

CRANFIELD UNIVERSITY

Joseph Philip Martlew

Quantifying and alleviating subsoil compaction in arable soils

School of Water, Energy and Environment

Doctor of Philosophy
Academic Year: 2018 - 2021

Supervisor: Dr L.K. Deeks
Associate Supervisors: Professor W Otten; Dr N Morris
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the degree of Doctor of Philosophy

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ABSTRACT

Modern agricultural machinery and the intensity of arable field operations has increased the risk and incidence of subsoil compaction. There is potential to improve the management of subsoil compaction through addressing the current spatial and temporal limitations of characterisation methods and determining the potential of alternative alleviation approaches. Therefore, the aim of this thesis was to determine the suitability of alternative methods to quantify and alleviate subsoil compaction in arable soils. A combination of literature, field and laboratory studies were used to consider the appropriateness of different methods.

The long-term, repeated use of a cover crop in rotation with winter wheat improved subsoil physical properties compared to a control. Cultivation treatments had a significant interaction with this, where reducing the intensity and depth of cultivation resulted in the greatest subsoil benefits. Combining alternate season cover cropping and non-inversion, shallow depth cultivation produced the largest advantage to subsoil properties. High subsoil compaction had a significant negative effect on arable crop performance under controlled conditions. Although both brassica and graminaceous cover crops increased root proliferation in compacted subsoil compared to a control, neither significantly improved arable crop performance after two consecutive seasons.

Electromagnetic conductivity soil scanning presented significant spatial and temporal advantages for use at a large spatial scale. However, data interpretation requires further development for application to subsoil compaction. Visual soil evaluation using the SubVESS approach provided the greatest detail on the position of compact subsoil layers and the underlying cause but was limited by the time-consuming methodology. A combination of characterisation methods was most applicable to provide the highest level of detail for subsoil management.

Overall, the work presented in this thesis indicated that the characterisation and alleviation of subsoil compaction may be improved through the adoption and further investigation of the alternative approaches presented.

Keywords: Soil function, yield, biopore, roots, soil management, cover crops, cultivation, characterisation

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1 Introduction

1.1 Subsoil compaction

Subsoil compaction is a process by which the space within and/or between soil structural units is rearranged, which decreases pore space and increases the bulk density (Defossez and Richard, 2002). This change in pore space causes the deterioration of one or more soil functions (van den Akker and Schjonning, 2004). Maintaining and improving soil functions is key to sustainable agriculture and associated ecosystem services (Lal, 2008). However, drive for efficiency in modern agriculture has resulted in a marked increase in the weight of agricultural machinery and the intensity of field management, which has increased the occurrence and severity of subsoil compaction, negatively affecting soil functions such as water and gas transport, and crop yield (Alakukku et al., 2003; Keller et al., 2019). Subsoil compaction has a significant cost to agriculture both on-site, in terms of sustainability and productivity (Stoessel et al., 2018), and off-site, in terms of negative environmental consequences, such as increase flood risk (Graves et al., 2015; Rickson et al., 2015). Once formed, subsoil compaction has been shown to be cumulative and to persist long-term (Berisso et al., 2012; Etana et al., 2013a; Håkansson and Reeder, 1994). Estimates suggests that c. 40 % of European agricultural subsoils may be detrimentally compacted (Brus and van den Akker, 2018a; van den Akker, 2004). However, estimates vary (D'Or and Destain, 2014; Jones et al., 2003), and are limited by a lack of sufficient data on subsoil compaction at a variety of spatial and temporal scales (Alaoui and Diserens, 2018), and how subsoil compaction processes are linked to soil management (Keller et al., 2019).

1.1.1 Formation and drivers of subsoil compaction

Although subsoil compactness may be formed by both natural and anthropogenic processes (Or et al., 2021), the focus of this thesis is anthropogenic. A series of expert working groups have addressed the formation and drivers of subsoil compaction through laboratory and field studies (Håkansson, 1994; Van Den Akker et al., 2003), which have been translated into practical advice (Schjønning et al., 2012; Spoor et al., 2003). Anthropogenic subsoil compaction is formed

when the ground contact pressure, which is a function of axle load and contact surface area, exceeds the carrying capacity of a soil profile (Hamza and Anderson, 2005). The degree and depth of compaction is determined by several factors interacting, of which axle load has been shown to be the dominant factor when considering subsoil compaction caused by machinery (Lamandé and Schjønning, 2011a; Pulido-Moncada et al., 2019) (Fig 1.1). Higher axle loads generate higher ground contact pressures, which result in a corresponding increase in the depth of compaction (Alakukku, 1999; Lamandé and Schjønning, 2018; van den Akker and Schjønning, 2004), negatively affecting subsoil structure and function (Pulido-Moncada et al., 2019). The frequency of vehicle passes has been shown to have a contributory impact, where repeated passes increases the depth and degree of subsoil compaction (Botta et al., 2009; Horn et al., 2003; Naderi-Boldaji et al., 2018) until a plateau is reached (Zink et al., 2011). Though the exact impact of pass frequency has been shown to be difficult to determine in heterogeneous field soil (Horn et al., 2003). The construction and inflation pressure of tyres or the use of agricultural tracks has primarily been related to compaction in the topsoil (Godwin et al., 2015; Lamandé and Schjønning, 2011b). However, some evidence has indicated that the role of inflation pressure in subsoil compaction should be further explored (Lamandé and Schjønning, 2011b; Schjønning et al., 2012) but differentiating between the effect of axle load and inflation pressure for subsoil has, historically, been challenging (Keller and Arvidsson, 2007).

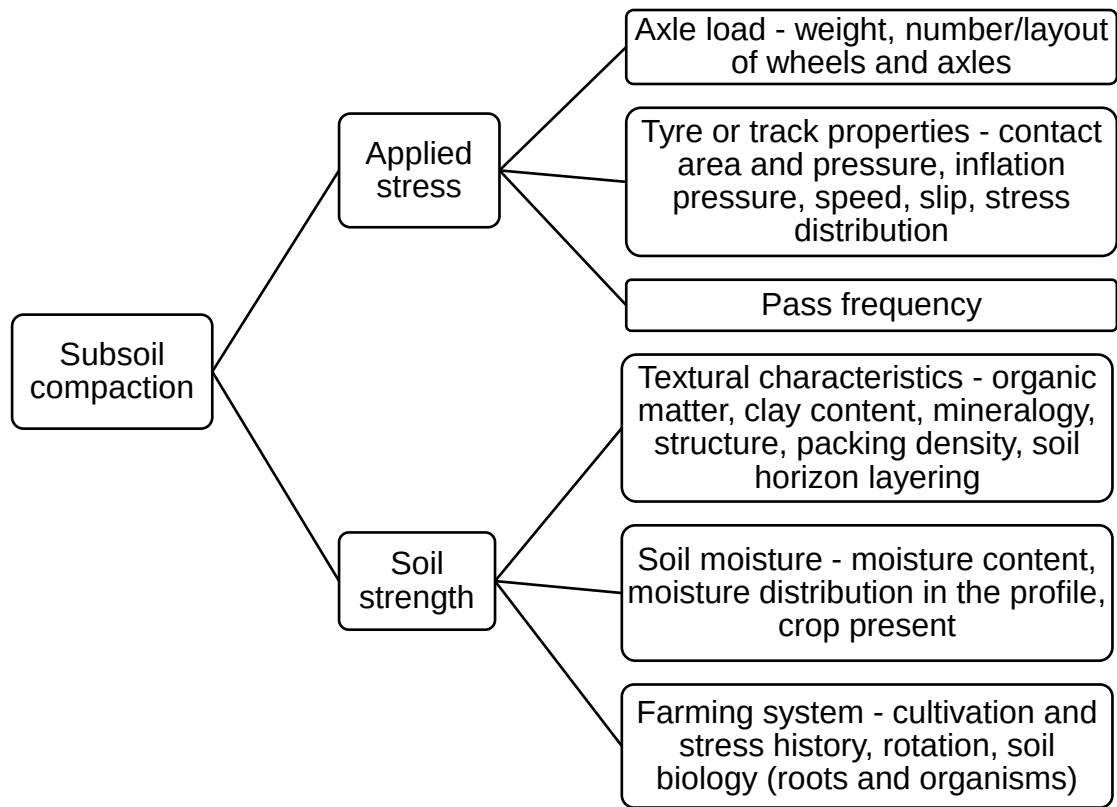


Figure 1.1 Simplified model of the interacting factors that determine the degree and depth of subsoil compaction by applied load (adapted from Alakukku et al., 2003).

Intensity of cultivation is dictated by the type of cultivation operation (e.g. inversion, non-inversion), the amount of soil moved (e.g. cultivation depth, forward speed) and the frequency of cultivation operations (Spoor, 2006). High input cultivation intensity negatively affects the carrying capacity of the soil profile (Munkholm and Schjønning, 2004) and the depth of pressure transmission from applied load (Arvidsson, 2001). Intensive cultivation can therefore increase the risk of subsoil compaction. More intense and/or deeper cultivation generally requires vehicles with high power (and consequently higher axle load) to operate the associated implement, creating a linked negative cycle between high cultivation intensity and the risk of subsoil compaction (Chamen et al., 2003). Cultivation operations that bring axle load closer to the upper subsoil, such as in-furrow ploughing, and operations that cause significant disruption to the soil

profile, such as subsoiling, further increase the risk of subsoil compaction and recompaction (Alakukku et al., 2003; Chamen et al., 2000; Kooistra and Boersma, 1994). In addition, cultivation implements themselves may also create compaction by repeated exertion of downward pressure or smearing, particularly in the upper subsoil, immediately below the maximum working depth of annual cultivations (Alakukku et al., 2003). These compact 'pan layers' may have a negative effect by restricting the movement of water, gas and roots (Olesen and Munkholm, 2007) or, provided they retain an appropriate level of soil function for the specific situation, provide a positive function by spreading contact pressure over a larger area and protecting deeper subsoil (Chamen et al., 2003; Poodt et al., 2003). Pan layers commonly form below the depth of annually repeated inversion plough cultivation (approximately between 22 – 35 cm depth) or slightly shallower as a result of repeated disc cultivation (approximately between 12 – 20 cm depth) (Birkas et al., 2004; Chen and Tessier, 1997).

Soil profile resilience to subsoil compaction is improved by reducing the intensity of cultivation (Chamen et al., 2003; Sommer, 2000) and there is some limited evidence that the soil structure formed in the absence of cultivation by soil ecosystem engineers (i.e. plant roots and soil fauna) is more resilient to applied pressure (Gut et al., 2015). Compaction avoidance measures, such as controlled traffic farming, that reduce the field surface area subject to load (Kroulík et al., 2011) may be used to reduce the risk of subsoil compaction (Hernanz and Sanchez-Giron, 2000).

1.1.2 Susceptibility factors for subsoil compaction

Susceptibility of a soil profile to subsoil compaction is mainly dependent on soil water content, and structural and textural characteristics (Keller and Dexter, 2012; Spoor et al., 2003) (Fig. 1.1). Higher soil water content corresponds to a decrease in the carrying capacity of a soil profile (Koolen and Kuipers, 1983; Lipiec et al., 2002), which increases the susceptibility to compaction (Saffih-Hdadi et al., 2009). High soil water content increases the incidence of negative soil structural change as a result of applied pressure and concentrates pressure transmission more directly below the centre of the load applied, which results in

deeper stress transmission and a higher risk of subsoil compaction compared to low soil water content (Arvidsson, 2001; Defossez and Richard, 2002). Field operations are dictated by crop rotation, and therefore crops that require field operations to be carried out during wetter periods increase subsoil compaction risk. In addition, advances in machinery power have allowed field operations to take place at higher soil water contents compared to the lower powered machinery used historically, which forms a negative cycle between field operations at high soil water contents and subsoil compaction (Chamen et al., 2003). Interaction between the water content of the topsoil with the subsoil, affects the depth and degree of subsoil compaction but has proven difficult to model due to textural heterogeneity (Lamandé and Schjønning, 2011c; Trautner, 2003).

Spoor et al. (2003) stated that subsoil in the coarse, medium and medium/fine soil textures have a lower potential to resist compaction compared to subsoil in the fine and very fine soil textures. However, this is an oversimplification as the heterogeneity of texture, and the interaction with water content and other parameters such as management history and organic matter, mean in reality risk is far more site specific (Alakukku et al., 2003; Chamen et al., 2003; Trautner and Arvidsson, 2003).

1.2 Characterisation of subsoil compaction

Soil compaction is spatially and temporally variable, depending on soil characteristics and agricultural management (Bonnin et al., 2010). Methods of characterisation should therefore include a range of spatial scales, from pore to landscape scale, and be applicable over time from short-term change to long-term patterns of land use (Alaoui et al., 2018; Alaoui and Diserens, 2018). Although reliable characterisation of subsoil compaction is critical to inform management and policy, methodological limitations mean there remains a lack of appropriate data (Jones et al., 2003; Schwilch et al., 2011).

Traditional approaches have focused on inferring the degree of compaction through single soil functions (e.g. hydraulic properties) or physical properties (e.g. bulk density) (Raper, 2005). At the small spatial scale, these may poorly reflect

overall soil function (Rabot et al., 2018). Whereas at the large spatial scale, a high degree of replication is required to capture field heterogeneity (Gao et al., 2012; Lipiec and Hatano, 2003). This limits the suitability of sampling due to the time-consuming and costly nature of sufficient sample collection. Advances in non-disturbance, image analysis such as X-ray computed tomography (CT) allow the inference of soil function and physical properties, and the interaction with plant growth, in-situ over time (Atkinson et al., 2020; Mooney et al., 2012; Pöhlitz et al., 2018). These advancements are developing an understanding of the direct interaction between soil compaction, and soil and plant response (Pandey et al., 2021; Schneider et al., 2021; Vanhees et al., 2021). Although imaging techniques remain reliant on physical samples and artificial conditions, these limitations are being addressed to some extent by the automation of scanning and the increased size of samples able to be scanned (Bouma et al., 2000; Mooney et al., 2012; Tracy et al., 2011).

At the larger spatial scale, visual soil evaluation (VSE) methods have become popular due to practicality and the soil management specific results produced (Ball et al., 2015; Ball et al., 2017; Emmet-Booth et al., 2020; Obour et al., 2017c). However, although VSE methods may agree well with traditional approaches, they do not overcome limitations of replication and time consumption (Emmet-Booth et al., 2020; Mueller et al., 2013), are destructive (McKenzie, 2013), and produce data that is challenging to analyse statistically (Mueller et al., 2009). Therefore, there has also been a focus on non-disturbance methods to overcome spatial and temporal limitations of traditional approaches (Hoefer et al., 2009; Weiss et al., 2020) and to improve characterisation of subsoil compaction for decision making and modelling (Alaoui and Diserens, 2018; Brevik et al., 2003; Hemmat and Adamchuk, 2008). Methods such as measuring apparent soil electromagnetic conductivity (EC_a) (Domsch and Giebel, 2004; Lück et al., 2009) have shown potential to be practical and to correlate with traditional approaches (Doolittle et al., 1994; Hoefer et al., 2010, Hoefer et al., 2009; O'Leary et al., 2003). Further research to explore the relationships between subsoil compaction and EC_a data interpretation is required (Carroll and Oliver, 2005; Inman et al., 2002; Lilienthal et al., 2005).

1.3 Alleviation of subsoil compaction

Alleviation of subsoil compaction aims to generate porosity in the compacted region without causing excessive disruption to the soil profile, benefitting compacted soil functions and supporting crop production (Schneider et al., 2017; Spoor et al., 2003). Natural processes such as shrink/swell and freeze/thaw cycles can contribute to the remediation of soil compaction (Dexter, 1991; Jabro et al., 2014) but evidence suggests natural processes are not sufficient to alleviate anthropogenic compaction in the subsoil (Batey, 2009; Etana and Håkansson, 1994; Schjonning et al., 2017).

Use of mechanical deep cultivation (i.e. subsoiling) to alleviate compacted subsoil layers has been covered extensively in the literature and best practice guidance has been produced (Chamen et al., 2003; Raper, 2005; Spoor et al., 2003; Spoor and Foot, 2000). Subsoiling can effectively alleviate subsoil compaction, improving subsoil functions and crop yield (Cai et al., 2014; Ekelöf et al., 2015a; He et al., 2019). However, mechanical cultivation greatly increases the risk of recompaction by subsequent field operations (Chamen et al., 2003; Olesen and Munkholm, 2007) and natural compaction processes (Schneider and Don, 2019a). The evidence for the positive impact of subsoiling on crop yield is inconsistent and the long-term positive benefits often overestimated (Chamen, 2011; Gill et al., 2008; Munkholm et al., 2005; Chamen et al., 2015).

Utilising the properties of plant roots to create and extend porosity in compacted soil layers has been proposed as an alternative to mechanical cultivation (Cresswell and Kirkegaard, 1995; Hamza and Anderson, 2005). Although a variety of species and rotation opportunities may be suitable to integrate this into arable agriculture, cover crops have had a particular focus to allow the inclusion of specific root traits beneficial to specific soil problems (Rosolem et al., 2002), such as subsoil compaction. The 'biopores' created during this process have been shown to benefit soil functions in compacted layers (Lipiec and Hatano, 2003; Uteau et al., 2013), support crop growth (Kirkegaard et al., 2008; Perkons et al., 2014; Pulido-Moncada et al., 2021) and may be more resilient to recompaction compared to those created by mechanical cultivation (Schaffer et

al., 2008, Schaffer et al., 2007). Evidence suggests that the root traits of some species are more effective in the alleviation of subsoil compaction (Beck-Broichsitter et al., 2020; Clark et al., 2003; Materechera et al., 1992a). However, further investigation is required to determine the relative importance of different species and root traits (Burr-Hersey et al., 2017; Hudek et al., 2021), and the evidence concerning subsoil compaction, especially long-term at field-scale, is lacking. Improving the specificity of advice regarding biological alternatives to mechanical cultivation has been highlighted as a key limitation in the uptake of these approaches (Freluh-Larsen et al., 2018; Storr et al., 2019). Change in rotation and/or cultivation approach, as is proposed to alleviate subsoil compaction, has been shown to have a significant and potentially positive impact on soil microbiological communities, which is directly related to the management of sustainable soil functions (Beylich et al., 2010; Kim et al., 2020). However, the interactions between field operations, soil microbiology and agricultural soil functions remains an active research question and is beyond the scope of this thesis.

1.4 Research aims and objectives

Aim: To determine the suitability of alternative methods to quantify and alleviate subsoil compaction in arable soils. The following objectives were addressed to meet this aim:

Objective 1: To evaluate whether current subsoil compaction alleviation and characterisation approaches may be improved by alternative methods. This was addressed by a literature review (Chapter 2).

Objective 2: To determine whether long-term rotation and cultivation management have an impact on subsoil compaction at field-scale. This was addressed by field experiments (Chapter 3).

Hypothesis: Repeated, alternate season cover crop rotation combined with reduced cultivation intensity will decrease the long-term formation of subsoil compaction compared to continuous cereal rotation and conventional cultivation.

Objective 3: To determine the potential of two cover crop species to alleviate subsoil compaction and provide a benefit to a following arable crop, and if this effect increases over two consecutive seasons. This was addressed by a controlled conditions soil column experiment (Chapter 4).

Hypothesis 1: Cover crops will provide greater alleviation of subsoil compaction compared to a control and will increase following crop performance.

Hypothesis 2: Brassica cover crop species will provide greater alleviation of subsoil compaction compared to graminaceous species.

Objective 4: To determine the applicability of subsoil visual evaluation of soil structure (SubVESS) and electromagnetic conductivity (EC_a) in characterising subsoil compaction as a result of experimental treatments, in comparison to penetration resistance (PR) and bulk density (BD). This was addressed through field experiments (Chapter 5).

Hypothesis: SubVESS and EC_a are equally applicable compared to conventional methods PR and BD in characterising subsoil compactness.

1.5 Thesis outline

This thesis has been written in a paper format and therefore the research activities have been written in the form of academic journal publications (Chapters 2 – 5). Chapters 2 and 3 are intended for publication in *Soil and Tillage Research*, Chapter 4 is intended for publication in journal *Soil Use and Management*, and Chapter 5 is intended for publication in *Frontiers in Environmental Science*. Chapters 2 – 5 will be reformatted and submitted for publication after the completion of this thesis. Chapters 1, 6 and 7 provide the background of the research topic, and discuss the wider context for applying research outcomes and the overall research conclusions. The chapter structure of this thesis has the following progression:

Chapter 2: ‘A review of methods used to characterise and alleviate subsoil compaction in agriculture’, provides a critical appraisal of the existing methods used to characterise and alleviate subsoil compaction. Alternative methods are

considered, knowledge gaps are identified and future recommendations for research are made.

Chapter 3: '*Long-term impact of repeated cover cropping and cultivation approach on subsoil compaction*', determines whether the repeated, long-term growth of a cover crop in an arable rotation has an impact on subsoil compaction and the interaction of this with three cultivation approaches.

Chapter 4: '*The effect of cover crops on arable crop performance under three levels of subsoil compaction*', explores the effect of three levels of subsoil compaction on arable crop performance under controlled conditions, and assesses the ability of two cover crop species to alleviate subsoil compaction and provide a benefit to a following arable crop.

Chapter 5: '*Applicability of three field methods to identify subsoil compaction as a result of different soil management strategies in a long-term field experiment*', compares the applicability of contrasting characterisation methods to measure subsoil compaction in a field experiment compared to standard methodologies.

Chapter 6: '*Integrated Discussion*', considers the potential impact of the research outcomes in context. This chapter demonstrates how the aim of the research was delivered, how the results from each chapter contribute, and puts forward suggestions for further research.

Chapter 7: '*Conclusions*', draws together the main outcomes from the three-year experimental programme of work.

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2 A review of methods used to characterise and practices to alleviate subsoil compaction in agriculture

Objective: To evaluate whether current subsoil compaction alleviation and characterisation approaches may be improved by alternative methods

Hypothesis: This chapter has no testable hypothesis

Target Journal Publication: Soil and Tillage Research

2.1 Abstract

This review sought to appraise current approaches used to characterise and alleviate subsoil compaction, and to consider whether potential alternatives present significant advantages. Characterisation methods should provide appropriate measurement of subsoil compaction from the soil pore scale through to field scale and beyond. Ideally, measurements should also be applicable to characterise change over repeated time points. The digitisation of conventional characterisation approaches alongside non-disturbance imaging represent significant improvement at the small spatial scale, and characterisation may be repeated through time without sample disturbance. However, as with conventional approaches, these alternatives remain limited by sufficient sample creation or collection. Non-invasive scanning and visual soil evaluation present some spatial and temporal advantages for subsoil characterisation at the large spatial scale compared to conventional approaches. Evidence suggests that non-invasive scanning methods require further experimentation to develop application to subsoil compaction. It is essential to have effective methods of quantifying compaction in order to appraise how successful different methods of alleviation may be.

Although subsoil compaction may be alleviated by mechanical cultivation, this approach generates significant profile disruption, increases the risk of recompaction and is limited by depth. Utilising the root growth of specific cover crop species to generate bioporosity to improve soil function in compacted subsoil

layers meets the objectives of alleviation and avoids the drawbacks associated with mechanical cultivation. Further research to define the role of specific species, the relative importance of root traits and the expected benefits to arable agriculture are required.

2.2 Introduction

Incidence and risk of subsoil compaction has increased as a result of the intensification of arable agricultural management (Schonning et al., 2018). Fundamental drawbacks exist in the current approaches used to characterise and alleviate subsoil compaction. Current characterisation approaches have methodological limitations both spatially and temporally (Alaoui and Diserens, 2018), which has resulted in a lack of quantitative data to support subsoil management (Otte et al., 2012; Prager et al., 2011; Thorsoe et al., 2019). Improvement in characterisation from small to large spatial scales to monitor both short and long-term change is required (Schonning and Thorsoe, 2019). At the small spatial scale, advances in imaging technologies present an opportunity to study soil functions and plant response in relation to subsoil compaction over time (Helliwell et al., 2013; Mooney et al., 2012). At the large spatial scale, visual soil evaluation (VSE) and non-disturbance scanning approaches present opportunities to improve characterisation of subsoil compaction and avoid some limitations of traditional approaches (Ball et al., 2017; Weiss et al., 2020).

Alleviation of subsoil compaction has conventionally centred on mechanical cultivation (Spoor et al., 2003). However, mechanical cultivation presents significant drawbacks both in its ability to remediate subsoil compaction, alongside the risk of recompaction and resilience over time (Chamen et al., 2003). Biological alternatives that utilise natural properties of plant roots to create and extend porosity in compacted subsoil layers present a promising alternative to improve compacted subsoil functions and may avoid some of the negative consequences of mechanical cultivation (Chen and Weil, 2009; Pulido-Moncada et al., 2020). Although some benefits have been demonstrated, there is a lack of experimental evidence to inform management decisions and guide future research.

The aim of this review is to provide a critical appraisal of the existing methods used to characterise and alleviate subsoil compaction, consider alternative methods, and make future recommendations.

2.3 Definition of subsoil compaction

The definition of three layers was highlighted as useful when discussing subsoil compaction (Alakukku et al., 2003): topsoil, pan layer and uncultivated subsoil. The topsoil represents the layer that extends from the soil surface to the maximum depth of routine cultivation. Therefore, the depth of topsoil varies significantly depending on management approach and occurs approximately within 0 – 350 mm depth. Immediately below the topsoil, a narrow compacted layer or 'pan' (c. 20 – 50 mm width) can develop in response to field traffic and cultivation. Below either the topsoil or the pan layer is the uncultivated subsoil (subsoil). Normally the subsoil is not disturbed by annual cultivation and is only loosened during periodic field operations such as mole draining or infrequent deep cultivations such as subsoiling.

However, definitions of subsoil vary considerably in the literature. Experimental subsoil is often defined as occurring below the maximum depth of cultivation or below the working depth of plough cultivation (e.g. 250 mm, van den Akker and Schjønning, 2004), whereas other studies define the subsoil by the experimental methodologies employed (e.g. from 350 mm depth, Olesen and Munkholm, 2007; studied to 500 mm, Pulido-Moncada et al., 2020). Provided the subsoil is defined within the context of the experiment this does not present a problem, as informed comparison between studies can then be made. In the case of no-cultivation management, definitions based on cultivation approach are problematic. Authors instead either use supporting measurements (e.g. penetration resistance) to aid identifying appropriate sampling depths (e.g. Martínez et al., 2016), combine subsoil sampling with visual profile assessments to characterise profile layers (e.g. le profil cultural, Peigné et al., 2013), use pedological definitions (Jones et al., 2003), or root growth depth (e.g. Han et al., 2015). Overall, although a simple definition would be helpful for comparison under no-cultivation systems, classification of the subsoil on an experiment-by-experiment basis seems more sensible given the large variety of subsoil types, agricultural management approaches and experimental objectives considered within the topic.

2.4 Characterising subsoil compaction

2.4.1 Conventional approaches for characterising subsoil compaction – large spatial scale

2.4.1.1 Risk mapping and modelling

No reliable and practical method exists to measure the real-time carrying capacity of a subsoil in relation to applied load (Lipiec and Hatano, 2003). Therefore, risk assessment and modelling have been used as a proxy to estimate the extent and risk of subsoil compaction. Fraters (1996) moved previous estimates of general soil degradation (Oldeman, 1994), to estimating soil vulnerability to compaction at a European scale by spatially categorising soil using data from geological surveys. The authors acknowledge the potential seriousness of subsoil compaction as part of overall soil degradation but their estimates of compaction (19% and 32% soils moderately and highly vulnerable to compaction respectively) were applied to the profile as a whole. Jones et al. (2003), as part of a larger working group on subsoil compaction (van Den Akker et al., 2003), developed an approach specifically for subsoil compaction. Susceptibility classes based on texture and packing density were translated into vulnerability classes based on soil water parameters. The model did not consider load factors, which was subsequently achieved by combining the vulnerability classes with a separate prediction of load susceptibility (Spoor et al., 2003; van den Akker and Hoogland, 2011). van den Akker and Hoogland (2011) compared this modified risk assessment model to the mechanistic 'SOCOMO' method (van Den Akker, 2004) that considers the stress distribution of applied load in terms of subsoil physical properties, generating a maximum allowable wheel load for a given situation. Both methods agreed poorly with a subsoil compaction probability map based on empirical data (van den Akker and Hoogland, 2011) but the authors suggested the empirical data was outdated and on an unsuitable spatial scale (Brus and van Den Akker, 2018). Brus and van Den Akker (2018) combined a hybrid of these previous modelling approaches with improved empirical data from sampling, which they suggested improved the estimation of subsoil compaction (in this case at a national scale) but was limited in fine detail, only significantly identifying very high or very low risk. The authors attributed this to limitations in

understanding of how subsoil compaction develops and changes over time (Brus and van Den Akker, 2018). Progression with using modelling and risk assessment approaches to characterise subsoil compaction at a large spatial scale have limitations in common; a lack of qualitative data at an appropriate resolution and gaps in knowledge on the interaction of subsoil compaction processes with agricultural management.

There has also been a focus on developing models to assess the risk of subsoil compaction at a smaller 'on-site' spatial scale, mainly based on axle load and soil parameters. The earlier 'FRIDA' model, which considered the relationship between applied load, tyre construction and inflation pressure (Keller, 2005; Schjønning et al., 2008) was developed into the on-line compaction simulation model 'Terranimo' (Lassen et al., 2013; Settler et al., 2014). The model combines inputs of stress transmission (applied load and tyre variables), soil strength (precompression stress (Keller et al., 2012)) and soil water content, and has been validated in a variety of different settings (Lamandé et al., 2018; Ren et al., 2019; Stoessel et al., 2018; ten Damme et al., 2019).

Estimating the extent and risk of subsoil compaction at a large spatial scale combined with 'on-site' risk assessments at a smaller spatial scale have improved understanding of agricultural subsoil compaction. However, improvement in both the modelling methods themselves and the methods used to collect the empirical data that inform the models continues to be identified as a significant limitation (Brus et al., 2011; D'Or and Destain, 2014; Gabarron-Galeote et al., 2019; Hoefer and Hartge, 2010; Horn and Fleige, 2009; Vorderbrügge and Brunotte, 2011). Improvement in modelling and measurement at a variety of spatial and temporal scales will improve understanding of the extent and risk of subsoil compaction, and help to facilitate a more unified management approach (Kibblewhite et al., 2008; Panagos et al., 2012; Schwilch et al., 2011; Trautner et al., 2003a).

2.4.1.2 Penetration resistance

Characterisation of subsoil compaction in the field has mainly been limited to destructive methods that infer compactness through a soil property. Penetration resistance (PR), measured by cone penetrometers, has been used extensively

to investigate the effect of agricultural management on subsoil compaction (Aase et al., 2001; Batey, 2000; Etana et al., 2013; Medina et al., 2011; Patel and Mani, 2011). The mechanical impedance experienced by a penetrometer can be related to the mechanical impedance experienced by plant roots growing through the soil profile, and relationships have been established with the rate of root elongation and with crop yield (Dexter et al., 2007; Gao et al., 2016; Whalley et al., 2007, Whalley et al., 2005). Soil properties, such as moisture status, soil depth, bulk density and texture (Gao et al., 2012; Sojka et al., 2001; To and Kay, 2005; Whitmore et al., 2011) significantly affect PR measurements (Sojka et al., 2001; Vaz et al., 2011).

However, it is important to consider, as the understanding of root response to soil compaction develops (Pandey et al., 2021), whether PR continues to be a relevant indicator of subsoil compaction. Threshold values that indicate if root growth may be restricted by soil strength have been suggested (c. 2.5 MPa) (Whalley et al., 2007) but field experiments have suggested these values may differ widely with plants tolerating higher PR (Busscher et al., 1997; Sojka et al., 2001; To and Kay, 2005; Whalley et al., 2007). Evidence has shown that PR is less sensitive at high soil moisture contents, which presents a problem of misinterpreting results as soil water content varies through time (Bengough et al., 2001). Normalising PR measurements based on variables such as water content has been shown to reduce this influence (Busscher et al., 1997; Vaz et al., 2011). Tailoring the timing of PR measurement, with adequate replication (Lipiec and Hatano, 2003), to coincide with crop (and root) growth stages has been suggested as an approach to increase the relevance for PR measurement to root growth and reduce the influence of highly variable factors such as water content (Whalley et al., 2008, Whalley et al., 2006).

PR is a single-point measurement which limits spatial application due to requiring relatively high spatial and temporal replication to represent field soil heterogeneity (Lipiec and Hatano, 2003). Using soil PR as a proxy for compaction also does not provide any contextual information that links high or low PR to soil function and research has shown this may result in poor relationships with subsoil

functions (Spoor et al., 2003). Subsoil PR is inherently higher and less variable compared to shallower depths and PR measurement over deeper depths increases the likelihood of methodological error (Gao et al., 2016; Lynch and Wojciechowski, 2015). Automation of PR measurement and the use of geostatistical analysis has gone some way to resolve the resolution issues of PR (Medina et al., 2011).

2.4.1.3 Soil water content and hydraulic properties

Soil water content is important in determining susceptibility of subsoil compaction and soil hydraulic properties also help to measure the impact of subsoil compaction on subsoil functions (Hamza and Anderson, 2005). Methodological limitations in measuring soil water content limit the ability to capture sufficient spatial data to relate to soil compactness (Susha Lekshmi et al., 2018). Measurement in the field generally involves the installation of access tubes to allow the insertion of instrumentation into the soil profile, for example time domain reflectometry (TDR), capacitance or neutron probes. TDR and capacitance probes are popular and have been shown to be suitable to measure soil water (Susha Lekshmi et al., 2018). Although soil water measurement by neutron and capacitance probes have been shown to agree well with each other, the manual nature of neutron probe measurements and operator restrictions are limitations, whereas capacitance probes may be left in-situ to collect data over time (Vera et al., 2009). Installation is disruptive to the soil immediately surrounding the tube, and considering that the instruments generally measure a relatively small soil volume (Vera et al., 2009), disruption during installation likely impacts accuracy (Li et al., 2003; Nadler et al., 2002; Shanahan et al., 2015). However, despite limitations on measuring actual water contents, these methods have been shown to provide a good basis for relative water content comparison over time, provided limitations are acknowledged (Tomer and Anderson, 1995). In addition, further development on the placement of sensors in relation to plant and root has been suggested as an approach to better utilise sensors in the rhizosphere (Vera et al., 2009). This may be especially applicable to subsoil compaction where water utilisation at depth is a key issue and mirrors the increase in specificity of

instrumentation use as suggested for PR (Chapter 2, Section 2.4.1.2) (Whalley et al., 2008, Whalley et al., 2007).

Soil hydraulic conductivity can infer changes in soil physical properties such as compaction (Assouline, 2013). *In-situ* field measurement of saturated hydraulic conductivity has been widely used to infer subsoil compaction (Arvidsson, 2001; Bird et al., 1996; Etana et al., 2013; Keller et al., 2012; Logsdon et al., 1992; Moreno et al., 2003; Mossadeghi-Björklund et al., 2016; Zimmerman and Elsenbeer, 2008). The constant or single falling-head method were shown to be suitable for measuring subsoil hydraulic conductivity in the field (Bird et al., 1996; Jury et al., 1991). The addition of double-ring apparatus provided the most accurate measurements (Scotter et al., 1982) but portable tension infiltrometers provided an acceptable substitute (Madsen and Chandler, 2007; Thony et al., 1991). However, capturing sufficient data spatial resolution is difficult due to the time consuming measurements and the number of samples required to characterise the complexity of a heterogeneous field (Javaux and Vanclooster, 2006). In response, pedotransfer functions have been developed to model hydraulic conductivity from datasets with better spatial resolution but reliable estimates, especially concerning the subsoil, remain difficult (Pollacco et al., 2017). Other datasets such as PR (Tillmann et al., 2008) and X-ray CT (Zhang et al., 2019) have been used to successfully predict hydraulic conductivity but remain limited by adequate sample collection. More promisingly, contemporary hydraulic conductivity models are being developed that only rely on physical sampling for ground truthing models to a specific location (Agyei et al., 2007; Horn et al., 2020; Vogeler et al., 2019), which may form more reliable tools for field use (Zink et al., 2011).

2.4.2 Alternative approaches for characterising subsoil compaction – large spatial scale

2.4.2.1 Visual soil evaluation

Recently, visual soil evaluation (VSE) methods have attracted interest for application to subsoil compaction in the field. The visual evaluation of soil structure (VESS) method (Ball et al., 2007; Guimarães et al., 2011) was adapted

specifically for subsoil (SubVESS) to provide a VSE assessment to c. 1 m profile depth (Ball et al., 2017, Ball et al., 2015). SubVESS includes specific scoring for compacted pan layers and subsoil features (e.g. gleying) (Ball et al., 2015; Peigné et al., 2013). SubVESS has demonstrated good agreement with laboratory physical measurements (Ball et al., 2017; Obour et al., 2017; Pulido-Moncada et al., 2019b) and successfully highlighted locations in the profile where amelioration was necessary (Emmet-Booth et al., 2019). However, the numeric scoring outcomes of VSE methods are dependent on soil water content and may be limited by spatial variability without sufficient replication (Johannes et al., 2017). It is advised within the method to dig multiple pits across predefined zones, for example soil texture or crop rotation, to help reduce the influence of spatial variation (Ball et al., 2017, Ball et al., 2015). VSE methods are time consuming and destructive (McKenzie, 2013), which reduces their application spatially and temporally. Incidences have also been recorded where VSE methods have indicated compaction that was subsequently not supported by quantitative laboratory measurements, with significant variation between operators (Emmet-Booth et al., 2020). Numeric scores have, in some cases, been found to be misleading (Emmet-Booth et al., 2019) and the ordinal datasets generated do not suit statistical analysis (Mueller et al., 2009). Though it must be acknowledged that VSE methods on the most part, were not designed to create continuous datasets for statistical analysis and instead are intended for the identification and characterisation of restrictive layers by practitioners in the field (Ball et al., 2015). Following-up SubVESS scores with empirical measurements, for example further investigating SubVESS porosity scores using hydraulic conductivity, has been suggested as a means to improve and extend VSE observations (Ball et al., 2017).

