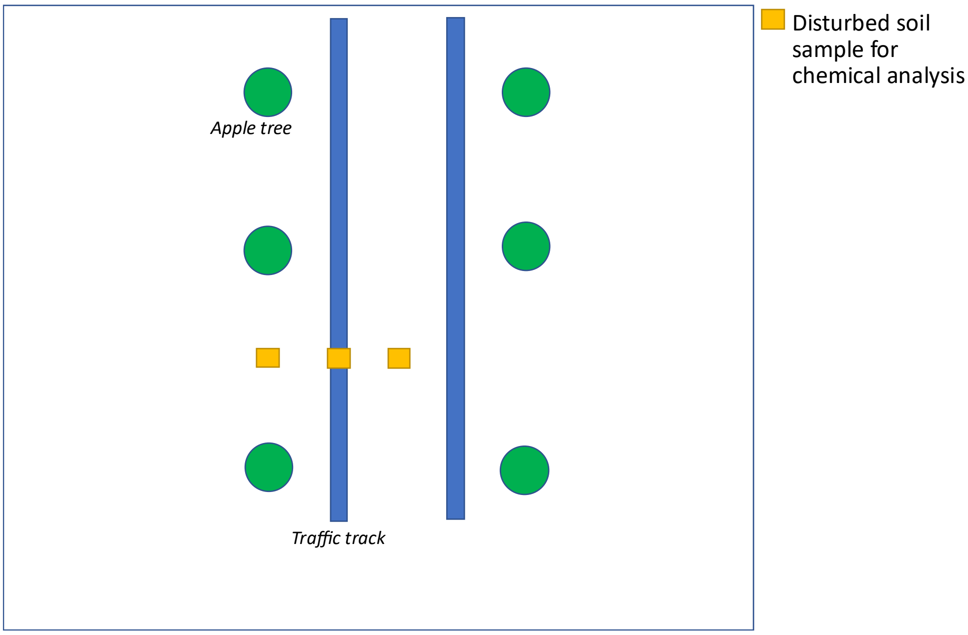


Figure 23. Sampling positions for collecting disturbed soil samples to assess soil chemical properties.

Measurement and calculation

5.4 Measurement and calculation

5.4.1 Soil chemical properties

A total of 216 disturbed soil samples were air-dried and sieved through a 2 mm sieve for total carbon and nitrogen analysis. Additionally, 216 field-moist samples (5 g each) were prepared for Mineral-N and hot water extractable carbon (HWEC) analysis, alongside 10 g of field-moist samples to determine the initial soil moisture content. Although, 216 samples were all measured for soil chemical properties, only 0 to 30 cm were presented in this study to align with the physical properties as described in previous chapter. Total carbon and nitrogen were examined by dry combustion method using Leco TruMac CN analyser (Leco Corporation, MI, USA). Carbon was detected as carbon dioxide using non-dispersive infrared absorption, and nitrogen was detected using a thermal conductivity detector after scrubbing carbon dioxide and oxygen. Hot water extractable carbon (HWEC) was extracted at 80 °C as described by Ghani et al. (2003). Soil mineral N (ammonium (NH_4^+) and nitrate (NO_3^-) were extracted in 2 M potassium (KCl). Specifically, 25 mL of the KCl solution was mixed with 5 g of field-moist soil, and the mixture was shaken for 1 hour. Then filter the solution through Whatman 42 filter paper and measured on a Lachat QuikChem 8500 Series 2 Flow Injection Analysis System (Lachat Instruments, Loveland, Colorado, USA) using standard colorimetric techniques (Keeney & Nelson, 1983). Soil carbon stock for top 0 -30 cm was calculated by Equation 18 adapted from Anokye et al. (2021) below:

$$SCs = SOC \times BD \times V \qquad (18)$$

Where SCs is the soil carbon stock (t/ha), SOC is the average soil carbon concentration (%) at soil depth 0-30 cm, BD is the average bulk density at soil depth 0-30 cm (g/cm^3), V is the volume of soil (cm^3).

5.4.2 Statistical analysis

The statistical analysis was carried out using RStudio. The "predictmeans" package was employed to perform multivariate analysis of variance (MNOVA) within the general linear model, assessing the impact of various factors such as age, position, and depth, along with their interactions, on soil chemical properties. For multiple comparisons, the Least Significant Difference (LSD) of means was employed.

5.5 Results

5.5.1 Soil chemical properties

Total carbon and nitrogen

Total carbon (C) content was strongly influenced by both traffic positions and planting ages in both orchards (Tables 7 and 8). In contrast, total nitrogen (N) content was significantly affected by both planting ages and traffic positions in the Belfast site, but in the Richmond site, it was only influenced by planting ages (Tables 7 and 8). The C concentrations exhibited consistent trends in response to traffic positions in both orchards. The position under the traffic tracks had the highest C concentration, with 2.8% at the Belfast site and 2.4% at the Richmond site. The position near the trees had the lowest C concentration, with 2.4% at the Belfast site and 2.1% at the Richmond site. The highest N concentration was found in the track positions in the Belfast site with 0.3% while the lowest N was found in near tree position (0.2%). In addition, both C and N concentrations decrease with the increase in soil depth. As expected, the lowest values were observed at 20 to 30 cm with 1.7% and 0.2% in Belfast site and 1.3% and 0.1% in Richmond site. Total carbon content showed an increase with planting age, peaking at 3.3% in the 12-year planting age at the Belfast site (Table 7) and 3.3% in the 17-

year planting age at the Richmond site (Table 8). The lowest C concentrations were observed at 2% in the 3-year planting age at the Belfast site and 2.2% in the 12-year planting age at the Richmond site. Total nitrogen content followed a comparable pattern, with the highest N concentrations recorded at 0.3% and 0.2% in the 12- and 17-year planting ages, respectively. The lowest N concentrations were measured at 0.2% in the 3 planting ages in Belfast and 0.19% in 12-year planting ages in Richmond.

As another important indicator of soil chemical health, the C/N ratio was strongly influenced by planting age and soil depth at the Richmond site (Table 8). No significant effects of planting ages or traffic positions were observed at the Belfast site (table 7). in the Richmond site, the lowest C/N ratio was detected in the 17-year planting age at 11.7, which profoundly differed from other planting ages. No substantial differences were found between the 12- and 28-year planting ages, with values of 12.8 and 12.4, respectively. Additionally, the C/N ratio in Richmond site showed an upward trend with increase in the soil depth, ranging from 10.2 (0-10 cm) to 14.6 (20-30 cm).

Substantial interactions between planting ages, traffic positions, and soil depth were observed for C, N, and the C/N ratio in Belfast site. In contrast, in the Richmond site, only C and N were substantially affected by planting ages, traffic positions, and soil depth. As illustrated in Figure 24, C and N concentrations exhibited similar trend in response to the interactions between planting ages and traffic positions at the Belfast site. With increasing planting ages, the C and N concentrations peaked at 12 years across all traffic positions. However, there was a marked decrease in C and N concentrations at the between track and near tree positions when the planting age reached 40 years. Conversely, a slight increase in C and N concentrations was observed at the track position at 40 years. The C in Richmond site showed an increase in track and between track positions with increase in planting ages (Figure 25). The C concentration in 28 years was substantially higher than in 12 years at these two positions (Figure 25). N in track position and between track position shared the same trend which peak at 17 years before it decreased at 28 years planting age (Figure 25). In contrast, the N in near tree position showed an upward trend with increase in planting ages. According to Figure 26, C and N concentrations exhibited the same pattern in relation to planting ages and soil depth in Belfast site. The C and N concentrations was notably higher in 0 -10 cm compared to other depth while the highest C and N concentrations observed in 12 years planting ages compared to other planting ages (Figure 26). Moreover, C/N ratio in Belfast site only showed substantial difference between 3 year and 12 years in 20-30 cm (Figure 26). In contrary, planting ages and soil depth only strongly influenced C concentration in Richmond, with C levels increasing with planting age and significantly differing across soil depths (Figure 27). Regarding to interactions between traffic position and soil depth, C and N shared the exact same trend in both orchards, with substantial higher concentration in track position compared to other positions. in addition, C and N concentrations differed significantly across soil depths (Figures 28 and 29).

Carbon stock

Traffic track position exhibited the highest carbon stock in both orchards across all traffic positions (Tables 7 and 8). At the Belfast site, the highest carbon stock was found in the track position with 108.3 t/ha, while the lowest amount was observed in the near tree position with 88.3 t/ha. Similarly, at the Richmond site, the highest carbon stock amount was recorded in the track position with 90.3 t/ha, followed by the near tree position with 82.5 t/ha.

Carbon stock generally showed an increase with planting age, peaking at 113.6 t/ha in the 12-year planting age at the Belfast site (Table 7) and 87.6 t/ha in the 28-year planting age at the Richmond site (Table 8). The lowest carbon stock was observed at 81.1 t/ha in the 3-year planting age at the Belfast site and 80.9 t/ha in the 12-year planting age at the Richmond site.

Noticeable interactions were found between traffic positions and planting ages on carbon stock at the Belfast site (Figure 25). With increasing planting age, carbon stock in the between track and near tree positions peaked at 12 years, then decreased at 40 years. From 3 to 40 years, carbon stock in the track position continuously increased, with the highest values at 40 years.

Table 7. Effect of age of planting (3, 12 and 40 years), traffic position (near tree, track, and between track), soil depth and their interactions on soil chemical properties in Belfast site. Values are means with different letters showing significant difference within group except where LSD and significance levels are noted. LSD: least significant difference calculated at a significant level of p< 0.05. Symbols "*", "**", "*" and "ns" indicates the main or interaction effect was significant at P<0.001,0.01, 0.05 and p >0.05, respectively.**

Variables		Carbon Stock (t/ha)	Total C (%)	Total N (%)	C/N ratio	Min-N (mg kg^{-1})	HWEC (mg kg^{-1})
Age	3	81.1^{a}	2^{a}	0.2^{a}	10.5^{a}	5.2^{a}	792^{a}
	12	113.6^{b}	3.3^{b}	0.3^{b}	10.6^{a}	10.5^{a}	1513^{b}
	40	$101.^{c}$	2.7^{c}	0.3^{c}	10.8^{a}	6.1^{a}	1163^{c}
Positions	Near tree	88.3^{a}	2.4^{a}	0.2^{a}	10.7^{a}	6.6^{a}	954^{a}
	Track	108.3^{b}	2.8^{b}	0.3^{b}	10.7^{a}	10.1^{a}	1331^{b}
	Between track	99.1^{ab}	2.7^{b}	0.3^{b}	10.5^{a}	5.1^{a}	1183^{c}
Depth (cm)	0-10		3.7^{a}	0.3^{a}	10.7^{a}	13.3^{a}	1784^{a}
	10-20		2.5^{b}	0.2^{b}	10.6^{a}	5.2^{ab}	1062^{b}
	20-30		1.7^{c}	0.16^{c}	10.5^{a}	3.3^{b}	621^{b}
LSD and Significant level	Age	11.2^{***}	0.2^{***}	0.02^{**}	0.3^{ns}	8.1^{ns}	96.4^{***}
	Position	11.2^{**}	0.2^{***}	0.02^{***}	0.3^{ns}	8.1^{ns}	96.4^{***}
	Depth		0.2^{***}	0.02^{***}	0.3^{ns}	8.1^{*}	96.4^{***}
	Age × Position	19.3^{**}	0.4^{***}	0.03^{***}	0.5^{ns}	14^{ns}	166.9^{***}
	Age × Depth		0.4^{***}	0.03^{***}	0.5^{***}	14^{ns}	166.9^{***}
	Position × Depth		0.4^{***}	0.03^{***}	0.5^{ns}	14^{ns}	166.9^{***}
	Age × Position × Depth		0.7^{*}	0.06^{*}	0.8^{ns}	24.2^{ns}	289.1^{***}

Table 8. Effect of age of planting (12, 17 and 28 years), traffic position (near tree, track, and between track), soil depth and their interactions on soil chemical properties in Richmond site. Values are means with different letters showing significant difference within group except where LSD and significance levels are noted. LSD: least significant difference calculated at a significant level of p< 0.05. Symbols "*", "**", "*" and "ns" indicates the main or interaction effect was significant at P<0.001,0.01, 0.05 and p >0.05, respectively.**