Alternatives to SubVESS include 'Le Profil Cultural' (Boizard et al., 2017; Gautronneau and Manichon, 1987; Peigné et al., 2013), 'SOILpak' (McKenzie, 2001), the 'Double-Spade Method' (Emmet-Booth et al., 2019) and 'Whole Profile Assessment' (Batey, 2000). Alongside similar drawbacks to SubVESS, they do not offer improvement on numeric scoring and/or are not specifically aimed at the subsoil (Emmet-Booth et al., 2016).

2.4.2.2 Non-invasive methods

Non-invasive techniques present a cost effective approach to rapidly collect large spatial and temporal scale datasets (Alaoui and Diserens, 2018; Batte, 2000; Brevik et al., 2003). Improving the quality of large scale spatial and temporal datasets is likely to support better decision making (James and Godwin, 2003).

Measurement of soil geophysical properties such as electrical resistance tomography (ERT), electrical conductivity (EC_a) (via electromagnetic induction (EMI)) and ground penetrating radar (GPR) have been identified as approaches with potential to characterise subsoil compaction (Corwin, 2008; Lück et al., 2009; Shin et al., 2021). Although each is influenced by a wide range of soil characteristics, such as moisture and salinity, compaction may be inferred through the effect of pore connectivity and porosity on the generated signals, provided confounding variables are sufficiently resolved (Rhoades et al., 1989; Shin et al., 2021).

ERT has been used to describe physical properties of cultivated soil (Banton et al., 1997), may be scaled up for mapping these at farm-scale and used to inform agronomic decisions (Bourennane et al., 1998). ERT was found to be sufficiently sensitive to characterise soil physical properties (Cousin et al., 2009; Seger et al., 2009) but there was difficulty in attributing the cause of ERT change to a specific soil variable (Besson et al., 2013). Where confounding variables were resolved, changes in soil bulk density were found to be linearly related to ERT, and were used to successfully distinguish compacted plough pans, wheel tracks and large clods (Besson et al., 2004). There is potential with ERT to extend interpretation of data to also interpret cation exchange capacity (Sudduth et al., 2005) and root uptake of water (Vanella et al., 2018). Calibration and supporting measurements are required for ERT data to be of agronomic use when applied to soil physical properties (Samouëlian et al., 2005; Séger et al., 2014).

Similarly, evidence has shown EMI has potential to identify spatial variability of compaction through the profile (Corwin, 2008; Touthmalani, 2010). Doolittle and Brevik (2014) reviewed that bulk density was characterised by EMI provided confounding variables were resolved (Bekele et al., 2005; Brevik and Fenton,

2004; Carroll and Oliver, 2005; Farahani et al., 2005). EMI has been used in the field to determine the location of a compacted subsoil pan (Jeřábek et al., 2017), to compliment traditional soil survey practices (James et al., 2003), to accurately define subsoil series (Taylor et al., 2003), and produced good agreement with texture in the subsoil (Anderson-Cook et al., 2002). The most accurate EMI data has been observed where one variable is artificially changed between extremes (Al-Gaadi, 2012; Brevik and Fenton, 2004; Sudduth et al., 2010), which does not necessarily represent field application in reality. Application in the field to detect simulated vehicular compaction found significant EC_a differences between compacted and non-compacted treatments in the subsoil, which indicated EMI is applicable to measure compactness throughout the profile (Galambosova et al., 2020). In addition, this study found significant correlation between EMI and PR for the same sites over depth, which further suggested EMI suitability. Mouazen et al. (2014) used EMI as part a multi-sensor array to detect compaction in the field and concluded EMI made a weak contribution overall. A review by Kuang et al. (2012) concluded that the contribution of EMI (and other non-invasive, geophysical techniques) were limited in quantifying soil properties alone, without supporting datasets to account for confounding variables. Where ERT and EMI have been compared experimentally, both approaches were found to be effective at characterising the spatial patterns of soil (Allred et al., 2006) and both have been successfully extended to other soil properties such as salinity (Visconti and de Paz, 2020).

GPR has been used to measure groundwater depth in the subsoil (in combination with TDR; Doolittle et al., 2006) and to measure conductivity properties of the upper subsoil (<500 mm; Pettinelli et al., 2014). However, defining the relationship between PR, bulk density and GPR in the field was found to be challenging, and the interpretation of GPR datasets a significant obstacle (Wang et al., 2016). André et al. (2012) reported that a combination of GPR with ERT and EMI was effective at identifying anthropogenic compaction in a vineyard, supported by normalised differential vegetation index (NDVI) data and crop yield. In this case, ERT and EMI provided complimentary spatial characteristics and

GPR defined the soil stratigraphy, which together allowed the successful identification of compaction.

Overall, all methods of non-invasive measurement for characterising subsoil compaction have limitations but with further development on the interpretation of data have potential to overcome many of the spatial and temporal limitations of traditional sample collection in characterising compaction (Archer et al., 2014; Brevik and Hartemink, 2010). Field application of non-invasive techniques has been particularly challenging in differentiating inherent soil profile layers from anthropogenic compaction. Algorithms have been developed to improve EC_a interpretation in these cases, improving stratigraphy (Brosten et al., 2011; Monteiro Santos, 2004). Saey et al. (2015) observed that by using this method an improved 'pseudo-3D' map of estimated subsoil stratigraphy was obtained but to provide absolute values, physical sampling was required for calibration. However, calculations were noted to reduce the lateral data resolution when restricted to '1D' and any 'smoothing' approaches, although improving overall mapping, again reduced detail (Saey et al., 2015). However, developments in algorithms have been shown to return useful information on the horizontal and vertical conductivity in two-layered profiles, and future development will extend this application to more layers and agricultural use (Mester et al., 2011). Another contributory approach has been to increase the number of sensors in a scanning array to increase data gathered at a variety of depths, frequencies and/or apparatus orientations. Using more sensors in this way has been shown to provide better delineation of layered subsoil profiles (Hoefer et al., 2009; Lueck and Ruehlmann, 2013; Saey et al., 2009). Further work is required to agree the appropriate conditions for scanning, standardise the interpretation of data and to adequately account for confounding variables (Jeřábek et al., 2017; Seladji et al., 2010).

2.4.3 Conventional approaches for characterising subsoil compaction – small spatial scale

Application to characterise compaction at the small spatial scale generally involves the collection of samples from the field or the creation of simulated

compaction for study in a laboratory setting. Methods either directly measure compactness or infer compactness by measuring the impact of compaction on a soil function(s). Although studies share many common methodologies, there is no accepted standard or set of standards to characterise compaction and some methods have multiple accepted protocols (Alaoui and Diserens, 2018; Arvidsson, 1998; Díaz-Zorita et al., 2002).

2.4.3.1 Soil texture, organic matter and bulk density

Soil textural analysis and organic matter are important supporting measurements to characterise subsoil compaction. Textural analysis methodology is standardised (pipette method) and has not been satisfactorily superseded by less labour-intensive, faster optical methods (Šinkovičová et al., 2017). Organic matter determination has several accepted methods that vary in accuracy and time (Salehi et al., 2011). Wet oxidation via the Wakley-Black method (Wakley and Black, 1934) has been superseded by combustion approaches (Cambardella et al., 2001) due to the rapid and convenient methods, despite potential variation in results with temperature, heating duration and calcareous soils (Hoogsteen et al., 2018; Schulte et al., 1991).

Bulk density by the soil volume method provides a volumetric measurement of soil compactness (Hall et al., 1977) but lacks consideration of soil structure and function (Rabot et al., 2018). The volume of the core used for sampling and the presence of rock has been shown to have a significant impact on results (Håkansson, 1990; Håkansson and Lipiec, 2000; Schluter et al., 2011). Where sample collection for bulk density is not practical, pedotransfer functions have been developed to provide a prediction parameter (Van Ranst et al., 1995). Attempts to improve bulk density methodology have been made using a reference bulk density value to provide a relative measurement (degree of compactness) and by using corrections for clay content (packing density). Both suffer significant drawbacks with methodology and spatial variation that mean applicability in an agricultural context is not greatly improved (Kaufmann et al., 2010; Reichert et al., 2009). In addition, direct image analysis methods (e.g. using X-ray CT

images) for bulk density have been suggested but not widely explored (Timm et al., 2005).

2.4.3.2 Aggregate stability

The stability of soil particle aggregation is most often associated with the soil surface layer and with erosion (Amézketa, 1999; Corstanje et al., 2017) but the stability of soil aggregates is also related to properties and functions of the subsoil, such as water holding capacity and air permeability (Bronick and Lal, 2005). Measuring soil aggregate stability does not have a standard method, although most approaches use sieve(s) to ascertain aggregate stability under agitation in fluid. Although sieving methods have the drawbacks of a limited particle size fraction measured, no account of particle distribution and are generally time-consuming (Rawlins et al., 2013), they have been shown to correlate well with other measures of soil compaction (Amézketa, 1999; Pulido Moncada et al., 2015). Efforts have been made to improve manual sieving methods, for example through the application of laser technology (Rawlins et al., 2013) but these still require further development. Standardisation in aggregate stability measurement has been identified as a requirement but other research has highlighted that retaining multiple methods is useful so the most appropriate method for a situation may be chosen (Almajmaie et al., 2017; Le Bissonnais, 2016), such as the different characteristics of aggregate stability for topsoil surface vs. subsoil research. Hudek et al. (2021), for example, used a modified approach of fractioning aggregates through intact root sample soaking to improve the method representation of root and subsoil association.

2.4.3.3 Porosity, pore continuity and pore function

Determination and/or inference of soil porosity, pore continuity and pore function provides an indication of subsoil compaction (de Lima et al., 2017). Characterisation of the soil water retention curve provides an estimate of soil water content at critical matric heads (e.g. field capacity, permanent wilting point), can be used to calculate hydraulic conductivity and is strongly related to subsoil physical properties such as compaction (Agrawal, 1991; Berisso et al., 2012; Durner, 1994; Glab, 2014; Mualem, 1976; Trautner and Arvidsson, 2003). In

order to plot a soil water retention curve with accuracy, determination of soil water retention over a range of matric heads is required to reduce error (Schelle et al., 2011, Schelle et al., 2010). However, no single device is capable of determining soil water retention over the entire soil moisture range and therefore multiple approaches are combined. Significant differences have been shown to occur depending on the combination of approaches (Bittelli and Flury, 2009; Cancela et al., 2006; Solone et al., 2012). Schelle et al. (2013) compared a range of method combinations to measure soil water retention in the laboratory. They concluded that the conventional combination of a hanging water column followed by pressure plate apparatus was time-consuming and error prone due to differing estimations of equilibration time and the difficulty in ensuring sufficient contact was maintained between the sample and the porous surfaces. In addition, to correctly interpret results the right distinction between 'pore pressure' and 'pore neck pressure' is essential (Giesche, 2006). Schelle et al. (2013) suggested that the evaporation method (Peters and Durner, 2008) and the dew point method (Durner and Iden, 2011) provide acceptable alternatives, that allow the use of larger sample sizes to reduce sampling variation, do not require estimation of equilibrium times, and are less time-consuming.

The permeability of air through a soil volume provides an indicator of the effect of porosity and pore continuity (Chen et al., 2014) on aeration (Menezes et al., 2018). Air permeability has been shown to be sensitive to changes in agricultural management approach (Cavaliere et al., 2009; Dorner and Horn, 2009; Tuli et al., 2005) and to correlate with related soil physical structure indicators such as saturated hydraulic conductivity (Chief et al., 2008; Loll et al., 1999). A variety of air permeameters have been designed, are commercially available and have been used to measure the impact of compaction on soil properties from field samples or *in-situ* (not with subsoil) (Chen et al., 2014; Iversen et al., 2001; Schjønning et al., 2019; Tuli et al., 2005). Air permeability measurements have demonstrated a relationship with air-filled porosity and the creation of critical values for compaction (da Silva et al., 1994; Poulsen et al., 2007), have been modified to supplement other soil physical data (Kuncoro and Koga, 2012; Zhang

et al., 2019), and have been used to develop a 'soil health' index (Bispo de Carvalho et al., 2019).

Although these methods have been used to characterise subsoil compaction for samples collected from field sites and those artificially created, their limitations on inferring compactness, methodological drawbacks and lack of contextual, functional information restricts characterisation through their use. Non-disturbance characterisation of soil physical structure and functions has been suggested as an alternative approach to characterise the impact of soil compaction on the entire soil system (Pulido-Moncada et al., 2021; Rabot et al., 2018).

2.4.4 Alternative approaches for characterising subsoil compaction – small spatial scale

Alternative approaches to characterise compactness at the small spatial scale tends to focus on the application of non-disturbance, imaging technologies to observe soil physical structure and function without samples disturbance. These approaches may improve the characterisation of compaction and although are limited by physical sample collection or creation, have less temporal limitation as scans may be repeated without sample destruction (Batey, 2009; Hatley et al., 2005; Miedema, 1997).

2.4.4.1 Undisturbed soil characterisation

X-ray CT provides a method to measure the 3D properties of undisturbed subsoil samples at resolutions that are suitable to characterise functions relevant for agriculture (Helliwell et al., 2013; Langmaack et al., 2002; Mooney et al., 2011; Otten et al., 2010; Pierret et al., 2003). Compared to traditional techniques that infer compaction through related properties or functions, image analysis characterises soil heterogeneity without sample disturbance in response to compaction (Bacq-Labreuil et al., 2020; Cimpoiasu et al., 2021; Houston et al., 2017; Kim et al., 2010; Pandey et al., 2021; Pöhlitz et al., 2018), cultivation (Atkinson et al., 2009; Papadopoulos et al., 2009) and variation in soil water (Anderson et al., 2003; Grayling et al., 2018; Peth et al., 2010).

As reviewed in Helliwell et al. (2013), in order to analyse images collected, segmentation processes are applied to differentiate between soil particles, pore space and organic components. Creating a histogram to threshold the image to one set of values (global thresholding) or using a variety of thresholding values (dynamic thresholding) are used to segment image constituents (Issanov et al., 2009; Wang et al., 2011). This segmentation process has been shown to 'over-segment' images or to misclassify soil constituents (Clausnitzer and Hopmans, 2000; Mooney et al., 2012), which generates error in subsequent analyses. Automation processes have been developed to reduce segmentation error but these may in turn reduce overall detail in the process (Mooney et al., 2012; Peth et al., 2010). Baveye et al. (2010) demonstrated a large variation in results between different research groups asked to segment and analyse the same image, which hinders the ability to compare soil properties between experiments using this approach. The size and power of scanning apparatus also means there is a trade-off between the size of the sample and the resolution of the image available, which means all spatial classes of, for example, pores cannot be represented by a single scan (Helliwell et al., 2013). However, many methodological limitations are being overcome with improving automated machinery able to repeatedly scan larger samples over time or at different resolutions (Atkinson et al., 2020).

Alternative imaging techniques have been identified as potentially useful in characterising soil samples: nuclear magnetic resonance (NMR) (Hemminga and Buurman, 1997), magnetic resonance (MRI) (Gregory and Hinsinger, 1999; Votrubová et al., 2003), neutron radio imaging (Carminati et al., 2010) and high resolution digital photography (Papadopoulos et al., 2006). Of all options, X-ray CT has been shown to be least affected by scanning artefacts due to magnetic soil constituents and access to facilities is generally the highest (Helliwell et al., 2013; Macedo et al., 1998; Mooney et al., 2012). MRI, although applicable to soil science, is limited by scan times (Nagel et al., 2009). Combinations of the methods above, such as X-ray CT and neutron CT have been shown to complement each other in the characterisation of soil volumes due to differing

resolutions combined to provide greater overall detail (Moradi et al., 2011; Vontobel et al., 2006).

2.4.4.2 Root response to subsoil compaction

Examining the response of roots to subsoil compaction has been widely used to assess impact on crop performance and the suitability of alleviation methods (Bengough et al., 2011, Bengough et al., 2006; Clark et al., 2008; Ishaq et al., 2001; Lynch and Wojciechowski, 2015; Materechera et al., 1992; Valentine et al., 2012). Traditional methods to characterise root systems are limited by their ability to measure small changes (Bland, 1989; Gregory, 2006), in large part due to the high proportion (20 – 40%) of root weight lost during sample processing (van Noordwijk and Floris, 1979). This loss includes the fine roots that may constitute >50% of total root length and hampers understanding of root system response to compaction (Pierret et al., 2005). Alternative *in-situ* methods have been developed, for example burying mesh with simulated biopores was shown to provide useful results to determine root growth into subsoil layers (McKenzie et al., 2009) but these approaches are limited by significant soil disturbance.

Image analysis methods have been developed to overcome limitations with traditional methods. High resolution digital scanning of root systems still relies on disturbed samples and root washing but expands and standardises root system characterisation (Bouma et al., 2000). Quantitative measurement of root properties such as length, size classes through to differentiation between root axes may be measured in a less time-consuming and standardised manner. Although root sample overlap has caused concern (Harris and Campbell, 1989; Pan and Bolton, 1991; Smit et al., 1994), more recent method comparisons have shown good agreement between image analysis and traditional approaches, provided a protocol is recorded to aid comparison between experiments (Pang et al., 2011; Pornaro et al., 2017). Though commercially marketed systems form the bulk of the literature (e.g. Reagent Instruments, WinRHIZO), good agreement with open source software options has also been reported (e.g. ImageJ, Schindelin et al., 2012) (Tajima and Kato, 2013, Tajima and Kato, 2011).

Observing roots using non-disturbance methods that allow repeated observations over time presents a significant opportunity to improve understanding of root morphology in response to compaction, avoid root loss during sample processing and has yielded significant results (Atkinson et al., 2020; Gregory et al., 2009; Pandey et al., 2021; Vanhees et al., 2021). The same image segmentation issues as for soil physical properties (Chapter 2; Section 2.4.4.1) have previously limited the application of these approaches to the organic soil constituents. However, advancements in segmentation and automation now means image analysis of roots systems is now possible (Atkinson et al., 2020; Mooney et al., 2012, 2007; Pandey et al., 2021; Pierret et al., 2007; Tracy et al., 2012). Helliwell et al. (2013) reviewed that segmentation between organic and inorganic constituents was challenging, and authors have reported characterisation using X-ray CT underestimating total root length by c.10% (Flavel et al., 2012; Gregory et al., 2003; Perret et al., 2007). Methodological advances such as combining multiple resolution scans and the development of automated root segmentation software have become more common to address segmentation difficulties (Clark et al., 2011; Iyer-Pascuzzi et al., 2010; Sleutel et al., 2008). Consequently, comparative experiments between X-ray CT and destructive methods have concluded reliable representation of a root system may be achieved using an image analysis approach (Kaestner et al., 2008; Mairhofer et al., 2012; Tracy et al., 2012).

Similar alternatives to X-ray CT in soil characterisation have been considered for root system characterisation. NMR, MRI and positron emission tomography (PET) have been used to characterise root systems (Jahnke et al., 2009; Pohlmeier et al., 2008). Neutron CT in particular, has significant potential for root system characterisation, due to the relationship between water movement and root morphology, and it has been used to observe water supply and distribution within roots (Carminati et al., 2010; Esser et al., 2010; Menon et al., 2006). Access to facilities, again, is a major limitation in the uptake of alternative imaging approaches compared to X-ray CT (Mooney et al., 2012).

2.5 Alleviation of subsoil compaction

Utilising technologies and management approach to avoid creating and accumulating subsoil compaction is the most effective method to reduce subsoil compaction in terms of effect on agricultural production, economics and off-site impact. Avoidance technologies and approaches are beyond the scope of this review but the following publications present detailed information on the subject (Alakukku et al., 2003; Chamen et al., 2003; Schjønning et al., 2012; Spoor et al., 2003; Chamen et al., 2015).

2.5.1 Natural alleviation

A combination of inherent soil properties, climate and soil biology are thought to alleviate anthropogenic subsoil compaction without intervention, and some studies have demonstrated limited benefits to subsoil compaction over time (Gameda et al., 1987; Gregory et al., 2009; Munkholm et al., 2005; Römkens and Prasad, 2006). However, overall the literature has not indicated a significant role for natural alleviation on anthropogenic subsoil compaction (Batey, 2009; Beylich et al., 2010; Schonning et al., 2018).

Freeze and thaw cycles have shown a benefit to compaction in the topsoil but positive evidence is limited concerning subsoil compaction with many studies reporting a non-significant impact (Besson et al., 2013; Froehlich et al., 1985; Jabro et al., 2014; Thorud and Frissell, 1976; Voorhees, 1983). Across a variety of soil types, evidence showed that 6 – 11 years after the application of vehicle load treatments applied to create subsoil compaction, freeze and thaw cycles occurring at up to 1 m depth did not result in significant subsoil compaction amelioration (Blake et al., 1976; Etana and Håkansson, 1994; Håkansson, 1985; van Ouwerkerk, 1968). Similarly, shrink and swell cycles were found to have inconsistent effects and were better related to topsoil compaction (Håkansson et al., 1988; Schonning et al., 2017).

2.5.2 Mechanical alleviation – the conventional approach

Periodic mechanical cultivation (subsoiling) is the most common alleviation method for addressing subsoil compaction. A survey by ADAS (1996) reported

that 90% of 868 respondents carried out subsoiling on a rotation of between 1 and 6 years (Chamen et al., 2015). The lowest percentage of subsoiling was conducted on chalk and loam soils, and the majority (75%) of subsoiling was carried out between depths 310 – 500 mm (Chamen et al., 2015). More recent UK survey work found subsoiling remains a common primary cultivation option (DEFRA, 2005).

Mechanical alleviation of subsoil compaction has been covered extensively in the literature and recommendations for different soil types and farming systems have been made (Alakukku et al., 2003; Chamen et al., 2003; Spoor et al., 2003; Spoor and Godwin, 1978). Mechanical alleviation aims to improve subsoil structure by causing fissuring and cracking to improve soil function and root growth but to avoid excessively disrupting inherent soil strength, which risks recompaction (Raper, 2005; Spoor et al., 2003). Spoor et al. (2003), summarising decades of development, recommended that varying the combination of implement wing type, tine spacing, working depth, forward speed and soil moisture allowed the farmer to tailor the subsoiling operation specifically to their subsoil compaction situation.

2.5.2.1 Effect of mechanical alleviation on subsoil properties

Subsoiling has a significant impact on compacted subsoil, reducing bulk density and increasing the porosity of target subsoil layers (Evans et al., 1996; Gameda et al., 1994; He et al., 2019). Subsoiling has also been shown to increase soil water retention (Cai et al., 2014; Motavalli et al., 2003) and hydraulic conductivity (Allen and Musick, 2001; Said, 2003). However, in many studies the positive impacts of subsoiling were reversed after a relatively short period, particularly in areas exposed to subsequent vehicle traffic. Botta et al. (2006), Duval et al. (1989) and Schjønning and Rasmussen (1994) on loam, clay and coarse sand respectively, found the benefits of subsoiling were eliminated by subsequent vehicle traffic, and the subsoil returned to its original state after one season. Positive effects may persist long-term where no subsequent traffic occurs but where no management change occurred subsoil was recompacted within approximately 1 – 3 seasons (Kooistra and Boersma, 1994; Munkholm et al.,

2005b; Sojka et al., 1997; Van Den Akker et al., 2003). Therefore, while subsoil loosening via mechanical cultivation has been shown to improve subsoil properties, these positive changes are at high risk of reversal through recompaction, especially where annual field operations follow.

2.5.2.2 Effect of mechanical alleviation on crop performance

Emergence, rooting depth, and the yield of cereals and root crops across a variety of soil types has increased as a result of subsoiling (Cai et al., 2014; Ekelöf et al., 2015; He et al., 2019; Ide et al., 1984; Schjønning and Rasmussen, 1994; Sojka et al., 1997). Conversely, across a variety of soil types and subsequent field traffic approaches a non-significant or negative impact of subsoiling on cereal crop performance has also been recorded (Chamen, 2011; Evans et al., 1996; Gill et al., 2008; Munkholm et al., 2005; Olsen, 1994). Yield decreases due to subsoiling of 18 – 27% have been reported in cereals (Gameda et al., 1994) and in root crops Stalham et al. (2007) reviewed that 66.3% of the potato studies considered (n = 11) indicated a non-significant or negative crop performance effect as a result of subsoiling. Results from yield studies should be treated with caution as they have generally been conducted under controlled conditions, examining the short-term impact, without considering the persistent and cumulative nature of subsoil compaction over time and interaction with factors such as seasonal weather extremes (Batey, 2009; Jakobs et al., 2017; Marks and Soane, 1987).

Mechanical alleviation of subsoil compaction is experimentally less effective than perceived by farmers, requires caution to avoid recompaction and is economically viable only when highly targeted (Chamen et al., 2015). Subsoiling fared unfavourably in comparison to avoidance technologies (e.g. controlled traffic farming) that consistently produced an economic return (Chamen et al., 2015). In their meta-analysis of 1530 observations (Germany) Schneider et al. (2017) found subsoiling provided a 6% increase in yield, improved crop resilience to drought stress, increased soil water infiltration and retention, and consistently improved barriers to root growth. However, these data were highly scattered with 60% of observations recording a yield increase and 40% a decrease, made up of mainly short-term observations (<5 years). In agreement with Chamen et al.

(2015), where subsoiling was targeted specifically at a problem area (for example an identified root restricting layer), the impact on yield was 20% higher than the mean.

2.5.3 Biological alleviation – an alternative approach

Although subsoil compaction can cause physical restraint to root elongation (Valentine et al., 2012), in turn the action of plant roots can modify soil structure and alleviate compaction (Hinsinger et al., 2009). Selecting plant species with specific root traits for this purpose and integrating them in agricultural rotations as a cover crop to create and extend biopores through compacted subsoil layers may be an effective measure to negate the negative effects of subsoil compaction (Barão et al., 2019; Dexter, 1991). Physiological and biochemical root response to soil compaction is currently poorly defined but developing (Atkinson et al., 2020; Clark et al., 2003; Pandey et al., 2021; Wahlström et al., 2021). Application in the field has progressed as part of the conservation agriculture movement but is hampered by lack of supporting quantitative evidence (Roesch-Mcnally et al., 2018).

2.5.3.1 Species variety and choice

Research has indicated that root systems differ in their ability to alleviate subsoil compaction. Dicotyledonous (dicot) species, in particular those with taproot structures, have been shown to be more efficient compared to monocotyledonous (monocot) species at penetrating compacted layers (Beck-Broichsitter et al., 2020; Clark et al., 2003; Materechera et al., 1991a). Tap rooted species are able to modify the thickness of their roots in response to compaction (Bodner et al., 2014; Herrera et al., 2017; Materechera et al., 1992b; Wendling et al., 2016; Yu et al., 2016), which may improve penetration of compacted layers and formation of stable biopores within them (Chen and Weil, 2011; Hamza and Anderson, 2005). In response to compaction dicot root systems have been observed to generate significantly higher root densities in comparison to monocot root systems (Chen and Weil, 2010; Perkons et al., 2014), and enhance the movement of water and gas (Pulido-Moncada et al., 2021). Biopores formed by dicot root systems have also been shown to be more stable over time (Kautz,

2015), record a higher proportion of colonisation by following crops (Han et al., 2015), and cross soil cracks and re-enter adjacent compacted layers significantly better compared to monocots (Whiteley and Dexter, 1984).

However, there is contrasting evidence on the relative importance of root traits in response to soil compaction. Studies have also shown monocot species have higher root densities compared to dicots in compacted soils (Rosolem et al., 2002) and evidence has been presented that shows monocots have similar potential to alleviate compaction, with the importance of traits such as total root biomass as important as root diameter (Hudek et al., 2021). Burr-Hersey et al. (2017) observed that black oat (*Avena strigosa*) (monocot) roots had significantly higher surface area and root proliferation within a compacted soil compared to dicot species. In a long-term (10 years) field rotation experiment a barley crop (*Hordeum vulgare*) (monocot) significantly increased water retention between depths 40 – 80 cm that better supported the growth of other arable crops (Gabriel et al., 2019). Species mixtures of grass and clover leys were found to increase total porosity and moisture content where they made up a significant proportion of the arable rotation (c. 75%) compared to arable alone (Riley et al., 2008). However, the authors combined topsoil and subsoil results (0 – 75 cm depth) and did not distinguish between the effect of grass and clover root action. Red clover (*Trifolium pratense*) and other legumes have also been highlighted as candidates for subsoil compaction alleviation due to their large taproot different from those found with brassica tap rooted species (McKenna et al., 2018; Yu et al., 2016) but little evidence exists specifically for subsoil compaction.

2.5.3.2 Biopores and following crops

Cresswell and Kirkegaard (1995) suggested that to qualify biological alleviation of soil compaction, the root creation or exploration of biopores and subsequent performance benefit to a following crop must be established. Roots have an increasingly important association with biopores over depth (White and Kirkegaard, 2010) with the proportion of root association with biopores increasing with depth and reaching a maximum of approximately 25% in barley (*Hordeum vulgare*) (Kautz et al., 2013). At depths <60 cm, 30 – 40% of wheat (*Triticum*

aestivum) root biomass was found within biopores, whereas at depths of >60 cm, 85 – 100% were within biopores. However, most biopores contained no roots at all, with only 20% of total biopores associated with roots at <60 cm and 5% of total biopores associated with roots at >60 cm (White and Kirkegaard, 2010). The authors suggest targeting an increase in the utilisation of total biopores by root networks presents an opportunity for future genetic improvement for plant interaction with subsoil resources (White and Kirkegaard, 2010).

Although biopores make up a small percentage of the total soil volume, following crop roots utilise existing biopores as a low strength passage through compacted layers (Ehlers et al., 1983). Biopores left by forage radish (*Radish sativus* var. Diachon) and rye (*Secale cereal*) cover crops significantly increased the yield of soybean (*Glycine max* var. Merr) (Williams and Weil, 2004) and barley (*Hordeum vulgare*) (McKenzie et al., 2009), with both authors highlighting that biopores created routes through compacted layers to access subsoil resources. Colonisation of existing biopores has been shown to be an important strategy for crops to exploit soil resources in the presence of subsoil compaction (Atkinson et al., 2020; Wahlström et al., 2015). Where cover crop roots are using existing biopores to move through compacted layers and re-enter the subsoil, the ability of a root to re-enter may be a limiting factor that warrants further investigation (Lynch and Wojciechowski, 2015; White and Kirkegaard, 2010; Whiteley and Dexter, 1984).

Perennial cover crops have been shown to be particularly effective at forming biopores due to their increased residence times (McCallum et al., 2004). Permanent grass species pastures and lucerne (*Facaceae medicago*) grown for 3 or more years were shown to improve subsequent crop water extraction and root density in the subsoil (Gaiser et al., 2012; Kautz et al., 2014). Whereas, over shorter time periods perennials do not record comparative significant benefits (Botwright and Wade, 2012; Welch et al., 2016). Meta-analysis of experimental evidence from Germany showed that tap rooted dicots were most consistent at biopore formation (Schneider and Don, 2019a) and soil properties, such as

texture, were not significant factors in biopore formation (provided acidic or anoxic soils with high sand and gravel contents were excluded).

Cultivation has a significant impact on the stability of biopores over time and the minimal amount possible preserved biopore connectivity and function (Kautz, 2015; Landl et al., 2019; Williams and Weil, 2004). Lucas et al. (2020) and Lucas et al. (2019) found biopores formed by roots create a stable and connected pore system over time approximately in the 0.1 – 0.5 mm pore size range. Cultivation did not necessarily decrease overall porosity but shifted the predominant size distribution to different scales depending on cultivation approach. Avoiding cultivation with a no-tillage approach promotes the formation of biopores in itself due to reduced disturbance (Schluter et al., 2020; Wuest, 2001), and both monocot and dicot root structures have been shown to enhance the porosity benefits of a no-tillage approach, improving water, gas and root movement (Abdollahi et al., 2014; Carof et al., 2007).

Overall, including more root production, whatever the species, within agricultural rotations appears to be key to driving biopore formation and the associated benefits, and specific root traits (e.g. diameter, biomass) may provide an additive benefit to this. This suggests the approach to alleviate subsoil compaction with a biological approach has two parts. Firstly, biopore formation may be promoted through maintaining root growth throughout the year and reducing the intensity of cultivation (Basche et al., 2016; Jordan and Warner, 2010). Secondly, including species that have demonstrated root traits of particular use in alleviating subsoil compaction. Future research is required to determine the list of species most suitable for application to subsoil compaction but this may not be limited to the traditional set of cover crops often highlighted, depending on the relative importance of root traits (Frelih-Larsen et al., 2018; Pulido-Moncada et al., 2021; Storr et al., 2019). Agricultural crops, cover crops and cultivation may then work together to prevent and alleviate subsoil compaction.

2.6 Discussion

2.6.1 Characterisation of subsoil compaction

Despite the limitations outlined, a combination of traditional field and laboratory methods can be used to determine and/or infer the compactness of subsoil. However, spatial and temporal drawbacks, and the methodological disadvantages of disturbance methods, mean that characterisation can be improved. Risk assessment and modelling requires improved quantitative data at large spatial and temporal scales (Corstanje et al., 2017; Jones et al., 2003; Moreno et al., 2003; Stoessel et al., 2018; Thorsoe et al., 2018). Similarly, progressing the understanding of plant and soil response to subsoil compaction at the small spatial scale requires improvement upon traditional, disturbance methods that are limited over space and time (Helliwell et al., 2013; Pulido-Moncada et al., 2021).

The digitisation of previously manual, destructive techniques (e.g. digital root morphology scanning) provides improvements in data resolution and repeatability but remains limited by the physical processing of samples (e.g. root loss during washing) (Bouma et al., 2000). Moving understanding of soil and root system response to subsoil compaction from a combination of single measurements to instead characterising the whole, undisturbed rhizosphere over time is critical to advance knowledge and inform future management (Hinsinger et al., 2006, Hinsinger et al., 2009; Hodge et al., 2009). Non-destructive visualisation approaches, such as X-ray CT, present a significant contribution to this end. However, methods such as X-ray CT are limited by the difficulty in relating the results to physical soil properties. Studies often rely on and recommend a combination of scanning methods and calibration from other datasets to better understand the CT datasets collected (Baniya et al., 2019; Cimpoiasu et al., 2021; Lamandé et al., 2013; Millington et al., 2018; Turberg et al., 2014). Although limitations are apparent, advancements in data acquisition and processing are addressing drawbacks (Helliwell et al., 2013; Mooney et al., 2012). For example, the size of samples suitable for X-ray CT has expanded from small samples to automated glasshouse facilities able to scan large soil columns multiple times

over a season without disturbance (Atkinson et al., 2020). However, they remain restricted by creating or collecting sufficient samples.

A variety of approaches has been taken to applying knowledge of subsoil compaction to a large spatial scale. Readily available vehicle and soil parameters may be used to assess the risk of subsoil compaction as close to 'real time' as possible, for example the 'Terranimo' model (Settler et al., 2014). Accuracy of risk assessment models that use a combination of known soil and vehicle parameters have advanced (Keller, 2005) but are limited by significant differences between laboratory simulations and the dynamic load of a vehicle under heterogeneous field conditions (Keller et al., 2011; Keller and Lamandé, 2010). Risk assessment models continue to be improved to move from a desk-based pre-assessment of subsoil compaction risk, to real-time risk assessment during field operations (Lamandé et al., 2018; Rucknagel et al., 2015; Schjønning et al., 2015).

Non-disturbance scanning technologies allow comparatively rapid data collection over multiple time points over a large spatial scale. Provided soil characteristics can be reliably derived, these approaches can address the methodological gap in applying understanding of subsoil compaction to soil management at a large spatial scale. The geo-referenced data they create may be useful to integrate into precision farming solutions, such as variable depth subsoiling (Adamchuk et al., 2004; Wells et al., 2005) and provides improved data for policy-level soil management (Archer et al., 2014; Neumann et al., 2009). Datasets of this type are increasingly being combined to improve understanding of the interaction of subsoil compaction with other variables at a large spatial scale, for example using NDVI (André et al., 2012; McKenzie et al., 2009).

The alternative methods explored in this review are likely to complement one another in practice. Non-disturbance scanning methods allow practitioners to understand the occurrence of subsoil compaction for monitoring and management, and these data collated at national and international scales better informs policy. Improved field and laboratory characterisation techniques (e.g. SubVESS, X-ray CT) can then be deployed to understand areas where subsoil compaction may be a problem and inform an appropriate solution. Where subsoil

compaction alleviation measures are appropriate to the problem identified and targeted, a financial return and successful alleviation result is more likely (Chamen et al., 2015). This approach to measuring and monitoring subsoil compaction at a variety of spatial scales over time goes some way to address limitations identified with appreciating the scale of the subsoil compaction problem (Louwagie et al., 2011; Otte et al., 2012; Posthumus et al., 2011; Prager et al., 2011; Thorsoe et al., 2019).