Variables		Carbon Stock (t/ha)	Total C (%)	Total N (%)	C/N ratio	Min-N (mg kg^{-1})	HWEC (mg kg^{-1})
Age	12	80.9^{a}	2.2^{a}	0.19^{a}	12.8^{a}	2.8^{a}	874^{a}
	17	86.6^{ab}	3.3^{b}	0.2^{b}	11.7^{b}	6.8^{a}	824^{a}
	28	87.6^{b}	2.4^{b}	0.2^{b}	12.4^{a}	3.9^{a}	772^{a}
Positions	Near tree	82.5^{a}	2.1^{a}	0.2^{a}	12.5^{a}	9^{a}	860^{a}
	Track	90.3^{b}	2.4^{b}	0.2^{a}	12.3^{a}	2.4^{b}	875^{a}
	Between track	82.3^{a}	2.3^{b}	0.2^{a}	12.1^{a}	2^{b}	735^{b}
Depth (cm)	0-10		3.4^{a}	0.3^{a}	10.7^{a}	9.8^{a}	1301^{a}
	10-20		2.1^{b}	0.2^{b}	11.6^{b}	2.8^{b}	747^{b}
	20-30		1.3^{c}	0.1^{c}	14.6^{c}	0.8^{b}	422^{c}
LSD and Significant level	Age	5.2^{*}	0.1^{***}	0.01^{***}	0.6^{**}	4.9^{ns}	91.2^{ns}
	Position	5.2^{**}	0.1^{**}	0.01^{ns}	0.6^{ns}	4.9^{**}	91.2^{**}
	Depth		0.1^{***}	0.01^{***}	0.6^{***}	4.9^{**}	91.2^{***}
	Age × Position	9.1^{ns}	0.2^{**}	0.02^{*}	1^{ns}	8.5^{ns}	157.9^{ns}
	Age × Depth		0.2^{*}	0.02^{ns}	1^{ns}	8.5^{ns}	157.9^{ns}
	Position × Depth		0.2^{***}	0.02^{***}	1^{ns}	8.5^{*}	157.9^{*}
	Age × Position × Depth		0.3^{*}	0.3^{ns}	1.8^{ns}	14.7^{ns}	273.5^{*}

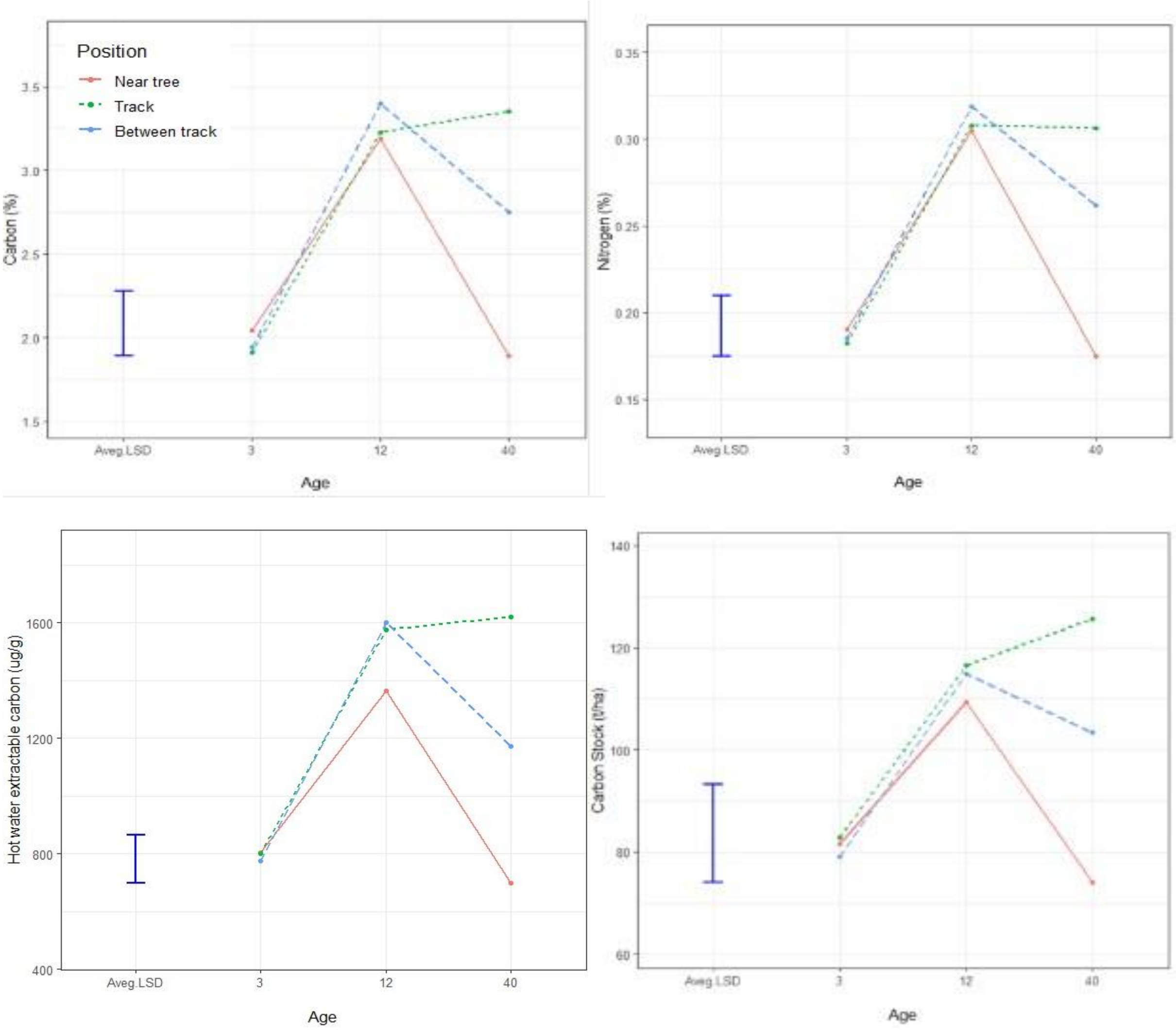


Figure 24. The interaction effect of traffic position and planting ages on soil chemical properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$), including Carbon (%), Nitrogen (%), Hot water extractable carbon (mg kg-1), and Carbon stock (t/ha).

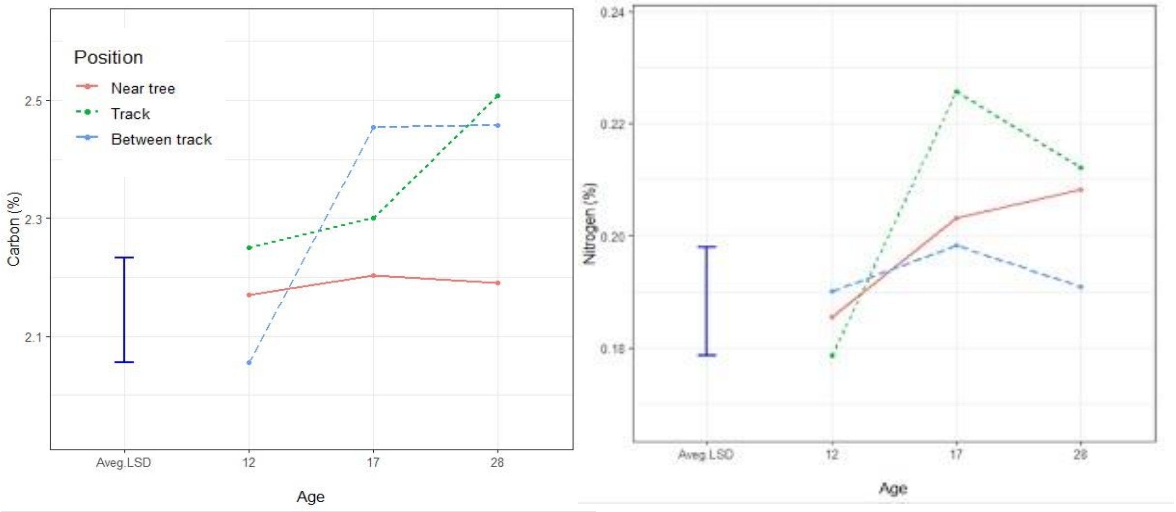


Figure 25. The interaction effect of traffic position and planting ages on soil chemical properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$), including Carbon (%), Nitrogen (%).

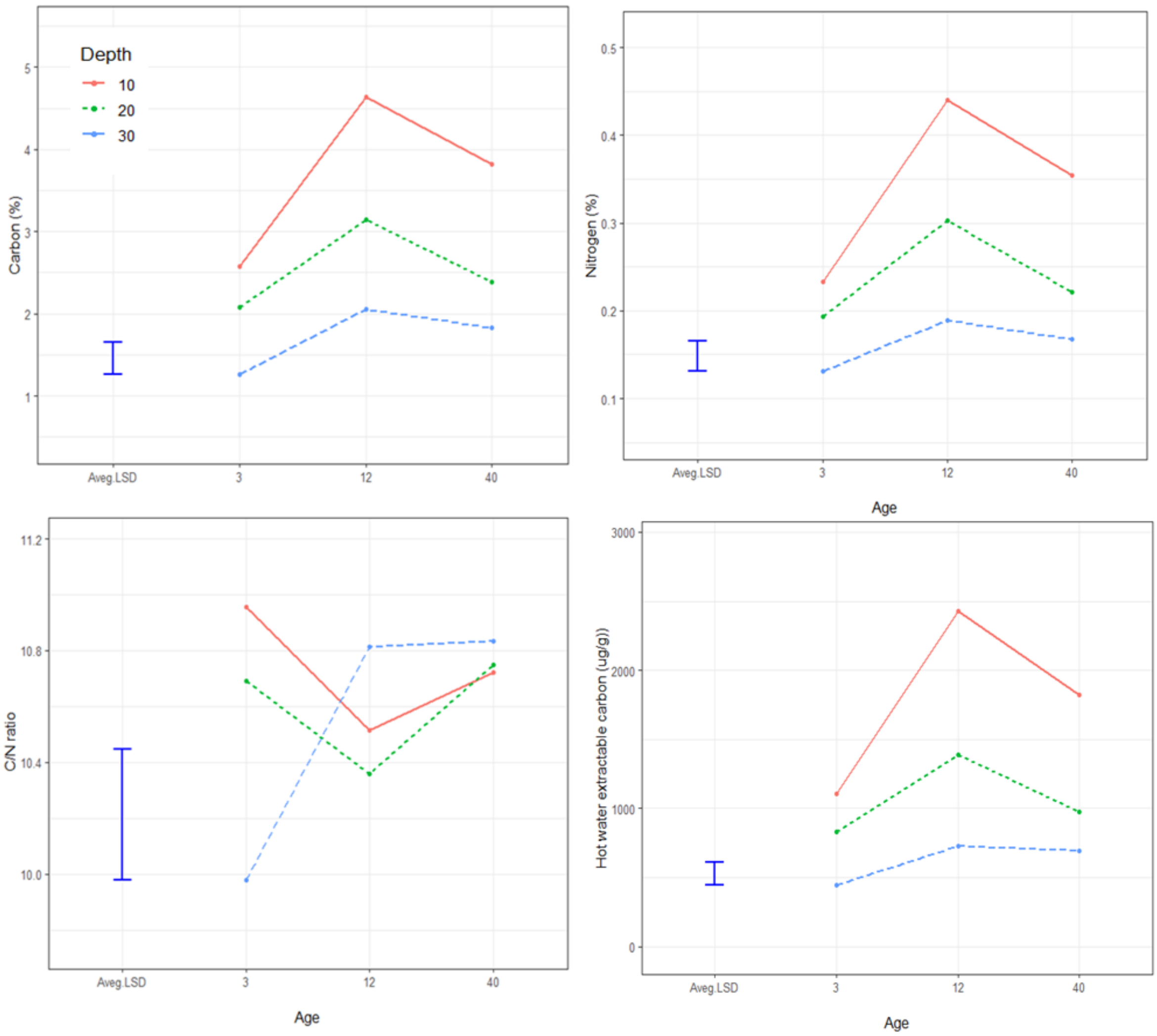


Figure 26. The interaction effect of planting ages and soil depth on soil chemical properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$), including Carbon (%), Nitrogen (%), C/N ratio, and Hot water extractable carbon (mg kg-1).

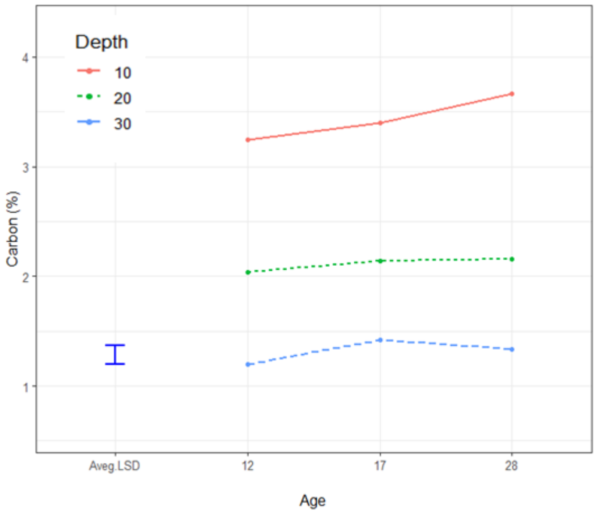


Figure 27. The interaction effect of planting ages and soil depth on soil chemical properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$), including Carbon (%).