2.6.2 Alleviation of subsoil compaction

Natural alleviation, relying on inherent soil and climate properties, appears to be insufficient to alleviate anthropogenic subsoil compaction in the short-term and in most cases subsoil compaction persisted long-term. However, soil structure more resilient to subsoil compaction has been shown to develop over-time, especially where cultivation intensity is reduced or removed (Blanco-Canqui and Ruis, 2018).

Mechanical cultivation is by far the most common approach currently used to alleviate subsoil compaction. As discussed in this review, the application and limitation of subsoiling have been investigated with advice issued at policy level (DEFRA, 2009; Dobbie et al., 2011; NSRI, 2001; Schjonning et al., 2009). Yet review work suggests that the correct application of subsoiling to alleviate compaction, avoiding recompaction risk and generating a gross margin, remains an issue (Pikul and Aase, 2003; Chamen et al., 2015). Management plans that consider soil compaction are a feature of compulsory integrated farm management (Morris et al., 2017). However, a recent survey of farmers in England found that 45% did not carry out any soil structural surveys and of the 55% that did, 32% only carried out surveys when compaction was obvious from the surface and only 23% dug more than one inspection hole (DEFRA, 2019). These results suggest that subsoil compaction is either not widely prevalent (evidence suggests this is not the case (Brus and van den Akker, 2018; Jones et al., 2003)) or is poorly understood and continues to be dealt with using a non-targeted, rotational approach to alleviation (ADAS, 1996; Chamen et al., 2015).

Biological alleviation meets the primary aims of subsoil compaction alleviation for soil functions and crop performance, whilst addressing one of the main drawbacks of mechanical cultivation in avoiding excessive soil disruption and weakening the soil profile. Although evidence exists that suggests avoiding cultivation generates a soil structure resilient to compaction/recompaction (Blanco-Canqui and Ruis, 2018), it would be useful for future work to understand the difference in bearing capacity between a mechanically subsoiled profile compared to subsoil compaction alleviated with root biodrilling.

Biological alleviation is achieved by a specific application of cover cropping. However, the evidence suggests that the focus of biological alleviation, rather than replacing a specific cultivation operation, should be on the integration of 'continuous living cover' into arable rotations that, dependent on species selection, has the potential to prevent and alleviate subsoil compaction. This forms a long-term strategy that better reflects the long-term benefits from biological alternatives and is a fairer comparison than directly comparing to results from short-term, mechanical cultivations. Unlike mechanical cultivation, the level of advice on the correct selection of cover crop species, residence period and site-specific variables is not currently available for biological alleviation of subsoil compaction (Bhogal et al., 2020). A recent survey found that UK farmers were selecting cover crop species based on soil texture and cultivation approach but falling short of specifically identifying, for example, subsoil compaction first and then tailoring cover crop species choice to target alleviation (Storr et al., 2019). Greater adoption of these alternative approaches would be benefitted through advice that is more specific (Blanco-Canqui et al., 2015), training of decision influencers (DEFRA, 2019), policy and legislation support (Roesch-Mcnally et al., 2018), and dissemination through influential projects (AHDB, 2018; UK Research and Innovation, 2018).

2.7 Conclusions

Improvements made in the characterisation of subsoil compaction advance both the understanding of the mechanisms of subsoil compaction, and provides

evidence to support the selection and application of alternative alleviation methods.

The impact, risk factors, avoidance measures and mechanical alleviation of subsoil compaction have been well defined. Existing, destructive field and laboratory methods can adequately infer subsoil compaction but are limited by reliance on physical samples and a lack of contextual information on subsoil function, which leaves knowledge gaps at both the large and small spatial scales. Digital imaging methods represent a significant step in improving the characterisation of subsoil compaction through the undisturbed observation of soil and root response over multiple time points at the small spatial scale. This increased understanding of subsoil and plant interaction with compaction may then be better applied at the large spatial scale for soil management by utilising non-invasive scanning techniques and visual analyses to supplement traditional field methods.

Mechanical alleviation methods are well studied in the literature and used appropriately, are capable of alleviating subsoil compaction, at least in the short-term. The effectiveness of these methods is limited by misapplication in the field and subsequent negative consequences such as recompaction. Biological alleviation meets the requirements of subsoil compaction alleviation, avoids excessive profile disruption and subsequent recompaction risk. However, specific advice on species selection, expected outcomes and application within agricultural rotations is required for practical application in the field. Therefore, continued development to determine specific roots traits suitable for subsoil compaction in order to create a list of appropriate species is required.

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3 Long-term impact of repeated cover cropping and cultivation approach on subsoil compaction

Objective: To determine whether long-term rotation and cultivation management have an impact on subsoil compaction at field-scale

Hypothesis: Repeated, alternate season cover crop rotation combined with reduced cultivation intensity will decrease the long-term formation of subsoil compaction compared to continuous cereal rotation and conventional cultivation

Target Journal Publication: Soil and Tillage Research

3.1 Abstract

The intensification of arable agriculture has resulted in an increase in vehicle wheel load and the intensity of field operations, which has increased the risk and incidence of subsoil compaction. Biopores generated by the long-term, repeated use of specific cover crops within an arable rotation has been suggested as an approach to improve subsoil physical properties, as opposed to traditional mechanical cultivation. Therefore, the aim of this paper was to determine the impact of long-term repeated cover cropping and the interaction of rotation with different cultivation approaches on subsoil physical properties. Data was collected at the NIAB 'Sustainable Trial for Arable Rotations' long-term rotation and cultivation field experiment. Rotation treatments comprised a brassica cover crop alternated annually with winter wheat (ALTCC) compared to continuous winter wheat (CWW). Cultivation treatments comprised plough (250 mm depth), and non-inversion cultivation at 250 and 100 mm depth. Penetration resistance and volumetric soil moisture were collected at bi-monthly intervals during the 2018/19 growing season. Undisturbed soil cores were collected for laboratory analyses of soil water retention, infiltration rate, water stable aggregates, root morphology digital scanning and biomass, and X-ray computed tomography (CT). Results showed that treatment ALTCC combined with non-inversion cultivation at shallow depth resulted in lower penetration resistance and increased moisture in the subsoil. The increased subsoil moisture persisted later into the season compared to the control. Non-inversion cultivation at shallow depth provided the

most significant benefits to soil water retention, root morphology and pore characteristics as measured by X-ray CT. Benefits from treatment ALTCC were not observed where combined with higher intensity, deeper cultivation. Overall, the combination of treatments ALTCC with non-inversion shallow cultivation produced the most significant benefits to physical subsoil properties, and therefore the greatest potential to improve compacted subsoil.

3.2 Introduction

Pursuit of greater agricultural efficiency has driven increases in vehicle wheel load and field management intensity that have increased the risk of subsoil compaction (Keller et al., 2019; Schonning et al., 2018). Risk modelling suggests that c. 40 % of European subsoils may already be over compact, with agricultural management a significant factor (Brus and van den Akker, 2018b; Schneider and Don, 2019b; Schonning and Thorsoe, 2019). This is of concern because subsoil compaction is known to be highly persistent over time (Etana and Håkansson, 1994), negatively impacts soil functions (Arvidsson, 2001; Berisso et al., 2012; Lipiec et al., 2003; Poodt et al., 2003; Trautner et al., 2003) and reduces crop performance (Håkansson, 1994; Håkansson and Reeder, 1994; McKenzie et al., 2009). The negative impacts of subsoil compaction on soil functions increases the risk of erosion, flooding and loss of agricultural inputs to the wider environment (Alaoui et al., 2018; Jones et al., 2003; Rickson et al., 2015).

The definition of three specific soil layers are useful when discussing subsoil compaction: topsoil, pan layer and uncultivated subsoil (Alakukku et al., 2003). The topsoil represents the managed layer that extends from the soil surface to the maximum depth of annual cultivation. Thus, the depth of topsoil varies dependant on rotation and cultivation approach. Immediately below the topsoil, a narrow compacted layer (c. 20 – 50 mm), the pan layer, can develop. Pan layers are formed in response to both vehicle load and cultivation. Below either the topsoil or the pan layer is the uncultivated subsoil. Typically, the subsoil is not disturbed by annual cultivation and is only loosened during exceptional field operations such as mole draining or periodic deep cultivations such as subsoiling.

Alleviation of subsoil compaction should aim to improve water, gas and root movement by creating fissuring and cracking of the compacted subsoil layer without excessive disruption and weakening of the soil profile (Spoor et al., 2003). Mechanical cultivation through subsoiling has a positive short-term effect but leaves the soil vulnerable to recompaction through subsequent field operations and some natural processes (Chamen et al., 2003; Olesen and Munkholm, 2007; Schneider and Don, 2019a). Plant roots are able to modify compacted soil

structure (Hinsinger et al., 2009) and exploiting the inherent characteristics of specific cover crop roots has been proposed as an alternative to mechanical cultivation for subsoil compaction (Bengough et al., 2011; Cresswell and Kirkegaard, 1995; Pulido-Moncada et al., 2020). Roots are able to improve soil physical properties by creating pore space and exploiting existing pores to penetrate compacted layers, which combine to improve the connectivity of pore space from the soil surface to depth in the soil profile (Chen and Weil, 2009; Clark et al., 2003). Colonisation of pre-existing 'biopores' has been shown to be a significant approach by arable crops to cope with compacted soil layers (Atkinson et al., 2020). Channels created by roots through compacted subsoil have been shown to improve water and gas transport (Lipiec and Hatano, 2003; Uteau et al., 2013), increase crop root depth through pore recolonisation (Dexter, 1991; Kautz, 2015; Landl et al., 2019; Perkons et al., 2014) and to be resistant to recompaction (Schaffer et al., 2008, Schaffer et al., 2007). Deep-rooted brassicas (Clark et al., 2003; Materechera et al., 1992; Williams and Weil, 2004) and some graminaceous species (Burr-Hersey et al., 2017; McKenzie et al., 2009) have demonstrated potential to modify soil structure but the application to subsoil compaction, especially at field-scale, requires further investigation (Carof et al., 2007; Frelih-Larsen et al., 2018; Storr et al., 2019).

Cultivation approach is directly linked to soil bearing capacity and therefore subsoil compaction risk (Alakukku et al., 2003; Botta et al., 2010). Cultivation may have a positive impact, for example a plough pan decreasing vehicular pressure transmission depth (Schäfer-Landefeld et al., 2004), or a negative impact, for example in-furrow ploughing reducing the distance between the load applied to the soil surface and the subsoil, therefore increasing the risk of subsoil compaction (Poodt et al., 2003; Wiermann et al., 2000). Reducing cultivation intensity has been shown to improve the structural stability of the soil profile and reduce the risk of subsoil compaction (Chamen et al., 2003; Hernanz and Sanchez-Giron, 2000; Sommer, 2000). Although the impact of cultivation on subsoil compaction has been well established, as summarised by Spoor et al. (2003), the long-term interaction of cultivation approach and cover cropping on subsoil compaction in the field has not been adequately investigated.

The aim of this paper is to determine whether the long-term, repeated growth of a cover crop in an arable rotation had an impact on subsoil compaction and the interaction of rotation treatments with cultivation approach. Although the main consideration of this paper is the subsoil, the impact of management practices on the subsoil are inextricably linked to the whole profile and therefore results will be presented as so.

3.3 Materials and methods

3.3.1 Experimental site and design

The NIAB 'Sustainable Trial for Arable Rotations' (NIAB STAR) project is a long-term, field-scale rotation and cultivation experiment, established in 2006 at Stanway Farm, Suffolk, UK (58.8,18.9708"N, 1.11,20.9868"E). The experiment is a fully replicated factorial design, replicated over three blocks with plots of 36 x 36 m (l x w), and is achieved using commercial scale equipment on a Beccles/Hanslope soil series. The full experiment comprised four rotation and four cultivation treatments as detailed in Stobart and Morris (2011) (n = 48 plots). Two rotation and three cultivation treatments were selected from the full experiment for the purposes of this paper, resulting in six treatments that were triple replicated over the three treatment blocks (n = 18 plots total).

The historic application of rotation and cultivation treatments are outlined in Table 3.1. Rotation treatments consisted of continuous winter wheat (*Triticum aestivum*) (CWW), where winter wheat was grown every season, and an alternate season mustard brassica (*Brassica* spp.) cover crop (ALTCC), where a cover crop was alternated annually with winter wheat (WW). Annual cultivation treatments consisted of plough (PLOUGH) (inversion cultivation 250 mm depth), deep cultivation (DEEP) (non-inversion cultivation using a combination of tines and discs 250 mm depth) and shallow cultivation (SHALLOW) (non-inversion cultivation using a combination of tines and discs 100 mm depth). The date of rotation and cultivation treatment application varied annually dependent on soil and climatic conditions but always occurred during the autumn period (Sep – Nov). Rotation treatment cover crops were terminated in early summer (May – Jun) and the plots left fallow until the next autumn (Sep – Nov) rotation treatment

(WW) was applied. Therefore, the ALTCC treatment represented a full season cover crop that replaced a cash crop in the rotation. Permanent tramlines were used for the application of agrochemicals and fertilisers. These were established through each plot at a 90° angle to the direction of treatment application.

Treatment ALTCC was substituted with a perennial herbal ley (HL) from September 2018. The existing ALTCC treatment plots were cultivated to 100 mm depth and the HL treatment was established 03.09.2018. No further cultivations took place on these plots, but cultivation treatments continued as before for the CWW treatment. The full list of field operations and HL treatment species list are included in Appendix A. The treatment that combines both ALTCC and HL will be referred to as ALTCC.

Table 3.1 Rotation and cultivation treatment annual summary and definitions.

Annual rotation treatment application													
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CWW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW
ALTCC	CC	WW	CC	WW	CC	WW	CC	WW	CC	WW	CC	WW	HL
Rotation treatment													
CWW	Winter wheat (<i>Triticum aestivum</i>) grown every season												
WW	Winter wheat (<i>Triticum aestivum</i> spp.)												
ALTCC	Mustard brassica (<i>Brassica</i> spp.) cover crop (CC)												
HL	Perennial herbal ley species mixture (full species list Appendix A)												
Cultivation treatment													
PLOUGH	Inversion ploughed to depth 250 mm annually												
DEEP	Non-inversion cultivated using disc and tine combination to depth 250 mm annually												
SHALLOW	Non-inversion cultivated using disc and tine combination to depth 100 mm annually												

3.3.2 Field monitoring methods

Data was collected at intervals throughout the 2018/2019 growing season. Field monitoring was carried out at approximately bi-monthly intervals (Nov 2018 – Aug 2019).

Penetration resistance (PR) was collected using a manually operated digital penetrometer (Eijelkamp, Digital Penetrologger V.6.13). Ten randomised penetrations were collected for each plot to 600 mm depth using a 1.2 cm² 30° cone. Measurements were obtained in Nov 2018 and Jan, Mar and May 2019 (reference Fig.3.1.1 – Fig.3.1.4). Volumetric soil moisture (VSM) was measured using a capacitance probe (Delta-T Devices, Profile Probe PR1) with sensors at 150, 250, 350, 450 and 650 mm depths. Each plot had one access tube installed, 5 x 5 m inside the southwest plot corner. Parallel to the PR data, VSM was collected in Mar and May 2019 and additional readings were obtained during Aug 2019 (reference Fig.3.2.1 – Fig.3.2.3).

3.3.3 Undisturbed soil core methods

Undisturbed soil cores (800 x 84 mm, h x d) were collected from each plot (n = 18) (Jan 2019) using a pneumatic cylinder auger (Eijelkamp, Soil Column Cylinder Auger). Cores were divided into four layers (200 x 84 mm, h x d) and refrigerated at 5°C within 24 hrs of extraction. Soil texture (hand method, BS 3882:1994; BSI, 1994), organic matter (%) (loss on ignition) and bulk density (g cm⁻³) (drying for 24 hours at 105°C, BS 8601:13, BSI, 2013) were determined for each layer.

Soil water retention (cm³ cm⁻³) was determined using a combination of sand table and pressure plate apparatus (BS EN ISO 11274:2019; BSI, 2019). Water retention at soil water potentials of 0 kPa (saturation), 5 and 10 kPa (field capacity), 200 kPa (easily available water) and 1500 kPa (permanent wilting point) were determined. Infiltration rate (mm hr⁻¹) was measured using a tension infiltrometer (Decagon Devices METER Group, Minidisk Infiltrrometer) (tension - 0.5 cm) and unsaturated hydraulic conductivity (K_{unsat}) calculated using the

supplied calculations based on van Genuchten parameters (Carsel and Parrish, 1988; Decagon Devices METER Group, 2014).

Water stable aggregates (WSA) (%) were determined using wet sieving apparatus (Eijelkamp, Wet Sieving Apparatus). Air dried aggregates (1 – 2 mm size fraction) were moistened using a fine mist sprayer in a 0.25 mm mesh sieve, agitated for 3 minutes in distilled water, followed by continuous agitation in a 2 g l⁻¹ sodium hexametaphosphate solution ((NaPO₃)₆). Sand particles remaining were discarded, leachates oven dried (24 hrs at 110°) and mass recorded. The WSA was calculated as in Equation 3.1.

$$\text{WSA (\%)} = (\text{soil}^a / (\text{soil}^a + \text{soil}^b)) * 100 \quad \text{Equation 3.1}$$

soil^a – mass of oven dried 3 minute distilled water fraction (minus the mass of drying tin (g))

soil^b – mass of oven dried continuous agitation 2 g l⁻¹ sodium hexametaphosphate solution fraction (minus the mass of drying tin (g) and minus 0.2 g sodium hexametaphosphate solute mass correction)

Root samples were obtained by washing samples over a 1 mm sieve and all root material retained. Root material was optically scanned (Reagent Instruments, SDT4800) at 400 dpi. Mean root diameter and total root length (mm) were measured using WinRHIZO root morphology software (Reagent Instruments, WinRHIZO Pro) and root material oven dried (24 hrs at 65°C) to determine total dry root biomass (g).

Samples from the 200 – 400 mm layer were selected for X-ray computed tomography (CT) carried out at the University of Nottingham Hounsfield Facility, UK. Subsamples of 30 x 30 mm (h x d) were scanned using Pheonix V|tome|X m X-Ray scanner (GE Measurement and Control Solutions) at 170 kV 150 µA. Total 2998 projections were collected at 28 µm voxel⁻¹ resolution. Images were reconstructed at 32-bit (Pheonix Datosx 2, GE Measurement and Control Solutions) and processed to 8-bit .bmp stacks (VG Studio Max 2.2.5., Volume

Graphics GmbH). Stacks were segmented into solid and pore (%), and analysed using Minkowski functionals to obtain measures of pore volume (%), connected pore volume (%), pore-solid surface area (voxels) and connected pore surface area (voxels) (Falconer et al., 2012; Houston et al., 2013; Vogel et al., 2010). Pore size distribution (n) was summarised in Fiji open-source image analysis software (Schindelin et al., 2012) using the BoneJ (Doubé et al., 2010) plugin 'particle analyser tool' (Houston et al., 2017). Pore size distribution were split into classes of 28 – 1000 μm (meso - macropores), 1000 – 2000 μm (macropores), 2000 – 5000 μm (macropores) and >5000 μm (soil cracks).

3.3.4 Statistical analyses

Results were analysed using IBM SPSS (IBM SPSS Statistics, V26). Data was checked for normality by plotting a histogram and quantile-quantile plots. Variables K_{unsat} , root biomass and pore size distribution were $\log_{10}$ transformed to normalise the data distribution. Variable K_{unsat} data from depth 0 – 200 mm was omitted from statistical analysis due to large data variation caused by the presence of plant material within the samples. Factorial ANOVA was used to analyse data without a depth factor and repeated measures factorial ANOVA was used to analyse data that had depth as a factor (treating depth as a within-subjects variable). Where significant effects were observed, these were followed by an unprotected Fischer's least significant difference (LSD) test. Standard error and error bars represent the standard error of the means for the treatment comparison and/or depth category discussed (SE). All tests were conducted at the 5% significance level (P).

3.4 Results

3.4.1 Bulk density, organic matter and soil texture

No significant differences were found between rotation or cultivation treatments in bulk density (SE = 0.03) or organic matter (SE = 0.24) (Table 3.2). Soil texture transitioned from sandy loam/sandy clay loam at 0 – 200 mm depth to an increased clay content with depth. Chalk fragments appeared from 200 mm and increased in frequency across the site with depth (Appendix B).

Table 3.2 Bulk density (BD) (g cm³⁻¹) and soil organic matter (OM) (%) over depth layers. Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S – SHALLOW.

Treatment	Depth (mm)							
	0 - 200		200 - 400		400 - 600		600 - 800	
	BD	OM	BD	OM	BD	OM	BD	OM
PCWW	1.47	3.91	1.54	2.80	1.48	2.40	1.57	1.94
DCWW	1.47	4.14	1.55	2.67	1.54	3.02	1.54	2.42
SCWW	1.43	4.17	1.56	2.24	1.55	2.62	1.58	2.07
PALTCC	1.50	4.01	1.55	2.80	1.54	2.68	1.53	2.62
DALTCC	1.40	4.31	1.52	3.05	1.48	2.86	1.62	1.93
SALTCC	1.43	4.01	1.56	2.13	1.55	2.45	1.60	1.67
CWW	1.46	4.07	1.55	2.57	1.52	2.68	1.56	2.14
ALTCC	1.44	4.11	1.55	2.66	1.52	2.66	1.58	2.07
PLOUGH	1.48	3.96	1.55	2.80	1.51	2.54	1.55	2.28
DEEP	1.44	4.22	1.53	2.86	1.51	2.94	1.58	2.18
SHALLOW	1.43	4.09	1.56	2.19	1.55	2.54	1.59	1.87

3.4.2 Penetration resistance

3.4.2.1 Rotation and cultivation treatments

PR for rotation treatments and cultivation treatments are presented in Fig.3.1. ALTCC had significantly higher PR compared to CWW within 0 – 250 mm depth (Fig. 3.1. A1, A2, A3, A4, A5). CWW had significantly higher PR compared to ALTCC within 400 – 600 mm depth (Fig. 3.1. A2, A3, A5). SHALLOW had significantly higher PR compared to PLOUGH within 50 – 250 mm depth (Fig. 3.1. B1, B2, B3). PLOUGH had significantly higher PR compared to DEEP within 250 – 450 mm depth (Fig. 3.1. B1, B2, B3, B5) and SHALLOW within 300 – 450 mm depth (Fig. 3.1. B4, B5).

3.4.2.2 Rotation and cultivation interaction

PR for rotation and cultivation treatment interaction are presented in Fig. 3.1. SHALLOW CWW had a significantly higher PR compared to DEEP CWW at 0 – 350 mm depth and PLOUGH CWW at 0 – 300 mm depth (Fig. 3.1. C1, C2, C3). PLOUGH CWW had significantly higher PR compared to DEEP CWW at 250 – 600 mm depth (Fig. 3.1. C1, C3, C4). SHALLOW ALTCC had significantly higher PR compared to DEEP ALTCC at 200 – 350 mm depth (Fig. 3.1. C1, C2). PLOUGH ALTCC had significantly higher PR compared to DEEP ALTCC at 200 – 300 mm depth (Fig. 3.1. C1). ALTCC had significantly higher PR compared to CWW at 0 – 250 mm depth when combined with both PLOUGH and SHALLOW cultivation treatments Nov 2018 (Fig. 3.1. C1) and all cultivation treatments Jan/Mar/May 2019 (Fig. 3.1. C3, C4). CWW had significantly higher PR compared to ALTCC at 350 – 600 mm depth when combined with PLOUGH and DEEP (Fig. 3.1. C2), SHALLOW (Fig. 3.1. C3) and PLOUGH (Fig. 3.1. C4). Treatment interaction averaged across all collection dates and significant differences are presented in Fig. 3.1. C5.

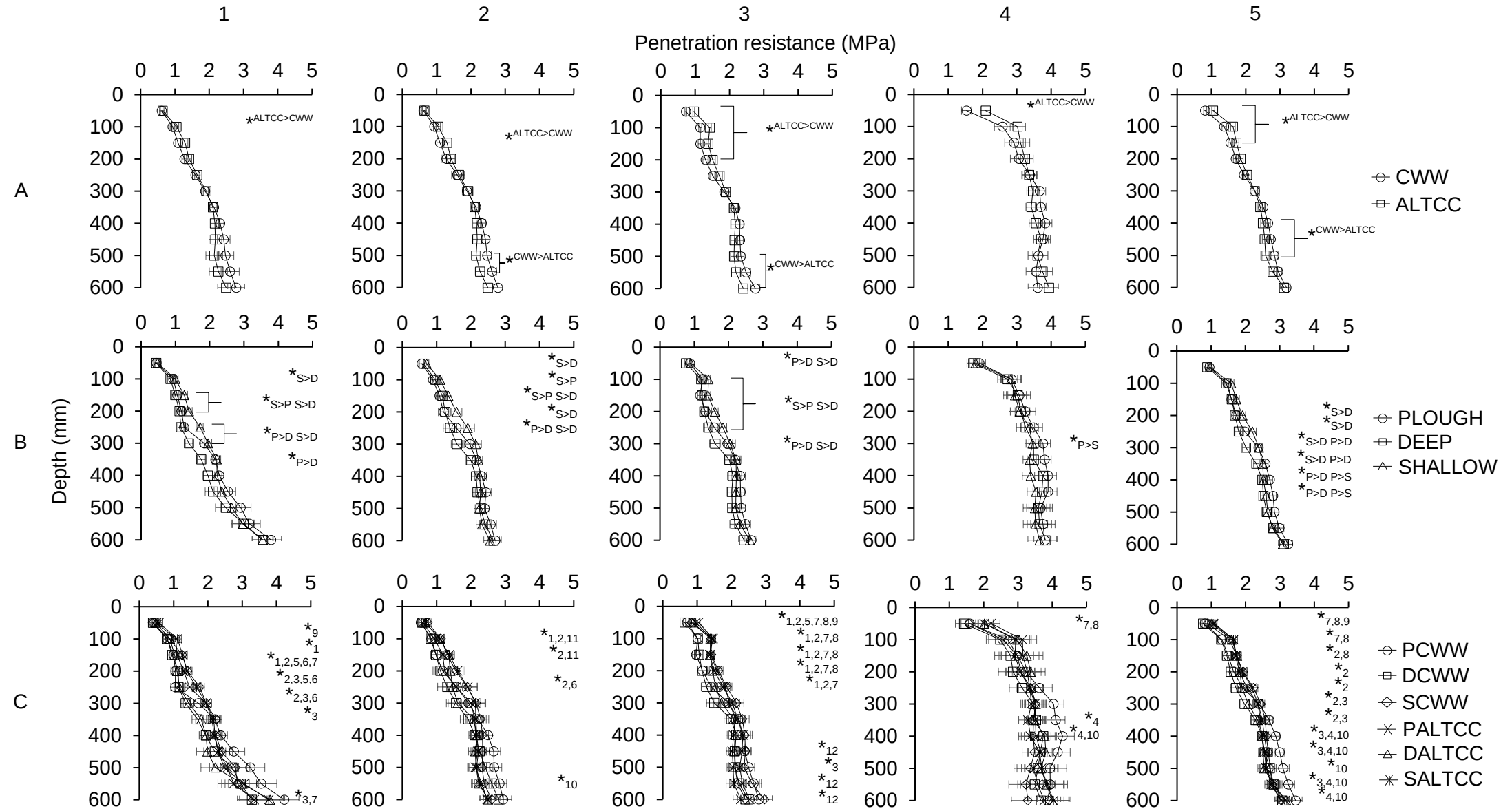


Figure 3.1. Penetration resistance (MPa) over depth. 1) Nov 2018 2) Jan 2019 3) Mar 2019 4) May 2019 5) mean all collection dates; A) mean rotation treatments B) mean cultivation treatments C) rotation and cultivation treatment interaction. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P \leq 0.05$) are indicated by treatments in sections A and B (e.g. *CWW>ALTCC) and by numbers in section C which correspond to the following: ¹S CWW>P CWW, ²S CWW>D CWW, ³P CWW>D CWW, ⁴P CWW>S CWW, ⁵P ALTCC>D ALTCC, ⁶S ALTCC>D ALTCC, ⁷P ALTCC>P CWW, ⁸D ALTCC>D CWW, ⁹S ALTCC>S CWW, ¹⁰P CWW>P ALTCC, ¹¹D CWW>D ALTCC, ¹²S CWW>S ALTCC. Error bars represent standard error of the mean between treatments at each depth category.

3.4.3 Volumetric soil moisture

3.4.3.1 Rotation and cultivation treatments

VSM for rotation treatments and cultivation treatments are presented in Fig. 2. ALTCC had significantly higher VSM compared to CWW at 150 – 450 mm depth (Fig. 3.2. A2), 650 mm depth (Fig. 3.2. A3) and 450 mm depth (Fig. 3.2. A4). CWW had significantly higher VSM compared to ALTCC at 150 – 250 mm depth (Fig. 3.2. A3). SHALLOW had significantly higher VSM compared to PLOUGH at 150 – 350 mm depth (Fig. 3.2. B1, B4) and at 250 – 350 mm depth (Fig. 3.2. B3). SHALLOW also had significantly higher VSM compared to DEEP at 150 – 250 mm depth (Fig. 3.2. B1). DEEP had significantly higher VSM compared to PLOUGH at 350 mm (Fig. 3.2. B4).

3.4.3.2 Rotation and cultivation interaction

VSM for rotation and cultivation treatment interaction are presented in Fig. 3.2. SHALLOW CWW had significantly higher VSM compared to PLOUGH CWW at 250 – 350 mm depth (Fig. 3.1. C1 and C3) and compared to DEEP CWW at 150 mm depth (Fig. 3.1. C3). SHALLOW ALTCC had significantly higher VSM compared to PLOUGH ALTCC at 150 mm depth (Fig. 3.1. C1). In combination with all cultivation treatments, ALTCC had significantly higher VSM compared to

CWW within 250 – 450 mm depth, whereas CWW had significantly higher VSM compared to ATLCC only in combination with SHALLOW at 150 mm depth (Fig. 3.1. C3). Treatment interaction averaged across all collection dates and significant differences are presented in Fig. 3.2. C4.

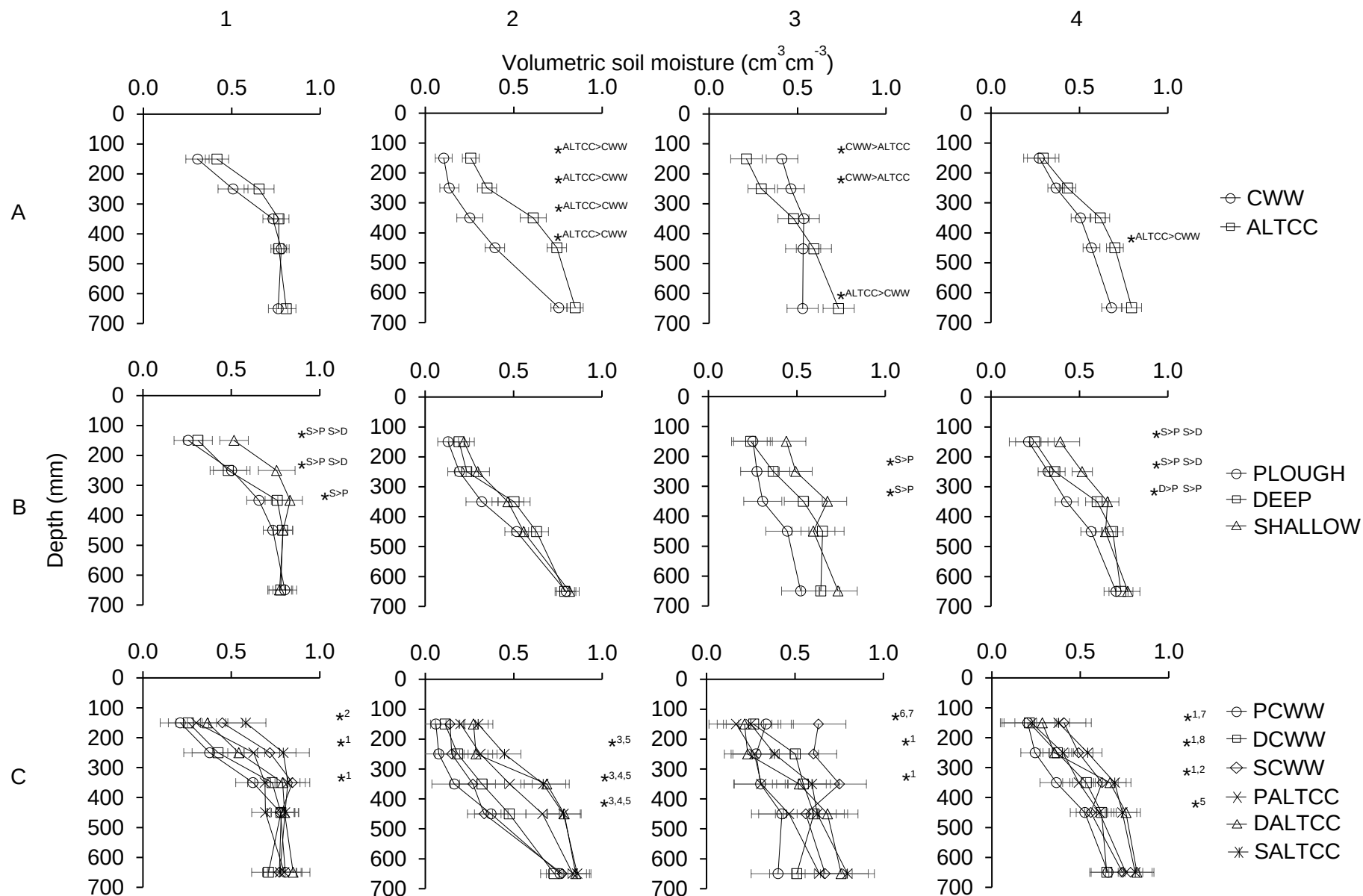


Figure 3.2 Volumetric soil moisture ($\text{cm}^3 \text{ cm}^{-3}$) over depth. 1) Mar 2019 2) May 2019 3) Aug 2019 4) mean all collection dates; A) rotation treatments B) cultivation treatments C) rotation and cultivation treatment interaction. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P \leq 0.05$) are indicated by treatments in sections A and B (e.g. *CWW>ALTCC) and by numbers in section C which correspond to the following: ¹S CWW>P CWW, ²S ALTCC>P ALTCC, ³P ALTCC>P CWW, ⁴D ALTCC>D CWW, ⁵S ALTCC>S CWW, ⁶S CWW>S ALTCC, ⁷S CWW>D CWW, ⁸SALTCC>DALTCC. Error bars represent standard error of the mean between treatments at each depth category.

3.4.4 Unsaturated hydraulic conductivity

No significant differences in K_{unsat} were recorded between mean rotation, cultivation or treatment interaction ($\text{SE} = 0.36$) (Table 3.3).

3.4.5 Water stable aggregates

No significant differences were recorded between mean rotation, cultivation or interaction ($\text{SE} = 4.60$) (Table 3.3). Where cultivation treatments were compared over depth, SHALLOW had significantly higher WSA compared to PLOUGH at 0 – 200 mm depth ($P = 0.02$; $\text{SE} = 7.03$) (Table 3.3). Where interaction was compared over depth, DEEP ALTCC had significantly higher WSA compared to PLOUGH ALTCC at 0 – 200 mm depth ($P = 0.03$; $\text{SE} = 9.95$) (Table 3.3).

Table 3.3 NIAB STAR experiment treatment means over depth layers and mean all layers. Unsaturated hydraulic conductivity (K_{unsat}) (mm hr^{-1}) and water stable aggregates (WSA) (%). Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S - SHALLOW. Lowercase letters represent differences within a section e.g. ^{a,b,c}.

Depth (mm)	200 - 400	400 - 600	600 - 800	Mean	0 – 200	200 - 400	400 - 600	600 - 800	Mean
Treatment	K_{unsat} (mm hr^{-1})				WSA (%)				
PCWW	10.68	3.02	3.27	5.66	74.2	83.7	80.6	80.4	79.7
DCWW	15.55	13.85	6.64	12.01	77.6	89.4	89.5	74.8	82.8
SCWW	11.62	13.93	6.53	10.69	93.7	91.1	83.9	82.1	87.7
PALTCC	5.23	1.69	4.21	3.71	66.1 ^a	79.7	90.0	75.2	77.8
DALTCC	13.03	1.73	7.23	7.32	90.7 ^b	92.4	89.0	71.8	86.0
SALTCC	0.82	2.13	20.45	7.82	85.9	91.1	76.2	79.1	83.1
CWW	12.45	8.35	5.21	8.69	81.8	88.0	84.7	79.1	83.4
ALTCC	3.83	1.84	8.54	4.74	80.9	87.7	85.1	75.4	82.3
PLOUGH	7.48	2.26	3.71	4.48	70.2 ^a	81.7	85.3	77.8	78.7
DEEP	14.23	4.90	6.93	8.68	84.1	90.9	89.3	73.3	84.4
SHALLOW	3.09	5.45	11.56	6.71	89.8 ^b	91.1	80.1	80.6	85.4

3.4.6 Soil water retention

Soil water retention (SWR) ($\text{cm}^3 \text{ cm}^{-3}$) for rotation treatments, cultivation treatments and treatment interaction is presented in Fig. 3.3. No significant differences were recorded at depths 0 – 200 mm and 400 – 600 mm. DEEP cultivation had significantly higher SWR compared to PLOUGH cultivation at the 200 – 400 mm depth, at potentials 200 and 1500 kPa ($P = 0.03$ and 0.03 ; $SE = 0.02$ and 0.02 respectively) (Fig. 3.3. B2).