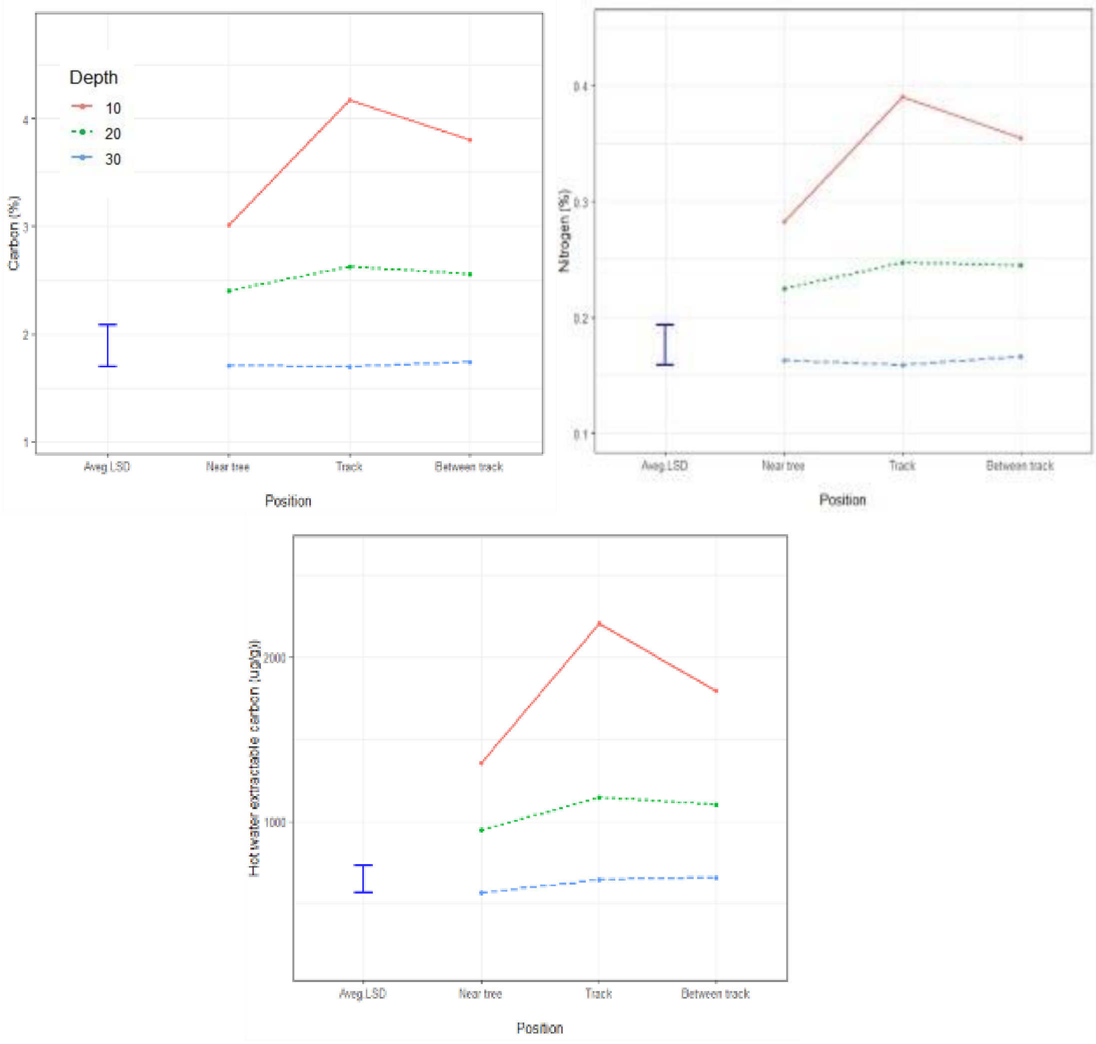


Figure 28. The interaction effect of traffic position and soil depth on soil chemical properties in Belfast site. Plotted values are means and capped lines are LSD ($p < 0.05$), including Carbon (%), Nitrogen (%), and Hot water extractable carbon (mg kg-1).

Mineral N

Soil depth significantly influenced Min-N in both orchards (Tables 7 and 8), while traffic positions only showed significant effects on Min-N at the Richmond site. Regarding the effect of traffic positions, the highest Min-N value was recorded in the near tree position at the Richmond site (9 mg kg^{-1}). The lowest Min-N values across all traffic positions were found in the between track position, with 2 mg kg-1 at the Richmond site. Additionally, Min-N decreased with increasing soil depth in both orchards.

Significant interactions between traffic position and soil depth were only observed for Min-N (Figure 29) in Richmond site. Min-N levels were notably higher in the near tree position near tree position in 0-10 cm compared to other depth. However, no considerable differences were detected in track and between track positions across all soil depth.

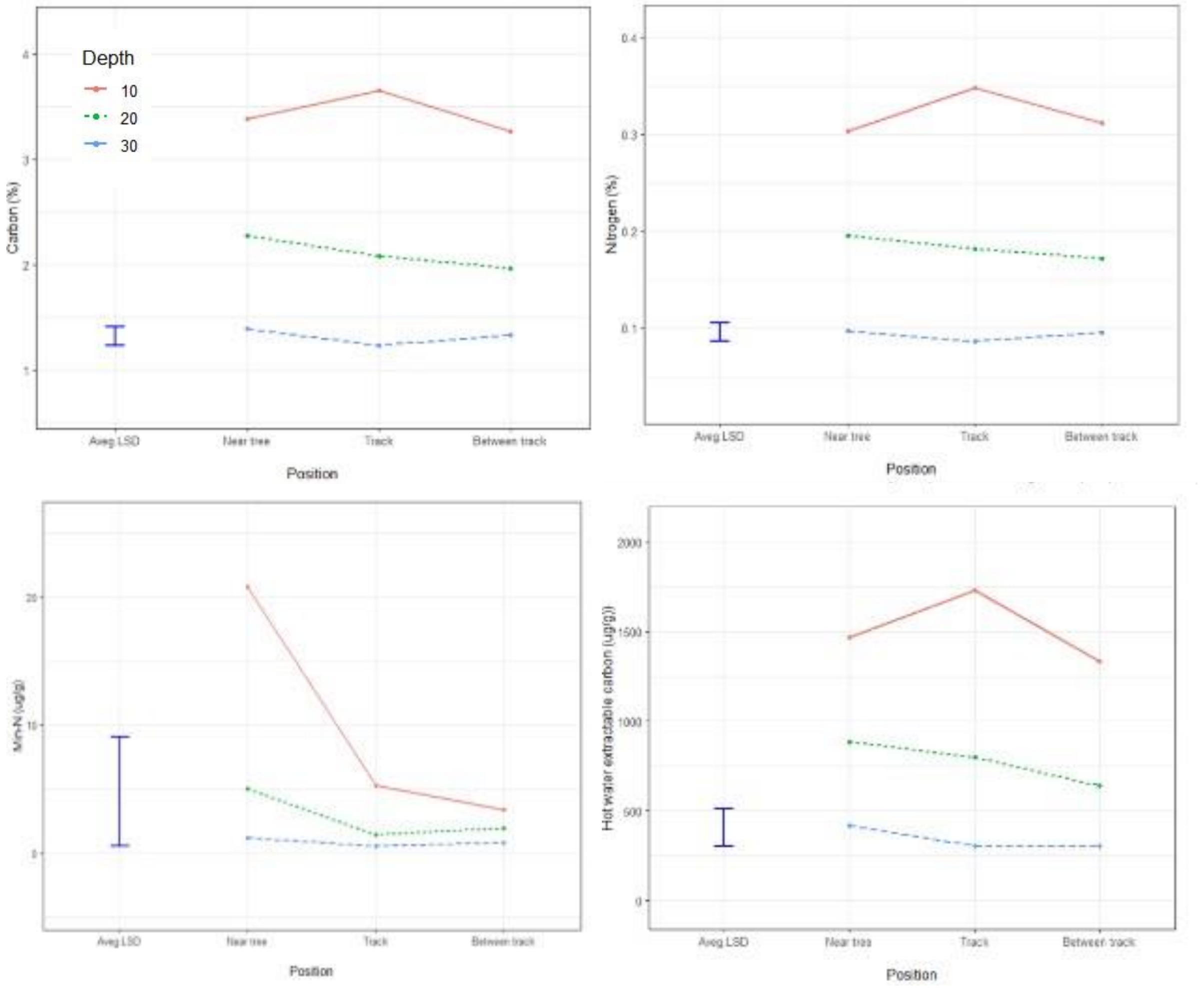


Figure 29. The interaction effect of traffic position and soil depth on soil chemical properties in Richmond site. Plotted values are means and capped lines are LSD ($p < 0.05$), including Carbon (%), Nitrogen (%), Mineral-N (mg kg-1) and Hot water extractable carbon (mg kg-1).

Hot water extractable carbon

The hot water extractable carbon (HWEC) content was noticeably influenced by planting ages, traffic positions, and soil depth in both orchards (Tables 7 and 8). Among traffic positions, the lowest HWEC values were measured at the position between tracks in the Richmond site (735 mg kg^{-1}) and at the near tree position in the Belfast site (954 mg kg^{-1}). in contrast, the track position exhibited the highest HWEC values, with 1331 mg kg-1 at the Belfast site and 875 mg kg^{-1} at the Richmond site.

HWEC values varied considerably across all planting ages and traffic positions at the Belfast site but did not vary noticeably with planting ages at the Richmond site. The highest HWEC values were recorded at the 12-year planting age, with 1513 mg kg-1 while the lowest HWEC values under the influence of planting age were found at the 3-year planting age, with 792 mg kg^{-1}. Additionally, HWEC values exhibited a downward trend with increasing soil depth, with no noticeable differences observed below the 10 cm depth in both orchards.

Marked interactions between planting age, traffic position, and soil depth on HWEC were observed in both orchards. As illustrated in Figure 24, HWEC values in the Belfast site showed a dramatic increase from 3 to 12 years in all traffic positions, noticeably higher in track and between track position compared to near tree position. At 40 years, HWEC values sharply decreased in both the near tree and between track positions. In contrast, HWEC values slightly increased in the track position, where they were noticeably higher compared to the other traffic positions. Regarding the effects of planting ages and soil depth on HWEC, there was a consistent trend for HWEC in each soil depth, with the lowest HWEC appeared in 3 years planting age while the highest in 12 years planting age (Figure 26). Besides, HWEC values decreased with increasing soil depth within each planting age. The significant interactions between traffic positions and soil depth on HWEC were also observed in Belfast site (Figure 28). HWEC values followed the same trend across all soil depths, with track positions exhibiting the highest HWEC values, followed by between track positions. Additionally, HWEC values decreased with increasing soil depth within each traffic position. In contrast, at the Richmond site, the track position had the highest HWEC in the top 10 cm across all traffic positions, while the lowest value was found in the between track position at the same depth (Figure 29). In deeper soil layers, the near tree position showed the higher HWEC values compared to other traffic positions.

5.5.2 Correlation relation analysis between chemical and physical properties

Figure 30 and 31 presented the Pearson correlation matrix between soil chemical properties, physical properties, and other factors in both orchards. Soil BD was found to be strongly linked to carbon stock, HWEC, nitrogen and carbon in both orchard ($p<0.001$). In the Richmond site, BD was also found to have a positive correlation with PR ($p<0.05$). Moreover, there were a strong positive correlation computed between carbon content (%) and carbon stock, HWEC, and nitrogen ($p<0.001$) in both orchards. The nitrogen content (%) in each orchard was noticeably correlated to carbon stock, HWEC, and Min-N ($P<0.05$). Additionally, the Min-N in Richmond site was found to have strongly positive relationship with BD, carbon and nitrogen content ($p<0.05$).

Figure 30. Pearson correlation matrix showcasing the interrelationships between soil chemical properties, physical properties, and other factors, including bulk density, penetration resistance, carbon, nitrogen, Min-N, and hot water extractable carbon in Belfast site. The colour gradient represents the correlation strength, with red indicating a positive correlation and blue a negative correlation. Asterisks denote the significance levels of the correlations (* p<0.05, ** p<0.01, *** p<0.001).

Figure 31. Pearson correlation matrix showcasing the interrelationships between soil chemical properties, physical properties and other factors, including, bulk density, penetration resistance, carbon, nitrogen, Min-N, and hot water extractable carbon in Richmond site. The colour gradient represents the correlation strength, with red indicating a positive correlation and blue a negative correlation. Asterisks denote the significance levels of the correlations (* p<0.05, ** p<0.01, *** p<0.001).