DEEP ALTCC had significantly higher SWR compared to PLOUGH ALTCC at the 200 – 400 mm depth, at potentials 200 and 1500 kPa ($P = 0.03$ and 0.04 ; $SE = 0.03$ and 0.03 respectively) (Fig. 3.3. C2). DEEP CWW had significantly higher SWR compared to DEEP ALTCC at the 600 – 800 mm depth, at potentials 0, 5 and 10 kPa ($P = 0.03$, 0.03 and 0.04 ; $SE = 0.02$, 0.02 and 0.02 respectively) (Fig. 3.3. C4). SHALLOW ALTCC had significantly higher SWR compared to DEEP ALTCC at the 600 – 800 mm depth, at potentials 5 and 10 kPa ($P = 0.04$ and 0.04 ; $SE = 0.02$ and 0.02 respectively) (Fig. 3.3. C4). DEEP ALTCC had significantly higher SWR compared to PLOUGH ALTCC at the 600 – 800 mm depth, at potential 1500 kPa ($P = 0.04$; $SE = 0.02$) (Fig. 3.3. C4).

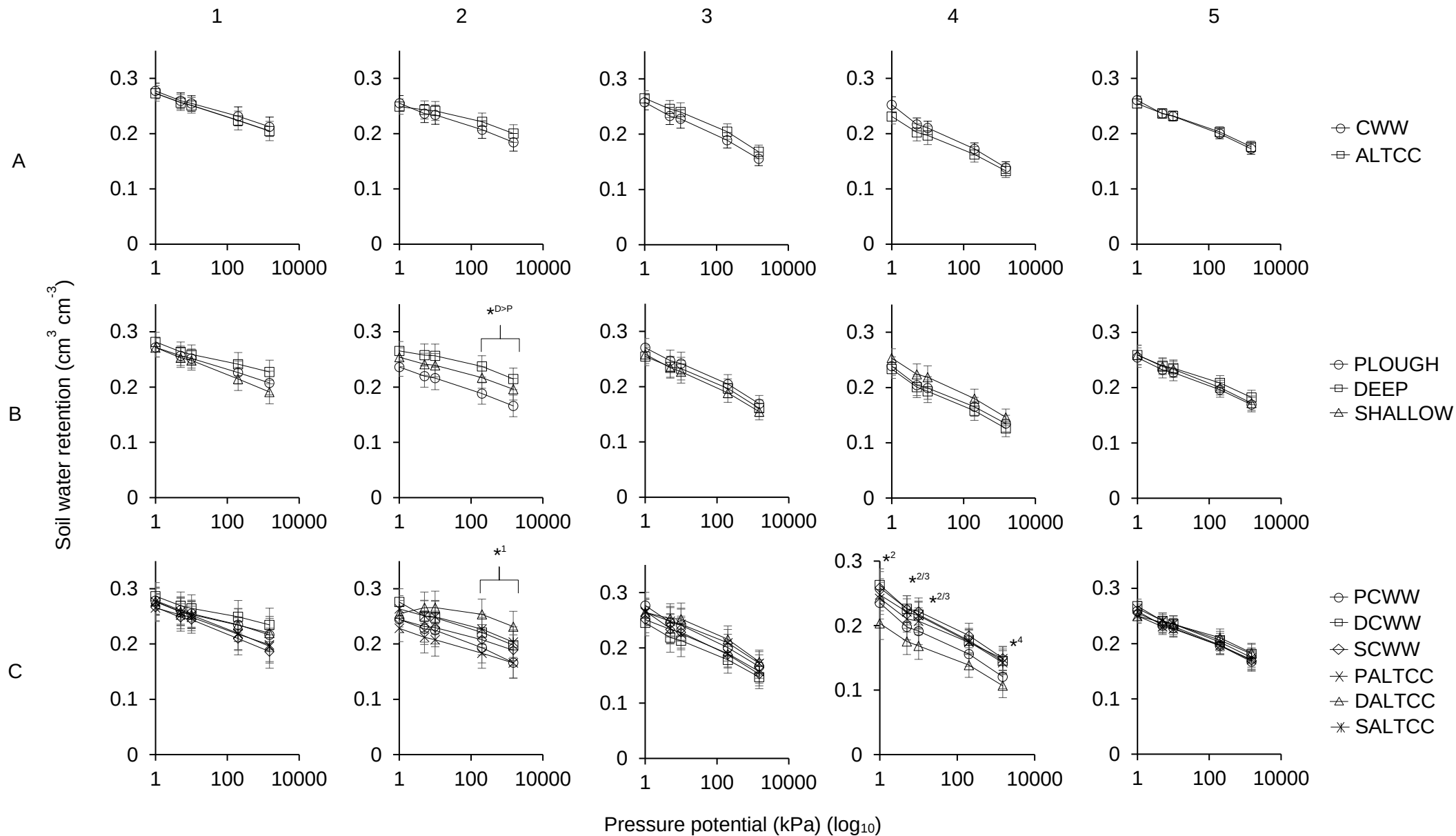


Figure 3.3 Soil water retention ($\text{cm}^3 \text{ cm}^{-3}$) over depth. 1) 0 – 200 mm 2) 200 – 400 mm 3) 400 – 600 mm 4) 600 – 800 mm 5) mean all depths; A) rotation treatments B) cultivation treatments C) rotation and cultivation treatment interaction. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P \leq 0.05$) are indicated by treatments in sections A and B (e.g. *CWW>ALTCC) and by numbers in section C which correspond to the following: ¹D ALTCC>P ALTCC, ²D CWW>D ALTCC, ³S ALTCC>D ALTCC, ⁴D ALTCC> P ALTCC. Error bars represent standard error of the mean between treatments at each soil water potential.

3.4.7 Root characteristics

3.4.7.1 Mean root diameter

SHALLOW had significantly higher mean root diameter compared to DEEP ($P = 0.04$; $SE = <0.01$), and ALTCC PLOUGH and ALTCC SHALLOW had significantly higher mean root diameter compared to ALTCC DEEP ($P = 0.02$ and 0.01 respectively; $SE <0.01$) (Table 3.4).

Where treatments were compared over depth, PLOUGH had a significantly higher mean root diameter compared to DEEP and SHALLOW at 200 – 400 mm depth ($P = <0.01$ and 0.04 respectively; $SE = 0.01$) (Table 3.4). SHALLOW had significantly higher mean root diameter compared to PLOUGH and DEEP at 600 – 800 mm depth ($P = 0.02$ and <0.01 respectively; $SE = 0.01$) (Table 3.4). SHALLOW ALTCC had significantly higher mean root diameter compared to SHALLOW CWW at 600 – 800 mm depth ($P = 0.05$; $SE = 0.01$) (Table 3.4). PLOUGH ALTCC had significantly higher mean root diameter compared to DEEP ALTCC and SHALLOW ALTCC at 200 – 400 mm depth ($P = <0.01$ and 0.02 respectively; $SE = 0.01$) (Table 3.4). SHALLOW ALTCC had significantly higher mean root diameter compared to PLOUGH ALTCC and DEEP ALTCC at 600 – 800 mm depth ($P = 0.03$ and <0.01 respectively; $SE = 0.01$) (Table 3.4).

3.4.7.2 Total root length

SHALLOW had significantly higher root length compared to PLOUGH ($P = 0.02$; $SE = 13.8$), and ALTCC SHALLOW had significantly higher root length compared to ALTCC PLOUGH ($P = 0.05$; $SE = 19.5$) (Table 3.4).

Where treatments were compared over depth, ALTCC had significantly higher root length compared to CWW at 600 – 800 mm depth ($P = 0.01$; $SE = 17.9$) (Table 3.4). DEEP had significantly higher root length compared to PLOUGH at 200 – 400 mm depth ($P = 0.01$; $SE = 20.6$), and SHALLOW had significantly higher root length compared to PLOUGH and DEEP at 600 – 800 mm depth ($P = 0.05$ and 0.02 respectively; $SE = 22.0$) (Table 3.4). ALTCC DEEP had significantly higher root length compared to ALTCC PLOUGH at 200 – 400 mm depth ($P = 0.02$; $SE = 29.2$) (Table 3.4). ALTCC SHALLOW had significantly higher root length compared to CWW SHALLOW and ALTCC DEEP at 600 – 800 mm depth ($P = 0.02$ and 0.02 respectively, $SE = 31.1$) (Table 3.4).

3.4.7.3 Total root biomass

SHALLOW had significantly higher root biomass compared to PLOUGH ($P = 0.01$ respectively; $SE = 1.42$) (Table 3.4). SHALLOW CWW had significantly higher root biomass compared to CWW PLOUGH ($P = 0.01$ and 0.04 respectively; $SE = 1.64$) (Table 3.4).

Where treatments were compared over depth, SHALLOW had significantly higher root biomass compared to PLOUGH at 0 – 200 mm and 200 – 400 mm ($P = 0.04$ and 0.01 ; $SE = 1.46$ and 1.43 respectively) (Table 3.4). SHALLOW CWW had significantly higher root biomass compared to PLOUGH CWW at 200 – 400 mm depth ($P = <0.01$; $SE = 1.66$) and significantly higher root biomass compared to DEEP CWW at 600 – 800 mm depth ($P = 0.02$; $SE = 1.78$) (Table 3.4). SHALLOW ALTCC had significantly higher root biomass compared to PLOUGH ALTCC at 0 – 200 mm depth ($P = 0.05$; $SE = 1.70$) (Table 3.4). SHALLOW CWW had significantly higher root biomass compared to SHALLOW ALTCC at 200 – 400 mm depth ($P = 0.03$; $SE = 1.66$), and DEEP ALTCC had significantly higher root biomass compared to DEEP CWW at 600 – 800 mm ($P = 0.03$; $SE = 1.78$) (Table 3.4).

Table 3.4 Mean root diameter (mm), total root length (cm) and total root biomass (mg) over depth categories and mean of all depths ('Mean'). Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S - SHALLOW. Significant ($P \leq 0.05$) differences are organised by column and section. Lowercase letters without parentheses represent differences within a section e.g.^{a,b,c}, and uppercase letters, numbers and symbols with parentheses represent differences between sections e.g.^{(A/B),(1/2),(*/**)}.

Depth (mm)	0 - 200	200 - 400	400 - 600	600 - 800	Mean	0 - 200	200 - 400	400 - 600	600 - 800	Mean	0 - 200	200 - 400	400 - 600	600 - 800	Mean
Treatment	Mean root diameter (mm)					Total root length (cm)					Total root biomass (mg)				
PCWW	0.24	0.22	0.18	0.17	0.20	18.8	13.6	86.1	43.0	40.4	18.7	21.6 ^a	44.0	41.2	34.6 ^a
DCWW	0.26	0.21	0.19	0.17	0.21	17.7	73.3	66.3	37.1	48.6	21.3	60.2	70.5	22.2 ^{a(A)}	49.7
SCWW	0.24	0.21	0.19	0.19 ^(A)	0.21	25.7	61.7	140.1	73.9 ^(A)	75.4	33.4	163.3 ^{b(1)}	146.6	104.5 ^b	119.2 ^b
PALTCC	0.24	0.24 ^a	0.18	0.18 ^a	0.21 ^a	21.9	39.8 ^a	80.5	91.6	58.5 ^a	22.4 ^a	36.0	62.6	61.2	50.4
DALTCC	0.24	0.17 ^b	0.18	0.17 ^a	0.19 ^b	16.2	118 ^b	90.7	73.1 ^a	74.4	30.1	60.5	44.2	92.7 ^(B)	69.9
SALTCC	0.27	0.19 ^b	0.19	0.21 ^{b(B)}	0.21 ^a	35.9	59.4	152.0	157.6 ^{b(B)}	101 ^b	73.1 ^b	45.4 ⁽²⁾	73.4	106.3	77.8
CWW	0.24	0.21	0.19	0.18	0.21	20.7	49.5	97.5	51.3 ^a	54.8	23.7	59.6	76.9	45.7	60.0
ALTCC	0.25	0.20	0.18	0.19	0.21	24.7	72.3	107.8	107.4 ^b	78.1	36.7	46.2	58.8	84.5	65.0
PLOUGH	0.24	0.23 ^a	0.18	0.18 ^a	0.21	20.4	26.7 ^a	83.3	67.3 ^a	49.4 ^a	20.5 ^a	27.9 ^a	52.5	50.3	41.8 ^a
DEEP	0.25	0.19 ^b	0.18	0.17 ^a	0.20 ^a	16.9	99.5 ^b	78.5	55.1 ^a	61.5	25.3	60.4	55.8	45.3	58.9
SHALLOW	0.25	0.20 ^b	0.19	0.20 ^b	0.21 ^b	30.8	60.6	146.1	115.8 ^b	88.3 ^b	49.4 ^b	86.1 ^b	103.7	105.4	96.4 ^b

3.4.8 X-ray computed tomography

SHALLOW ALTCC had significantly higher pore volume (%) compared to SHALLOW CWW ($P = 0.05$; $SE = 0.66$) and DEEP ALTCC ($P = 0.04$; $SE = 0.66$) (Table 3.5). SHALLOW ALTCC also had significantly higher pore surface area (voxels) compared to DEEP ALTCC ($P = 0.02$; $SE = 1.09$) (Table 3.5). SHALLOW cultivation treatment had significantly higher pore surfaces area (voxels) compared to both PLOUGH and DEEP ($P = 0.05$ and <0.01 respectively; $SE = 0.77$) (Table 3.5). No significant differences were recorded for connected pore volume (%) ($SE = 3.42$) or connected pore surface area (voxels) ($SE = 1.99$) (Table 3.5).

Table 3.5 Undisturbed soil core X-Ray CT analyses results (200 – 400 mm depth). Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S - SHALLOW. Significant ($P \leq 0.05$) differences are organised by column and section. Lowercase letters without parentheses represent differences within a section e.g. ^{a,b,c}, and uppercase letters, numbers and symbols with parentheses represent differences between sections e.g. ^{(A/B),(1/2),(*/**)}.

Treatment	Pore volume (%)	Connected pore volume (%)	Pore surface area (voxels)	Connected pore surface area (voxels)
PCWW	2.19	21.12	4.61	12.45
DCWW	2.06	27.88	4.02	16.59
SCWW	2.01 ^(A)	18.75	6.19	8.74
PALTCC	2.84	37.29	4.09	12.04
DALTCC	1.86 ^a	24.12	2.97 ^a	8.90
SALTCC	3.42 ^{b (B)}	30.61	5.86 ^b	11.76
CWW	2.08	22.59	4.94	12.59
ALTCC	2.71	30.67	4.31	10.90
PLOUGH	2.51	29.21	4.35 ^a	12.25
DEEP	1.96	26.00	3.49 ^a	12.75
SHALLOW	2.72	24.68	6.03 ^b	10.25

SHALLOW had a significantly higher pore frequency in the 28 – 1000, 1000 – 2000 and 2000 – 5000 μm categories compared to DEEP ($P = 0.01$, <0.01 and <0.01 ; $SE = 1.41$, 1.31 and 1.32 respectively) (Table 3.6). In category $>5000 \mu\text{m}$, SHALLOW, DEEP and PLOUGH were all significantly different from one another (PLOUGH/DEEP $P = 0.03$, PLOUGH/SHALLOW $P = 0.03$ and DEEP/SHALLOW $P = <0.01$; $SE = 1.23$) (Table 3.6).

SHALLOW CWW had significantly more pores in all PSD categories compared to PLOUGH CWW and DEEP CWW (28 – 1000 μm $P = 0.03$ and <0.01 ; $SE = 1.63$, 1000 – 2000 μm $P = 0.03$ and <0.01 ; $SE = 1.47$, 2000 – 5000 μm $P = 0.04$ and 0.01 ; $SE = 1.48$, 5000 $>$ $P = 0.04$ and <0.01 ; $SE = 1.34$) (Table 3.6). In category $>5000 \mu\text{m}$, SHALLOW ALTCC had significantly more pores compared to DEEP ALTCC ($P = 0.01$; $SE = 1.34$) (Table 3.6).

Table 3.6 Undisturbed soil core X-Ray CT pore size distribution (n) results (200 – 400 mm depth). Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S - SHALLOW. Significant ($P \leq 0.05$) differences are organised by column and section. Lowercase letters represent differences within a section e.g. ^{a,b,c}.

Treatment	Frequency (n)			
	28 - 1000 (μm)	1000 - 2000 (μm)	2000 - 5000 (μm)	>5000 (μm)
PCWW	1057.1 ^a	355.5 ^a	321.3 ^a	462.4 ^a
DCWW	720.8 ^a	234.6 ^a	240.0 ^a	301.0 ^a
SCWW	3464.1 ^b	893.1 ^b	817.0 ^b	894.0 ^b
PALTCC	1327.0	432.7	399.6	479.1
DALTCC	895.6	270.0	244.2	273.1 ^a
SALTCC	1794.5	518.8	507.0	666.1 ^b
CWW	1383.0	420.7	397.9	499.2
ALTCC	1286.9	392.8	367.1	443.4
PLOUGH	1184.4	392.2	358.3	470.6 ^a
DEEP	803.4 ^a	251.7 ^a	242.1 ^a	286.7 ^b
SHALLOW	2492.6 ^b	680.7 ^b	643.6 ^b	771.7 ^c

3.5 Discussion

The aim of this paper was to determine whether the long-term, repeated inclusion of a cover crop in an arable rotation had an impact on subsoil compaction, and to examine the interaction of cover crop and cultivation approach. Results demonstrated that repeated cover crop rotation (ALTCC) improved some subsoil physical properties compared to continuous winter wheat (CWW). Cultivation approach had a significant impact on soil physical properties and root characteristics in the subsoil. The benefits of ALTCC rotation were generally promoted by reducing the intensity of cultivation. The rotation treatment change to a perennial herbal ley (HL) was newly and poorly established during data collection period. Therefore, the significant differences recorded are likely to represent the historical rotation and cultivation treatment application rather than the change to HL.

Field monitoring results showed that ALTCC rotation, largely irrespective of cultivation treatment combination, had a lower PR in the subsoil (approx. 350 – 650 mm depth) compared to CWW throughout the data collection period. High PR in the subsoil may indicate compaction and results in less favourable conditions for arable crop growth (Whalley et al., 2008). Treatment PLOUGH resulted in the formation of a compacted layer with high PR (250 – 450 mm) immediately below the PLOUGH treatment implement working depth (250 mm). This compacted ‘pan layer’ was evident where the PLOUGH treatment was combined with CWW rotation but not where combined with ALTCC rotation. Cover crop root growth has been shown to alleviate soil compaction through the creation and exploration of biopores (Chen and Weil, 2010; Dexter, 1991; Pulido-Moncada et al., 2021), and these results may demonstrate that ALTCC rotation provided prevention or alleviation of the subsoil compaction that occurred where treatments PLOUGH and CWW were combined. That said, a compacted pan layer might not necessarily present a problem for arable crop growth provided sufficient pore functionality remains. In this case, a compacted pan layer may provide a useful function by distributing applied load to the soil surface and protecting deeper subsoil from compaction (Chamen et al., 2003). Pore volume

(%) results from X-ray CT showed that there was significantly higher porosity in the 200 – 400 mm depth for PLOUGH combined with ALTCC compared to CWW. High pore volume and lower PR is associated with better soil structure (Bengough et al., 2001) and therefore supports the PR pan layer results that ALTCC presented an advantage.

Field monitoring data showed that ALTCC treatment had higher subsoil VSM, which persisted later into the growing season and deeper in the subsoil compared to CWW. For example, ALTCC had significantly higher VSM compared to CWW between depths 150 – 450 mm at the May 19 collection date, whereas during the Aug 19 collection date the same significant difference occurred at 650 mm. Reducing the depth of cultivation (SHALLOW) or using non-inversion cultivation (DEEP) increased VSM compared to PLOUGH within the cultivated layer (150 – 250 mm) and in the upper subsoil (250 – 350 mm). These differences occurred at the same depths where cultivation treatments were combined with CWW but occurred slightly deeper where combined with ALTCC (250 – 350 mm only). Growing cover crops and reducing the intensity of cultivation have been shown to improve soil physical structure and function (Blanco-Canqui et al., 2015; Chen and Weil, 2011; Tebrügge and Düring, 1999). Improved soil physical structure and function, in turn, improves water infiltration, conductivity and storage (Alaoui and Goetz, 2008; Hamza and Anderson, 2005; Menon et al., 2015), which may explain why treatments ALTCC, SHALLOW and DEEP had a positive impact on subsoil VSM. Higher VSM in the subsoil may better support arable crop growth (Kirkegaard et al., 2007). However, it is also important to acknowledge that the risk of subsoil compaction increases with higher VSM (Alakukku et al., 2003). Therefore, the degree to which higher subsoil VSM may affect the risk of field operations causing further subsoil compaction should also be considered when assessing rotation and cultivation approach.

VSM was high for the soil type across all treatments and collection dates. Field measurement of VSM using capacitance probes has been shown to be prone to error in accurately recording absolute soil moisture due to soil disturbance during apparatus installation and variation between soil types (Nadler et al., 2002; Susha

Lekshmi et al., 2018). However, provided installation methodology is consistent across an experiment, field measurement of VSM using capacitance probes has been shown to provide a good basis for experimental comparisons regardless (Tomer and Anderson, 1995).

The laboratory analyses conducted on the undisturbed soil cores further investigated the field monitoring observations. Unsaturated hydraulic conductivity (K_{unsat}) data was highly variable and significant differences between treatments were not found. This may have been due to experimental treatments not significantly affecting K_{unsat} . However, it would be interesting to follow up the measurements obtained using alternative methods to investigate whether improved results for small volume, undisturbed soil samples may be achieved, and whether alternative methods may provide a more reliable measurement for water movement in subsoil compared to surface infiltration (Cimpoiasu et al., 2021; Madsen and Chandler, 2007).

Significant differences in water stable aggregates occurred in the 0 – 200 mm depth only. Reducing the depth of cultivation (SHALLOW) and combining cultivation treatment DEEP with ALTCC rotation both resulted in increased water stable aggregates compared to the PLOUGH treatment. Water stable aggregates have been related to subsoil properties (Bartlova et al., 2015; Bronick and Lal, 2004) but has been more widely applied to soil surface properties, for example soil erosion (Amézketa, 1999; Pulido Moncada et al., 2015). Further investigation using recently published wet aggregate stability methods that focus on below surface properties (Hudek et al., 2021) may help to clarify if any benefit from rotation or cultivation approach extends to the subsoil.

In agreement with the field monitoring VSM results, PLOUGH treatment recorded lower soil water retention compared to DEEP within the treatment working depths and into the subsoil (200 – 400 mm depth at 200 and 1500 kPa; 600 – 800 mm at 1500 kPa). Lower water retention at 200 and 1500 kPa water potentials indicated the subsoil under PLOUGH treatment was less able to retain water under drying field conditions at these depths. Lower subsoil water retention may limit the ability of the subsoil support arable plant growth in drying conditions

(Bengough et al., 2011; McKenzie et al., 2009). Water retention at 5 kPa (600 – 800 mm) was higher for SHALLOW treatment compared to DEEP where combined with ALTCC, and CWW rotation had higher water retention compared to ALTCC where combined with treatment DEEP, which contrasted the VSM field monitoring results.

Research has indicated that the root systems of different plant species vary in their ability to alleviate subsoil compaction, and root thickness (Chen and Weil, 2010; Clark et al., 2003; Materechera et al., 1992) and root density (Bodner et al., 2014; Burr-Hersey et al., 2017; Hudek et al., 2021) have been put forward as significant factors. However, there are contrasting results on the relevant importance of root characteristics for the alleviation of soil compaction (Chen and Weil, 2011; Gao et al., 2016; Pulido-Moncada et al., 2021, Pulido-Moncada et al., 2020). The root results presented in this paper showed that reducing the depth of cultivation (SHALLOW) resulted in benefits for root characteristics in the subsoil. Where data was averaged over all depths, SHALLOW cultivation had a higher root diameter compared to DEEP cultivation, higher root length compared to PLOUGH cultivation, and higher root biomass compared to both PLOUGH and DEEP cultivation. These trends were broadly the same whether cultivation treatments were combined with CWW or ALTCC rotation, which suggested cultivation treatment was the dominant factor.

Where root characteristics were compared over depth, results showed that the benefits occurred at the deepest subsoil depths measured and that rotation treatment had a significant effect. SHALLOW treatment averaged across the rotation treatments had higher root length compared to PLOUGH and DEEP treatments (600 – 800 mm depth), and ALTCC averaged across all cultivation treatments had higher root length compared to CWW (600 – 800 mm). Where combined with SHALLOW cultivation, ALTCC had higher root diameter and length compared to CWW (600 – 800 mm), and combined with either rotation the SHALLOW treatment had the highest root length (600 – 800 mm). Reducing the depth of cultivation (SHALLOW treatment) had a positive impact on root characteristics in the subsoil and ALTCC rotation appeared to provide an

additional benefit in combination, compared to CWW. Increased rooting in the subsoil leads to greater biopore formation through the cycling of root creation and exploration of pores, and subsequent root decay (Cresswell and Kirkegaard, 1995; Wahlström et al., 2021). This has been shown to improve soil functions in compacted layers (Han et al., 2015; Kautz, 2015; Perkons et al., 2014).

There was also a significant root diameter response to PLOUGH cultivation in the 200 – 400 mm depth. At this depth, PLOUGH treatment had a higher root diameter compared to both DEEP and SHALLOW cultivation, whereas deeper in the subsoil this trend was reversed with SHALLOW cultivation having higher root diameter compared to PLOUGH and DEEP treatment (600 – 800 mm). The same trend occurred where cultivation treatments were combined with ALTCC rotation but not with CWW, which at the 200 – 400 mm depth suggested parallels with the PR data. The ability to modify root diameter in response to compaction has been suggested to be an important trait in compaction alleviation (Clark et al., 2003; Hamza and Anderson, 2005). Therefore, the alleviation of the compacted pan layer observed in the PR data may be attributed to increased root diameter with ALTCC rotation (Szatanik-Kloc et al., 2019) compared to CWW and is worthy of future investigation. In this experiment root material was not separated by species and therefore it is not possible to expand on whether the differences in root characteristics were solely as a consequence of ALTCC rotation, or whether subsequent use and exploration by winter wheat was also influential. This would be useful to determine in future studies to improve understanding of biopore creation and utilisation with cover crops under field conditions, to attribute any subsoil compaction alleviation and to inform cover crop sequencing in the field.

X-ray CT was used to investigate soil pore characteristics in the 200 – 400 mm layer. SHALLOW cultivation had higher pore surface area compared to both PLOUGH and DEEP cultivation and, where combined with ALTCC rotation, SHALLOW cultivation had higher pore volume and pore surface area compared to DEEP treatment. ALTCC rotation had higher porosity compared to CWW but only where combined with SHALLOW cultivation. SHALLOW cultivation also had higher pore frequency across the 28 – 5000 µm pore size categories (meso to

macropores) compared to DEEP treatment, and higher pore frequency in the >5000 μm pore size category (soil cracks) compared to PLOUGH and DEEP. Where combined with CWW rotation, SHALLOW cultivation had higher pore frequency across all pore size categories compared to PLOUGH and DEEP. Whereas, where combined with ALTCC, SHALLOW cultivation only had higher pore frequency compared to DEEP in the >5000 μm pore size category (soil cracks).

The X-ray CT results showed that minimising cultivation (SHALLOW treatment) resulted in an improvement in soil pore volume, surface area and frequency. An additional benefit could be gained by combining SHALLOW treatment with ALTCC rotation in terms of soil pore characteristics and the frequency of large pores. Greater porosity and pore function are linked to reduced compaction and confer better subsoil conditions to support arable crop growth (de Lima et al., 2017). Pore frequency was high across all size categories, which may have been as a result of the segmentation process not adequately distinguishing pore continuity. In future, fitting PSD data derived from images to known distributions may provide a more accurate estimation of PSD, as suggested in Houston et al. (2017).

Repeated cover cropping (ALTCC) resulted in some benefits to subsoil physical structure and functions that indicated lower compaction compared to CWW rotation. However, reducing the depth of cultivation (SHALLOW) provided significant benefits to subsoil physical structure and functions, which suggested that overall, ALTCC rotation had a contributory role to cultivation. The three alternative management approaches considered (ALTCC rotation, DEEP cultivation and SHALLOW cultivation) increased subsoil moisture compared to the controls (CWW rotation, PLOUGH cultivation). Although this may increase the risk of subsoil compaction (Arvidsson et al., 2001; Horn, 1990), the potential benefits to crop growth in an increasingly variable climate outweigh potential negatives, especially where appropriate subsoil compaction avoidance technology is used (e.g. controlled traffic farming (Chamen et al., 2003)).

The compacted pan layer observed with PLOUGH cultivation, subsequent root responses and potential alleviation, highlights the requirement to consider the whole approach to field operations when choosing alternative approaches to mechanical cultivation for subsoil compaction. Despite SHALLOW treatment providing the greatest benefits to the subsoil, if inversion cultivation is a requirement then perhaps ALTCC rotation presents a mitigation measure. Further work to define this relationship under a wider variety of soil types is required.

Improved understanding of biological alternative methods to mechanical alleviation of subsoil compaction are likely to enable practitioners to utilise technologies in the field and increase adoption (Freluh-Larsen et al., 2018; Storr et al., 2019). Evidence presented here suggested repeated cover cropping and reducing the intensity of cultivation over the long-term have potential to avoid the need and negative impacts of mechanical cultivation for subsoil compaction. Although economic analysis of the rotation and cultivation approaches was outside the scope of this paper, it is relevant to acknowledge that replacing a cash crop with a long season cover crop (treatment ALTCC) would have a significant negative impact on economic output (Bergtold et al., 2017; Brady et al., 2019). It would be useful to replicate the research presented here with a cover crop treatment that is terminated following the UK winter period to allow for the inclusion of a summer cash crop in the annual cycle, which would provide a more realistic representation of on-farm application (Bhogal et al. 2020).

3.6 Conclusions

Subsoil compaction in arable soils reduces the efficiency of arable crop production and has the potential to affect the wider environment. Repeated cover cropping (ALTCC) demonstrated positive benefits to subsoil physical structure and function compared to the control (CWW) and avoids the negative consequences of mechanical subsoil compaction alleviation. However, reducing the intensity of cultivation through cultivating at shallower depths (SHALLOW) or using non-inversion (DEEP) had a generally positive impact on subsoil properties and strongly influenced any benefit garnered from ALTCC rotation. The

combination of ALTCC rotation and SHALLOW cultivation produced the greatest benefits to subsoil properties. These results were observed after 13 consecutive seasons of treatment application and therefore, it is likely that repeated cover cropping does not replace mechanical subsoil alleviation in the short-term but instead forms part of a long-term, proactive not reactive strategy to preventing and alleviating subsoil compaction. Further characterisation of cover crop rotation and cultivation approach across a wider variety of subsoil types and arable rotations is required to provide useful advice for industry practitioners.

3.7 References

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4 The effect of cover crops on arable crop performance under three levels of subsoil compaction

Objective: To determine the potential of two cover crop species to alleviate subsoil compaction and provide a benefit to a following arable crop, and if this effect increases over two consecutive seasons

Hypotheses:

1. Cover crops will provide greater alleviation of subsoil compaction compared to a control and will increase following crop performance
2. Brassica cover crop species will provide greater alleviation of subsoil compaction compared to graminaceous species

Target Journal Publication: Soil Use and Management

4.1 Abstract

The biopores created by the growth of cover crops in compacted subsoil have been suggested as an approach to improve compacted subsoil function and subsequent arable crop performance. However, there is not adequate evidence to support cover crop species choice or the expected benefits to arable crops. Therefore, this paper aimed to determine the interaction of cover cropping with subsoil compaction and the subsequent effect on arable crop performance. A glasshouse experiment using 1 m deep growth tubes was established and run over two consecutive growing seasons. Subsoil layers (300 – 1000 mm depth) received one of three compaction treatments (bulk densities 1.2, 1.4 and 1.6 g cm⁻³). Three cover crop treatments (no cover crop, SMART radish and black oat) were applied during the autumn/winter period and all growth tubes grew a spring barley arable crop during the spring and summer period. The experiment was duplicated in the first season to allow destructive sampling after both seasons. Throughout both seasons, plant morphology and yield components were collected, soil physical functions were characterised, root morphology was digitally imaged and biomass determined. The results showed that high subsoil compaction had a negative effect on spring barley performance and neither cover crop treatment significantly alleviated this effect compared to the control.

However, both cover crop treatments significantly increased root proliferation in compacted subsoil compared to the control. Furthermore, cover crop treatments SMART radish and black oat presented different root traits in response to compacted subsoil, which depending on future research as to the relative importance of root traits for subsoil compaction, may indicate one may be preferable. Further research is required to determine the relative importance of root traits under field conditions over a longer term.

4.2 Introduction

Subsoil compaction is a significant soil challenge for the sustainability of arable agriculture (Keller et al., 2019; Schonning et al., 2018). Risk modelling shows that c. 40 % of arable subsoils in European countries may already be detrimentally affected by subsoil compaction (Brus and Van Den Akker, 2018; Schonning and Thorsoe, 2019). Subsoil compaction results in a decrease in soil pore volume and connectivity (Berisso et al., 2012) that are key to support sustainable, resilient crop growth (Alakukku, 1999). Reduction in subsoil pore volume and connectivity reduces water availability and gaseous exchange (Lipiec and Hatano, 2003; Tracy et al., 2011), which combined with high subsoil strength, may limit root growth and crop performance (Pandey et al., 2021; Valentine et al., 2012; White and Kirkegaard, 2010).

Alleviation of subsoil compaction to support crop growth should aim for the creation of fissures and cracking in the subsoil to improve water and gas transport, and facilitate rooting, without excessive disruption and weakening of the soil profile (Spoor et al., 2003). Mechanical cultivation of compacted subsoil has a positive short-term effect, however benefits are generally short-lived, and mechanical cultivation leaves the soil vulnerable to recompaction from subsequent field operations (Chamen et al., 2003; Olesen and Munkholm, 2007) and natural processes (Schneider and Don, 2019).

Biological alleviation methods that exploit natural characteristics of plant roots to improve compacted soil properties have been suggested as an alternative to mechanical cultivation (Cresswell and Kirkegaard, 1995; Hamza and Anderson, 2005). Growing 'cover crops' between arable crops allows the integration of root growth traits aimed specifically at compaction alleviation into the rotation (Rosolem et al., 2002). Channels created by roots through compacted subsoil ('biopores') have been shown to increase crop root depth by recolonisation (Dexter, 1991; Kautz, 2015; Landl et al., 2019; Perkons et al., 2014), improve water and gas transport (Lipiec and Hatano, 2003; Uteau et al., 2013), and to be stable over time, resisting recompaction (Schaffer et al., 2008, Schaffer et al., 2007). Colonisation of pre-existing biopores has been shown to be a significant

approach by arable crops to cope with compacted soil layers (Atkinson et al., 2020).

Plants differ in their ability to penetrate compacted subsoil. Although monocotyledons (e.g. grasses) can penetrate compacted layers (Burr-Hersey et al., 2017), compaction alleviation has been shown to be more efficient with dicotyledons, particularly tap-rooted species (Beck-Broichsitter et al., 2020; Clark et al., 2003; Materechera et al., 1991). These tap-rooted species are able to modify their root diameter in response to compaction, which may improve the alleviation of compaction compared to other species (Chen and Weil, 2011; Hamza and Anderson, 2005). That said, evidence has also shown that grass species may have similar potential (Burr-Hersey et al., 2017), with the role of overall root biomass, as opposed to diameter, previously underestimated (Hudek et al., 2021).

Generation of biopores is positive in the biological remediation of subsoil compaction (Schneider and Don, 2019) and beneficial effects have been shown on arable crop root growth and yield components (Kirkegaard et al., 2008; Perkons et al., 2014; Pulido-Moncada et al., 2021). However, there is a lack of evidence on how specific cover crop species interact with subsoil compaction and the impact on arable crop performance. This is because the effectiveness of cover crop species varies dependent on the species root system, management practices, repetition (Blanco-Canqui and Jasa, 2019), soil conditions and type of soil compaction (Blanco-Canqui et al., 2015; Lofkvist, 2005; Welch et al., 2016). Lack of detailed knowledge has been highlighted as a limitation in the adoption of biological approaches in the field (Frelih-Larsen et al., 2018; Storr et al., 2019). Therefore, the objective of this study was to explore the potential of two different cover crop species to alleviate three levels of subsoil compaction, and provide a benefit to a following arable crop, over two consecutive seasons.