5.6 Discussion

5.6.1 Planting ages and traffic effect on soil chemical properties

The age of planting and traffic position substantially affected the soil chemical properties in both orchards, including total C, N, carbon stock, and HWEC. Total C was found to be the highest in track positions in both orchards, this implies in the compaction may lead to the SOC (organic matter) pooled in the compacted area. Similar findings was also reported by Brevik et al. (2002),Brevik and Fenton (2012) and Deurer et al. (2012). Moreover, total C was also found to increase with planting ages in both orchards as shown in Table 7 and 8. The possible reasons for this increase can be: (1) the accumulation over time of residues from the fall tree leaves, pruning, and material from the plants in the under-storey, these build up without tillage disturbance. Wang et al. (2024) found that with long-term plantation of apple trees, the deposition of the root and litter residues and exudates the soil would gradually increase SOC content. From the decomposition aspect, the increased soil bulk density and associated alterations in soil pore structure due to compaction can reduce the microbial activity by limiting the access to oxygen and space for microbes. Many authors have found that soil compaction negatively affected the activity of soil microbes or the abundance of bacteria and fungus (Brevik et al., 2002; Deurer et al., 2012; Frene et al., 2024; Li et al., 2004). This accumulation of soil organic matter can be preserved from microbial decomposition in compacted soils. Furthermore, due to the changes in pore system (decrease in macro-porosity and increase in microporosity), less dissolved soil organic matter would lose via drainage. As described in previous chapters, soil compaction reduces the proportions of larger pores and increases the smaller pores, which substantially affected the rate of water infiltration and movement under compacted area (Deurer et al., 2008; van Dijck & van Asch, 2002; Vogeler et al., 2006). Beare et al. (2009) reported that CO_2 emissions in compacted soils were 2.3 times less than in uncompacted soils due to the restriction of soil aeration. Our results from two apple orchards, corroborated by other studies, show higher carbon values in compacted areas, such as older orchard soils and track positions. This pattern likely reflects reduced microbial decomposition of organic matter and lower losses of organic carbon through drainage and emissions. A similar pattern of planting age and traffic position effects was also observed for soil total nitrogen. Higher total carbon content correlated with higher total nitrogen content. As discussed in above soil carbon section, the compaction preserved soil organic matter from microbial decomposition would like to result in the higher total N. Since no nitrogen fertiliser application in both orchards, the original source of soil N also may attribute to the vegetation fixation of nitrogen. Clovers, commonly used for nitrogen fixation(Ledgard et al., 2001; Ledgard et al., 1996; Oberson et al., 2013), were observed in both the between track and near tree positions. According to Sparling et al. (2008), the targeted range of total N concentration in pasture soil in New Zealand is between 0.25% to 0.70% and 0.1% to 0.7% in forest soil. However, no available data or target range for orchard due to the variations in N requirement of different crops (Ministry for the Environment & Stats NZ, 2021; Sparling et al., 2008).

This study was also calculated the C/N ratio in the soil. This was a key role in understanding the decomposition rates of organic matter, nutrient cycling, and soil fertility. The results from both orchards revealed no notable effect of traffic position on the C/N ratio. This finding was consistent with the observations by Brevik et al. (2002), who reported no statistical difference in the C/N ratio between compacted and uncompacted soil. However, the C/N ratio was notably lower at the 17-year planting age at the Richmond site compared to other planting ages. This is attributed to the higher total C and N reserves at the Richmond site (Table 8), which suggests a faster nutrient release rate.

Mineral-N tended to be affected by soil depth rather than planting ages and traffic position in both orchards (Table 7 and 8). In apple orchards, Mineral-N relies more on organic matter content than on nitrogen fertilisation, making it a crucial indicator of nitrogen availability in the soil. (Wrona & Sadowski, 2004). Since no fertilisers were applied to the apple trees in either orchard, the primary source of mineral nitrogen was the soil's organic matter reserves. This study has found no notable differences in soil Mineral-N with respect to compaction induced by planting ages. this corroborates reports by Blumfield et al. (2005), De Neve and Hofman (2000), and Jensen et al. (1996). However, traffic position significantly influenced Mineral-N levels at the Richmond site, with much lower values observed in the track and between-track positions compared to the near tree position. This suggested that compaction may protect organic matter, limiting microbial access and decomposition, and leading to lower ammonification rates and reduced Mineral-N production in compacted soils (Agbeshie et al., 2020; Hassink & Dalenberg, 1996). The increased soil compaction typically reduced the volume of larger pores, soil aeration, and water movement, restricting access to organic matter for microorganisms. Despite this, nitrogen mineralisation in compacted soils was still dominated by NO_3^--N, the most prevalent form of soil nitrogen under most conditions (Agbeshie et al., 2020; Logah et al., 2011). This indicates that nitrification processes were not strongly affected by compaction, likely because the existing habitat for nitrifying microbes was not strongly altered by further compaction. Furthermore, as the soils in both orchards had already undergone natural compaction due to long-term consolidation and traffic during orchard management, the available pore space for microbial activity was not notably changed by additional compaction as suggested by Jensen et al. (1996) and De Neve and Hofman (2000). These factors explain why planting age did not notably affect Mineral-N levels in both orchards: the organic matter in the near tree position was better protected, resulting in a lower rate of ammonification, while the compacted conditions did not further impact the nitrification processes due to stable microbial habitats. In addition, as soil depth increases, the amount of reserved soil organic matter decreases. This reduction in organic matter leads to a corresponding decrease in mineral nitrogen (Min-N) content in the deeper soil layers.

Hot water extractable carbon (HWEC) also exhibited similar patterns under the influence of planting ages and traffic positions and was strongly associated with other chemical properties in both orchards. HWEC consists of more stable components that serve as a reserve of nutrients and energy for plants and microorganisms(Hamkalo & Bedernichek, 2014). HWEC values were substantially affected by soil organic matter due to the microbial turnover rate and mineralisation rate of organic matter(Ghani et al., 2003; Saggar et al., 1994). Consequently, HWEC values tended to be higher in soils with higher organic matter content. For example, the HWEC value was substantially higher in the 12-year planting age (3.3% total C and 0.3% total N), as well as in track positions that had the highest total C and N content in the Belfast site (Table 7). These observations align with previous findings by Hamkalo and Bedernichek (2014) and Ghani et al. (2003), reinforcing the strong link between HWEC and soil organic matter. Additionally, HWEC is more associated with labile carbon as it reflects the changes in land use management (Weigel et al., 2011). HWEC generally declines with practices such as cultivation, excessive nitrogen fertilisation, or overgrazing (Ghani et al., 2003). Moreover, hot water can partially extract non-humified organic materials, like carbohydrates, which make up about 40–50% of the carbon in the HWEC pool (Ghani et al., 2003; Hamkalo & Bedernichek, 2014). Furthermore, hot water extraction can also capture higher microbial content, particularly fungal biomass (Hamkalo & Bedernichek, 2014). Therefore, the lack of cultivation disturbance and the accumulation of soil organic matter may lead to the formation of relatively stable soil structures that support microbial habitats.

Carbon stock was substantially influenced by planting ages and traffic positions due to their impact on total carbon content and bulk density. As discussed in the total carbon section above, a lower rate of organic matter decomposition and reduced carbon loss via emissions and drainage can lead to more organic carbon being preserved and accumulated in the soil profile. This pattern is supported by the data from this study, with the highest stocks from the most compacted soil, under the wheel tracks (Tables 7 and 8). Additionally, bulk density increased with planting age and traffic frequency (higher in track positions, lower in between-track positions, and the smallest in non-traffic near-tree positions). These factors resulted in higher carbon stocks in track positions and older planting ages.

Similar to the result in soil physical properties, the soil from orchard at intermediate planting ages expressed the better soil chemical properties with relative higher total C, N, and HWEC. Higher total carbon content could benefit soils in several ways, including enhancing soil structure, water retention, soil fertility and soil resilience to compaction (Blanco-Canqui et al., 2009; Frene et al., 2024; Sainju et al., 2021). Higher SOC contents are also beneficial for soils exposed to the compaction. SOC can act as binding agent, improving soil aggregates formation and hence enhancing the stability of soil structure (Bronick & Lal, 2005) and resistance to compaction (Frene et al., 2024; Hamza & Anderson, 2005). Improved soil structure influences positively other soil properties (eg, soil water movement and nutrient cycling, root penetration, nutrient availability and microbial activity) (Blanco-Canqui et al., 2009; Brevik et al., 2002; Deurer et al., 2012). Moreover, soils with higher soil organic matter tend to retain more moisture in pores that are available for plant uptake. Furthermore, higher carbon content also enhance the availability of soil nitrogen through the mineralisation process(Sainju et al., 2021). This probably helps to explain why the N content in the soils from the intermediate planting ages block was the highest across all planting ages. In terms of soil hot water extractable carbon (HWEC), the higher values observed in the intermediate planting age blocks indicate a better environment for microbial activity, allowing better cycling of soil nutrients compared to other planting ages. Therefore, the relatively better soil chemical properties observed in intermediate planting ages suggest a more stable soil structure in both orchards at these ages. This stability may be attributed to optimal conditions for soil health and nutrient availability. However, as the data indicates a decrease in soil structure stability beyond intermediate planting ages, it is important for orchard management to consider practices that maintain or enhance soil structure. Regular monitoring and implementation of soil conservation measures, such as controlled traffic patterns and organic matter addition, could help mitigate the decline in soil stability and sustain soil health over the long-term plantation.

5.6.2 Interactions between planting ages and traffic on soil chemical properties

This section examined how planting ages and traffic positions interacted and found that these factors significantly affected important soil chemical properties such as carbon (C), nitrogen (N), HWEC, and carbon stock in both orchards. Emphasising these interactions was crucial as they directly addressed the core hypothesis of the study. The section particularly underscored the intricate relationship between planting ages and traffic positions due to their considerable impact on soil chemical properties. The traffic positions and planting ages substantially influenced the C and N in both orchards. The C and N content in track positions increased consistently with planting ages in both orchards, likely due to the strong physical protection provided by compaction. However, this increases stabilised and become insignificant at certain content of C and N when the planting ages longer enough as shown in Figure 24. This was likely due to the SOC cannot continue to accumulate indefinitely and the annual rate of this accumulation declined as the soil near new equilibrium (Powlson et al., 2014). This process may take between 25 to 100 years depending on the soil texture and climate conditions. (Gollany et al., 2011; Powlson et al., 2012). The rapid accumulation rate of carbon was observed in the early years after the soil was no longer disturbed by tillage (Powlson et al., 2012; Powlson et al., 2014). Moreover, the nitrogen dynamics were closely linked to carbon content, as discussed in the previous section. Therefore, the combined effects of traffic and planting age likely led to rapid accumulation of soil organic matter in the early years, followed by stabilisation at longer planting ages in both orchards. This conclusion was also applied to the HWEC in Belfast site as it represents the labile, easily decomposable fraction of organic carbon.

The soil carbon stock was also found to be strong influenced by interactions between planting ages and traffic. The carbon stock was calculated by the carbon content, soil depth and bulk density. Therefore, the carbon stock showed similar trend to C but showed a higher increase in 40 years compared to C in 40 years planting ages. this attributed to the increase in bulk density as it increases with both planting ages and traffic.

For future studies on soil chemical properties under compaction in apple orchards, it is recommended to consider a variety of orchard types with different management strategies, such as those involving fertiliser applications or organic amendments. This approach would help explore the interactions between planting ages, orchard management practices, and soil compaction effects on soil chemical properties.

5. Conclusions

Overall, planting ages and traffic positions significantly influenced the chemical properties of the soil in both orchards, including total carbon (C), nitrogen (N), carbon stock, Mineral-N and hot water extractable carbon (HWEC). Higher concentrations of total C and N in older orchard soils and track positions was likely due to the reduced microbial decomposition of organic matter and decreased loss of organic carbon through drainage and emissions. Consequently, higher total C content and bulk density contributed to greater carbon stock in older planting ages and track positions. Conversely, planting ages and traffic positions did not significantly impact the C/N ratio in either orchard. Mineral-N levels were not significantly affected by planting ages, traffic-induced compaction at the Richmond site resulted in lower Mineral-N levels in track and between-track positions likely due to reduced microbial access to organic matter, although nitrification processes may remain relatively stable. The lack of cultivation disturbance and the accumulation of soil organic matter may help soil to form a relatively stable soil structures that support microbial habitats, thereby resulting in higher HWEC values. Additionally, the chemical properties observed in intermediate planting ages (12 to 17 years) indicated a more stable soil structure and relatively healthy soil chemical properties in both orchards.

In summary, the influence of traffic positions and planting ages on soil carbon and nitrogen varied over time. While traffic-induced compaction initially increased soil organic carbon and nitrogen content due to physical protection, this increases stabilised at longer planting ages as the soil approached equilibrium, with the rate of carbon accumulation declining over time. The soil carbon stock, which is a function of carbon content, soil depth, and bulk density, showed a similar trend but with a higher increase at 40 years of planting due to rising bulk density. The trends in soil organic matter and hot water extractable carbon were consistent with these findings, reflecting the interplay between compaction, planting age, and soil carbon dynamics.

Chapter 6

General Discussion

Soil compaction negatively affects soil functions; this occurs particularly through its impact on physical and chemical properties. The extent of compaction is determined by factors such as traffic intensity, soil moisture content during traffic, soil texture, and soil organic carbon (SOC) content (Défossez & Richard, 2002; Hamza & Anderson, 2005; Hu et al., 2023; Hu et al., 2022; Shah et al., 2017).Although compaction has been the subject of many studies, most research has focused on structural changes, such as bulk density (BD) or total porosity (TP), with limited attention to how these changes affect hydraulic properties and soil function derived from these. Compaction is a common issue in apple orchards due to repeated traffic and long-term planting and can impact production as well as the orchard environment negatively (Goh et al., 2001; Paltineanu et al., 2016; Ramos et al., 2022). Both of which are undesirable and critical issues to New Zealand's export horticulture industry (MPI, 2020). Despite this, there remains a significant gap in understanding of how compaction affects soil chemical and physical properties in New Zealand apple orchards, as studies in this area are limited (Deurer et al., 2012; Goh et al., 2001; Vogeler et al., 2006). In this context, this thesis aimed to explore the effects of traffic-induced compaction on orchard’s soil properties. The meta-analysis conducted in Chapter 3 addressed two key research questions: 1) how soil water retention-based properties and soil physical quality respond to different levels of traffic-induced compaction, and 2) how basic soil properties influence these responses. The investigation of the impact of soil compaction on physical properties (Chapter 4) and chemical properties (Chapter 5) further aimed to determine how planting ages, traffic positions, and the interaction between these factors affect soil properties in apple orchards.

Overall, the findings of Chapter 3 demonstrated that soil compaction is linked with significant increases in BD and field capacity at -10 kPa (FC_{10}), while adversely affecting macroporosity, available water capacity calculated from -10 to -1500 kPa (AWC_{10}), available water capacity calculated by the dynamic criteria introduced by Assouline and Or (2014) (AWC_{AO}), as well as the soil physical quality index (S index).Data collected in two New Zealand orchards showed that planting ages and traffic positions had a strong influence on soil physical properties (Chapter 3), including PR, BD, and mean weight diameter (MWD). The analyses also identified complex interactions between these properties and factors. Results presented in

Chapter 5 further revealed that planting ages and traffic positions also significantly influenced soil chemical properties such as total carbon (C), nitrogen (N), carbon stock, and hot water extractable carbon (HWEC), while having little impact on the C/N ratio and mineral nitrogen. Besides, intermediate planting ages (12 to 17 years) consistently exhibited healthier soil physical and chemical properties compared to both younger and older planting ages.

In chapter 3, the intensity of traffic, specifically the number of traffic passes, load weight, and tyre pressure, emerged as a critical factor influencing soil water retention properties and overall soil quality. Generally, higher levels of traffic passes, load weight, and tyre pressure led to a greater reduction in the soil's ability to retain water and maintain good physical conditions for plant growth. In contrast, lower levels of traffic intensity had less impact on soil water retention, suggesting that adjusting machinery operations with reduced traffic intensity can help mitigate negative effects on soil structure (Batey, 2009; Keller & Arvidsson, 2004). These findings highlight the importance of managing machinery traffic patterns—such as reducing tyre pressure and load weight—to lessen compaction impacts, particularly in soils prone to structural changes, and to maintain soil productivity (Boland et al., 2022; Labelle et al., 2022).

Moreover, the meta-analysis study also emphasised the importance of initial soil properties, such as clay content and soil organic carbon (SOC), in determining the extent of compaction effects. Soils with high clay content showed significant increases in BD and substantial reductions in macro-porosity and AWC, reinforcing the message that clay-rich soils are especially susceptible to compaction. This finding suggests that machinery operations on heavier-textured soils should minimise traffic intensity to reduce compaction effects (Chamen, 2011). Additionally, the relationship between SOC and soil physical properties upon compaction was noteworthy, soils with higher SOC content exhibited considerable increases in BD and FC_{10}, along with reductions in FC_{AO} and AWC_{AO}. This underscores SOC's dual role in both improving soil structure and potentially exacerbating compaction effects. Therefore, maintaining optimal SOC levels should be a priority in soil management to enhance soil resilience against compaction. Additionally, observations on moisture content at the time of compaction (MC at compaction) underscore the complexity of soil responses to compaction. As also noted by Adekalu and Osunbitan (2001), medium moisture content at the time of compaction often results in maximum compaction effects. Consequently, the non-linear relationship between soil moisture content and the extent of compaction must be considered when evaluating the impact of compaction on soil structure. For instance, the operation of field machinery should take into account the current soil moisture levels, and adjustments to tire pressure should be made to minimise the impact of compaction on the soil (Batey, 2009; Tim Chamen et al., 2015).

To evaluate the effects of planting ages, traffic positions, and their interactions on soil physical properties (Chapter 4), soil samples and penetration resistance (PR) data were collected from plots of different ages in two commercial apple orchards, in Belfast (Christchurch) and Richmond. It was hypothesised that orchard age could be a proxy for traffic pressure and that longer exposure to traffic would result in greater compaction effects on soil physical properties. The results showed that BD and PR increased with both planting age and traffic intensity, consistent with previous studies on traffic-linked compaction (de Moraes et al., 2019; Leij et al., 2002; McHugh et al., 2009; Ramezani et al., 2017; Startsev & McNabb, 2001; van Dijck & van Asch, 2002; Wei et al., 2021). In contrast to the results for BD and PR, mean weight diameter (MWD) of aggregates decreased with increasing planting age, indicating a decline in soil physical health. However, slightly higher MWD values were observed at both orchards in the track position, which was likely due to the accumulation of soil organic carbon (SOC) in compacted areas. This finding aligned with SOC results from Chapter 5 and the observations by (Deurer et al., 2012). Physical protection and reduced gaseous exchange in compacted soils may be responsible for the higher SOC levels, but specific experimentation is needed to better understand this relationship.

Soil water retention properties, the soil quality index (S index), and relative field capacity provided a deeper understanding of how the soil pore system was altered by planting age and traffic positions. The increased values of FC_{10}, AWC_{10}, and micro-porosity, in older orchard and in the track position are indicative of the conversion of macro-pores into meso- and micro-pores due to compaction. These were also linked with reduced saturated hydraulic conductivity. Lower values of FC_{AO} and AWC_{AO} indicated greater hydraulic continuity in compacted areas. These results were consistent with the meta-analysis in Chapter 3, which demonstrated that compaction significantly reduced macro-porosity and increased FC_{10} and AWC_{10}, while decreasing FC_{AO} and AWC_{AO} as compaction intensified.

Intermediate planting ages exhibited relatively better soil water retention properties, reflecting a better soil structure, which corresponded with good soil chemical properties, as discussed in Chapter 5. The interactions between planting age and traffic positions were further examined in Chapter 4, highlighting the cumulative effect of longer planting durations and increased traffic passes on soil PR, BD, and FC_{10} (meso- and micro-porosity). These findings were consistent with the meta-analysis (Chapter 3), showing that a higher number of traffic passes resulted in greater BD and FC_{10}, while significantly decreasing the S index and macro-porosity.

As shown in Chapter 4, planting ages and traffic positions had a strong influence on soil physical properties and, consequently, soil chemical properties were also substantially affected. This link was expected as the bio-chemical behaviour of soil depends on gas exchange and water movement, dictating oxygen availability and regulating the decomposition of soil organic matter (De Neve & Hofman, 2000; Frene et al., 2024; Keller et al., 2019; Ramos et al., 2022). Compaction often slows down the decomposition of organic matter due to reduced microbial activity, leading to its accumulation (Brevik et al., 2002; Deurer et al., 2012; Frene et al., 2024; Li et al., 2004). Higher total carbon was observed in older planting age blocks and traffic track positions, which improved soil aggregation and to some extent water retention. These improvements in physical properties can also enhance total nitrogen content, nitrogen mineralisation, and microbially active carbon (Norkaew et al., 2019; Sainju et al., 2022). Data from both orchards showed an increase in BD with planting age and traffic intensity, which consequently reduced organic matter turnover and led to the accumulation of SOC, although the accumulation eventually reached an apparent maximum over time. As the soil in the orchards is not disturbed and constantly under traffic pressure, soil structure seems likely to degrade beyond a certain planting age. This could explain why intermediate planting ages exhibited relatively healthier physical and chemical properties. The highest levels of total soil carbon were found in the track positions at both orchards coincided with the highest bulk density, this aligns with the elevated soil organic carbon (SOC, >3%) that corresponded to the highest BD from the meta-analyses in Chapter 3. Soil compaction can induce physical protection and thus the accumulation of SOC, at least over relatively short periods.

Furthermore, the findings of this study also suggest that the interactions between management practices and the natural recovery from compaction effects are likely to be complex. The accumulation of soil organic matter through likely improves the stability to against cumulative effect from compaction in during the longer plantation. Besides, the application of chemical spray such as fungicides or pesticides may result in the low microbial activity and diversity in soils (Wang et al., 2025).

Additionally, the apple orchards in Belfast (Canterbury) and Richmond (Nelson) together encapsulate essential features of New Zealand apple-growing operations. The soil type, climatic conditions, and management practice at the Richmond orchard closely mirror those of dominant soil types in major apple-producing regions such as Hawke's Bay and Marlborough, rendering it highly representative of the country's broader industry. In contrast, the soil type at the Belfast site is characteristic of Canterbury's apple-growing areas, and its management adheres to New Zealand's Integrated Fruit Production (IFP) guidelines—making it less universally applicable but still reflective of distinct subsets within the nation's orchard network. Therefore, they capture a range from widely representative (Richmond) to regionally specific but relevant (Belfast) soil and management traits. The findings of this study have thus provided valuable insights into the impact of soil compaction in New Zealand's apple orchards

To advance our understanding and management of soil health in apple orchards with compaction issues, future research should focus on a few key areas. One priority would be conducting long-term field trials to compare different levels of traffic intensity (such as varying tire inflation pressure, load weights, or the number of traffic passes) under various soil organic amendment levels and planting durations. These trials would assess their combined effects on both soil physical and chemical properties across different orchard soils. Such research would help develop for maintaining long-term soil physical and chemical health, particularly concerning traffic dynamics and planting age, and how they change due to compaction will provide more practical insights for more effective orchard soil management. Additional studies on soil chemical properties under compaction are needed to better understand the physical protection and carbon cycling. These should encompass a wider variety of orchard types and management practices, including different fertiliser applications and organic amendments. This research would help to elucidate the interactions between planting age and management practices, and how they affect soil properties and organic matter cycling.

Chapter 7

Conclusions and Recommendations

This thesis has provided insights into the effects of soil compaction on the physical and chemical properties of soils in New Zealand apple orchards. The findings demonstrate that soil compaction adversely affects essential soil functions, leading to increased bulk density (BD) and reduced macro-porosity and available water capacity (AWC). Factors such as traffic intensity, soil texture, and soil organic carbon (SOC) levels were shown to play important roles in modulating the extent of compaction effects. Soils with higher clay content and elevated SOC levels were particularly vulnerable to compaction, underscoring the need for careful management of traffic in these conditions to maintain soil health.

The investigation revealed that intermediate planting ages (12–17 years) consistently exhibited better soil physical and chemical properties compared to both younger and older planting ages. This suggests a non-linear interaction between these factors that could be explored to devise orchard management practices to reduce the impact of compaction that consider planting age and traffic dynamics. Furthermore, the research highlighted the dual role that SOC seem to play with regards to compaction vulnerability. Higher values for SOC are linked to greater levels of compaction, as shown in Chapter 3. On the other hand, higher SOC levels can enhance soil structure, helping to reduce the. effects of compaction. The first ‘relationship’ is likely due to better initial soil conditions of soils with high SOC, thus with great ‘room’ for compaction when put under pressure. These emphases the importance of SOC levels on determining soil resilience to compaction.

Based on the findings of this PhD study, the following recommendations can be made for future research and orchard management:

- Implement strategies to reduce traffic intensity in apple orchards, such as minimising the number of traffic passes, lowering load weights, and using appropriate tyre pressures. These adjustments can help reduce pressure on the soil and maintain soil structure and improve water retention capability.
- Regularly monitor soil physical and chemical properties, including BD, PR, total carbon, and nitrogen levels, to assess the impacts of compaction over time. This will provide valuable data for informing management decisions.

- Prioritise practices that enhance soil organic carbon content, such as incorporating organic amendments, and cover cropping. Maintaining optimal SOC levels is crucial for improving soil resilience against compaction.
- Studies on soil chemical properties under compaction should be prioritised to better understand the physical protection of organic matter and carbon cycling. These studies should involve a wider range of orchard types and management practices, including various fertiliser applications and organic amendments. This approach will help refine our understanding of how compaction influences soil chemical dynamics and inform more effective soil management practices in apple orchards.