4.3 Materials and methods

4.3.1 Experimental set up and design

A cover crop, subsoil compaction and yield experiment was established in a non-heated growth tunnel at Cranfield University (UK) in 2018. A polyester mesh voile base was fixed to 54 polyvinyl chloride (PVC) tubes to create columns of 1000 x 225 mm (h x d) (Fig. 4.1). The column volume was divided into two layers, the topsoil (0 – 300 mm depth) and the subsoil (300 – 1000 mm depth). A 50 mm (Ø) access hole was drilled into the centre of each layer (topsoil 150 mm and subsoil 650 mm) for volumetric soil moisture (VSM) measurement and the VSM access holes were double sealed with polyethylene cloth tape. The columns were placed in a PVC tray with drainage holes on a freely draining, level surface.

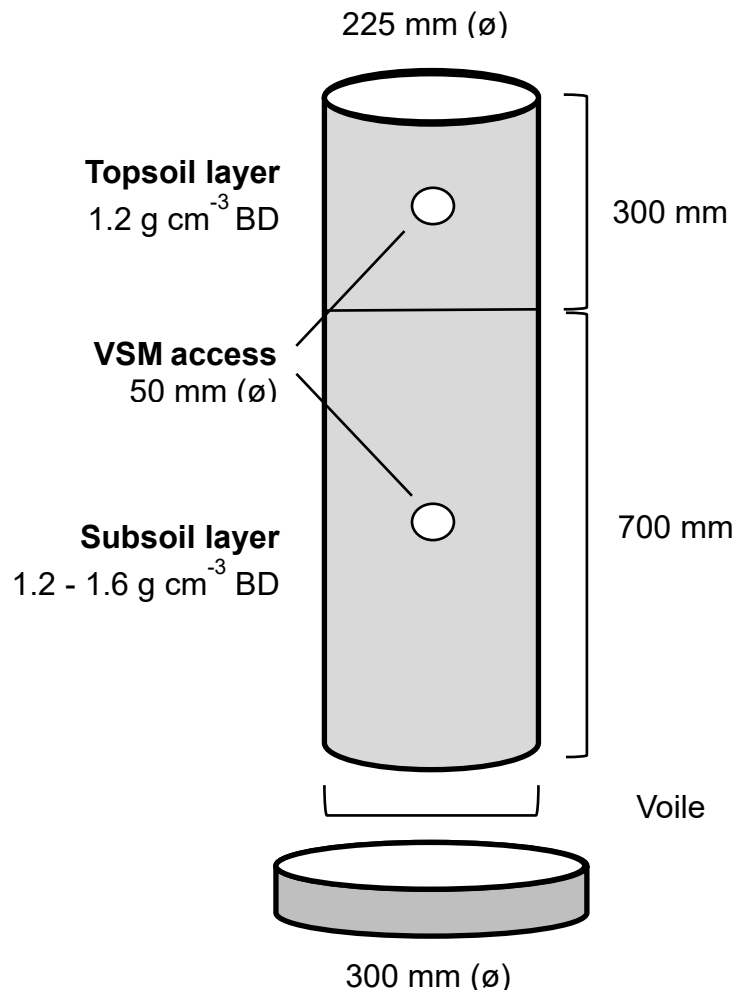


Figure 4.1 Soil column apparatus showing the topsoil layer, subsoil layer, PVC pot, tray and voile (BD – bulk density, VSM – volumetric soil moisture).

The topsoil layer texture was a sandy clay loam (Boughton Loam Ltd., UK) and the subsoil layer texture was a sandy loam (Bourne Amenity Ltd., UK) (Table 4.1). All topsoil layers were packed to a bulk density of 1.2 g cm⁻³ and the subsoil layers were packed to three different bulk densities 1.2, 1.4 and 1.6 g cm⁻³ (Table 4.2) following the treatment structure (detailed below). Compaction was achieved by compacting a known soil mass into a known volume, using a 200 mm (ø) wooden disk, struck with a 3 kg weight, in 100 mm layers for consistent compaction.

Table 4.1 Topsoil and subsoil layer properties

Layer	Bulk density (g cm ³⁻¹)	Depth (mm)	Soil texture (%)	pH	OM (%)
Topsoil	1.2	0 - 300	SCL S 52% Z 28% C 20%	7.2	6.2
Subsoil	1.2	300 - 1000	SL S 74% Z 12% C 14%	6.3	0.7
Subsoil	1.4				
Subsoil	1.6				

Cover crop and subsoil compaction treatments were applied to each column in a randomised, factorial design with each treatment triple replicated (n = 27 columns) (Table 4.2). Cover crop treatments included a control (no cover crop; NC) and two cover crops (SMART radish [*Raphanus sativus*; IAR Agri Ltd., UK] and black oat [*Avena strigose*]). Treatment NC was left fallow during the autumn/winter periods (C1/C3), while SMART radish (SR) and black oat (BO) were grown during the autumn/winter periods (C1/C3) (Table 4.2). Cover crops were grown without agrochemical and fertiliser inputs.

Table 4.2 Cover crop and subsoil compaction treatment application timeline and treatment descriptions (spring barley (*Hordeum vulgare*) var. Planet (RAGT Seeds Ltd., UK)).

	Season 1		Season 2	
	C1	C2	C3	C4
Treatment application timeline	Cover crops sown 15.10.18	Spring barley sown 11.03.19	Cover crops sown 14.10.19	Spring barley sown 16.03.20
	Cover crop harvested 23.01.19	Spring barley harvested 08.08.19	Cover crops harvested 21.01.20	Spring barley harvested 10.08.20
Cover crop treatments				
NC	‘No cover crop’ grown during the autumn/winter period (Oct - Jan)			
SR	‘SMART radish’ (<i>Raphanus sativus</i>) (IAR Agri Ltd., UK) grown during the autumn/winter period (Oct - Jan)			
BO	‘Black oat’ (<i>Avena strigosa</i>) grown during the autumn/winter period (Oct - Jan)			
Subsoil compaction treatments				
1.2	Subsoil layer compacted to bulk density 1.2 g cm ⁻³			
1.4	Subsoil layer compacted to bulk density 1.4 g cm ⁻³			
1.6	Subsoil layer compacted to bulk density 1.6 g cm ⁻³			

The experiment ran over two growing seasons. To allow for destructive sampling after both seasons, the experiment was duplicated in the first season ($n = 54$ columns total). The experiment was divided into four growth periods (Table 4.2); C1 first cover crop (sown 15.10.2018/harvested 23.01.2019), C2 first spring barley crop (sown 11.03.2019/harvested 08.08.2019), C3 second cover crop (sown 14.10.2019/harvested 21.01.2020) and C4 second spring barley crop (sown 16.03.20/harvested 10.08.2020). Periods C1 and C2 formed 'season 1' and periods C3 and C4 formed 'season 2'.

Spring barley (*Hordeum vulgare* var. Planet (RAGT Seeds Ltd., UK)) was grown in all pots during periods C2 and C4 of both seasons. Spring barley crops received two plant protection treatments of Siltra Xpro (Bayer, Germany) (60 g l^{-1} bixafen, 200 g l^{-1} prothioconazole) at rate equivalent to 0.4 l ha^{-1} and Bravo 500 (Syngenta, Switzerland) (500 g l^{-1}) (chlorothalonil) at rate equivalent to 1.0 l ha^{-1} . Plant protection treatments were applied at growth stage 25 – 30 (at end of tillering and before stem extension) and at growth stage 39 – 45 (between flag leaf emergence and booting) using a flat fan nozzle. A granular, blended NPK 7-7-7 fertiliser (Growmore, UK) was surface applied prior to periods C2 and C4 at rate equivalent to $140 \text{ kg nitrogen ha}^{-1}$ to meet requirements determined using the RB209 nutrient management guide (AHDB, 2018b). Regrowth of all crops was terminated after each growth period using 7.2 g l^{-1} solution of Glyphosate 360 (Bayer, Germany) (360 g l^{-1}) (glyphosate).

VSM (%) was measured at weekly intervals during each growth period using a soil moisture probe (Delta-T Devices, SM150T) via the VSM access holes. VSM (%) at field capacity (FC), 1/3 drainage, 2/3 drainage and permanent wilting point (PWP) was estimated for the soil layers (Knox et al., 2008; Zotarelli et al., 2019) and weekly surface applied irrigation rate adjusted to maintain both soil layers between 1/3 (VSM topsoil 19.0 %; VSM subsoil 11.5 %) and 2/3 drainage (VSM topsoil 13.9 %; VSM subsoil 8.7 %).

4.3.2 Cover crop and spring barley above ground methods

4.3.2.1 Cover crop tiller/leaf number and dry biomass

Cover crop above ground biomass was harvested at the end of growth periods C1 and C3. Leaf counts (n) were collected from the SR treatment and tiller counts (n) were collected from the BO treatment. All cover crop biomass was then oven dried at 65°C for 48 hours and mass (g) recorded.

4.3.2.2 Spring barley dry biomass and yield components

Spring barley above ground biomass was harvested at the end of growth periods C2 and C4. Ears and straw were separated, and straw was oven dried at 65°C for 48 hours and mass (g) recorded. Ears were oven dried at 30°C for 48 hours to attain a consistent grain moisture. Ear number (EN) (n) and grains per ear (GPE) (n) were recorded, grain was then threshed and residue discarded. Threshed grain was used to determine 1000 grain weight (TGW) (g), specific grain weight (SGW) (g) and total grain weight (GW) (g) (BS EN SIO 520:2010; 7971-3:2019; BSI, 2020). Grain protein content (%) was then determined by near infrared spectroscopy (NIR) (BSI EN 15948:2015, BSI (2015)) by NIAB LabTest (Cambridge, UK). NIR was carried out using an Infratec 1241 NIR Grain Analyser (FOSS Analytics, UK) collecting four replicates per sample.

4.3.3 Soil and root methods

4.3.3.1 Penetration resistance and saturated hydraulic conductivity

Penetration resistance (PR) (MPa) and saturated hydraulic conductivity (K_{sat}) (mm hr^{-1}) were measured prior to destructive sampling at the end of growth periods C2 and C4. Prior to the determination of PR and K_{sat} , all pots were gradually watered until soil was saturated and then left to drain for 72 hours.

Each pot had one PR measurement collected using a manually operated digital penetrometer (Eijelkamp Digital Penetrologger V.6.13) to 800 mm depth fitted with a 1.2 cm^2 30° cone. Each pot had one K_{sat} measurement collected using single ring apparatus (100 x 110 mm, h x d), driven 30 mm into the soil surface. A falling-head approach (Reynolds, 2008) was used to measure the time taken

for a ponded head to flow into the soil. Measurements were repeated until a K_{sat} plateau was reached. K_{sat} was calculated as in Equation 4.1.

$$K_{sat} \text{ (mm hr}^{-1}\text{)} = (TD/WLD)*60 \quad \text{Equation 4.1}$$

TD – time difference (min) between beginning and end of measurement

WLD – water level difference (mm) between beginning and end of measurement

4.3.3.2 Soil bulk density and root sampling

Bulk density (BD) (g cm^{-3}) and root material were collected following PR and K_{sat} measurement at the end of growth periods C2 and C4. Sampling was achieved by dividing the 1000 mm soil column into 5 x 200 mm layers and individually sampling each layer. BD (g cm^{-3}) was determined by taking one sample per layer, oven drying at 105°C for 24 hours and mass (g) recorded. After BD sampling, all remaining soil from each layer was washed over a 1 mm sieve and all root material retained. Root material was optically scanned (Reagent Instruments, SDT4800) at 400 dpi. Mean root diameter (RD) (mm) and total root length (RL) (mm) were measured using WinRHIZO software (Reagent Instruments, WinRHIZO Pro). Root material was then oven dried at 65°C for 24 hours to determine dry root biomass (RB) (g).

4.3.4 Statistical analyses

Results were analysed using IBM SPSS (IBM SPSS Statistics, V26). Data was checked for normality by plotting a histogram and quantile-quantile plots. The values of RD and RL were $\log_{10}$ transformed to normalise the data distribution. Factorial ANOVA was used to analyse data without a depth factor and repeated measures factorial ANOVA was used to analyse data that had depth as a factor (treating depth as a within-subjects variable). PR data was averaged at 50 mm intervals and the repeated measures factorial ANOVA was conducted with these intervals as the depth factor. Where significant effects were observed, these were followed by an unprotected Fischer's least significant difference (LSD) test. Standard error and error bars represent the standard error of the means for the

treatment comparison and/or depth category discussed (SE). Relationships between soil physical properties and plant characteristics were investigated using Pearson's correlation. All tests were conducted at the 5% significance level.

4.4 Results

4.4.1 Cover crop tiller/leaf number and dry biomass

After C1, BO had a significantly higher ($P = 0.05$; $SE = 1.37$) number of tillers at the 1.2 subsoil compaction treatment compared to 1.4 and 1.6 (Table 4.3). After C3, BO had a significantly higher ($P = 0.01$; $SE = 1.92$) number of tillers at the 1.6 subsoil compaction treatment compared to 1.2 and 1.4 (Table 4.3). No significant differences were recorded between the leaf counts for SR between subsoil compaction treatments or between the dry biomass measurements of the cover crops.

Table 4.3 Cover crop treatment leaf number (SMART radish - SR) and tiller (black oat - BO) counts (n) and cover crop dry biomass (g). Letters represent significant ($P \leq 0.05$) differences within a row.

			Subsoil compaction treatment (g cm ⁻³)		
	Growing season	Cover crop treatment	1.2	1.4	1.6
Leaf no. (SR) or tiller (BO) count (n)	Season 1	SR	16.0	17.3	18.5
	(C1)	BO	21.3 ^a	18.5 ^b	18.5 ^b
	Season 2	SR	18.3	18.7	19.7
	(C3)	BO	15.7 ^a	17.3 ^a	21.7 ^b
Cover crop dry biomass (g)	Season 1	SR	12.1	12.2	11.6
	(C1)	BO	12.3	11.9	11.3
	Season 2	SR	27.4	27.6	24.8
	(C3)	BO	13.3	14.6	13.6

4.4.2 Spring barley dry biomass and yield components

4.4.2.1 1000 grain weight

Mean cover crop treatment comparisons showed that following C2, NC had a significantly higher 1000 grain weight (TGW) compared to SR and BO ($P = <0.01$ and <0.01 respectively; $SE = 0.54$) (Table 4.4). Following C4, SR and BO had a significantly higher TGW compared to NC ($P = <0.01$ and 0.02 respectively; $SE = 0.72$) (Table 4.4). Mean subsoil compaction treatment comparisons showed that following C2, subsoil compaction treatments 1.2 and 1.4 had significantly higher TGW compared to 1.6 ($P = 0.01$ and 0.02 respectively; $SE = 0.54$), and following C4, subsoil compaction treatment 1.2 had significantly higher TGW compared to 1.4 ($P = <0.01$; $SE = 0.72$) (Table 4.4).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.2, NC had significantly higher TGW compared to SR and BO ($P = 0.01$ and 0.01 respectively; $SE = 0.94$) (Table 4.4). Combined with subsoil compaction treatment 1.4, NC had significantly higher TGW compared to SR and BO, and SR had significantly higher compared to BO ($P = 0.02$, <0.01 and <0.01 respectively; $SE = 0.94$) (Table 4.4). Similarly, in combination with subsoil compaction treatment 1.6, NC had significantly higher TGW compared to SR ($P = 0.01$; $SE = 0.94$) (Table 4.4). Combined with cover crop treatments NC and SR, 1.2 and 1.4 had significantly higher TGW compared to 1.6 (NC – $P = <0.01$ and 0.01 , SR $P = 0.03$ and <0.01 respectively; $SE = 0.94$), and in combination with cover crop treatment BO, 1.2 had significantly higher TGW compared to 1.6 ($P = 0.02$; $SE = 0.94$) (Table 4.4).

Following C4, combined with subsoil compaction treatment 1.4, SR had significantly higher TGW compared to NC and BO ($P = <0.01$ and <0.01 respectively; $SE = 1.24$), and in combination with cover crop treatment NC, 1.2 and 1.6 had higher TGW compared to 1.4 ($P = <0.01$ and <0.01 respectively; $SE = 1.24$) (Table 4.4).

4.4.2.2 Specific grain weight

Mean cover crop treatment comparisons showed that following C2, SR had significantly higher specific grain weight (SW) compared to NC and BO ($P = 0.01$ and <0.01 respectively; $SE = 0.33$) (Table 4.4). Mean subsoil compaction treatment comparisons showed that following C2, subsoil compaction treatment 1.4 had significantly higher SW compared to 1.6 ($P = 0.04$; $SE = 0.33$) (Table 4.4).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.2, SR and BO had significantly higher SW compared to NC ($P = <0.01$ and 0.01 respectively; $SE = 0.57$) (Table 4.4). Combined with subsoil compaction treatment 1.4, NC and SR had significantly higher SW compared to BO ($P = <0.01$ and 0.01 respectively; $SE = 0.57$) (Table 4.4). Combined with cover crop treatment NC, 1.4 had significantly higher SW compared to 1.2 ($P = <0.01$; $SE = 0.57$) and in combination with both SR and BO, 1.2 had significantly higher SW compared to 1.6 ($P = <0.01$ and 0.04 respectively; $SE = 0.57$) (Table 4.4).

Following C4, in combination with subsoil compaction treatment 1.4, SR had significantly higher SW compared to both NC and BO ($P = 0.01$ and 0.03 respectively; $SE = 0.86$) (Table 4.4).

4.4.2.3 Ear number

Mean cover crop treatment comparisons showed that following C2, NC had significantly higher ear number (EN) compared to SR ($P = 0.04$; $SE = 0.72$) (Table 4.4). Mean subsoil compaction treatment comparisons showed that following both C2 and C4, subsoil compaction treatment 1.6 had significantly higher EN compared to 1.2 ($P = 0.01$; $SE = 0.72$ and $P = 0.02$; $SE = 1.61$ respectively) (Table 4.4).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.4, BO had significantly higher EN compared to SR ($P = 0.01$; $SE = 1.24$), and under subsoil compaction treatment 1.6, NC had significantly higher EN compared to BO ($P =$

0.01; SE = 1.24) (Table 4.4). Combined with NC cover crop treatment, 1.6 had significantly higher EN compared to both 1.2 and 1.4 ($P = <0.01$ and 0.01 respectively; SE = 1.24), and in combination with SR, 1.6 had significantly higher EN compared to 1.4 ($P = 0.03$; SE = 1.24) (Table 4.4).

Following C4, in combination with subsoil compaction treatment 1.4, NC had significantly higher EN compared to SR ($P = 0.03$; SE = 2.78). In combination with SR cover crop treatment, 1.6 had significantly higher EN compared to 1.4 ($P = 0.01$; SE = 2.78) (Table 4.4).

4.4.2.4 Grains per ear

Mean cover crop treatment comparisons showed that following C4, NC and BO had significantly more grains per ear (GPE) compared to SR ($P = 0.01$ and 0.01 respectively; SE = 0.52) (Table 4). Mean subsoil compaction treatment comparisons showed that following both C2 and C4, subsoil compaction treatment 1.2 had significantly more GPE compared to 1.6 ($P = 0.02$ and 0.02; SE = 0.36 and 0.52 respectively) (Table 4.4).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.4, NC had significantly more GPE compared to BO ($P = 0.02$; SE = 0.62), and in combination with NC cover crop treatment, 1.2 had more GPE compared to 1.6 ($P = 0.05$; SE = 0.62) (Table 4.4).

Following C4, in combination with subsoil compaction treatment 1.2, NC had significantly more GPE compared to SR, and in combination with subsoil compaction treatment 1.4, BO had significantly more GPE compared to SR ($P = 0.02$ and 0.02 respectively; SE = 0.89) (Table 4.4). Combined with cover crop treatment NC, 1.2 had significantly more GPE compared to 1.6, and in combination with cover crop treatment SR, 1.4 had significantly more GPE compared to 1.6 ($P = 0.04$ and 0.05 respectively; SE = 0.89) (Table 4.4).

4.4.2.5 Total grain weight

Mean cover crop treatment comparisons showed that following C2, NC had significantly higher total grain weight (GW) compared to SR and BO ($P = <0.01$

and 0.01 respectively; SE = 0.87) (Table 4.4). Following C4, NC had significantly higher GW compared to SR ($P = 0.03$; SE = 1.17) (Table 4.4). Mean subsoil compaction treatment comparisons showed that following C4, subsoil compaction treatment 1.6 had significantly higher GW compared to 1.2 ($P = 0.04$; SE = 2.21) (Table 4.4).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatments 1.4 and 1.6, NC had significantly higher GW compared to SR and BO (1.4 – $P = 0.01$ and 0.04 respectively, 1.6 – $P = 0.03$ and 0.02 respectively; SE = 1.50) (Table 4.4).

Following C4, in combination with subsoil compaction treatment 1.4, NC and BO had significantly higher GW compared to SR ($P = 0.01$ and <0.01 respectively; SE = 3.83) (Table 4.4). Combined with cover crop treatment SR, 1.2 and 1.6 both had significantly higher GW compared to 1.4 ($P = 0.01$ and 0.01 respectively; SE = 3.83) (Table 4.4).

4.4.2.6 Grain protein

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.2, NC had significantly higher grain protein (GP) compared to SR and BO ($P = 0.03$ and 0.02 respectively; SE = 0.24) (Table 4.4).

Following C4, in combination with subsoil compaction treatment 1.2, NC had significantly higher GP compared to SR ($P = 0.04$; SE = 0.17) (Table 4.4). Combined with cover crop treatment NC, 1.2 had significantly higher GP compared to 1.6 ($P = 0.04$; SE = 0.17) (Table 4.4).

4.4.2.7 Straw dry biomass

Mean cover crop treatment comparisons showed that following C2, NC had significantly higher straw dry biomass (SB) compared to BO ($P = <0.01$; SE = 0.75), and BO had significantly higher SB compared to SR ($P = <0.01$ and 0.02 respectively; SE = 0.75) (Table 4.4). Following C4, NC had significantly higher SB compared to SR ($P = 0.01$; SE = 1.17) (Table 4.4). Mean subsoil compaction

treatment comparisons showed that following C1, subsoil compaction treatment 1.2 had significantly higher SB compared to 1.6 ($P = 0.01$; SE 0.75) (Table 4.4).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, NC had higher SB compared to SR and BO where combined with all the subsoil compaction treatments ($P = <0.01$; SE = 1.30), and in combination with NC, 1.2 had significantly higher SB compared to 1.6 ($P = 0.03$; SE = 1.30) (Table 4.4). Combined with subsoil compaction treatment 1.2, BO had significantly higher SB compared to SR ($P = 0.02$; SE = 1.30) (Table 4.4).

Following C4, in combination with SR cover crop treatment, 1.2 had significantly higher SB compared to 1.4 ($P = 0.01$; SE = 2.03), and in combination with BO rotation treatment, 1.4 had significantly higher SB compared to 1.6 ($P = 0.05$; SE = 2.03) (Table 4.4). Combined with subsoil compaction treatment 1.4, BO had significantly higher SB compared to SR ($P = <0.01$; SE = 2.03) (Table 4.4).

Table 4.4 Spring barley (*Hordeum vulgare* var. Planet (RAGT Seeds Ltd., UK)) characteristics. Cover crop treatments: NC – ‘no cover crop’, SR – ‘SMART radish’ (*Raphanus sativus*), BO – ‘black oat’ (*Avena strigosa*); subsoil compaction treatments: 1.2 – ‘1.2 g cm⁻³, 1.4 – ‘1.4 g cm⁻³, 1.6 – ‘1.6 g cm⁻³. Significant ($P \leq 0.05$) differences are separated into seasons 1 and 2, and are organised by column. Lowercase letters without parentheses represent differences within a section e.g.^{a,b,c}, and uppercase letters, numbers and symbols with parentheses represent differences between sections e.g.^{(A/B),(1/2),(*/**)}.

	Treatment	1000-grain weight (g)	Specific weight (kg hl ⁻¹)	Ear no. (n)	Grains per spike (n)	Total grain weight (g)	Grain protein (g 100g ⁻¹ dmb)	Straw dry biomass (g)
Season 1	NC	60.8 ^a	70.6 ^a	28.8 ^a	20.6	32.9 ^a	15.0	25.0 ^a
	SR	58.1 ^b	71.4 ^b	27.3 ^b	20.1	30.1 ^b	14.8	16.9 ^b
	BO	57.6 ^b	70.4 ^a	28.4	19.9	30.4 ^b	14.8	18.8 ^c
	1.2	59.7 ^a	71.0	27.3 ^a	20.6 ^a	31.5	14.8	21.2 ^a
	1.4	59.0 ^a	71.1 ^a	27.9	20.2	31.0	14.9	20.2
	1.6	57.8 ^b	70.4 ^b	29.3 ^b	19.7 ^b	30.9	14.9	19.3 ^b
	NC 1.2	61.9 ^{a(a)}	69.5 ^{a(A)}	26.7 ^a	21.1 ^a	32.2	15.2 ^(A)	26.6 ^{a(A)}
	NC 1.4	61.5 ^{a(A)}	71.7 ^{b(1)}	28.3 ^a	20.8 ^(A)	33.3 ^(A)	14.8	24.9 ⁽¹⁾
	NC 1.6	59.1 ^{b(1)}	70.6	31.3 ^{b(A)}	19.8 ^b	33.3 ⁽¹⁾	14.8	23.5 ^{b(*)}
	SR 1.2	58.6 ^{a(b)}	72.2 ^{a(B)}	27.0	20.5	31.1	14.7 ^(B)	17.0 ^{a(B)}
	SR 1.4	59.3 ^{a(B)}	71.6 ⁽¹⁾	26.0 ^{a(1)}	20.3 ^(B)	29.4 ^(B)	14.9	16.9 ^{b(2)}
	SR 1.6	56.4 ^{b(2)}	70.5 ^b	28.8 ^b	19.4	29.8 ⁽²⁾	14.8	16.8 ^(**)
	BO 1.2	58.6 ^a	71.1 ^{a(B)}	28.3	20.3	31.3	14.6 ^(B)	20.1 ^{a(C)}
	BO 1.4	56.3 ^{b(C)}	70.0 ⁽²⁾	29.3 ⁽²⁾	19.4	30.1 ^(B)	14.8	18.8 ⁽²⁾
	BO 1.6	57.8	70.0 ^b	27.7 ^(B)	20.0	29.7 ⁽²⁾	15.1	17.6 ^{b(**)}

Season 2	NC	68.6 ^a	70.3	26.4	24.0 ^a	41.1 ^a	13.6	25.8 ^a
	SR	70.9 ^b	70.8	25.0	22.5 ^b	36.0 ^b	13.5	22.0 ^b
	BO	70.3 ^b	70.3	24.1	24.1 ^a	38.4	13.5	24.1
	1.2	71.2 ^a	70.6	23.3 ^a	24.1 ^a	37.8	13.6	25.2
	1.4	68.6 ^b	70.2	24.8	23.7	36.4 ^a	13.6	23.9
	1.6	70.0	70.6	27.4 ^b	22.8 ^b	41.2 ^b	13.5	22.9
	NC 1.2	71.6 ^a	70.9	23.3	25.0 ^{a(A)}	39.9	13.8 ^{a(A)}	27.1
	NC 1.4	64.6 ^{b(A)}	69.3 ^(A)	27.3 ^(A)	24.0	40.0 ^(A)	13.7	25.5
	NC 1.6	69.6 ^a	70.8	28.7	23.0 ^b	43.3	13.4 ^b	24.9
	SR 1.2	71.7	70.5	25.7	22.8 ^(B)	39.8 ^a	13.4 ^(B)	25.1 ^a
	SR 1.4	71.6 ^(B)	71.6 ^(B)	20.7 ^{a(B)}	23.4 ^a	28.0 ^{b(B)}	13.5	19.5 ^{b(A)}
	SR 1.6	69.3	70.3	28.7 ^b	21.5 ^{b(1)}	40.1 ^a	13.6	21.4
	BO 1.2	70.4	70.4	21.0	24.5	33.7	13.5	23.4
	BO 1.4	69.5 ^(B)	69.7 ^(A)	26.3	23.8	41.2 ^(A)	13.5	26.7 ^{a(B)}
	BO 1.6	71.0	70.7	25.0	23.9 ⁽²⁾	40.4	13.5	22.3 ^b

4.4.3 Root morphology and root biomass

4.4.3.1 Total root length

Mean cover crop treatment comparisons showed that following C4, SR had significantly higher total root length (RL) compared to NC and BO at depth 200 – 400 mm ($P = 0.02$ and <0.01 respectively; $SE = 1.25$) (Table 4.5). Whereas, at depth 400 – 600 mm, BO had significantly higher RL compared to NC and SR ($P = 0.03$ and <0.01 respectively; $SE = 1.26$) (Table 4.5). Mean subsoil compaction treatment comparisons showed that following C2, at the 400 – 600 mm depth, subsoil compaction treatment 1.2 had significantly higher RL compared 1.4 and 1.6 ($P = < 0.01$ and <0.01 respectively; $SE = 1.35$), and 1.4 had significantly higher RL compared to 1.6 ($P = 0.05$; $SE = 1.35$) (Table 4.5). Subsoil compaction treatments 1.2 and 1.4 had significantly higher RL compared to 1.6 at depths 600 – 800 ($P = <0.01$ and <0.01 respectively; $SE = 1.38$) and 800 – 1000 mm ($P = <0.01$ and <0.01 respectively; $SE = 1.37$) (Table 4.5). Following C4, subsoil compaction treatment 1.2 had significantly higher RL compared to 1.6 at depth 800 – 1000 mm ($P = 0.03$; $SE = 1.34$) (Table 4.5).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with cover crop treatment NC, 1.2 had significantly higher RL compared to 1.6 at depths 400 – 600 mm ($P = 0.02$; $SE = 1.71$) and 800 – 1000 mm ($P = 0.01$; $SE = 1.72$). However, at depth 600 – 800 mm, in combination with cover crop treatment NC, 1.6 was had significantly higher RL compared to 1.2 and 1.4 ($P = 0.01$ and 0.01 respectively; $SE = 1.74$) (Table 4.5). Combined with cover crop treatment SR, the same trends occurred at depths 400 – 600 mm ($P <0.01$; $SE = 1.71$) and 600 – 800 mm ($P = <0.01$ and <0.01 respectively; $SE = 1.74$), however at depth 800 – 1000 mm, 1.6 had significantly higher RL compared to both 1.2 and 1.4 ($P = <0.01$ and <0.01 respectively; $SE = 1.72$) (Table 4.5). Combined with cover crop treatment BO, 1.2 had higher RL compared to 1.4 and 1.6 at depth 400 – 600 mm ($P = 0.03$ and 0.01 respectively; $SE = 1.71$) and subsoil compaction treatment 1.6 had significantly higher RL compared to 1.2 and 1.4 at depth 800 – 1000 ($P = <0.01$ and 0.04 respectively; $SE = 1.72$) (Table 4.5).

Following C4, in combination with subsoil compaction treatment 1.2, NC had significantly higher RL compared to BO at depth 400 – 600 mm ($P = 0.01$; $SE = 1.48$) (Table 4.5). Whereas, combined with subsoil compaction treatment 1.4, SR had significantly higher RL compared to both NC and BO at depths 200 – 400 mm ($P = 0.02$ and <0.01 respectively; $SE = 1.48$) and 400 – 600 mm ($P = 0.01$ and 0.02 respectively; $SE = 1.48$) (Table 4.5). Combined with cover crop treatment NC, 1.2 had significantly higher RL compared to 1.4 at depth 400 – 600 mm ($P = 0.02$; $SE = 1.48$) and 1.6 at depth 600 – 800 mm ($P = 0.03$; $SE = 1.55$) (Table 4.5). Combined with cover crop treatment SR, 1.2 had significantly higher RL compared to 1.6 at depth 800 – 1000 mm ($P = 0.02$; $SE = 1.66$) (Table 4.5).

4.4.3.2 Mean root diameter

Mean cover crop treatment comparisons showed that following C2, SR had significantly higher mean root diameter (RD) compared to NC and BO at depth 800 – 1000 mm ($P = 0.01$ and 0.01 respectively; $SE = 0.02$) (Table 4.5). Following C4, cover crop treatment BO had significantly higher RD compared to SR at depth 200 – 400 mm ($P = 0.04$; $SE = 0.004$) (Table 4.5). Mean subsoil compaction treatment comparisons showed that following C2, 1.6 had significantly higher RD compared to 1.2 and 1.4 at depth 800 – 1000 mm ($P = <0.01$ and 0.01 respectively; $SE = 0.02$) (Table 4.5). Following C4, subsoil compaction treatment 1.4 had significantly higher RD compared to 1.6 at depth 200 – 400 mm ($P = 0.04$; $SE = 0.02$) and 800 – 1000 mm ($P = 0.05$; $SE = 0.02$) (Table 4.5).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.6, SR had significantly higher RD compared to NC and BO at depth 800 – 1000 mm ($P = <0.01$ and <0.01 respectively; $SE = 0.03$) (Table 4.5). Combined with cover crop treatment SR, 1.6 had significantly higher RD compared to treatments 1.2 and 1.4 at depth 800 – 1000 mm ($P = <0.01$ and <0.01 respectively; $SE = 0.03$) (Table 4.5).

Following C4, in combination with subsoil compaction treatment 1.2, BO had significantly higher RD compared to SR at depth 200 – 400 mm ($P = 0.03$; $SE = 0.01$) (Table 4.5). At the 200 – 400 mm depth, in combination with cover crop

treatment NC, 1.2 had significantly higher RD compared to 1.6 ($P = 0.04$; $SE = 0.01$) (Table 4.5). At the 400 – 600 mm depth, in combination with cover crop treatment BO, 1.2 had significantly higher RD compared to 1.6 ($P = 0.04$; $SE = 0.02$) (Table 4.5). At the 800 – 1000 mm depth, in combination with cover crop treatment SR, 1.4 had significantly higher RD compared to 1.2 ($P = 0.02$; $SE = 0.01$) (Table 4.5).

4.4.3.3 Root biomass

Mean subsoil compaction treatment comparisons showed that following C2, 1.2 had significantly higher root biomass (RB) compared to 1.6 at depths 200 – 400 and 800 – 1000 mm ($P = 0.04$ and 0.01 respectively; $SE = 1.32$ and 1.36 respectively) (Table 4.5). Subsoil compaction treatment 1.2 had significantly higher RB compared to 1.4 and 1.6 at depths 400 – 600 ($P = <0.01$ and <0.01 respectively; $SE = 1.29$) and 600 – 800 mm ($P = <0.01$ and 0.01 respectively; $SE = 1.28$) (Table 4.5). Following C4, 1.2 had significantly higher RB compared to 1.4 and 1.6 at depth 200 – 400 mm ($P = 0.04$ and 0.01 respectively; $SE = 1.32$) and significantly higher RB compared to 1.6 at depth ($P = 0.01$; $SE = 1.34$) (Table 4.5).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.4 SR had significantly higher RB compared to BO at depth 200 – 400 mm ($P = 0.01$; $SE = 1.62$) (Table 4.5). Combined with cover crop treatment NC, 1.2 had significantly higher RB compared to 1.4 and 1.6 at depth 600 – 800 mm ($P = <0.01$ and 0.01 respectively; $SE = 1.53$) (Table 4.5). Combined with cover crop treatment SR, 1.2 had significantly higher RB compared to 1.6 at depth 400 – 600 mm ($P = <0.01$; $SE = 1.56$), and 1.4 had significantly higher RB compared to 1.6 at depth 600 – 800 mm ($P = 0.01$; $SE = 1.62$) (Table 4.5). Combined with cover crop treatment BO, 1.2 had significantly higher RB compared to 1.4 and 1.6 at depths 400 – 600 mm ($P = 0.01$ and <0.01 respectively; $SE = 1.56$) and 600 – 800 mm ($P = 0.01$ and 0.02 respectively; $SE = 1.53$) (Table 4.5).

Following C4, combined with subsoil compaction treatment 1.6, SR and BO had significantly higher RB compared to NC at depth 600 – 800 mm ($P = 0.03$ and

0.02 respectively; SE = 1.65) (Table 4.5). Combined with cover crop treatment NC, 1.2 had significantly higher RB compared to 1.4 and 1.6 at depths 200 – 400 mm ($P = 0.02$ and 0.01 respectively; SE = 1.61) and 600 – 800 mm ($P = 0.03$ and <0.01 respectively; SE = 1.65) (Table 4.5). Combined with cover crop treatment NC, 1.2 had significantly higher RB compared to 1.6 at depths 400 – 600 mm ($P = 0.05$; SE = 1.81) and 800 – 1000 mm ($P = 0.03$; SE = 2.11) (Table 4.5).

Table 4.5 Total root length (mm), mean root diameter (mm) and root dry biomass (mg). Cover crop treatments: NC – ‘no cover crop’, SR – ‘SMART radish’ (*Raphanus sativus*), BO – ‘black oat’ (*Avena strigosa*); subsoil compaction treatments: 1.2 – ‘1.2 g cm⁻³, 1.4 – ‘1.4 g cm⁻³, 1.6 – ‘1.6 g cm⁻³. Significant (P ≤0.05) differences separated into seasons 1 and 2, and organised by column (lowercase letters without parentheses represent differences within a section e.g.^{a,b,c}; uppercase letters, numbers and symbols with parentheses represent differences between sections e.g.^{(A/B),(1/2),(*/**)}).

	Depth (mm)	Total root length (cm)				Mean root diameter (mm)				Root biomass (mg)			
		200 - 400	400 - 600	600 - 800	800 - 1000	200 - 400	400 - 600	600 - 800	800 - 1000	200 - 400	400 - 600	600 - 800	800 - 1000
	NC	11.53	4.00	2.64	2.02	0.23	0.23	0.23	0.23 ^a	13.52	5.44	3.25	2.81
	SR	13.53	2.95	2.46	2.85	0.23	0.23	0.22	0.27 ^b	16.17	4.61	3.36	4.62
	BO	14.28	2.82	2.30	1.53	0.22	0.22	0.23	0.23 ^a	13.86	3.39	2.80	4.03
	1.2	17.13	7.90 ^a	4.54 ^a	4.69 ^a	0.22	0.23	0.23	0.22 ^a	20.13 ^a	9.51 ^a	5.15 ^a	6.11 ^a
	1.4	12.49	2.87 ^b	3.50 ^a	2.60 ^a	0.22	0.22	0.23	0.23 ^a	13.64	3.69 ^b	3.58 ^a	3.25
	1.6	10.45	1.48 ^c	0.94 ^b	0.72 ^b	0.23	0.23	0.23	0.27 ^b	11.03 ^b	2.42 ^b	1.66 ^b	2.63 ^b
Season 1	NC 1.2	19.48	8.38 ^a	4.49 ^a	4.12 ^a	0.23	0.24	0.24	0.21	22.75	8.71	6.21 ^a	5.31
	NC 1.4	11.78	3.84	4.50 ^a	2.12	0.23	0.23	0.22	0.24	11.87	4.72	4.38 ^b	2.29
	NC 1.6	6.68	1.99 ^b	0.91 ^b	0.94 ^b	0.23	0.23	0.23	0.22 ^(A)	9.16	3.91	1.26 ^b	1.82
	SR 1.2	14.53	7.84 ^a	4.82 ^a	6.41 ^a	0.22	0.22	0.21	0.21 ^a	17.02	10.56 ^a	3.63	6.80
	SR 1.4	14.30	2.93	4.86 ^a	4.82 ^a	0.20	0.22	0.24	0.23 ^a	15.04	4.64	5.77 ^{a(A)}	5.52
	SR 1.6	11.93	1.12 ^b	0.64 ^b	0.75 ^b	0.26	0.23	0.22	0.36 ^{b(B)}	16.52	2.00 ^b	1.82 ^b	2.62
	BO 1.2	17.76	7.50 ^a	4.32	3.91 ^a	0.22	0.22	0.24	0.22	21.07	9.34 ^a	6.04 ^a	6.32
	BO 1.4	11.57	2.09 ^b	1.97	1.73 ^a	0.23	0.21	0.21	0.21	14.23	2.29 ^b	1.82 ^{b(B)}	2.71
	BO 1.6	14.31	1.44 ^b	1.43	0.53 ^b	0.19	0.22	0.22	0.24 ^(A)	8.88	1.82 ^b	2.00 ^b	3.83

Season 2	NC	18.04 ^a	10.05 ^a	10.44	33.36	0.18	0.18	0.16	0.15	21.40	6.80	4.14	11.13
	SR	32.57 ^b	13.82 ^a	12.25	31.67	0.17 ^a	0.17	0.16	0.16	22.93	8.76	7.11	11.63
	BO	13.59 ^a	5.95 ^b	9.83	28.80	0.19 ^b	0.19	0.16	0.15	14.06	4.51	5.95	10.60
	1.2	25.82	10.30	12.82	43.77 ^a	0.18	0.19	0.16	0.15 ^a	31.04 ^a	8.27	8.44 ^a	16.27
	1.4	19.46	9.70	11.70	32.45	0.19 ^a	0.18	0.16	0.16 ^b	17.16 ^b	7.07	5.76	12.12
	1.6	16.33	8.26	8.38	21.42 ^b	0.17 ^b	0.17	0.17	0.15	13.03 ^b	4.60	3.60 ^b	6.96
	NC 1.2	25.82	16.87 ^{a(A)}	18.29 ^a	49.43	0.19 ^a	0.18	0.17	0.15	53.46 ^a	14.19 ^a	12.27 ^a	25.18 ^a
	NC 1.4	14.91 ^(A)	6.24 ^{b(1)}	9.49	39.65	0.18	0.18	0.15	0.16	15.50 ^b	5.52	3.63 ^b	12.82
	NC 1.6	15.25	9.63	6.55 ^b	18.94	0.16 ^b	0.17	0.17	0.15	11.83 ^b	4.02 ^b	1.59 ^{b(A)}	4.27 ^b
	SR 1.2	35.74	12.27	15.14	63.94 ^a	0.16 ^(A)	0.17	0.16	0.15 ^a	25.85	7.61	9.00	20.26
	SR 1.4	42.41 ^(B)	20.10 ⁽²⁾	14.05	27.09	0.18	0.17	0.16	0.17 ^b	27.54	13.28	7.69	11.29
	SR 1.6	22.80	10.80	8.64	18.35 ^b	0.17	0.16	0.17	0.15	16.94	6.65	5.19 ^(B)	6.87
	BO 1.2	18.64	5.33 ^(B)	7.61	26.54	0.19 ^(B)	0.21 ^A	0.16	0.15	21.63	5.24	5.45	8.44
	BO 1.4	11.65 ^(A)	7.28 ⁽¹⁾	12.00	31.82	0.19	0.19	0.16	0.15	11.63	4.82	6.84	12.30
	BO 1.6	12.53	5.43	10.41	28.28	0.18	0.17 ^B	0.16	0.16	11.04	3.63	5.65 ^(B)	11.48

4.4.4 Soil physical properties

4.4.4.1 Penetration resistance

Mean cover crop treatment comparisons showed that following C2, BO had significantly higher penetration resistance (PR) at 0 – 50 mm depth compared to NC (Fig. 4.2 A1). Mean subsoil compaction treatment comparisons showed that following C2, 1.6 had significantly higher PR compared to 1.2 and 1.4 at 300 – 800 mm depth (Fig. 4.2 A2). Following C4, subsoil compaction treatment 1.6 had significantly higher PR compared to 1.2 at depths 0 – 50 mm and 750 – 800 mm (Fig. 4.2 B2). Subsoil compaction treatment 1.6 had significantly higher PR compared to 1.2 and 1.4 at 300 – 750 mm depth (Fig. 4.2 B2).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, cover crop treatment SR had significantly higher PR compared to NC, where combined with subsoil compaction treatment 1.2, at 200 mm depth (Fig. 4.2 A3). Combined with subsoil compaction treatment 1.6, cover crop treatment NC had significantly higher PR compared to BO at 550 mm depth (Fig. 4.2 A3).

Following C4, in combination with subsoil compaction treatment 1.6, cover crop treatments SR and BO had significantly higher PR compared to NC at depths 0 – 100 mm and 250 mm, and BO had significantly higher PR compared to SR at depth 250 mm (Fig. 4.2 B3). Combined with subsoil compaction treatment 1.2, cover crop treatment NC had significantly higher PR compared to SR at depth 100 mm (Fig. 4.2 B3).

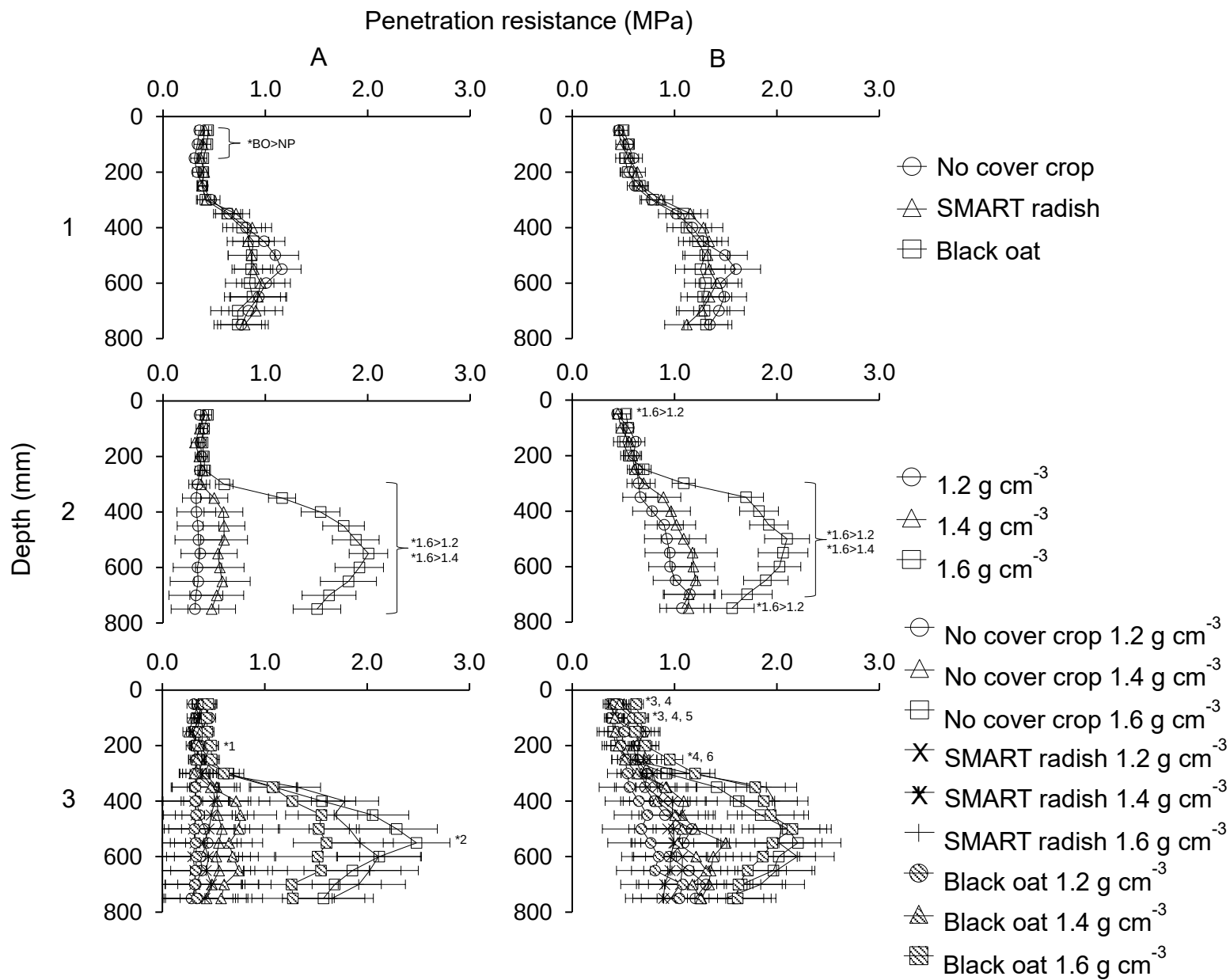


Figure 4.2 Penetration resistance (MPa) over depth (mm). 1 – mean rotation treatments, 2 mean subsoil compaction treatments, 3 – rotation and subsoil compaction treatment interaction. A - season 1 (C1/C2), B - season 2 (C3/C4). Cover crop treatments: NC - 'no cover crop', SR - 'SMART radish' (*Raphanus sativus*), BO - 'black oat' (*Avena strigosa*), subsoil compaction treatments: 1.2 - 1.2 g cm⁻³, 1.4 - 1.4 g cm⁻³, 1.6 - 1.6 g cm⁻³. Numbers denote a significant difference ($P \leq 0.05$) (¹SR 1.2>NC 1.2, ²NC 1.6>BO 1.6, ³SR 1.6>NC 1.6, ⁴BO 1.6>NC 1.6, ⁵NC 1.2>SR 1.2, ⁶BO 1.6>SR 1.6). Error bars represent standard error of the mean between treatments for each depth.

4.4.4.2 Saturated hydraulic conductivity

No significant differences were recorded for mean cover crop treatment, mean subsoil compaction treatment or the interaction between cover crop and subsoil compaction treatments (SE season 1 = 2.55; season 2 = 9.64) (Table 4.6).

Table 4.6 Saturated hydraulic conductivity (K_{sat}) (mm hr^{-1}). Cover crop treatments: NC – ‘no cover crop’, SR – ‘SMART radish’ (*Raphanus sativus*), BO – ‘black oat’ (*Avena strigosa*); subsoil compaction treatments: 1.2 – ‘1.2 g cm^{-3} ’, 1.4 – ‘1.4 g cm^{-3} ’, 1.6 – ‘1.6 g cm^{-3} ’, 1.6 – ‘1.6 g cm^{-3} subsoil BD).

Treatment	K_{sat} (mm hr^{-1})	
	Season 1	Season 2
NC	9.5	23.1
SR	11.7	29.9
BO	11.8	29.9
1.2	11.2	24.9
1.4	10.4	25.7
1.6	11.4	32.3
NC 1.2	10.3	23.7
NC 1.4	8.9	25.3
NC 1.6	9.2	20.2
SR 1.2	10.0	26.0
SR 1.4	12.3	25.3
SR 1.6	12.9	38.3
BO 1.2	13.3	25.2
BO 1.4	10.0	26.3
BO 1.6	11.9	38.3

4.4.4.3 Bulk density

Mean cover crop treatment comparisons showed that following C2, SR had significantly higher bulk density (BD) compared to NC and BO ($P = 0.01$ and 0.03 respectively; $SE = 0.03$) at depth 200 – 400 mm (Table 4.7). Following C4, BO had significantly higher BD compared to NC ($P = 0.03$; $SE = 0.03$) at depth 200 – 400 mm (Table 4.7). Mean subsoil compaction treatment comparisons showed that following C2, at depth 400 – 600 mm, subsoil compaction treatment 1.6 had significantly higher BD compared to 1.2 and 1.4 ($P = 0.01$ and 0.03 ; $SE = 0.03$), and subsoil compaction treatment 1.4 had significantly higher BD compared to 1.2 ($P = <0.01$; $SE = 0.03$) (Table 4.7). At depth 600 – 800 mm, subsoil compaction treatment 1.6 had significantly higher BD compared to 1.2 and 1.4 ($P = 0.03$ and 0.02 ; $SE = 0.02$) (Table 4.7). Following C4, at depths 400 – 600 and 600 – 800 mm, subsoil compaction treatments 1.4 and 1.6 had significantly higher BD compared to 1.2 (400 – 600 $P = <0.01$ and <0.01 respectively; $SE = 0.03$, 600 – 800 mm $P = 0.05$ and 0.01 respectively; $SE = 0.03$) (Table 4.7).

Cover crop and subsoil compaction treatment interaction demonstrated that following C2, in combination with subsoil compaction treatment 1.2, SR had significantly higher BD compared to NC ($P = 0.05$; $SE = 0.04$) at depth 200 – 400 mm (Table 4.7). At depth 400 – 600 mm, in combination with cover crop treatments NC and BO, 1.6 had significantly higher BD compared to 1.2 ($P = 0.01$ and 0.05 respectively; $SE = 0.05$), and in combination with SR, 1.6 had significantly higher BD compared to both 1.2 and 1.4 ($P = <0.01$ and 0.02 respectively; $SE = 0.05$) (Table 4.7). At depth 600 – 800 mm, in combination with cover crop treatments NC and SR, 1.6 had significantly higher BD compared 1.2 ($P = 0.03$ and 0.02 respectively; $SE = 0.04$) (Table 4.7).

Following C4, in combination with subsoil compaction treatment 1.2, BO had significantly higher BD compared to NC ($P = 0.05$; $SE = 0.04$) at depth 200 – 400 mm, and SR had significantly higher BD compared to NC at depth 400 – 600 mm ($P = 0.03$; $SE = 0.05$) (Table 4.7). Combined with subsoil compaction treatment 1.4, NC had significantly higher BD compared to BO at depth 800 – 1000 mm ($P = 0.03$; $SE = 0.11$) (Table 4.7). Combined with cover crop treatments NC and SR,

1.4 and 1.6 had significantly higher BD compared to 1.2 at depth 400 – 600 mm (NC – $P = < 0.01$ and < 0.01 respectively, SR – $P = 0.03$ and 0.01 respectively: SE 0.05) (Table 4.7). Combined with cover crop treatment BO, at depth 400 – 600 mm, 1.6 had significantly higher BD compared to 1.2 and 1.4 ($P = < 0.01$ and 0.02 respectively; SE = 0.05), and 1.4 had significantly higher BD compared to 1.2 ($P = 0.03$: SE = 0.05) (Table 4.7). Combined with cover crop treatment BO, 1.6 had significantly higher BD compared to 1.2 at depth 600 – 800 mm ($P = 0.04$: SE = 0.05), and subsoil compaction treatment 1.6 had significantly higher BD compared to 1.4 at depth 800 – 1000 mm ($P = 0.04$; SE = 0.11) (Table 4.7).

Table 4.7 Bulk density (BD) (g cm^{-3}). Cover crop treatments: NC – ‘no cover crop’, SR – ‘SMART radish’ (*Raphanus sativus*), BO – ‘black oat’ (*Avena strigosa*); subsoil compaction treatments: 1.2 – ‘1.2 g cm^{-3} ’, 1.4 – ‘1.4 g cm^{-3} ’, 1.6 – ‘1.6 g cm^{-3} ’. Significant ($P \leq 0.05$) differences are separated into seasons 1 and 2, and are organised by column (lowercase letters without parentheses represent differences within a section e.g. ^{a,b,c}, uppercase letters, numbers and symbols with parentheses represent differences between sections e.g. ^{(A/B),(1/2),(*/**)}).

		Depth (mm)				
Treatment		0 - 200	200 - 400	400 - 600	600 - 800	800 - 1000
Season 1	NC	1.02	1.06 ^b	1.23	1.25	1.31
	SR	1.09	1.13 ^a	1.24	1.29	1.32
	BO	1.04	1.07 ^b	1.24	1.27	1.34
	1.2	1.07	1.11	1.15 ^a	1.26 ^a	1.33
	1.4	1.06	1.08	1.25 ^b	1.25 ^a	1.31
	1.6	1.02	1.07	1.32 ^c	1.31 ^b	1.33
	NC 1.2	1.03	1.07 ^(A)	1.15 ^a	1.26	1.35
	NC 1.4	1.04	1.08	1.24	1.20 ^a	1.25
	NC 1.6	1.00	1.03	1.31 ^b	1.30 ^b	1.33
	SR 1.2	1.10	1.17 ^(B)	1.12 ^a	1.24 ^a	1.28
	SR 1.4	1.11	1.13	1.26 ^b	1.28	1.34
	SR 1.6	1.05	1.10	1.35 ^b	1.35 ^b	1.32
	BO 1.2	1.08	1.09	1.19 ^a	1.27	1.34
	BO 1.4	1.02	1.04	1.25	1.26	1.35
	BO 1.6	1.02	1.08	1.29 ^b	1.28	1.34

Season 2	NC	1.12	1.04 ^a	1.22	1.33	1.43
	SR	1.04	1.08	1.26	1.32	1.44
	BO	1.02	1.10 ^b	1.23	1.32	1.35
	1.2	1.04	1.08	1.12 ^a	1.27 ^a	1.44
	1.4	1.05	1.08	1.27 ^b	1.33 ^b	1.36
	1.6	1.09	1.06	1.31 ^b	1.35 ^b	1.43
	NC 1.2	1.07	1.03 ^(A)	1.08 ^{a(A)}	1.28	1.39
	NC 1.4	1.13	1.05	1.30 ^b	1.36	1.46 ^(A)
	NC 1.6	1.17	1.05	1.28 ^b	1.34	1.43
	SR 1.2	1.02	1.08	1.18 ^{a(B)}	1.29	1.50
	SR 1.4	1.03	1.11	1.29 ^b	1.30	1.41
	SR 1.6	1.06	1.04	1.31 ^b	1.36	1.41
	BO 1.2	1.02	1.13 ^(B)	1.12 ^a	1.25 ^a	1.42
	BO 1.4	0.99	1.09	1.22 ^b	1.34	1.19 ^{a(B)}
	BO 1.6	1.05	1.10	1.34 ^c	1.36 ^b	1.45 ^b

4.4.5 Pearson correlation coefficient

4.4.5.1 Soil and root parameters over depth by cover crop treatment and season

Across all cover crop treatments and most depth layers, RB had a significant positive correlation with RL after seasons 1 and 2 (Table 4.8). Combined with cover crop treatment NC, RB and RL had a significant negative correlation with PR at depth 600 – 800 mm (season 1), and BD had significant negative correlation with RL at depth 400 – 600 mm (season 2) (Table 4.8). Combined with cover crop treatment SR, BD had a significant negative correlation with RL at depth 200 – 400 mm (season 1), and with RB at depths 200 – 400 mm and 800 – 1000 mm (season 1) (Table 4.8). In addition, RL had a significant negative correlation with RD at depth 800 – 1000 mm (season 1) (Table 4.8). Combined with cover crop treatment BO, BD had a significant positive correlation with RL at depth 0 – 200 mm (season 1) and a significant negative correlation with RD at 400 – 600 mm (season 2) (Table 4.8). In addition, RB had a significant positive correlation with RD at depth 400 – 600 mm (season 2) (Table 4.8).

Table 4.8 Pearson correlation coefficient (*r*) of soil and root parameters over depth by cover crop treatment and season. NC – ‘no cover crop’, SR – ‘SMART radish’ (*Raphanus sativus*), BO – ‘black oat’ (*Avena strigosa*). BD – bulk density, RB – root biomass, RL – root length, RD – root diameter, PR – penetration resistance. D1 = 0 – 200 mm, D2 – 200 – 400 mm, D3 – 400 – 600 mm, D4 – 600 – 800 mm, D5 – 800 – 1000mm. Season 1 – C1/C2, season 2 – C3/C4. Significant differences are indicated by superscript P values (e.g. n^P).

			NC					SR					BO				
			BD	RB	RL	RD	PR	BD	RB	RL	RD	PR	BD	RB	RL	RD	PR
			Season 1					Season 1					Season 1				
BD	Season 2	D1		-0.32	-0.26	0.20	0.44		0.14	0.26	-0.14	0.07		0.50	0.76 ^{.02}	-0.62	0.26
RB			-0.29		0.37	0.61	-0.65	0.01		0.96 ^{<.01}	0.15	0.23	-0.12		0.84 ^{<.01}	0.21	-0.17
RL			0.42	0.41		-0.34	-0.43	0.16	0.86 ^{<.01}		0.14	0.13	-0.55	0.31		-0.17	-0.15
RD			-0.49	0.59	-0.46		-0.32	-0.20	0.51	0.11		-0.57	0.18	0.76 ^{.02}	-0.33		-0.34
PR			-0.53	0.42	-0.07	0.29		-0.65	-0.27	-0.38	0.31		0.50	-0.43	-0.35	-0.22	
			Season 1					Season 1					Season 1				
BD	Season 2	D2		0.08	0.09	0.37	-0.56		-0.04	-0.59	0.31	-0.45		-0.42	-0.25	-0.05	0.12
RB			0.34		0.96 ^{<.01}	-0.25	-0.42	0.49		0.37	0.57	0.23	0.39		0.92 ^{<.01}	0.04	-0.36
RL			0.01	0.24		-0.45	-0.32	0.63	0.94 ^{<.01}		-0.46	0.15	0.32	0.57		-0.23	-0.18
RD			-0.35	0.51	0.13		-0.44	0.12	-0.02	-0.16		0.25	0.15	0.03	-0.54		-0.50
PR			0.28	-0.21	0.26	-0.52		-0.60	-0.44	-0.56	0.24		-0.03	-0.43	-0.23	-0.53	
			Season 1					Season 1					Season 1				
BD	Season 2	D3		-0.54	-0.64	-0.27	0.70 ^{.03}		-0.78 ^{.01}	-0.79 ^{.01}	0.10	0.73 ^{.03}		-0.15	-0.35	0.00	0.63
RB			-0.61		0.90 ^{<.01}	0.04	-0.45	0.19		0.97 ^{<.01}	-0.27	-0.60	-0.61		0.92 ^{<.01}	0.32	-0.57
RL			-0.71 ^{.03}	0.72 ^{.03}		-0.05	-0.56	0.16	0.68 ^{.04}		-0.34	-0.57	-0.27	0.15		0.30	-0.73 ^{<.01}
RD			-0.03	0.34	-0.27		-0.12	-0.20	-0.13	-0.45		0.14	-0.73 ^{.03}	0.68 ^{.04}	-0.38		-0.21
PR			0.49	-0.46	-0.18	-0.25		0.40	-0.39	-0.40	-0.41		0.81 ^{.01}	-0.43	-0.23	-0.61	

		Season 1				Season 1				Season 1				
BD	Season 2	D4	-0.46	-0.53	-0.02	0.58	-0.33	-0.41	-0.05	0.71 ^{.03}	0.23	-0.04	0.63	-0.23
RB			-0.31	0.82 ^{.01}	0.07	-0.77 ^{.02}	-0.19	0.92 ^{<.01}	0.03	-0.54	0.47	0.88 ^{<.01}	0.53	-0.55
RL			-0.36	0.94 ^{<.01}	-0.32	-0.90 ^{<.01}	-0.20	0.98 ^{<.01}	-0.22	-0.55	0.47	0.67 ^{.05}	0.34	-0.63
RD			0.28	-0.05	-0.29	0.03	-0.16	-0.56	-0.64	-0.41	0.00	0.25	-0.33	-0.52
PR			0.15	0.06	0.20	-0.17	0.69 ^{.04}	-0.34	-0.33	-0.22	0.57	-0.16	0.26	-0.66
		Season 1				Season 1				Season 1				
BD	Season 2	D5	0.26	0.30	-0.30	-0.67 ^{.05}	-0.38	-0.17	0.15	-0.11	-0.04			
RB			0.14	0.64	0.15	0.40	0.87 ^{<.01}	-0.36	0.24	0.34	0.32			
RL			0.31	0.97 ^{<.01}	-0.32	0.53	0.92 ^{<.01}	-0.75 ^{.02}	0.24	0.99 ^{<.01}	-0.56			
RD			-0.09	0.45	0.34	0.28	0.15	0.00	0.15	0.35	0.33			

4.4.5.2 Soil, root and plant parameters by cover crop treatment and season

Combined with cover crop treatment NC, PR had a significant positive correlation with EN and GP (season 1) and with EN and GW (season 2) (Table 4.9). Whereas, PR had a significant negative correlation with TGW and GPE season (season 1) (Table 4.9). The only other significant correlation where subsoil compaction treatments were combined with cover crop treatment NC was a positive correlation between GP and RL (season 1) (Table 4.9). Combined with cover crop treatment SR, SGW had a significant positive correlation with RB and RL, and EN had a significant positive correlation with RD (season 1) (Table 4.9). Whereas, after season 2, EN had a significant negative correlation with RD, and PR had a significant negative correlation with RB and RL (Table 4.9). After seasons 1 and 2, RB and RL had a significant positive correlation (Table 4.9). Combined with cover crop treatment BO, RD had a significant positive correlation with SGW (season 1) and RB (season 2) (Table 4.9). Whereas, RD had a significant negative correlation with EN and GP in season 1 (Table 4.9). Root biomass had a significant negative correlation with TGW in season 1 (Table 4.9).

Table 4.9 Pearson correlation coefficient (r) of soil parameters and spring barley (*Hordeum vulgare*) crop performance. TGW – thousand grain weight, SB – straw biomass, GPE – grains per ear, SGW – specific grain weight, GW – total grain weight, BD – bulk density, RB – root biomass, RL – root length, RD – root diameter, PR – penetration resistance. Season 1 – C1/C2, season 2 – C3/C4. Significant differences are indicated by superscript P values (e.g. n^P).

		TGW	SB	Ear no.	GPE	SGW	GW	GP	BD	RB	RL	RD	PR
		Season 1											
NC	TGW		0.68 ^{<.01}	-0.63 ^{.01}	0.82 ^{<.01}	0.05	0.64 ^{<.01}	-0.10	-0.32	0.42	0.35	0.53	-0.71 ^{.03}
	SB	0.05		-0.15	0.44	0.03	0.59 ^{.01}	-0.07	-0.51	0.53	0.58	0.30	-0.55
	Ear no.	-0.55	0.21		-0.68 ^{<.01}	0.30	0.03	-0.42	0.25	-0.60	-0.45	-0.31	0.93 ^{<.01}
	GPE	0.34	0.09	-0.83 ^{.01}		0.01	0.64 ^{<.01}	-0.06	-0.17	0.56	0.28	0.65	-0.73 ^{.03}
	SGW	0.57	0.57	-0.02	0.01		0.32	-0.51 ^{.03}	-0.52	-0.14	0.15	-0.15	-0.21
	GW	-0.07	0.49	0.83 ^{.01}	-0.63	0.32		-0.47 ^{.05}	-0.43	0.21	0.18	0.41	-0.12
	GP	-0.17	-0.28	-0.49	0.36	-0.69 ^{.04}	-0.62		-0.52	0.39	0.74 ^{.02}	-0.63	-0.20
	BD	-0.46	-0.58	0.35	-0.25	-0.38	0.03	-0.21		-0.59	-0.65	0.15	0.43
	RB	-0.05	0.45	-0.07	0.17	-0.27	0.10	0.57	-0.48		0.73 ^{.03}	0.18	-0.61
	RL	0.27	0.38	-0.23	0.46	0.03	0.12	0.23	-0.13	0.68 ^{.04}		-0.39	-0.63
	RD	0.06	0.40	-0.24	0.42	0.14	-0.09	0.20	-0.37	0.27	0.28		-0.12
	PR	-0.28	-0.02	0.80 ^{.01}	-0.62	-0.11	0.76 ^{.02}	-0.40	0.46	-0.12	-0.01	-0.44	
		Season 1											
SR	TGW		0.13	-0.50 ^{.04}	0.48 ^{.05}	0.40	0.28	-0.55 ^{.02}	-0.45	-0.11	0.01	-0.57	-0.40
	SB	0.16		0.06	0.27	-0.07	0.32	-0.26	-0.54	-0.23	-0.02	-0.63	-0.12
	Ear no.	-0.62	0.31		-0.71 ^{<.01}	-0.29	0.34	-0.07	0.08	0.16	-0.03	0.72 ^{.03}	0.76 ^{.02}
	GPE	0.54	0.04	-0.88 ^{<.01}		0.21	0.33	-0.35	0.02	-0.23	-0.12	-0.44	-0.64
	SGW	0.32	-0.57	-0.53	0.18		0.18	-0.25	-0.09	0.82 ^{.01}	0.92 ^{<.01}	-0.36	0.04

	GW		0.13	0.57	0.61	-0.38	-0.50	-0.69 ^{<.01}	-0.10	0.42	0.31	0.02	-0.12
	GP		-0.12	-0.33	0.09	-0.32	0.50	-0.27	-0.11	0.37	0.15	0.48	0.32
	BD		0.00	0.14	0.18	-0.13	-0.52	0.26	-0.10	-0.16	-0.07	0.27	0.34
	RB		0.51	-0.20	-0.55	0.34	0.29	-0.27	-0.37	0.00	0.87 ^{<.01}	0.06	0.04
	RL		0.28	-0.18	-0.27	0.08	0.26	-0.16	-0.14	0.05	0.87 ^{<.01}	-0.27	0.01
	RD		0.27	-0.53	-0.76 ^{.02}	0.57	0.29	-0.60	-0.22	0.23	0.45	0.13	0.54
	PR		-0.40	0.06	0.43	-0.19	-0.47	0.30	0.05	-0.01	-0.81 ^{.01}	-0.84 ^{.01}	-0.28
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		Season 1											
	TGW		0.40	-0.18	0.48 ^{.04}	0.34	0.69 ^{<.01}	-0.26	0.15	0.62	0.63	0.40	-0.18
	SB		-0.66	0.51 ^{.03}	0.17	-0.02	0.64 ^{<.01}	0.02	-0.25	0.54	0.42	-0.17	-0.40
	Ear no.		-0.63	0.72 ^{.03}	-0.48 ^{.04}	-0.36	0.37	0.28	-0.03	-0.37	-0.32	-0.79 ^{.01}	0.37
	GPE		-0.37	0.42	0.03	0.38	0.25	-0.02	-0.29	0.57	0.36	0.42	-0.12
	SGW		0.61	-0.54	-0.56	0.07	0.25	-0.64 ^{<.01}	0.38	0.66	0.63	0.82 ^{<.01}	-0.36
BO	GW	Season 2	-0.52	0.69 ^{.04}	0.98 ^{<.01}	0.10	-0.42	-0.20	0.32	0.86 ^{<.01}	0.93 ^{<.01}	0.41	-0.36
	GP		0.38	-0.09	-0.17	0.04	0.67 ^{.05}	-0.08	-0.09	-0.24	-0.24	-0.79 ^{.01}	0.51
	BD		0.42	-0.28	0.10	0.06	0.45	0.26	0.34	0.03	0.41	0.05	0.10
	RB		0.00	0.24	-0.33	0.62	-0.12	-0.31	-0.24	-0.30	0.90 ^{<.01}	0.44	-0.68 ^{.05}
	RL		0.22	-0.25	-0.37	-0.09	0.26	-0.34	-0.18	0.09	0.21	0.30	-0.56
	RD		-0.38	0.59	-0.03	0.66	-0.34	-0.08	-0.25	-0.58	0.74 ^{.02}	-0.17	-0.49
	PR		-0.11	-0.08	0.53	0.02	0.04	0.61	0.04	0.71 ^{.03}	-0.51	-0.36	-0.55
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4.5 Discussion

The objective of this paper was to explore the potential of two contrasting cover crop treatments to alleviate subsoil compaction, and to provide a benefit to a following spring barley crop, over two successive growing seasons. We assessed cover crops through observing the impact of the treatments on yield components of spring barley, root morphology and biomass, and soil physical properties.

High subsoil compaction (treatment 1.6) had a significant negative effect on spring barley yield, adversely affecting TGW, SW, GPE and SB after season 1, and TGW and SB after season 2. Treatment 1.6 had the opposite effect on EN, significantly increasing EN across all cover crop treatments, in particular where combined with treatment NC. Treatment NC generally recorded the best values for spring barley yield after season 1 (TGW, GW and SB) and this trend was similar across all compaction treatments. After season 1, TGW and SB were highest for treatment NC across the subsoil compaction treatments, and highest for NC combined with low subsoil compaction (treatment 1.2). GW was also highest for treatment NC, for either subsoil compaction treatments 1.4 and 1.6 compared to SR or BO. After season 2, treatment SR resulted in significantly higher TGW and lower SB compared to NC and BO. Whereas, NC and BO both recorded significantly higher GW compared to SR combined with 1.4 and 1.6, and SR had the lowest GW where combined with 1.6. In contrast, after season 2, treatments SR and BO had significantly higher TGW compared to NC, and treatment SR had the greatest SW and GPE compared to both NC and BO. The treatment interaction results followed the same trend, that the clear benefit of NC on spring barley yield after season 1 was not as clear after season 2, with SR and BO recording significantly higher values for TGW, EN and GPE, even in the presence of high subsoil compaction.

These results showed subsoil compaction had a significant, negative impact on key components of spring barley yield. Treatments SR and BO did not confer a significant positive effect on components of yield after season 1 but indicated some limited improvements after two successive seasons, compared to NC. The negative effect of treatments SR and BO on spring barley yield, particularly after

season 1, could be attributed to the additional cover crop plant introduced into the rotation scavenging nutrients and negatively impacting spring barley growth (Hirsh et al., 2021; Mohammed et al., 2020; Reese et al., 2014). However, as the cover crop treatments were grown without fertiliser additions and the spring barley crop only received fertiliser immediately prior to periods C2 and C4, it is unlikely the significant differences observed may be solely ascribed to treatments SR and BO restricting nutrient availability for the spring barley, especially after season 1. In addition, other experiments have shown cover crops to have a positive impact on crop growth, even after a relatively short period (Calonego et al., 2017; Chen and Weil, 2011). Instead, it may be the case that within the finite, artificially structured volume, a higher proportion of the available porosity was occupied by cover crops SR and BO compared to NC after season 1, resulting in less productive spring barley growth which lessened in season 2 after the root cycling process had begun (Dexter, 1991).

Root growth and interaction with soil compaction is closely associated with crop yield (Hamza and Anderson, 2005; Lipiec et al., 2012). The cover crop and subsoil compaction treatments had a significant impact on root morphology and biomass, which may explain some of the spring barley yield differences recorded. The root material was not separated by species and therefore the root results represent the effect of the spring barley and/or the cover crop as a whole. After season 1, high subsoil compaction (treatment 1.6) significantly decreased RL and RB across the cover crop treatments. Root growth in the subsoil is an important element for components of crop yield (Botta et al., 2016) and therefore these results supported the spring barley yield data, that high subsoil compaction negatively affected growth.

At 800 – 1000 mm depth, both SR and BO treatments resulted in significantly higher RL compared to NC, even where in combination with treatment 1.6. This suggested that the inclusion of an extra plant in the rotation, regardless of species, increased the amount of roots in the deepest subsoil, even in the presence of high subsoil compaction. A corresponding benefit to spring barley yield was not observed but other experiments have shown that biopore formation

by roots takes repeated application over time to show a significant benefit to yield and subsoil compaction, and negative effects may persist long-term (Berisso et al., 2012; Etana et al., 2013; Pulido-Moncada et al., 2021). Additional root growth may provide positive impacts on water, gas and root movement in the meantime (Pulido-Moncada et al., 2021). Also, in light of evidence that root growth restriction may be due to gas movement in the soil (Pandey et al., 2021), any improvement in bioporosity by increased root growth in compacted subsoil is positive.