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Appendix A

Supplementary result for Meta-analysis chapter

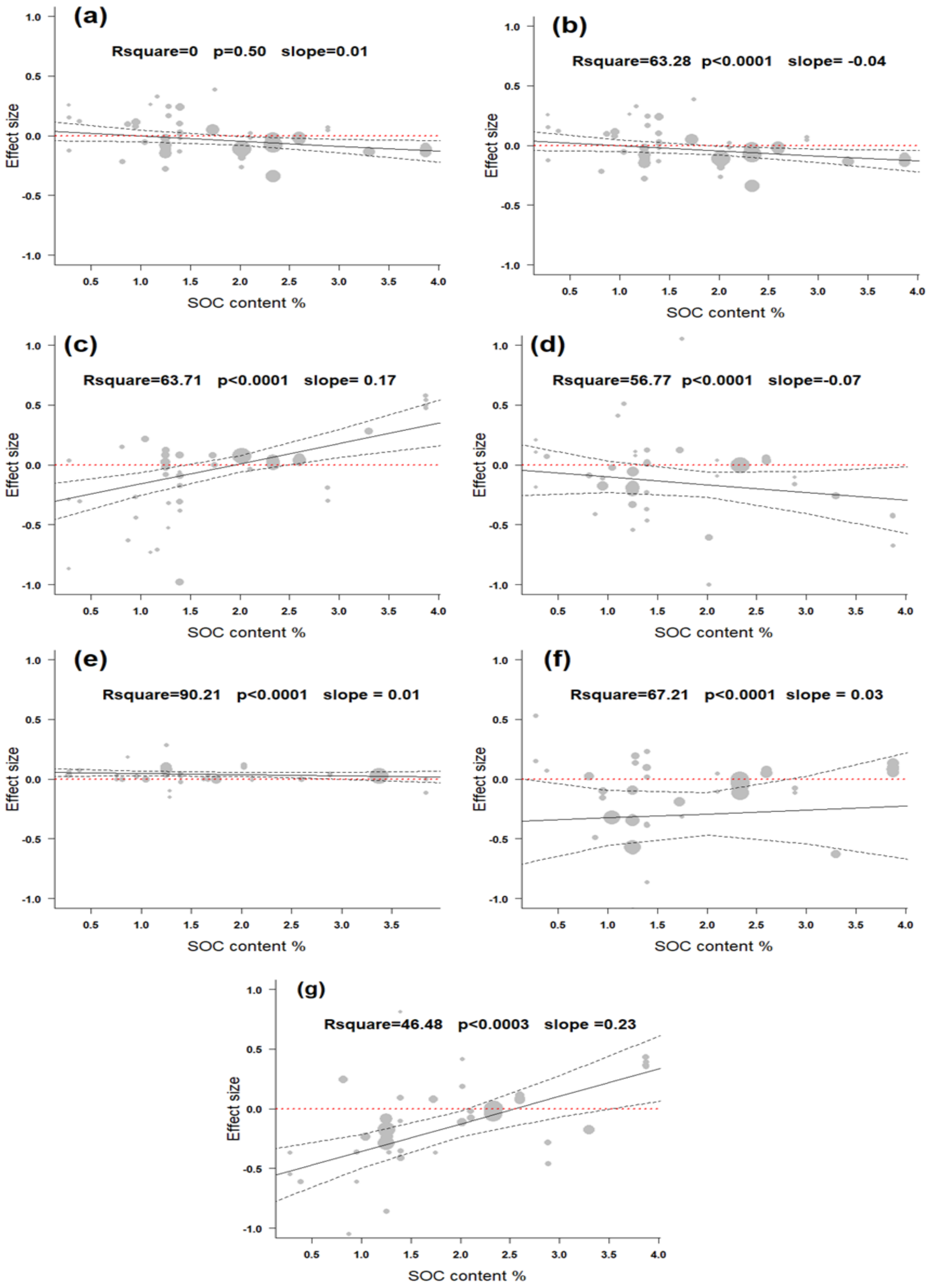

Figure A 1 Influence of SOC content on selected soil physical and hydraulic properties ((a) FC_{10}, (b) FC_{AO}, (c) AWC_{10}, (d) AWC_{AO}, (e)BD, (f) macro-porosity, (g) S index. Points are the weight of each paired comparisons. Significant trends ($p<0.05$) are shown with black solid line and black dash line. (upper and lower CI line).

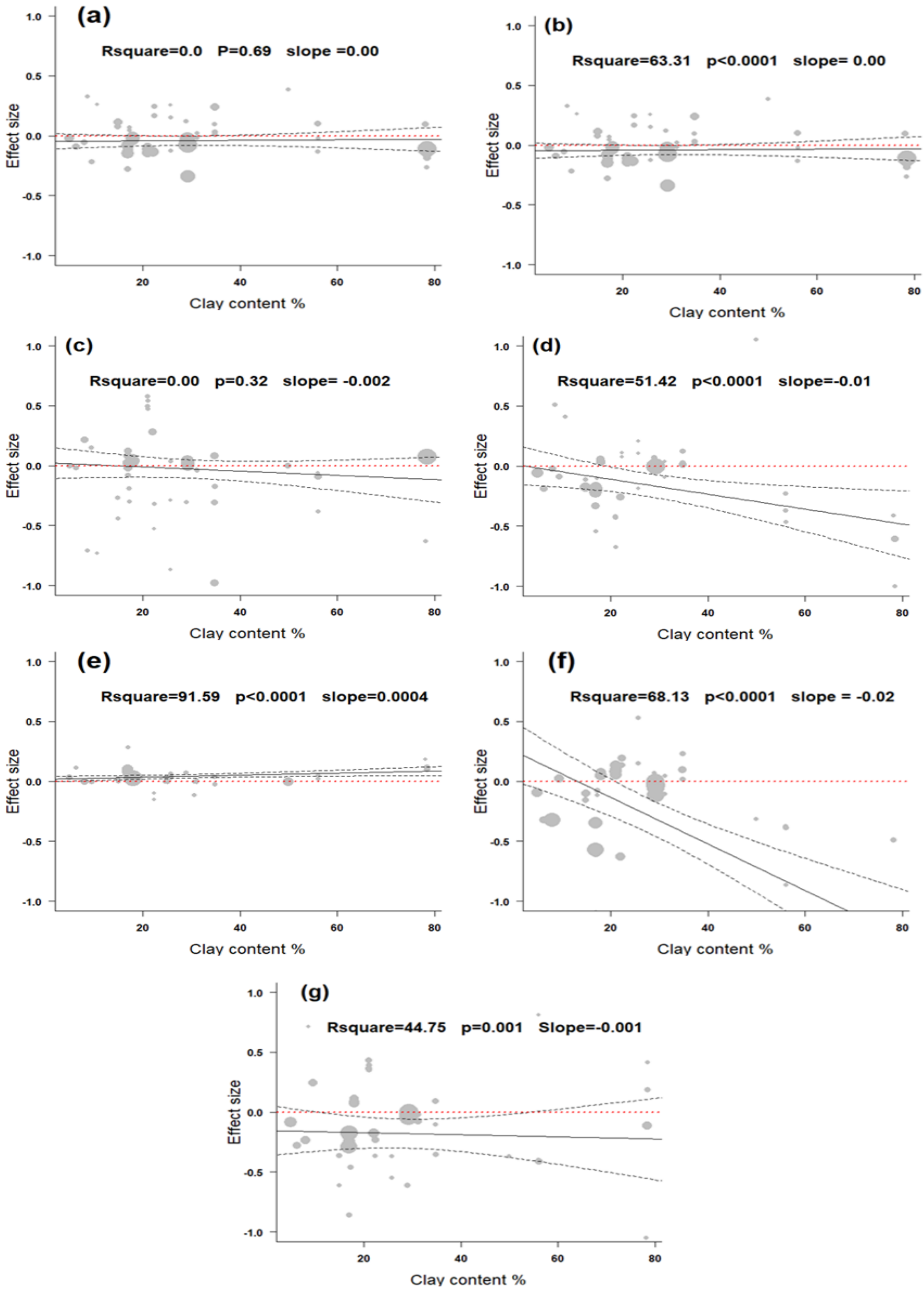

Figure A 2. *Influence of clay content on selected soil physical and hydraulic properties. ((a) FC_{10}, (b) FC_{AO}, (c) AWC_{10}, (d) AWC_{AO}, (e)BD, (f) macro-porosity, (g) S index, points are the weight of each paired comparisons. black dash line. (upper and lower CI line).*

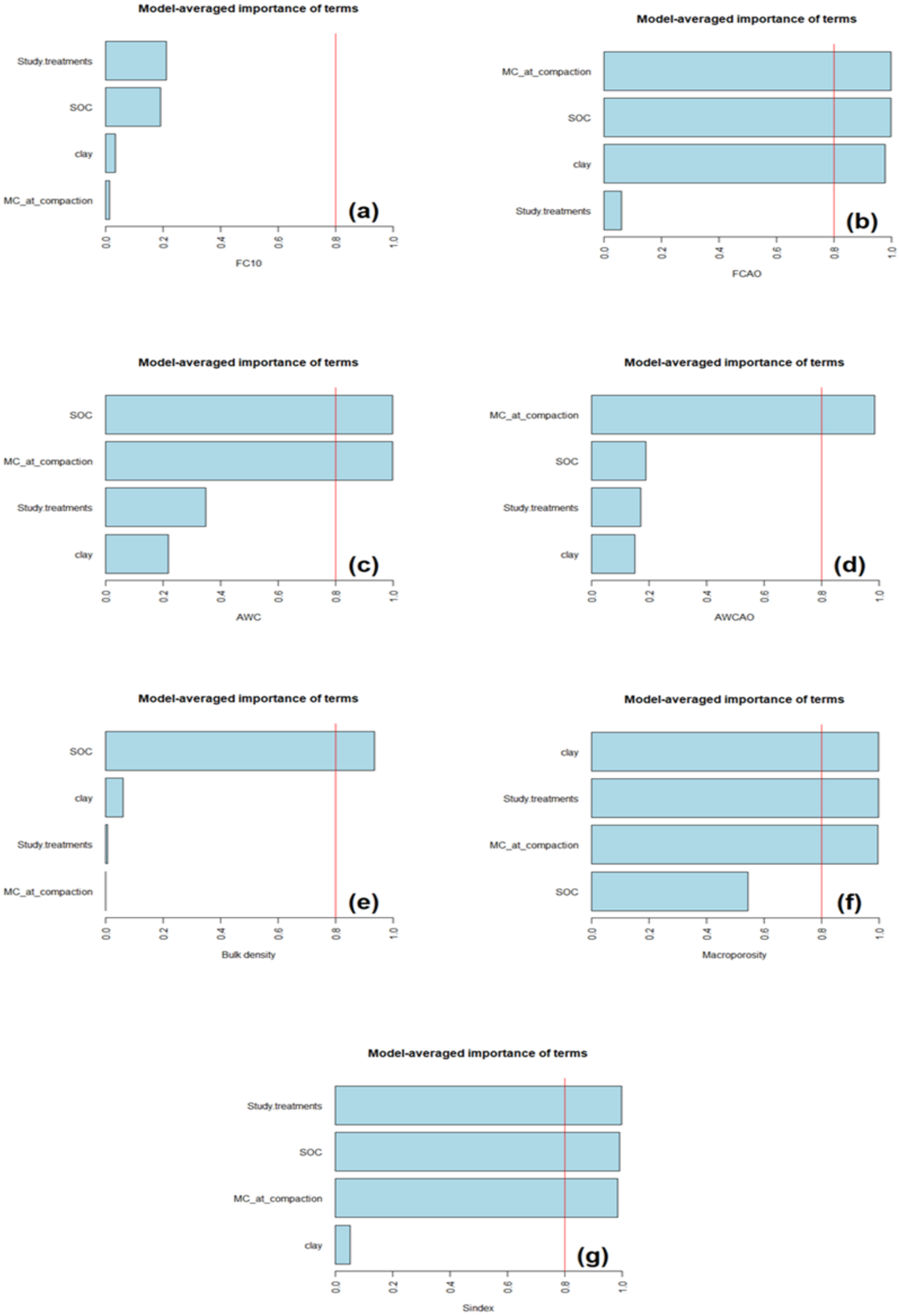

Figure A 3. Importance of SOC content, clay content, moisture content at compaction and study treatment (traffic pass, inflation pressure, and axle-load) on the selected soil physical and hydraulic properties; (a) is FC_{10}, (b) is FC_{AO}, (c) is AWC from -10 to -1500 kPa, (d) is AWC_{AO}, (e) is BD, (f) is macroporosity, (g) is S index. The importance is based on the sum of Akaike weights derived from model selection.