At the same depth (800 – 1000 mm), treatment SR recorded a significant increase in RD compared to BO and NC, in response to treatment 1.6, and these corresponded to significant correlations between RL and RD for treatment SR at this depth. As treatments NC and BO both represent grass species (spring barley and spring barley + black oat, respectively), our results support previous evidence that dicotyledonous, tap-rooted species such as the SMART radish (treatment SR), may modify and increase root diameter in response to soil compaction or have thicker roots in general (Clark et al., 2003; Materechera et al., 1992). Thicker roots and/or the ability to modify RD in response to compaction has been shown to be a beneficial trait in biopore formation and compaction alleviation (Hamza and Anderson, 2005). The significant correlation between RL and RD for treatment SR at this depth was negative. Although Pearson's correlation was not able to predict causality, it is interesting to note that increase in RD may consequently have reduced the RL. This result for RD in treatment SR supports that there is a benefit to including cover crop species with particular root traits (e.g. SMART radish (SR)) compared to just including more plants from similar groups (e.g. black oat and spring barley (BO)) to achieve increased rooting and biopore formation in compacted subsoil.

After season 2, RL and RB were higher for all treatments compared to season 1. Treatment combinations with NC recorded similar trends in RL as in season 1, whereas treatments SR and BO root data became more homogenous across all the compaction treatments between 400 – 1000 mm depth. This suggested that the repetition of an additional plant per season for treatments SR and BO,

irrespective of species, increased the amount of root material through the subsoil, even in the presence of high subsoil compaction. The formation of biopores (and therefore compaction alleviation) is dependent on root growth and decay through compacted layers (Cresswell and Kirkegaard, 1995) and our results suggest that repeatedly growing a cover crop of either species is more effective than a spring barley crop alone (NC). Whether the RD increase of treatment SR provides an advantage over treatment BO could not be determined in this experiment. However, although evidence has suggested that increased RD may make a significant contribution, the involvement of root traits is not fully understood (Clark and Barraclough, 1999; Hudek et al., 2021; Rosolem et al., 2002). The significant increase in RD seen for treatment SR in response to treatment 1.6 after season 1 was not repeated after season 2. This may suggest that SR treatment response in RD is an initial reaction to high subsoil compaction and is not repeated once a compacted layer has been penetrated. Although there is some evidence and speculation on the plasticity of RD in response to compaction (Chen and Weil, 2010; Hamza and Anderson, 2005), it would make an interesting future study to help plan sequencing of cover crop species in the field.

Overall, the root results indicated that root growth was limited by treatment 1.6 and to a lesser extent 1.4. These results mirrored the spring barley yield that showed a similar negative impact of high subsoil compaction. There was significant advantage, in terms of RL and RB, of including an additional crop per season with treatments SR and BO compared to NC, and evidence suggests this would increase biopore formation (Kirkegaard et al., 2008). However, these benefits were not reflected in the spring barley yield of either season. It is likely then, that these results just suggest there was more root material in the subsoil due to the addition of an extra plant per season. It is understood that more root material is likely to contribute to greater biopore formation (Wahlström et al., 2021) and greater biopore formation has been related to improved crop performance and soil functions (Han et al., 2015; Kautz, 2015), key targets of compaction alleviation. Biological methods are acknowledged as slower than mechanical cultivation, requiring repetition (Bronick and Lal, 2005; Pulido-Moncada et al., 2021) Therefore, the changes observed in root morphology may

have contributed to crop yield and subsoil function if repeated over a longer period.

Correlation results between yield components, root and soil properties supported that root growth was related to the trends observed in yield components (Atkinson et al., 2020; Whalley et al., 2008), and suggested subsoil compaction may be related to these relationships. PR was correlated with some yield components for treatment NC but less for treatments SR or BO, and root properties were correlated with yield components irrespective of cover crop treatment. For treatment NC, PR was negatively correlated with TGW and GPE after season 1, positively correlated with GW after season 2, and positively correlated with EN after both seasons. GP was also positively correlated with RL. These results suggested that soil strength and root morphology had a significant relationship with yield components. Whereas, for treatment SR, PR was positively correlated with EN after season 1, and negatively correlated with RB and RL after season 2. For treatment BO, PR was negatively correlated with RB after season 1. This suggested that the cover crop treatments reduced the number of significant relationships between soil strength and yield components compared to NC. For treatment SR, SGW was positively correlated with RB and RD after season 1, and for treatment BO, GW was positively correlated with RB and RL, and RD negatively correlated with EN and GP but positively correlated with SGW after season 1. After season 2, for treatment SR, RD was negatively correlated with EN. Over depth, PR was positively correlated with RL after season 1 and with RB after season 2 at depth 600 – 800 mm for treatment NC. PR was negatively correlated with RL after season 1, and BD positively correlated with RD after season 2 at 400 – 600 mm for treatment BO. There were no significant correlations between root and soil properties over depth for treatment SR. These results support that root growth was related to yield components but there were no clear trends to distinguish between cover crops or between seasons 1 and 2 to differentiate the effect of repeating cover crop application.

Subsoil compaction has been shown to produce detrimental yield results especially where water resources are scarce (Birkás et al., 2009; Stenitzer and

Murer, 2003). Therefore, the more prolific root systems that were observed following the cover crop treatments in high subsoil compaction might have provided improved resilience of crop performance if exposed to stress compared to the control. For example, the deeper, more extensive roots system may have been able to access water and/or nutrients unavailable to the control (McKenzie et al., 2009; Wahlström et al., 2021). Similar experimental work conducted under crop stress situations would be interesting to understand the potential value of the root system results reported in this paper.

The cover crop treatments did not have a significant impact on the soil physical properties measured. This is perhaps unsurprising given that previous evidence shows soil physical property response to cover cropping as variable (Calonego et al., 2017; Welch et al., 2016), and perhaps methods with a more suitable resolution to observe root formation of biopores, for example X-ray computed tomography (Helliwell et al., 2017), may have provided more detailed results compared to PR and K_{sat} . Although there were no significant differences in K_{sat} as a result of cover crop treatments, it was interesting to observe that the largest change in K_{sat} (a surface property) compared to the control treatments (NC and 1.2), was largest where subsoil compaction was highest (treatment 1.6) with SR and BO. This may show the additional root mass recorded for SR and BO had a non-significant but observable effect on soil function, increasing water movement into the soil profile.

Single species cover crops were tested in isolation during this experiment. Other studies have suggested that a mixture of cover crop root architectures would be most suitable in the field to meet the complexity of alleviating heterogeneous compaction at field-scale (Bronick and Lal, 2004; Chen and Weil, 2011; Hudek et al., 2021). That said, results from this experiment aid the selection of species for cover crop mixtures where the alleviation of subsoil compaction is part of the aim. Results suggested that subsoil compaction treatments were not alleviated completely following two successive seasons of cover cropping which supports previous experiments (Pulido-Moncada et al., 2021; Wahlström et al., 2015). The limitations of assessing root growth dynamics using intact soil columns due to

preferential root growth with plastic tubing, alongside the changes in temperature and the physics of soil packing within a finite column compared to the field (Gao et al., 2016) should be considered when interpreting results. Therefore, these initial results should be replicated long-term at field scale to explore species suitability in alleviating subsoil compaction in heterogeneous field conditions.

4.6 Conclusions

High subsoil compaction had a negative effect on spring barley yield and neither cover crop treatment significantly reduced this effect after two successive seasons. Both cover crop treatments increased the amount of roots in the subsoil, even where subsoil compaction was high, compared to a control. Treatment SR also increased the diameter of roots in response to high subsoil compaction. A greater amount of roots and an increase root diameter have been shown to be positive factors in the development of biopores that are key to alleviating subsoil compaction through cover crops. In addition, repeating the application of cover crop treatments also improved root properties compared to the control. However, these rooting benefits were not translated into significant spring barley yield benefits after two successive seasons and did not significantly improve the soil physical properties measured. The evidence presented supports the notion that cover crops may be used to increase the root exploration and biopore formation of the subsoil in the presence of subsoil compaction. Cover crop species may be chosen to incorporate specific roots traits aimed at alleviating subsoil compaction, for example selecting SMART radish to include larger root diameter in response to compacted subsoil. Further work is required to explore biopore formation over time by cover crop roots in response to subsoil compaction and to apply the principles in the field.

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5 Applicability of three field methods to identify subsoil compaction as a result of different soil management strategies in a long-term field experiment

Objective: To determine the applicability of subsoil visual evaluation of soil structure (SubVESS) and electromagnetic conductivity (EC_a) in characterising subsoil compaction as a result of experimental treatments, in comparison to penetration resistance (PR) and bulk density (BD)

Hypothesis: SubVESS and EC_a are equally applicable compared to conventional methods PR and BD in characterising subsoil compactness

Target Journal Publication: Frontiers in Environmental Science

5.1 Abstract

There is potential to improve the spatial and temporal characterisation of subsoil compaction through alternative field methods compared to conventional approaches. Improved characterisation of subsoil compaction will better inform subsoil management. Therefore, this experiment aimed to compare the applicability of two alternative characterisation approaches (electromagnetic conductivity (EC_a) and SubVESS visual evaluation (SubVESS)) compared to conventional field methods (penetration resistance (PR) and bulk density (BD)) to characterise subsoil compactness as a result of a long-term field experiment. Data collection was carried out at the NIAB 'Sustainable Trial for Arable Rotations' long-term rotation and cultivation field experiment. Rotation treatments of a cover crop alternated annually with winter wheat compared to continuous winter wheat, and cultivation treatments of plough (250 mm depth), deep non-inversion (250 mm depth) and shallow non-inversion (100 mm depth) had been applied for 14 consecutive seasons. All methods were found suitable to characterise subsoil compaction but each had specific spatial and temporal limitations. EC_a presented significant spatial and temporal advantages at the large spatial scale and results mirrored those collected by the other methods. However, further refinement is required to improve the applicability of data interpretation for subsoil compaction. SubVESS provided the highest level of

detail on the position and underlying cause of subsoil compaction but was significantly limited by labour intensive methodology. PR provided a spatial and temporal compromise but did not generate contextual information on the underlying cause of compacted subsoil layers. It is suggested that utilising a combination of methods to first capture large-scale spatial and temporal variation (e.g. EC_a or PR) to target more detailed characterisation (e.g. SubVESS) would provide the most applicable dataset for subsoil management.

5.2 Introduction

Subsoil compaction is a significant problem for the sustainability of arable agriculture (Etana et al., 2013; Schonning et al., 2018; Trautner et al., 2003). Estimates suggest that subsoil compaction is widespread and that c. 40 % of EU agricultural subsoils may already be detrimentally compacted (Brus and van den Akker, 2018; Schonning and Thorsoe, 2019). Although measurement methodologies for subsoil compaction have progressed since Jones et al. (2003) highlighted the need for fundamental improvement, a recent review highlighted that development is still required to generate data relevant to soil management (Alaoui and Diserens, 2018). High strength in the subsoil caused by compaction can decrease root growth, limit crop performance and increase the incidence of negative, off-site environmental impacts such as run-off, flood risk and pollution (Passioura, 2002; Rickson et al., 2015; Whalley et al., 2008). Subsoil compaction is highly variable both spatially and temporally, and accurate characterisation is critical to target and maximise the benefit from any alleviation (Chamen et al., 2015). Therefore, there is a requirement to continue the investigation of alternative methods to characterise subsoil compaction at a variety of spatial and temporal scales to improve acceptance, understanding and management (Thorsøe et al., 2019).

Bulk density is the base indicator of soil compactness and can provide a basis for deriving other properties such as porosity (Håkansson and Lipiec, 2000). However, this approach, especially in terms of accessing the subsoil for sample collection, is time consuming and bulk density may not easily be related to subsoil functions and root growth (Rabot et al., 2018). Approaches to characterise subsoil compaction fall into three main categories: invasive methods that infer compaction from mechanical disruption, non-invasive methods that infer compaction from a remote signal, and visual assessments that attribute numerical values to soil attributes (Hoefer and Hartge, 2010).

Cone penetrometers are a widely used invasive method of collecting soil penetration resistance (PR). Measuring the force required for the cone penetrometer to pass through the soil profile (PR), provides an estimation of the

force required for roots to extend through the soil (Tracy et al., 2011) and therefore indirectly, soil compactness. PR has been used extensively to investigate the impact of soil management on subsoil compaction (Batey, 2000; Etana et al., 2013; Ishaq et al., 2001). Negative relationships and critical values (c. 2.5 – 3.0 MPa) have been established with root elongation and crop yield (Clark et al., 2003; Dexter et al., 2007; Gao et al., 2016; Whalley et al., 2007; Whalley et al., 2005). However, spatially and temporally dynamic soil properties, such as moisture status, soil depth, bulk density and texture (Gao et al., 2012; Sojka et al., 2001; To and Kay, 2005; Whitmore et al., 2011) significantly affect the interpretation of PR measurements and may result in misleading interpretation (Sojka et al., 2001; Vaz et al., 2011). These limitations mean a high degree of replication is required to characterise PR at field-scale, though a standard degree of replication is not defined absolutely (Lipiec and Hatano, 2003). Specifically for the subsoil, PR has been reviewed as relating poorly to porosity, root proliferation, aeration and drainage (Spoor et al., 2003). Despite these limitations, probably due to the relative convenience of data collection and availability of apparatus, PR remains widely used to infer compaction in-situ, and provide data for modelling and risk assessment (Hartge and Bachmann, 2004; Mueller et al., 2009).

Remote sensing methods that incorporate geophysics have been put forward as an approach to overcome the spatial and temporal limitations of invasive methods to characterise subsoil compaction (Hoefer et al., 2009; Weiss et al., 2020). Electromagnetic induction (EMI) is currently one of the most promising techniques for use in the field to measure the apparent electrical conductivity (EC_a) of the subsoil (Domsch and Giebel, 2004; Lück et al., 2009). EMI measures the EC_a of the liquid, solid-liquid and solid soil constituents by generating and measuring an electromagnetic field, the amplitude of which will differ from the inherent properties of the field as a result of soil properties (Corwin and Lesch, 2005a). The amplitude of soil EC_a is affected by soil salinity, water content, clay content, cation exchange capacity, organic matter and bulk density (Corwin and Lesch, 2005b). Soil compaction generally increases bulk density, which in turn increases the EC_a as the solid soil pathway is made increasingly contiguous.

Therefore, soil compaction can be inferred through higher EC_a. However, it is critical that the interpretation of EC_a is made with consideration of the numerous other confounding variables (Corwin and Lesch, 2005b; Doolittle and Brevik, 2014).

Experimental evidence has shown that EC_a may be used to characterise soil compaction (Corwin and Lesch, 2005b, Corwin and Lesch, 2005c), with good correlation with PR and the location of compacted pan layers, provided confounding variables are accounted for (Doolittle et al., 1994; Hoefer et al., 2010, Hoefer et al., 2009; O'Leary et al., 2003). However, other studies have observed weaker correlation of EC_a with soil properties, with texture negatively affecting the ability to distinguish between textural change and other soil properties (James et al., 2003; Taylor et al., 2003). EMI has been noted to suffer from other limitations, such as significant variation between experiments caused by the orientation and setup of equipment and consequently, standardisation has been suggested (Hossain, 2008; Sudduth et al., 2001). Application of EC_a measurements to subsoil compaction requires further investigation to better define relationships with subsoil properties and to improve data interpretation (Carroll and Oliver, 2005; Inman et al., 2002; Lilienthal et al., 2005).

Visual soil evaluation (VSE) methods assess soil attributes based on structural qualities, and multiple methods exist that vary in their focus and methodology (Emmet-Booth et al., 2016). Visual assessment of subsoil structure (SubVESS) is a subsoil specific VSE method, focused on agriculture, that attributes numeric scores to subsoil structure and root growth properties to evaluate the interaction between the inherent subsoil characteristics and agricultural management (Ball et al., 2015; Ball et al., 2017). VSE methods explore soil functions and agricultural management but relationships tend to be site specific, and comparability between studies has been shown to be limited by factors such as texture, soil moisture, the operator, and the type of agricultural management (Emmet-Booth et al., 2020; Mueller et al., 2013). In addition, relatively few studies have examined the applicability of SubVESS to experimentally imposed conditions, especially

regarding long-term field experiments (Ball et al., 2015; Emmet-Booth et al., 2020; Obour et al., 2017).

Reliable methods to characterise subsoil compaction are required to improve soil management, progress modelling and risk assessment, and better support policy (Frelih-Larsen et al., 2018; Jones et al., 2003; Schonning et al., 2018; Trautner et al., 2003; van den Akker and Hoogland, 2011). Therefore, the objective of this work was to explore the applicability of SubVESS and EC_a in characterising subsoil compaction as a result of experimental treatments, in comparison to PR and BD. The strengths and weaknesses of each method will be discussed.

5.3 Materials and methods

5.3.1 Experimental site and design

The NIAB ‘Sustainable Trial for Arable Rotations’ (STAR) project was established at Stanway Farm (Suffolk, UK) in 2006. The project is a long-term, field-scale rotation and cultivation experiment, with individual plots of 36 x 36 m (l x w) over three replicate blocks, in a fully factorial design. Rotation and cultivation treatments were achieved using farm-scale machinery on a Beccles/Hanslope soil series. The full experiment comprised four rotation and four cultivation treatments replicated over three blocks as previously detailed in Stobart and Morris (2011) (n = 48 plots). Two rotation and three cultivation treatments replicated over three blocks were selected from the full experiment for the purposes of this paper, that resulted in six treatments that were triple replicated over the three treatment blocks (n = 18 plots total).

The application of rotation and cultivation treatments are outlined in Table 5.1. During the period 2006 – 2018, rotation treatments comprised continuous winter wheat (*Triticum aestivum* var.) (CWW), where winter wheat was grown every season, and an alternate season mustard brassica (*Brassica* spp.) cover crop (ALTCC), where a cover crop was alternated annually with winter wheat. Annual cultivation treatments consisted of plough (PLOUGH) (inversion cultivation 250 mm depth), deep cultivation (DEEP) (non-inversion cultivation using a combination of tines and discs 250 mm depth) and shallow cultivation

(SHALLOW) (non-inversion cultivation using a combination of tines and discs 100 mm depth). The date of rotation and cultivation treatment application varied annually dependent on soil and climatic conditions but always occurred during the UK autumn period (Sep – Nov). Permanent tramlines were used for the application agricultural inputs, established through each plot at a 90° angle to the direction of treatment application.

Rotation treatment ALTCC was replaced with a perennial herbal ley treatment (HL) from September 2018. All plots that previously received ALTCC treatment were cultivated to 100 mm depth, the HL treatment was established 03.09.2018 and no further cultivations took place on these plots. Cultivation treatments continued as before for the CWW rotation treatment. The full list of establishment operations and HL treatment species mixture is listed in Appendix A. The rotation treatment that includes ALTCC and HL will be referred to as ALTCC for the remainder of this paper.

Table 5.1 Rotation and cultivation treatment annual summary and treatment definitions.

Rotation treatment application	Growing season														
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
CWW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW
ALTCC	CC	WW	CC	WW	CC	WW	CC	WW	CC	WW	CC	WW	HL	HL	HL
Rotation treatment															
CWW	Winter wheat (<i>Triticum aestivum</i>) grown every season														
ALTCC	Mustard brassica (<i>Brassica</i> spp.) cover crop														
WW	Winter wheat (<i>Triticum aestivum</i>)														
CC	Mustard brassica (<i>Brassica</i> spp.) cover crop														
HL	Perennial herbal ley species mixture (full species list Appendix A)														
Cultivation treatment															
PLOUGH	Inversion ploughed to depth 250 mm annually														
DEEP	Non-inversion cultivated using disc and tine combination to depth 250 mm annually														
SHALLOW	Non-inversion cultivated using disc and tine combination to depth 100 mm annually														

Table 5.2 is a repetition of the relevant characterisation work (bulk density (BD) and soil organic matter (OM)) carried out at the same field experiment in Chapter 3 (from section 3.4.1; Table 3.2) and the soil texture for each plot is recorded in Appendix B (from Chapter 3; section 3.4.1). These data will be used in the discussion to place the characterisation method results generated within this chapter into context of the soil profile. There were no significant differences found in Chapter 3 for BD (SE = 0.03) or OM (SE = 0.24) (Table 3.2) (Chapter 3; section 3.4.1).

Table 5.2 Bulk density (BD) (g cm^{-3}) and soil organic matter (OM) (%) over depth layers. Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S – SHALLOW (Chapter 3; section 3.4.1).

Treatment	Depth (mm)							
	0 - 200		200 - 400		400 - 600		600 - 800	
	BD	OM	BD	OM	BD	OM	BD	OM
PCWW	1.47	3.91	1.54	2.80	1.48	2.40	1.57	1.94
DCWW	1.47	4.14	1.55	2.67	1.54	3.02	1.54	2.42
SCWW	1.43	4.17	1.56	2.24	1.55	2.62	1.58	2.07
PALTCC	1.50	4.01	1.55	2.80	1.54	2.68	1.53	2.62
DALTCC	1.40	4.31	1.52	3.05	1.48	2.86	1.62	1.93
SALTCC	1.43	4.01	1.56	2.13	1.55	2.45	1.60	1.67
CWW	1.46	4.07	1.55	2.57	1.52	2.68	1.56	2.14
ALTCC	1.44	4.11	1.55	2.66	1.52	2.66	1.58	2.07
PLOUGH	1.48	3.96	1.55	2.80	1.51	2.54	1.55	2.28
DEEP	1.44	4.22	1.53	2.86	1.51	2.94	1.58	2.18
SHALLOW	1.43	4.09	1.56	2.19	1.55	2.54	1.59	1.87

5.3.2 Subsoil characterisation methodologies

Soil bulk density, soil moisture, penetration resistance and SubVESS visual soil assessments were collected between dates 16.11.2020 – 19.11.2020. Electromagnetic conductivity scanning was carried out on 23.11.2020.

5.3.2.1 Soil bulk density and soil moisture

Utilising the soil pits dug for SubVESS assessments, three replicate soil cores (55 x 30 mm) (h x d) were collected from the centre of each subsoil layer (approx. 350 mm depth) at each plot (n = 18). Soil cores were dried for 24 hours at 105°C, and soil bulk density (BD) (g cm^{-3}) and volumetric soil moisture (VSM) ($\text{cm}^3 \text{ cm}^{-3}$) were calculated.

Three replicate VSM measurements were also obtained using a soil moisture probe (VSMp) (%) (Delta-T Devices, ML3 Theta Probe) at the same depth (approx. 350 mm). Soil probe standard integrated calibration for ‘mineral soils’ was used (offset 1.6; slope 8.4) (Delta-T Devices Ltd, 2017).

5.3.2.2 Penetration resistance

Penetration resistance (PR) was measured using a manually operated digital penetrometer (Eijelkamp, Digital Penetrologger V.6.13). Ten randomised penetrations were collected at each plot to 500 mm depth using a 1.2 cm^3 30° cone. The ten randomised penetrations per plot were averaged at 50 mm intervals to provide mean PR over depth.

5.3.2.3 Electromagnetic conductivity

Apparent electromagnetic conductivity (EC_a) data was generated through electromagnetic induction (EMI) measurement using a Dualem-1S EC scanner (Dualem Inc., Canada) and was carried out by Precision Decisions Ltd. (York, UK). The scanner was towed behind an all-terrain vehicle (ATV) equipped with a TOPCON (TOPCON Precision Agriculture, Europe S.L.) GPS device that plotted individual EC_a scan locations to <0.5 m accuracy using the European Geostationary Navigation Overlay System (EGNOS). The distance between the transmitter and receiver was 1 m, collecting dual depth EC_a measurements at 0

– 500 mm and 0 – 1500 mm. The 0 – 500 mm depth represents where cultivation treatments were active and the 0 – 1500 mm depth represents the deeper subsoil that may be accessed by crop roots but also may be affected by subsoil compaction (Keller and Arvidsson, 2004; Lynch and Wojciechowski, 2015).

Data was collected at 6 m swath widths across the experiment site. Open-source geographical information system (GIS) software QGIS (QGIS, 2021) was used to process EC_a data into surface maps. Experiment plot boundaries were identified visually and data points within 3 m of the plot boundary were discarded, leaving plots of 33 x 33 m (l x w). Mean EC_a was calculated for each depth using the remaining data points. The full, non-averaged EC_a dataset per plot is included in Appendix C.

5.3.2.4 SubVESS visual soil assessment

The visual evaluation of subsoil structure ‘SubVESS’ method (Ball et al., 2015) was carried out once per plot (n = 18). A soil pit of 600 x 400 mm (l x w) was excavated to 500 mm depth in the centre of each plot. For each plot, layers of contrasting colour and hardness were identified, marked, and each layer was then individually scored using the following categories (Ball et al., 2015):

1. Mottling (degree of anaerobism)
2. Strength (resistance of the soil to penetration with a knife)
3. Porosity (presence of visible pores and voids)
4. Pattern and depth of root penetration
5. Aggregate size and shape

Categories were scored on a scale of 1 – 5 (integers), where 1 is the best and 5 is the worst, following descriptions given in the method flowchart (Ball et al., 2015). These scores were then used to assign an overall subsoil quality score (Ssq) for each layer.

The two most frequently occurring subsoil layers were at 242 – 335 mm (D1) and 335 – 500 mm (D2). Scores that fell within these depths were averaged for the two layers (non-integers) to give mean treatment scores at D1 and D2. These

means were averaged to give a mean (non-integer) for each treatment without depth as a factor ($D\bar{x}$). Digital photographs and notes on each layer were taken at each assessment for reference.

5.3.3 Statistical analyses

Data was checked for normality by plotting a histogram and quantile-quantile plots. Variable 'VSM' was $\log_{10}$ transformed to normalise the data distribution. Factorial ANOVA was used to analyse data without a depth factor and repeated measures factorial ANOVA was used to analyse data that had depth as a factor (treating depth as a within-subjects variable). Where significant effects were observed, these were followed by an unprotected Fischer's least significant difference (LSD) test. Standard error (SE) and error bars represent the standard error of the means for the treatment comparison and/or depth category discussed (SE). SubVESS data was analysed using a Kruskal-Wallis H Test (H) and followed up with a post hoc Mann-Whitney U Test to identify significant differences between groups where necessary. Spearman's Rank-Order Correlation (ρ) was used to investigate the relationship between the methods. All tests were conducted at the 5% significance level (P). Replicate block results are included in Appendix D. EC_a data from the 0 – 1500 mm depth was excluded from Spearman's rank correlations and comparative figures due to the maximum depth of other methods being restricted to 500 mm, therefore only EC_a 0 – 500 mm was included.

5.4 Results

5.4.1 Soil bulk density and soil moisture

No significant differences ($P = >0.05$) were recorded between mean treatments (SE = rotation 0.03; cultivation 0.04) or treatment interactions (SE = 0.05) for soil bulk density (BD) (Table 5.3). No significant differences ($P = >0.05$) were recorded between mean treatments (SE = rotation 0.01; cultivation 0.02) or treatment interactions (SE = 0.02) for volumetric soil moisture (VSM) (Table 5.3). No significant differences ($P = >0.05$) were recorded between mean treatments (SE = rotation 1.28; cultivation 1.57) or treatment interactions (SE = 2.21) for

probe soil moisture (VSMp) (Table 5.3). No significant differences ($P = >0.05$) were recorded between replicate blocks (Appendix D).

Table 5.3 Soil bulk density (BD) (g cm^{-3}), volumetric soil moisture (VSM) ($\text{cm}^3 \text{cm}^{-3}$) and soil moisture probe (VSMp) (%) at 350 mm depth. Mean rotation treatment (CWW – continuous winter wheat, ALTCC – alternate cover crop), mean cultivation treatment (PLOUGH, DEEP, SHALLOW) and treatment interaction (PCWW – PLOUGH CWW, DCWW – DEEP CWW, SCWW – SHALLOW CWW, PALTCC – PLOUGH ALTCC, DALTCC – DEEP ALTCC, SALTCC – SHALLOW ALTCC) (as defined in Table 5.1).

	BD (g cm^{-3})	VSM ($\text{cm}^3 \text{cm}^{-3}$)	VSMp (%)
CWW	1.40	0.20	35.0
ALTCC	1.45	0.20	33.8
PLOUGH	1.42	0.21	35.6
DEEP	1.45	0.20	34.7
SHALLOW	1.41	0.20	32.9
PCWW	1.41	0.22	37.3
DCWW	1.44	0.21	34.9
SCWW	1.37	0.17	32.9
PALTCC	1.43	0.19	34.0
DALTCC	1.46	0.19	34.4
SALTCC	1.46	0.22	32.9

5.4.2 Penetration resistance

Results for PR are shown in Fig. 5.1: mean rotation treatments are shown in Fig. 5.1a, mean cultivation treatments are shown in Fig. 5.1b, and the interaction between rotation and cultivation treatments are shown in Fig. 5.1c. Mean rotation treatment PR results showed that between depths 0 – 250 mm ALTCC treatment had significantly higher penetration resistance compared to CWW (Fig. 5.1a). Mean cultivation PR results showed that SHALLOW treatment had significantly higher PR compared to PLOUGH between depths 50 – 300 mm (Fig. 5.1b). SHALLOW treatment also had significantly higher PR compared to DEEP between depths 200 – 300 mm (Fig. 5.1b). DEEP treatment had significantly higher PR compared to PLOUGH treatment at depth 200 mm (Fig. 5.1b). The interaction of rotation and cultivation treatments showed that combined with rotation treatment CWW, SHALLOW had significantly higher PR compared to PLOUGH at depth 100 – 250 mm and DEEP at depth 100 – 300 mm (Fig. 5.1c). Where combined with rotation treatment CWW, DEEP had significantly higher PR compared to PLOUGH at depth 200 mm (Fig. 5.1c). Where combined with rotation treatment ALTCC, SHALLOW had significantly higher PR compared to PLOUGH at depth 200 – 250 mm and DEEP at depth 250 – 300 mm (Fig. 5.1c). Rotation treatment ALTCC had significantly higher PR compared to CWW where combined with PLOUGH at depth 50 – 250 mm, DEEP at depth 50 – 250 mm, and SHALLOW at 50 – 100 mm (Fig. 5.1c). There were no significant differences between the replicate blocks ($P = 0.75$; $SE = 0.11$) (Appendix D).

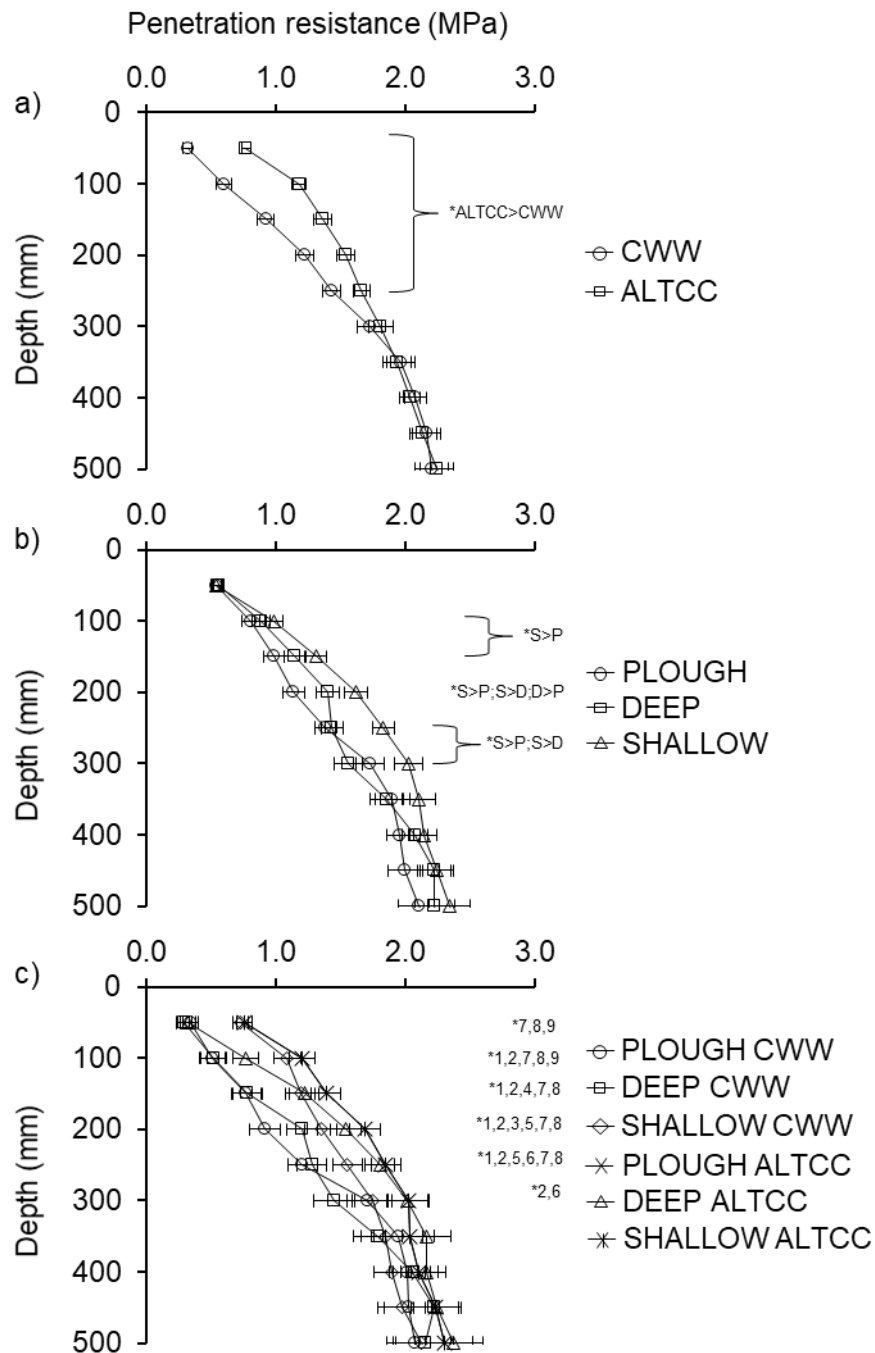


Figure 5.1 Penetration resistance (MPa) a) rotation treatments (CWW – continuous winter wheat, ALTCC – alternate cover crop), b) cultivation treatments (P – PLOUGH, D – DEEP, S – SHALLOW) and c) rotation and cultivation treatment interaction (1 - SCWW>PCWW, 2 - SCWW>DCWW, 3 - DCWW>PCWW, 4 - DALTCC>PALTCC, 5 - SALTCC>PALTCC, 6 - SALTCC>DALTCC, 7 - PALTCC>PCWW, 8 - DALTCC>DCWW, 9 - SALTCC>SCWW). Error bars represent standard error of the mean between treatments at each depth.

5.4.3 Electromagnetic conductivity

Mean rotation treatment CWW had significantly higher EC_a compared to ALTCC at scan depth 0 – 500 mm ($P = <0.01$; $SE = 0.06$) and 0 – 1500 mm ($P = <0.01$; $SE = 0.09$) (Table 5.4). At scan depth 0 – 500 mm, mean cultivation treatment showed PLOUGH had significantly higher EC_a compared to DEEP and SHALLOW ($P = <0.01$; $SE = 0.07$) (Table 5.4). Whereas, at scan depth 0 – 1500 mm, PLOUGH and DEEP were significantly higher compared to SHALLOW ($P = <0.01$ and 0.01 respectively; $SE = 0.11$), and PLOUGH was significantly higher than DEEP ($P = <0.01$; $SE = 0.11$) (Table 5.4).

Treatment interaction demonstrated that combined with rotation treatment CWW, SHALLOW had significantly higher EC_a compared to PLOUGH and DEEP at scan depth 0 – 500 mm ($P = <0.01$ and < 0.01 respectively; $SE = 0.10$) (Table 5.4). Whereas, SHALLOW was significantly higher compared to PLOUGH and DEEP ($P = <0.01$ and <0.01 respectively; $SE = 0.16$), and PLOUGH significantly higher compared to DEEP ($P = 0.04$; $SE = 0.16$) at scan depth 0 – 1500 mm (Table 5.4). Combined with rotation treatment ALTCC, PLOUGH had significantly higher EC_a compared to DEEP and SHALLOW ($P = <0.01$ and <0.01 respectively; $SE = 0.01$), and DEEP had significantly higher EC_a compared to SHALLOW at scan depth 0 – 500 mm ($P = <0.01$; $SE = 0.01$) (Table 5.4). In parallel, PLOUGH had significantly higher EC_a compared to DEEP and SHALLOW ($P = <0.01$ and <0.01 respectively; $SE = 0.16$), and DEEP had significantly higher EC_a compared to SHALLOW at scan depth 0 – 1500 mm ($P = <0.01$; $SE = 0.16$) (Table 5.4). Combined with cultivation treatments PLOUGH or SHALLOW, CWW had significantly higher EC_a compared to ALTCC at scan depth 0 – 500 mm ($P = <0.01$ and <0.01 respectively; $SE = 0.01$ and 0.16 respectively) and 0 – 1500 mm ($P = <0.01$ and <0.01 respectively; $SE = 0.01$ and 0.16 respectively) (Table 5.4). Combined with cultivation treatment DEEP, CWW had significantly higher EC_a compared to ALTCC at scan depth 0 – 1500 mm ($P = <0.01$; $SE = 0.16$) (Table 5.4). Replicate Block 1 had a significantly higher EC_a compared to Blocks 2 and 3 at scan depth 0 – 500 mm ($P = <0.01$; $SE = 0.08$), and all replicate blocks were

significantly different from one another at scan depth 0 – 1500 mm ($P = <0.01$; $SE = 0.13$) (Appendix D).