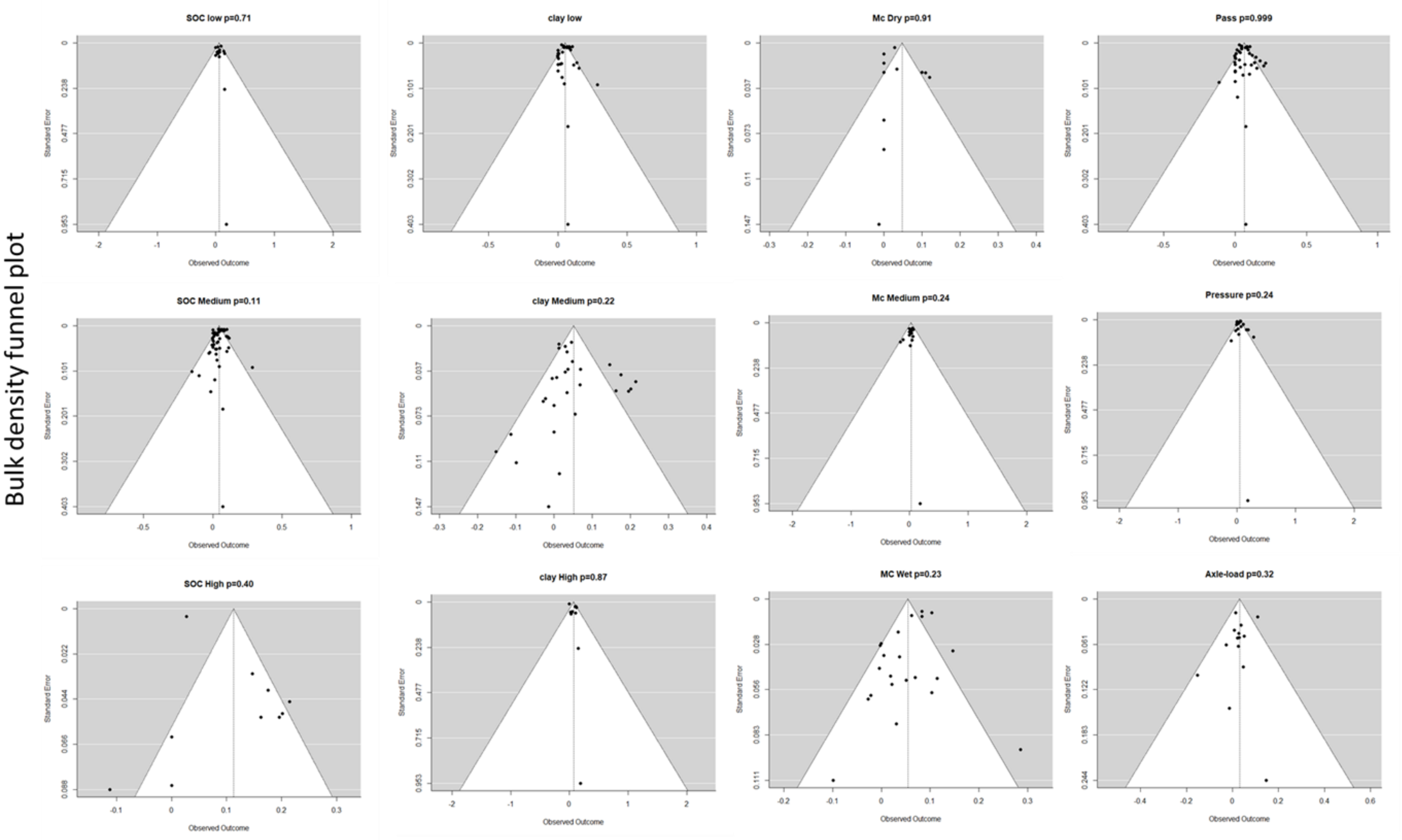

Figure A 4. Funnel plots for the bulk density according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity.

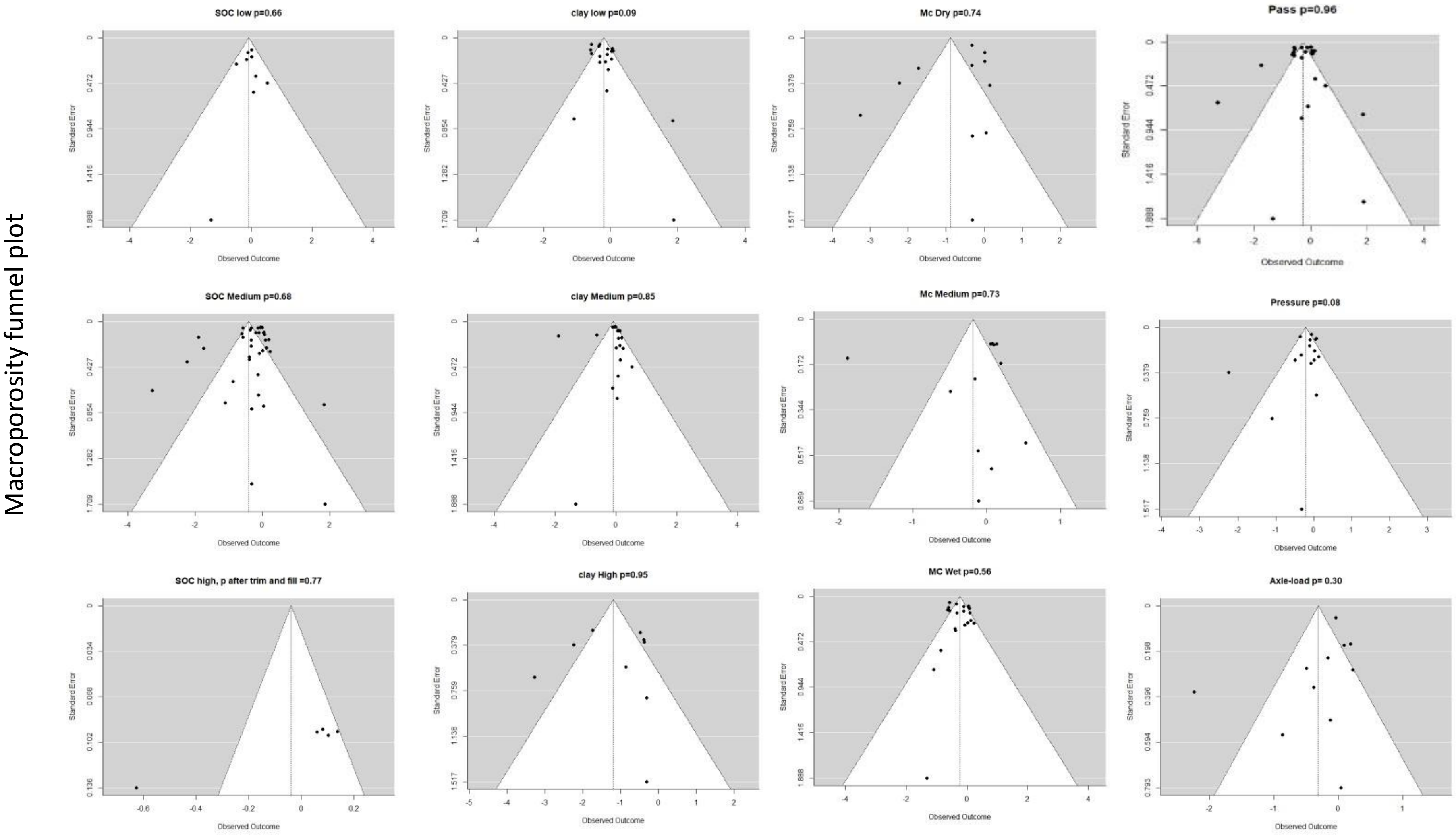

Figure A 5 Funnel plots for the Macro-porosity according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity.

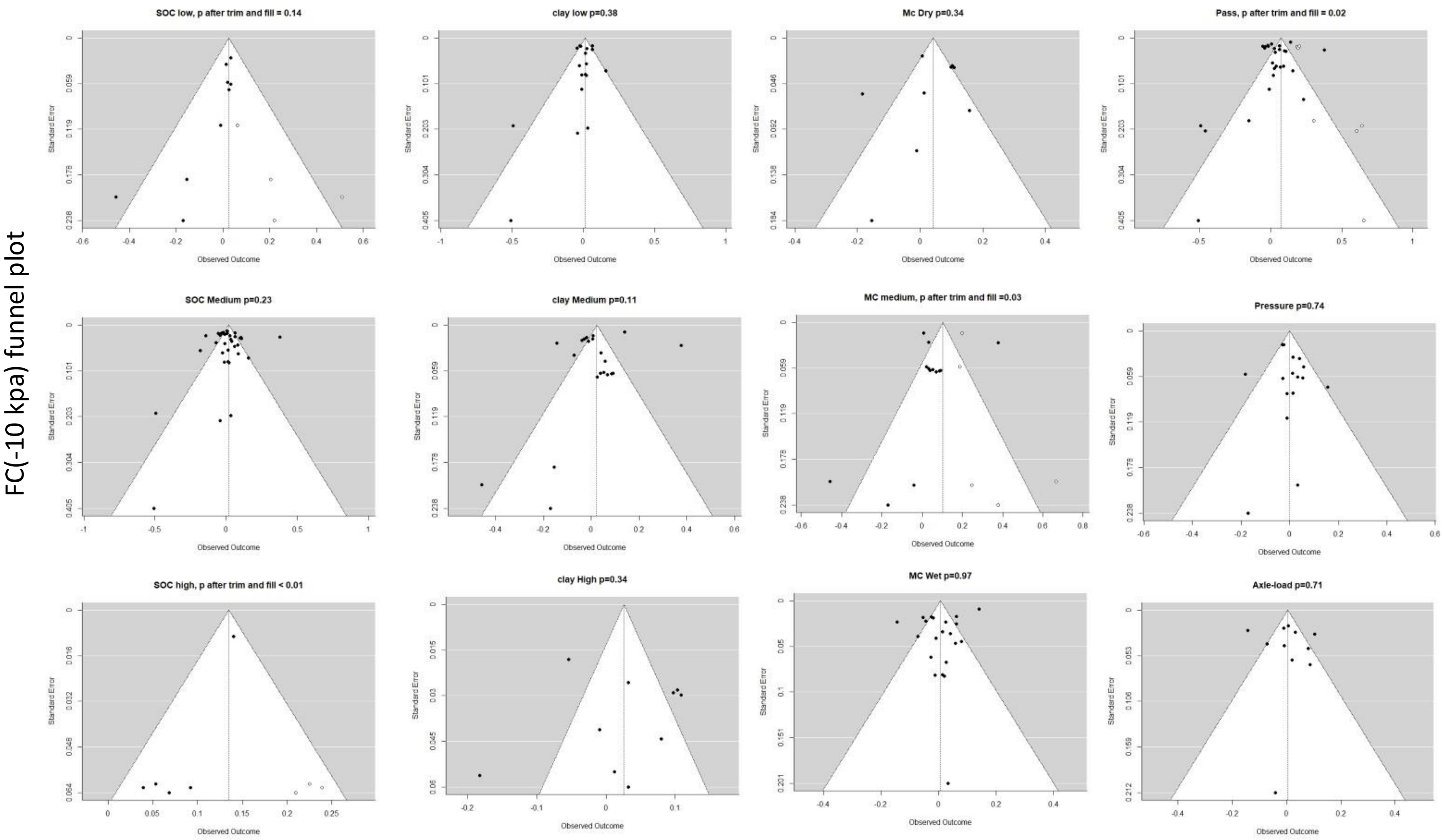

Figure A 6. Funnel plots for the FC (-10 kPa) according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity.

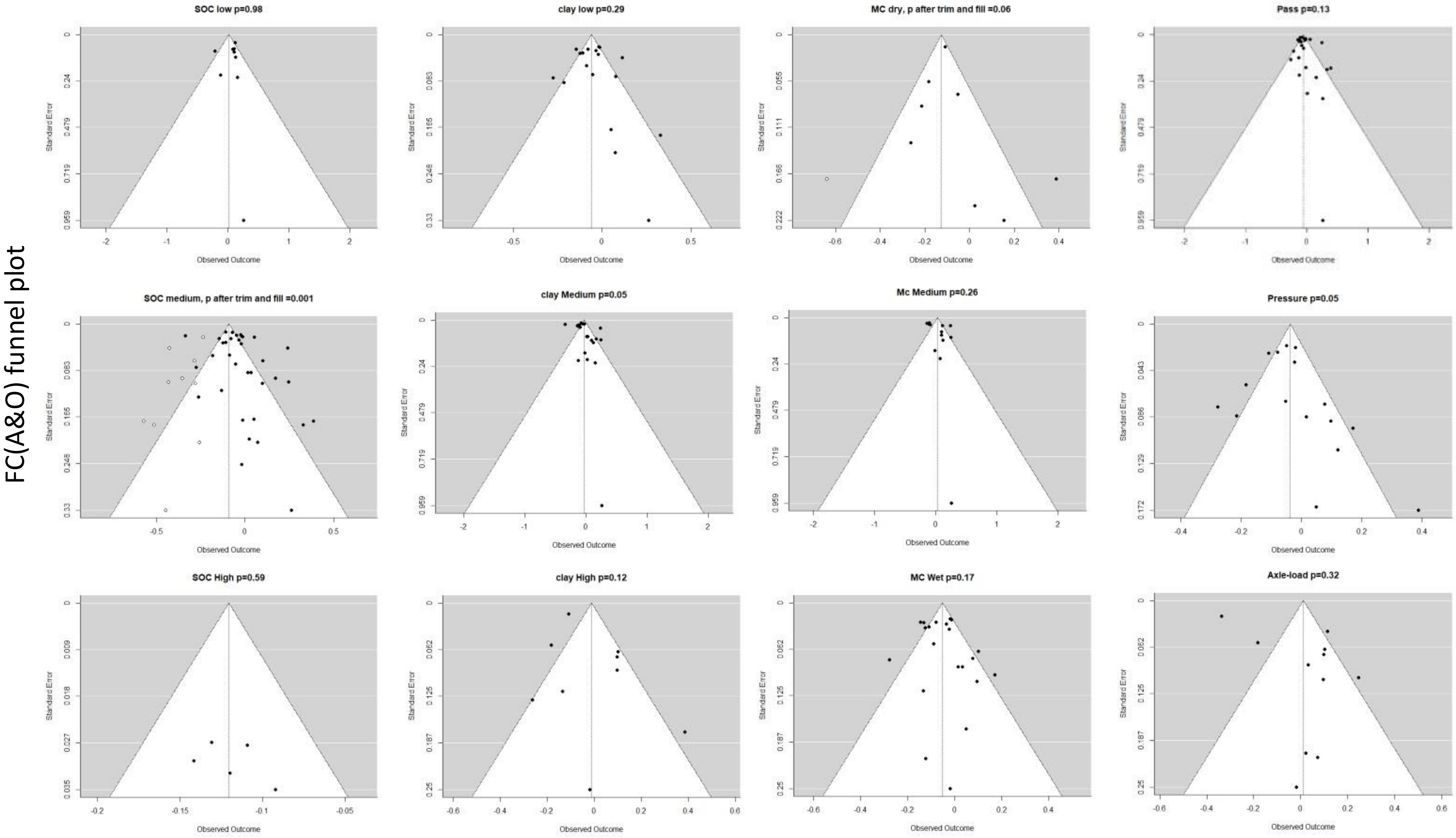

Figure A 7. Funnel plots for the FC (dynamic criteria used to define field capacity) according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity.

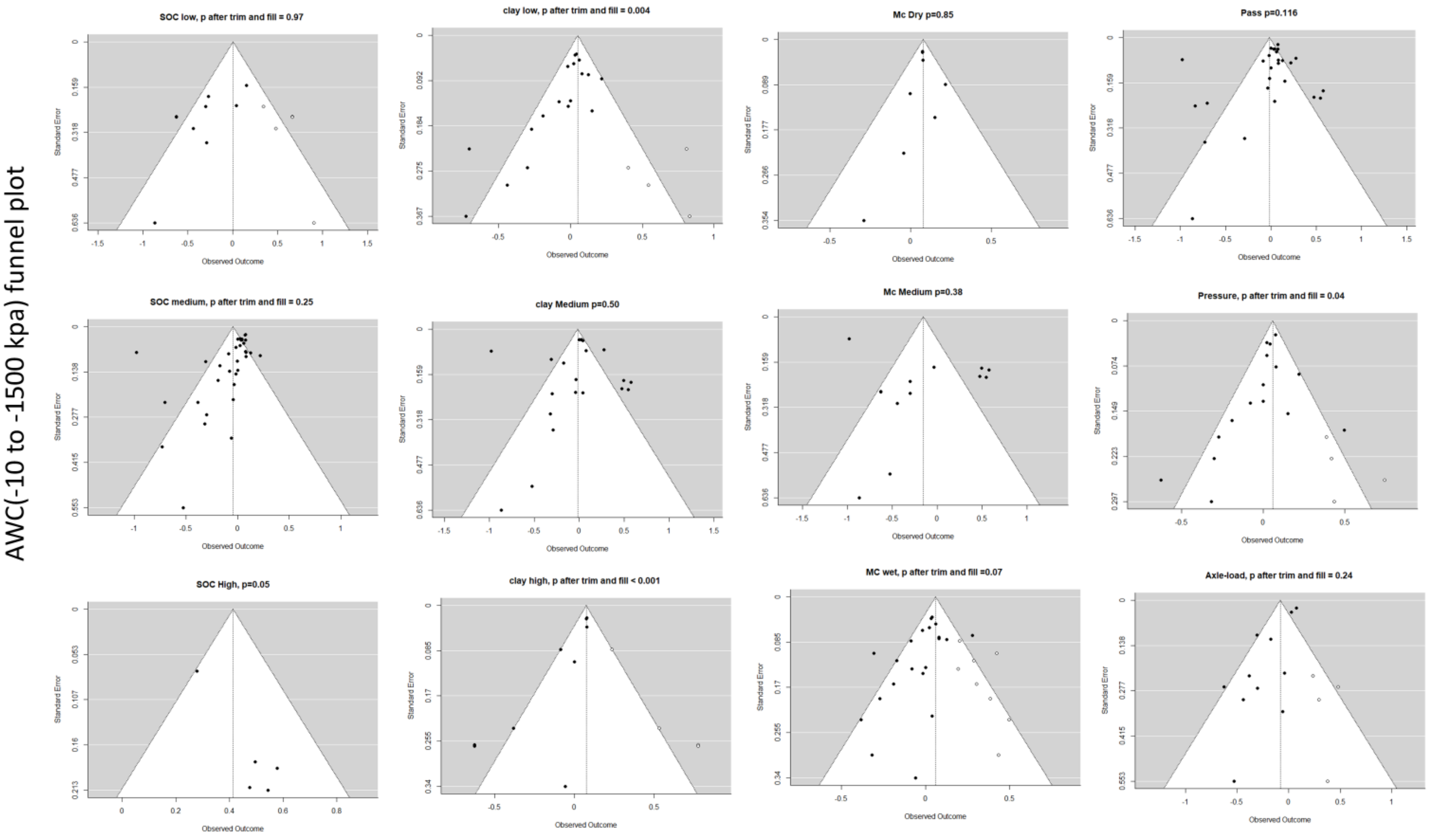

Figure A 8. Funnel plots for the AWC (-10 to -1500 kPa) according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity

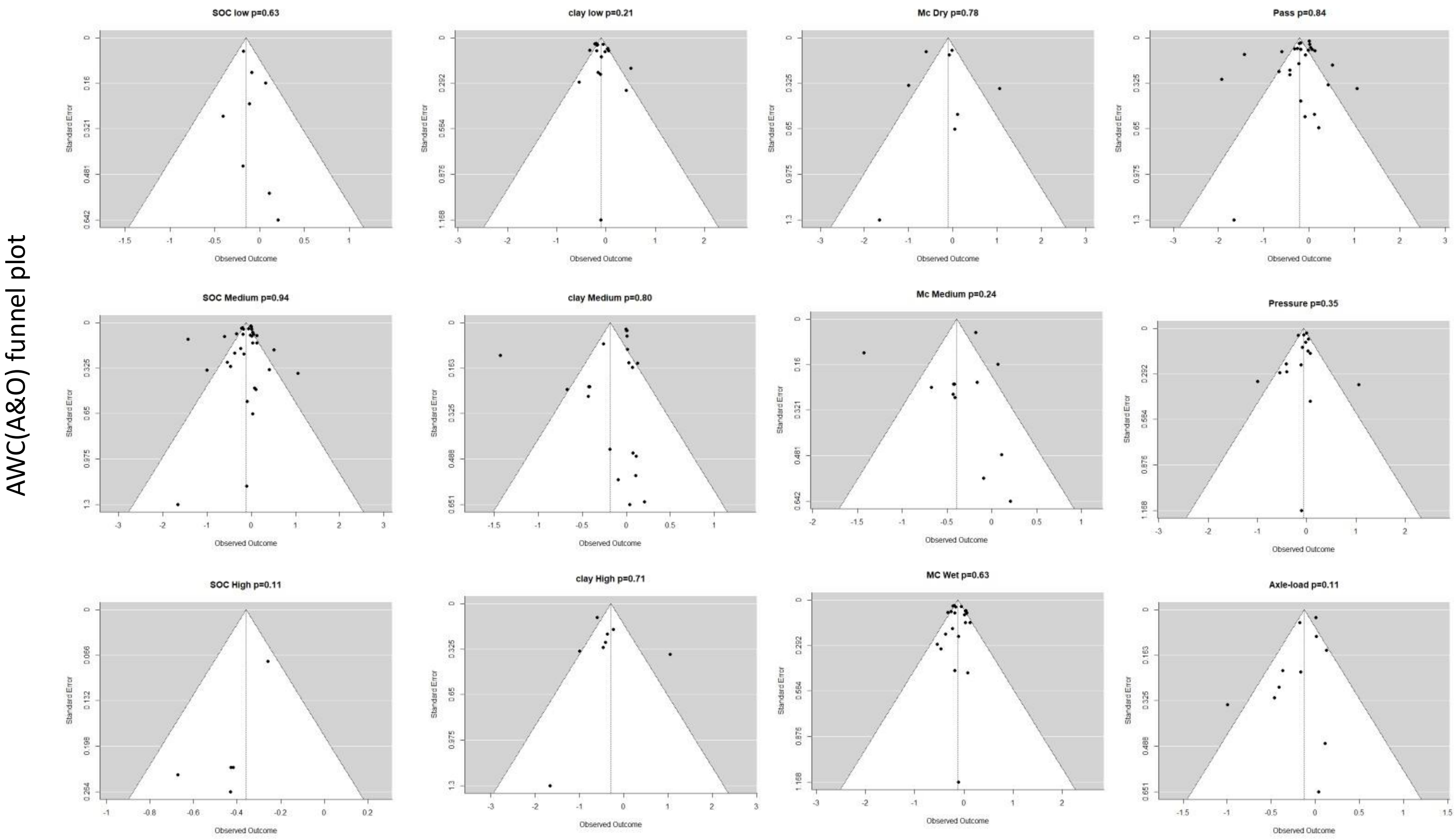

Figure A 9. Funnel plots for the AWC (dynamic criteria used to define field capacity) according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity.

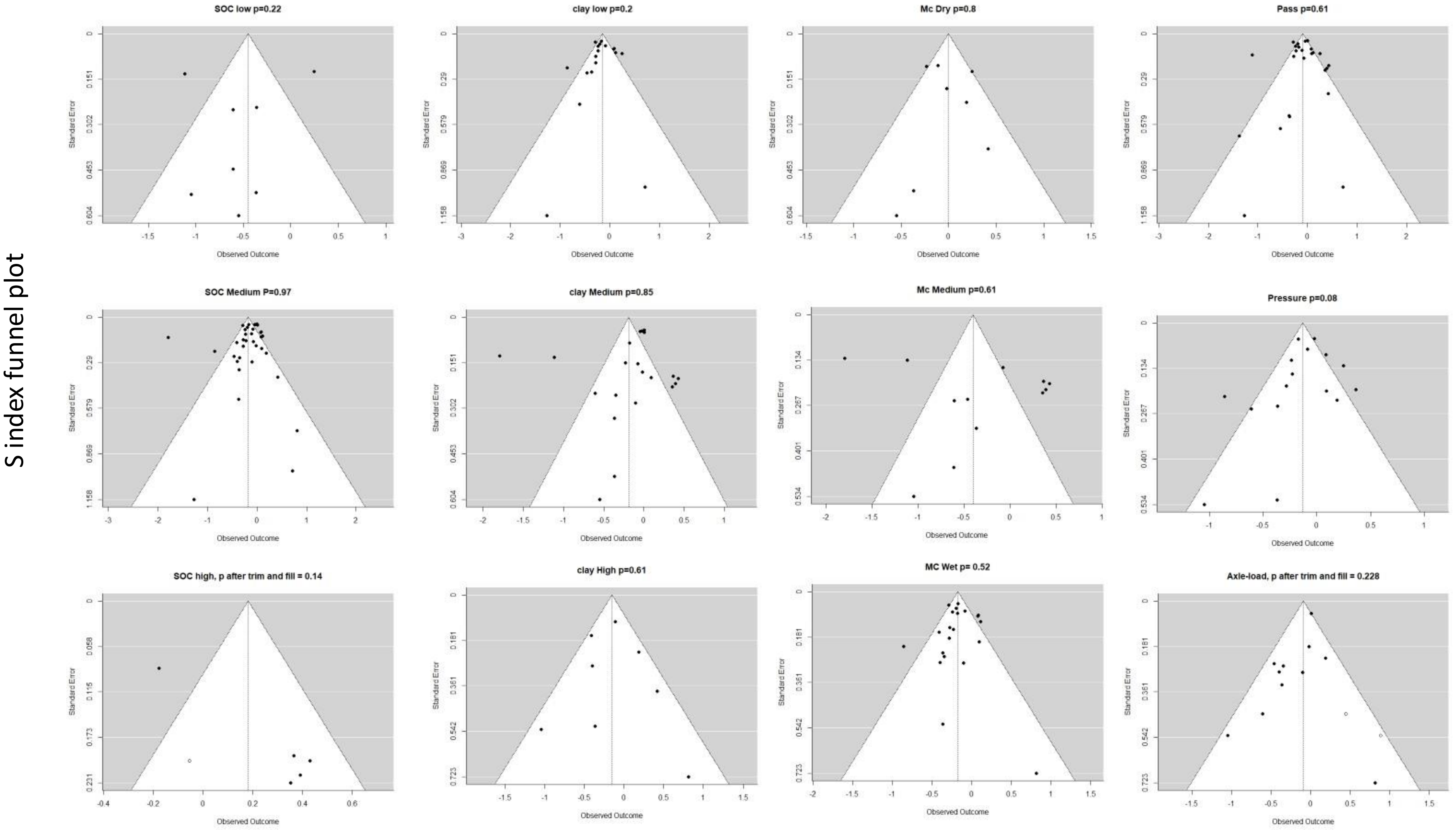

Figure A 10. Funnel plots for the S index according to the egger`s test. The whiter area bordered by dashed lines represents the region of 95% confidence intervals where 95% of studies are expected to fall in the absence of bias and heterogeneity.