Table 5.4 Mean electromagnetic conductivity (EC_a) for shallow (500 mm) and deep (1500 mm), and mean centred coefficient of variation (CV) (%). Mean rotation treatment (CWW – continuous winter wheat, ALTCC – alternate cover crop), mean cultivation treatment and treatment interaction (PCWW – PLOUGH CWW, DCWW – DEEP CWW, SCWW – SHALLOW CWW, PALTCC – PLOUGH ALTCC, DALTCC – DEEP ALTCC, SALTCC – SHALLOW ALTCC) (as define in Table 5.1). Significant ($P \leq 0.05$) differences are separated by depth (500/1500 mm), and are organised by column (lowercase letters without parentheses represent differences within a section e.g.^{a,b,c}, uppercase letters, numbers and symbols with parentheses represent differences between sections e.g.^{(A/B),(1/2),(*/**)}).

	Mean EC (mS m ⁻¹) (500 mm)	CV (%) (500 mm)	Mean EC (mS m ⁻¹) (1500 mm)	CV (%) (1500 mm)
CWW	18.0 ^a	5.7	42.1 ^a	3.6
ALTCC	17.2 ^b	6.1	40.2 ^b	4.0
PLOUGH	17.8 ^a	6.3	41.7 ^a	4.1
DEEP	17.5 ^b	5.5	41.1 ^b	3.7
SHALLOW	17.5 ^b	5.9	40.7 ^c	3.7
PCWW	17.9 ^a	6.8	42.1 ^{a(A)}	4.5
DCWW	17.8 ^{a(A)}	5.2	41.8 ^{b(1)}	3.5
SCWW	18.4 ^{b(1)}	5.2	42.6 ^{c(*)}	2.8
PALTCC	17.8 ^a	5.8	41.4 ^{a(B)}	3.6
DALTCC	17.3 ^{b(B)}	5.7	40.4 ^{b(2)}	3.9
SALTCC	16.7 ^{c(2)}	6.6	38.9 ^{c(**)}	4.6

5.4.4 SubVESS visual soil assessment

Results averaged over both depths ($D\bar{x}$) showed that rotation treatment had a significant impact on the SubVESS scores for categories Ssq, porosity and roots. Rotation treatment ALTCC had significantly lower SubVESS scores compared to CWW for Ssq (2.7 and 3.2 respectively; $H = 6.17$; $P = 0.01$), porosity (2.6 and 3.1 respectively; $H = 4.83$; $P = 0.03$) and roots (1.6 and 2.4 respectively; $H = 4.49$; $P = 0.03$) (Table 5.5). Where depths D1 and D2 were analysed separately, rotation treatment again had a significant impact on SubVESS scores. At D1, rotation treatment ALTCC had significantly lower SubVESS scores compared to CWW for categories Ssq (2.3 and 2.9 respectively; $H = 5.52$; $P = 0.02$) and roots (1.3 and 2.3 respectively; $H = 5.81$; $P = 0.02$) (Table 5.5). Whereas at D2, rotation treatment ALTCC had significantly lower SubVESS scores compared to CWW for category porosity (2.9 and 3.3 respectively; $H = 4.03$; $P = 0.05$) (Table 5.5). Replicate Block 3 had a significantly lower SubVESS score for category mottling compared to Block 1 (1.7 and 2.8 respectively; $H = 7.66$; $P = 0.01$) (Appendix D).

Table 5.5 SubVESS score analysis of mean rotation treatment (CWW – continuous winter wheat, ALTCC – alternate cover crop), mean cultivation treatment and treatment interaction (PCWW – PLOUGH CWW, DCWW – DEEP CWW, SCWW – SHALLOW CWW, PALTCC – PLOUGH ALTCC, DALTCC – DEEP ALTCC, SALTCC – SHALLOW ALTCC). H – Kruskal-Wallis test statistic, significant differences are denoted with ‘*’, and mean rotation has 1*df*, mean cultivation has 2*df* and treatment interaction has 5*df*.

		Ssq			Mottling			Strength			Porosity			Roots			Aggregate		
		Mean	Rank mean	H	Mean	Rank mean	H	Mean	Rank mean	H	Mean	Rank mean	H	Mean	Rank mean	H	Mean	Rank mean	H
Mean D $\bar{x}$	CWW	3.2	12.5	6.17*	1.7	8.6	0.60	2.9	9.4	0.01	3.1	12.1	4.83*	2.4	12.1	4.49*	3.1	10.3	0.53
	ALTCC	2.7	6.5		1.8	10.4		2.9	9.6		2.6	6.9		1.6	6.9		2.9	8.7	
	PLOUGH	3.1	12.0	2.53	1.7	8.8	2.39	3.0	10.4	1.66	2.8	9.7	0.02	2.4	12.4	3.73	3.1	11.7	4.60
	DEEP	2.9	9.2		2.0	12.1		2.8	7.6		2.8	9.6		2.1	9.5		3.1	10.8	
	SHALLOW	2.3	7.3		1.3	7.7		2.5	10.5		2.3	9.3		1.3	6.6		2.3	6.1	
	PCWW	3.3	14.2	8.96	1.7	7.8	3.03	3.2	12.8	5.69	2.8	9.7	7.91	3.0	16.0	8.66	3.0	9.5	9.62
	DCWW	3.2	12.8		1.8	10.8		2.5	4.8		3.0	12.3		2.5	12.2		3.3	14.5	
	SCWW	3.0	10.5		1.5	7.0		3.0	10.5		3.3	14.3		1.8	8.2		2.8	7.0	
	PALTCC	3.0	9.8		1.8	9.7		2.8	8.0		2.8	9.7		1.8	8.8		3.3	13.8	
	DALTCC	2.7	5.5		2.2	13.3		3.0	10.3		2.7	6.8		1.7	6.8		2.8	7.0	
	SALTCC	2.5	4.2		1.6	8.3		3.0	10.5		2.2	4.2		1.3	5.0		2.7	5.2	
D1 (24.2 - 33.5 cm)	CWW	2.9	12.0	5.52*	1.2	8.7	0.83	2.8	9.8	0.08	2.8	11.3	2.57	2.3	12.3	5.81*	2.9	10.1	0.32
	ALTCC	2.3	7.0		1.3	10.3		2.8	9.2		2.2	7.7		1.3	6.7		2.8	8.9	
	PLOUGH	2.8	11.5	1.77	1.2	8.9	0.44	3.0	10.8	4.09	2.5	9.5	<0.01	2.3	12.4	3.22	3.0	10.8	1.15
	DEEP	2.5	8.5		1.3	10.3		2.3	6.7		2.5	9.5		1.7	8.6		2.8	9.6	
	SHALLOW	2.5	8.5		1.3	9.3		3.0	11.0		2.5	9.5		1.5	7.5		2.7	8.2	

D2 (33.5 - 50.0 cm)	PCWW	3.0	13.0		1.0	7.5		3.3	13.3		2.3	8.2		3.0	16.0		2.7	8.2	
	DCWW	2.7	10.0		1.0	7.5		2.0	5.0		2.7	10.8		2.0	10.5		3.0	11.0	
	SCWW	3.0	13.0	9.05	1.7	11.0	5.68	3.0	11.0	7.16	3.3	15.0	8.61	2.0	10.5	9.38	3.0	11.0	6.88
	PALTCC	2.7	10.0		1.3	10.3		2.7	8.3		2.7	10.8		1.7	8.8		3.3	13.3	
	DALTCC	2.3	7.0		1.7	13.2		2.7	8.3		2.3	8.2		1.3	6.7		2.7	8.2	
	SALTCC	2.0	4.0		1.0	7.5		3.0	11.0		1.7	4.0		1.0	4.5		2.3	5.3	
	CWW	3.4	11.0	2.35	2.1	8.7	0.42	3.0	8.6	1.89	3.3	11.3	4.03*	2.6	11.2	2.12	3.2	10.1	0.32
	ALTCC	3.1	8.0		2.4	10.3		3.1	10.4		2.9	7.7		1.8	7.8		3.1	8.9	
	PLOUGH	3.5	11.5		2.3	9.2		3.0	9.5		3.2	9.9		2.5	12.0		3.3	10.8	
	DEEP	3.3	10.0	3.66	2.7	12.7	4.25	3.2	9.5	<0.01	3.2	9.9	0.42	2.5	10.4	4.45	3.3	10.8	3.66
	SHALLOW	2.0	7.0		1.2	6.7		2.0	9.5		2.0	8.7		1.1	6.1		1.9	6.8	
	PCWW	3.7	13.0		2.3	9.8		3.0	9.5		3.3	11.3		3.0	14.5		3.3	10.8	
	DCWW	3.7	13.0		2.7	12.7		3.0	6.7		3.3	11.3		3.0	12.3		3.7	13.7	
	SCWW	3.0	7.0	7.59	1.3	3.7	6.45	3.0	9.5	5.67	3.3	11.3	4.87	1.7	6.8	6.93	2.7	5.7	6.88
	PALTCC	3.3	10.0		2.3	8.5		3.0	9.5		3.0	8.5		2.0	9.5		3.3	10.8	
	DALTCC	3.0	7.0		2.7	12.7		3.3	12.3		3.0	8.5		2.0	8.5		3.0	8.0	
	SALTCC	3.0	7.0		2.2	9.7		3.0	9.5		2.7	6.0		1.5	5.3		3.0	8.0	

5.4.5 Spearman's rank correlation between quantitative and qualitative soil measurements

There were no significant correlations between quantitative and/or qualitative soil measurements (Table 5.6).

Table 5.6 Spearman's rank correlations (ρ) between quantitative and qualitative soil measurements, and P-value (P). PR – penetration resistance (mean – average D1 and D2, D1 – 242 – 335 mm, D1 – 335 – 500 mm), EC – electromagnetic conductivity (0 – 500 mm), Ssq – SubVESS assessment score (mean – average D1 and D2, D1 – 242 – 335 mm, D1 – 335 – 500 mm), VSM – volumetric soil moisture, VSMp – theta probe soil moisture, BD – bulk density. Sample size $n = 18$.

	PR (D1)		PR (D2)		EC (0 – 500 mm)	
	ρ	P	ρ	P	ρ	P
PR (D $\bar{x}$)					-0.10	0.69
PR (D1)					-0.22	0.37
PR (D2)					0.03	0.91
Ssq (D1)	-0.27	0.27			0.25	0.31
Ssq (D2)			-0.39	0.11	-0.27	0.27
VSM	-0.06	0.81	-0.24	0.34	-0.18	0.47
VSMp	-0.28	0.25	-0.22	0.37	-0.25	0.32
BD	-0.26	0.31	0.15	0.54	0.06	0.81

5.4.6 Method comparison charts

Combined comparison charts were created to compare the characterisation for each method side by side. The 0 – 500 mm depth was used as each method had this depth in common. Values correspond to those already presented but a combined visual comparison is worthwhile to support the discussion. Mean rotation and cultivation treatment comparisons for PR, SubVESS and EC at the 0 – 500 mm depth are presented in Fig. 5.2 and treatment interactions at depth 0 – 500 mm are presented in Fig. 5.3.

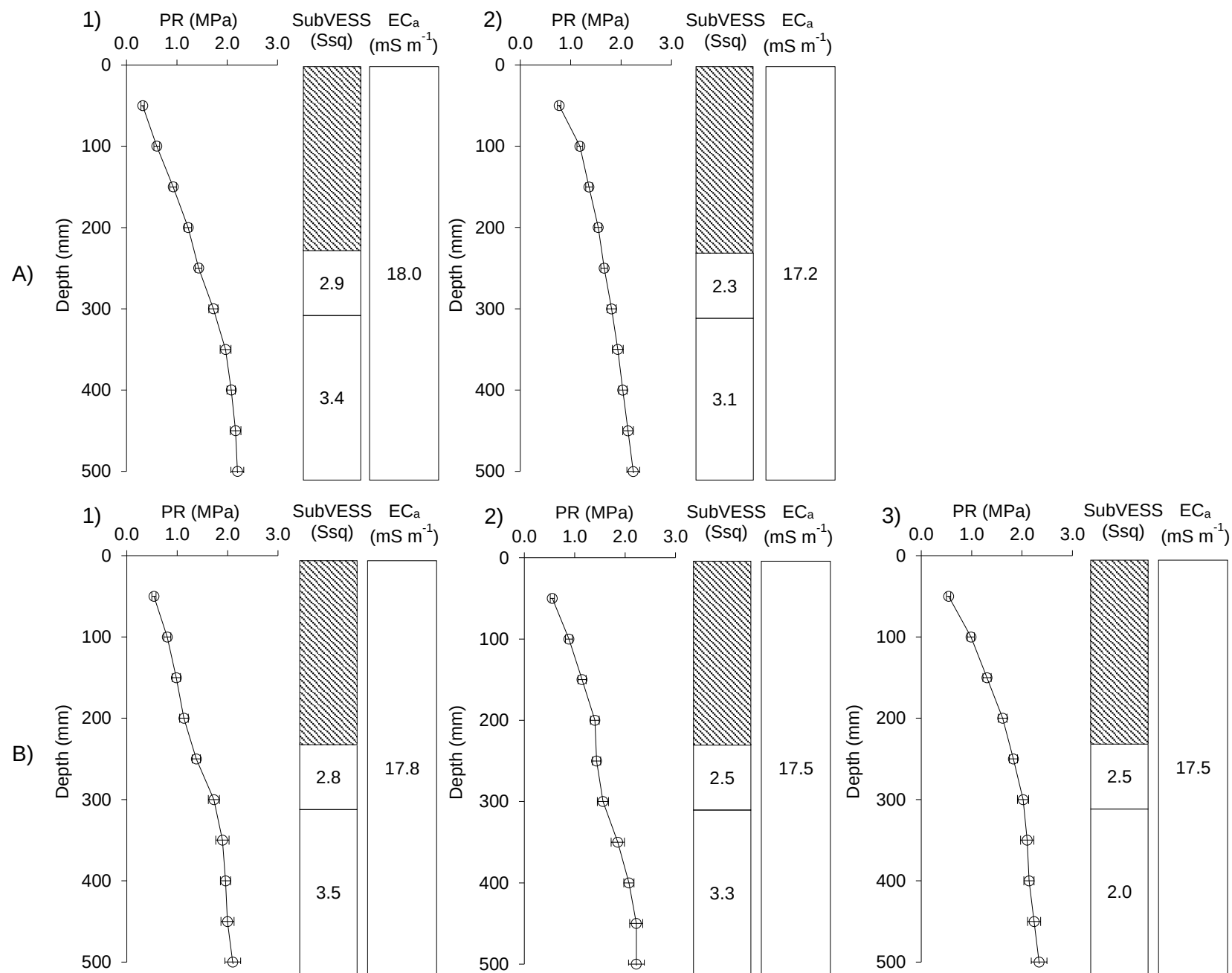


Figure 5.2 Penetration resistance (PR) (MPa), SubVESS assessment (Ssq) and electromagnetic conductivity (EC_a) (mS m⁻¹) for mean rotation and mean cultivation treatments. Mean rotation treatments A1 – CWW and A2 – ALTCC. Mean cultivation treatments B1 – PLOUGH, B2 – DEEP and D3 – SHALLOW. Error bars represent standard error of the mean between treatments at each depth.

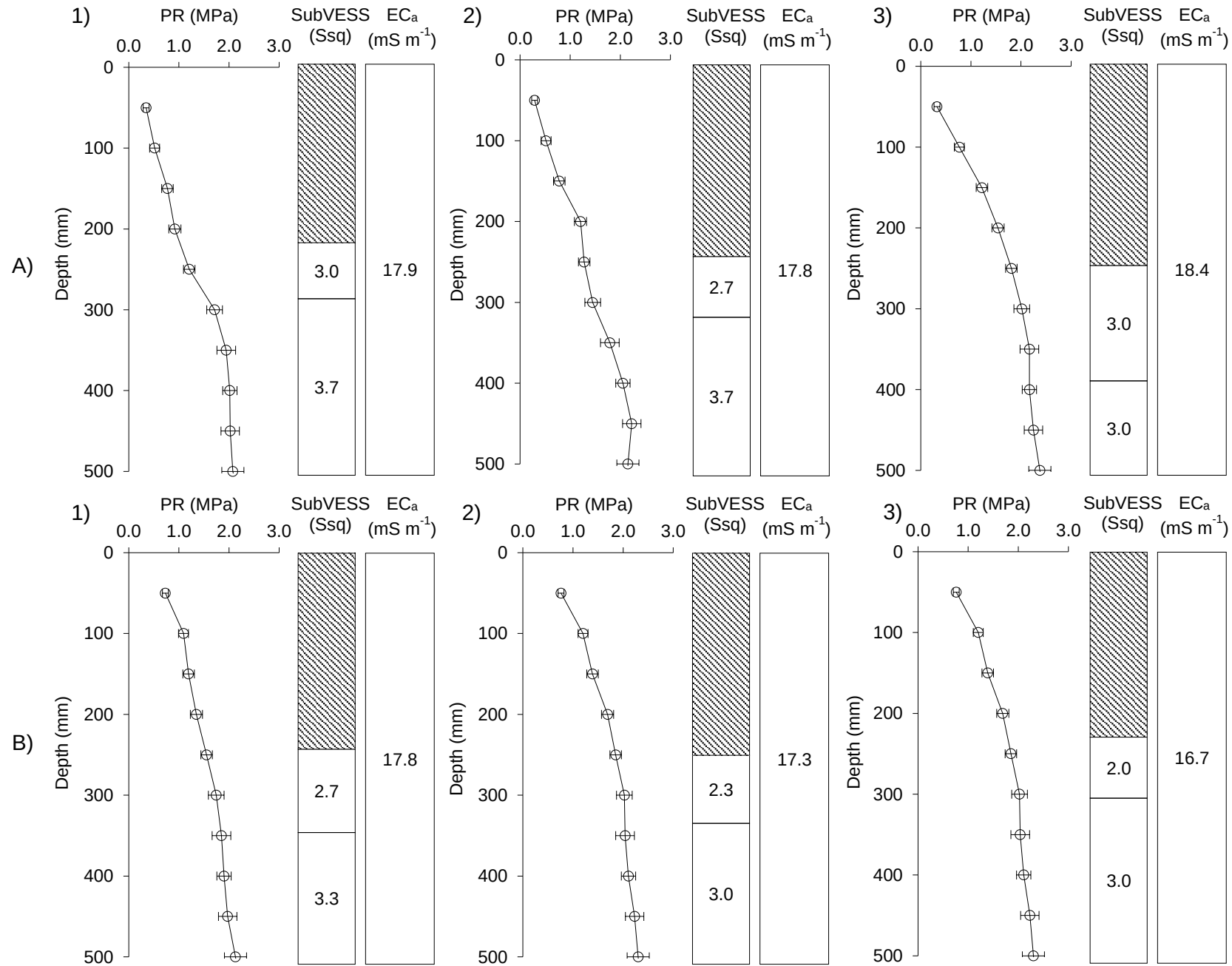


Figure 5.3 Penetration resistance (PR) (MPa), SubVESS assessment (Ssq) and electromagnetic conductivity (EC_a) (mS m⁻¹) for rotation and mean treatment interaction. A1 – PCWW, A2 – DCWW, A3 – SCWW, B1 – PALTCC, B2 – DALTCC, B3 – SALTCC (P – PLOUGH, D – DEEP, S – SHALLOW). Error bars represent standard error of the mean between treatments at each depth.

5.5 Discussion

This paper sought to explore the applicability of two alternative methods to characterise subsoil compaction as a result of rotation and cultivation treatments at a long-term field experiment. The results, strengths and limitations of each method will be discussed separately and then methods compared to each other.

Bulk density (BD) and soil organic matter (SOM) results, both from the experimental work in this chapter and also those included from Chapter 3, showed there were no significant differences between treatments throughout the measured profile (0 – 800 mm). Therefore, from a volumetric standpoint (BD), the subsoil (and topsoil) were at the same level of compactness throughout. However, this is not necessarily disappointment from the standpoint of comparing the applicability of alternative characterisation methods. Research has suggested that BD may not be fit for purpose as a standalone measurement, as although it defines compactness, it lacks consideration of the soil structure and functions that are not necessarily linearly related to bulk density (Rabot et al., 2018). Therefore, significant differences recorded by the alternative methods may demonstrate modes of characterisation that supplement and/or improve on a purely volumetric approach. The lack of significant differences in subsoil moisture measurements indicate that this variable may be discounted as far as possible, given the methods used (i.e. replicate moisture samples from a single depth).

Measurement of PR using a penetrometer represented the most conventional method and identified significant differences between the treatments in the profile. In particular, PR strongly reflected the working depths of the cultivation implements and indicated a reduction in subsoil PR where cultivations had ceased as part of the ALTCC rotation treatment change from ALTCC to HL. This is supported by previous research that suggested the introduction of perennial species has been linked to increasing pore formation and reducing compaction in the subsoil (McCallum et al., 2004). The significant PR differences between cultivation treatments followed similar trends combined with either rotation treatment. The significant differences occurred over a narrower depth range and

only at the bottom of implement working depths where cultivation treatments were combined with ALTCC compared to CWW.

Overall, results indicated that all treatments had relatively low PR for the soil type, with none exceeding the approximate 2.5 – 3.0 MPa value, over which root ability to deform and penetrate soil may become restricted (Clark et al., 2003; Whalley et al., 2007). However, data was collected during the UK autumn season and soil moisture results show the field was near field capacity for the soil texture (Hanson et al., 2000). Evidence has shown that PR is less sensitive at high moisture contents and as a result may misrepresent the resistance roots encounter as soil moisture (and consequently PR) changes throughout the season with drying soil (Bengough et al., 2001). As a comparison, results presented in Chapter 3 at the same site using the same treatment plots showed PR exceeded 3.0 MPa in subsoil for the same treatments, when PR was monitored throughout a growing season at various soil moistures (Chapter 3; Section 3.4.2). Normalising PR data for soil moisture has been shown to reduce the influence of moisture status on PR (Busscher et al., 1997; Vaz et al., 2011) and some digital penetrometers are able to record a surface soil moisture measurement for each penetration (for example Eijelkamp, Digital Penetrologger V.6.13). However, this approach seems rarely employed, perhaps due to the complexity of interpreting the subsequent datasets over depth using a single surface moisture measurement. In addition, field experiments have shown that healthy crop growth may be supported at significantly higher PR values than c. 2.5 MPa (Busscher et al., 1997; Sojka et al., 2001; To and Kay, 2005; Whalley et al., 2007). These points represent significant limitations in the characterisation of subsoil compaction with PR, and support the notion that a high degree of replication is required (Lipiec and Hatano, 2003). Instead, tailoring the timing of PR sampling to coincide with crop (root) growth stages, may provide the greatest opportunity to encompass seasonal subsoil moisture variability in results, and therefore best inform characterisation and soil management decisions (Whalley et al., 2008, Whalley et al., 2006).

Although PR generated information on subsoil strength, it was not able to indicate the cause of the significant PR differences observed between the rotation and cultivation treatments. High subsoil PR is usually assumed to correlate with poor function but this is not always the case, as high PR does not always correlate linearly with poorer soil function (Chamen et al., 2003). This suggests that PR is relevant as a measurement of subsoil compaction but less so for the impact of compaction on subsoil function. With subsoil compaction in an agricultural context, it is important to characterise compactness and function over depth, not just soil strength (Lynch and Wojciechowski, 2015). These are significant limitations on relying solely on PR to characterise subsoil compaction. Especially given PR is generally higher in the subsoil and, due to the increase in soil-metal friction, internal friction between soil particles and increased pressure at the cone surface with depth, PR may further lose accuracy in the subsoil (Gao et al., 2016; Whitmore et al., 2011).

Significant differences in EC_a were observed between treatments and the experiment EC_a fell within the expected boundaries for the soil texture (Al-Gaadi, 2012). However, previous studies indicate that the differences reported in this paper may be relatively small and perhaps do not relate to a magnitude of change in soil properties that would be significant for crop growth, despite significant statistical differences (Al-Gaadi, 2012; Brevik and Fenton, 2004). Brevik and Fenton (2004) found that three different soil series in agricultural use (USA) had an inherent EC_a variation of 15 to 40 $mS\ m^{-1}$, which is within the context of the total field variation of 9.4 $mS\ m^{-1}$ found in this paper. Replication of this work or a meta-analysis for a variety of common UK agricultural soil series would produce extremely helpful information for the interpretation of subsoil EC_a measurements. That said, reliably relating EC_a to subsoil compaction is a current open research question and the observed trends in EC_a broadly followed trends in PR and SubVESS, alongside the expected effects of rotation and cultivation treatments on subsoil compaction.

High intensity cultivation treatments (e.g. PLOUGH and DEEP) and no rotation (e.g. CWW) have been linked to increased subsoil compaction (Alakukku et al.,

2003; Spoor et al., 2003) and so may be expected to generate higher EC_a (Hoefer et al., 2010), as was observed in this experiment. Cultivation treatments PLOUGH and DEEP had a similar EC_a difference compared to SHALLOW when combined with either rotation treatment, which indicated that EC_a was able to distinguish between high intensity cultivation and minimal cultivation, but not between inversion and non-inversion cultivation carried out at the same depth. Reduced intensity cultivation such as SHALLOW, although beneficial to subsoil functions, may increase BD (Holland, 2004) and therefore EC_a , as a consequence of reduced mechanical disturbance compared to PLOUGH or DEEP. This was observed where cultivation treatments were combined with rotation treatment CWW but the opposite was observed where combined with rotation treatment ALTCC at the 0 – 500 mm depth. This suggested that EC_a may have detected change in subsoil due to the difference between rotation treatments, the consequence of ALTCC shifting to a perennial crop (HL) where combined previously with SHALLOW or the cessation of cultivation. A more detailed investigation on the ability of EC_a to detect differences in rotation would form an interesting future study. As previously mentioned, the introduction of perennial species has been linked to increasing pore formation in the subsoil, which may have changed the EC_a due to the presence of voids or perhaps increased organic matter (roots at various states of decomposition).

Using EC_a data to generate plot treatment means was useful for the comparison purposes of this paper but was an oversimplification of the large, georeferenced dataset collected. Using EC_a 's integrated georeferenced data opens up the possibility for geostatistics and integration into precision farming approaches that have been shown to improve overall soil management (Lück et al., 2009; Wadoux et al., 2019). The main advantage is that the horizontal spatial scale of subsoil characterisation through EC_a is sampled at a frequency not practically possible with the BD, PR or SubVESS. However, the significant disadvantage of this approach is that EC_a is only able to provide data over fixed depths (i.e. during this experiment 0 – 500 mm or 0 – 1500 mm). The orientation and spacing of EC_a apparatus may be manipulated to target a variety of depths and resolutions (Doolittle and Brevik, 2014; Hossain, 2008; Samouëlian et al., 2005) but the data

remains limited to one value per fixed depth. This is of importance as understanding how change in compaction occurs over depth has an implication for crop growth and selecting appropriate alleviation (Chen and Weil, 2011; Jin et al., 2013). Scanning at a fixed depth also means EC_a is unable to easily discount topsoil in measurements and a large variation in, for example topsoil water content or texture, may skew EC_a. During the work presented in this paper, the potential impact of topsoil variation in the EC_a dataset could not be discounted and the textural survey conducted in Chapter 3 had to be relied upon to account for variation (Appendix B). However, in reality this may be of little importance, as an end user would likely be interested in the entire profile and the close association of topsoil and subsoil properties in agriculture (Peigné et al., 2013; Spoor et al., 2003). Developments for the application of EC_a in agriculture have gone some way to address the depth issue. Experimentation with a larger number of sensors, simultaneously scanning at multiple depths, was shown to increase the horizontal and vertical stratigraphy of EC_a datasets and improve the applicability to soil compaction (Lueck and Ruehlmann, 2013). Combining a variety of remote sensing methods (e.g. EC_a with ground penetrating radar and electrical resistivity) with satellite imagery, were also shown to improve soil characterisation, as each method compensated for limitations in another (André et al., 2012).

The SubVESS assessment is not intended to generate quantitative values for comparative statistics, and is instead designed to identify the position and likely cause of restrictive layers in the subsoil (Ball et al., 2015). Although the ordinal dataset produced makes statistical analysis challenging (Mueller et al., 2009), these analyses alongside the quantitative scores may aid understanding, especially in a research context. The statistical analysis showed that rotation treatment ALTCC had significantly better scores for categories 'roots', 'porosity' and 'Ssq' at depth D $\bar{x}$, 'Ssq' at depth D1, and 'porosity' at depth D2. However, although the scores were statistically different, they all represented a subsoil that would be classed as 'good' ('no management change needed') (Ball et al., 2015). The qualitative comparisons showed that category 'roots' followed a pattern of PLOUGH worst scores, followed by DEEP, and then SHALLOW best scores at

depth D1. This trend occurred when cultivation treatments were combined with either rotation treatment but occurred at slightly better overall scores when combined with ALTCC compared to CWW. Similarly, at depth D2 treatment combinations had slightly better overall scores where combined with ALTCC compared to CWW, especially for SHALLOW cultivation treatment. The overall Ssq scores were mostly 2's and 3's which represented 'good' subsoil, however the non-averaged dataset (Appendix E) did contain some 4 scores that would be classed as 'fair' subsoil ('medium to long-term changes needed') (Ball et al., 2015). These 'fair' scores were mostly associated with PLOUGH and DEEP cultivation treatments and occurred most frequently in combination with rotation treatment CWW (n = 4) in comparison to ALTCC (n = 1). The 'fair' scores were driven by lower scores particularly in categories 'porosity' and 'aggregates' at depth D2.

SubVESS provided the most detailed data regarding the position of subsoil layers and supplemented that with characterisation of individual elements of those layers i.e. porosity, mottling, presence of roots. This provided information to decide whether subsoil layer compactness was problematic and to select an appropriate management response. This was particularly useful in the case of the 'fair' scores, where it was possible to identify 'porosity' and 'aggregates' as causes. However, it was only possible to discount inherent subsoil variation due to the high number of replicate pits dug across a relatively small site.

Limitations of the spatial distribution of VSE methods have been addressed previously (Emmet-Booth et al., 2020) and the strength of these methods is best focused by targeting 'good' and 'bad' field areas, relying on other methods to provide indications on areas of concern, or using a reference soil sample (Ball et al., 2015). Ball et al. (2017) highlighted that visual scoring of 'porosity' may need to be followed up with additional measurements to determine how the SubVESS 'porosity' score relates to function, for example infiltration and conductivity of water. As 'porosity' was an influential category in our dataset, a follow up measurement of hydraulic conductivity would have provided useful supplementary information. The authors also highlighted that correctly

distinguishing between whether subsoil layers were caused by inherent soil characteristics or agricultural management may be challenging without reference samples (Ball et al., 2017). However, in this experiment, it was found that digital photographs and detailed notes were sufficient to make a judgement. SubVESS was time-consuming but the method yielded detailed results on the position and nature of subsoil layers, which is key to correctly inform decision making (Batey, 2009; Schonning et al., 2004). Compared to other VSE methods, SubVESS has been shown to be among the most practical and generate results relevant to agriculture, due to the agricultural specific scoring (Pulido-Moncada et al., 2019), which was supported by the dataset presented in this paper. Additionally, it is exciting to see the speed of publications adapting VSE methods such as SubVESS to specific agricultural applications (Boizard et al., 2017; Emmet-Booth et al., 2019, 2016; Ward et al., 2021).

Studies have mainly compared conventional laboratory methods with VSE to determine the validity of VSE approaches (Johannes et al., 2017; Obour et al., 2017), with few exploring the applicability of field methods (van Leeuwen et al., 2018). Encouragingly, PR, EC_a and SubVESS broadly identified the same trends in the subsoil but statistical correlation did not show a significant relationship between the methods. However, as the methods represent subsoil in very different ways, statistical correlation is not necessarily anticipated or desirable (Emmet-Booth et al., 2016). PR, EC_a and SubVESS may be influenced by soil moisture status at the time of sampling (Corwin and Lesch, 2005; Johannes et al., 2017; Whalley et al., 2007), and therefore it was reassuring to note no significant differences between moisture measurements or significant correlations between moisture and the method datasets occurred.

Methods PR and SubVESS appeared to agree well on the position of subsoil layers in the profile, with higher PR corresponding to poorer SubVESS scores. However, the limitation of PR to discern between high strength and subsoil properties was highlighted by the SHALLOW cultivation treatment, which in some cases had among the best SubVESS scores but also had high PR. Additionally, at very similar PR measurements, the overall SubVESS 'Ssq' scores varied.

However, when the time required and spatial scales of PR and SubVESS were compared, PR provided an efficient method to identify areas of concern and their position in the profile. Scanning subsoil properties remotely via EC_a provided less information over depth but mirrored the trends observed in the PR and SubVESS datasets. Therefore, in the context of EC_a as an approach to broaden the spatial scale of subsoil measurements, the results presented supported EC_a as a good candidate for routine characterisation and/or monitoring over large areas. Areas of concern from these EC_a measurements would require a follow up to fully characterise subsoil compaction over depth and decide whether intervention is appropriate. Either PR or SubVESS are good candidates to do this.

Subsoil compaction is difficult to characterise without measurement, with practitioners relying on visual cues such as water-logging or poor crop growth, which adds to the challenge of raising awareness and improving management (Frelih-Larsen et al., 2018). The results presented in this paper demonstrate that the choice of method to characterise subsoil compaction in the field depends on the question being addressed. PR is an efficient method, with well-documented limitations, that represented a midpoint between SubVESS and EC_a on spatial scale and the resolution of the dataset. Advances in integrating PR with geostatistical methods and automated, mechanical sampling have made significant steps to overcome the spatial limits of manual data collection, and allow PR to be integrated with precision farming (Svoray et al., 2015). However, over a large spatial scale or for routine measurement, the capabilities of EC_a using EMI (Doolittle and Brevik, 2014) present significant advantages over PR and SubVESS, and our dataset supports the applicability and continued development of this approach for subsoil compaction. Measurement of EC_a requires follow-up methods to characterise subsoil compaction and although developments have begun to address this (André et al., 2012; Hemmat and Adamchuk, 2008) this is a significant limitation of EC_a. SubVESS was the only method with the capacity to identify subsoil layers and attribute a cause to compaction, and therefore was the best method to inform soil management. Due to the limited spatial resolution of this method, this dataset supports that SubVESS is reserved for decision making on areas already identified as a

concern by alternative methods with more appropriate spatial and/or temporal resolution.

PR, EC_a and SubVESS recorded significant differences between experimental treatments, whereas BD (acting as the reference method) for the compactness of subsoil did not. Few replicate block significant differences were recorded and those that were did not mirror the significant differences observed between treatments. This suggested the effect of textural differences across the site (Appendix B) was not a significant factor in the significant differences recorded between treatments. Therefore, the alternative characterisation methods, which were inferring subsoil compactness in a variety of alternative ways in comparison to BD, were likely to be measuring differences caused by the experimental treatments, as far as discounting the confounding variables considered can allow. This highlights the limitations of relying on a purely volumetric approach but poses the question as to whether these alternative methods added anything over and above BD. PR, EC_a and SubVESS, despite individual drawbacks, have all been shown to be capable of inferring subsoil compaction and this was supported by the results presented in this paper. Therefore, using one or a combination of these methods with BD, is likely to reveal more regarding the status of subsoil compaction than relying on BD alone. This suggests that the alternative methods were not only applicable to measure subsoil compaction but also, in combination, strengthen the existing approaches. Each method has strengths and weaknesses spatially and temporally, that give flexibility depending on the research question at hand.

The results in this paper represent a single snapshot in time, conducted at a single field experiment, as the aim of the experiment was to explore the applicability of these characterisation approaches under these conditions. Repeated assessments, over a larger range of soil types and soil management approaches, throughout multiple growing seasons, would both serve to address that methodological limitation of this study and to provide key information on the wider applicability across the agricultural sector.

5.6 Conclusions

Accurate and efficient characterisation of subsoil compaction at a range of spatial and temporal scales is critical to improve awareness and to guide appropriate management in agriculture. All three methods tested were applicable to measure subsoil compaction but all had significant limitations. The interpretation of EC_a by EMI to change in the subsoil warrants further investigation but the approach appeared to follow the main trends identified by the other methods and has significant potential to address subsoil compaction at large spatial and temporal scales. Measurement of PR using a penetrometer was a good compromise between EC_a and SubVESS. Data was able to be collected over depth and the method is suitable for characterisation over spatial scales relevant to agriculture but PR was not able to contextualise high subsoil strength compared to SubVESS. Visual evaluation by SubVESS provided the position of limiting layers in the subsoil profile and indicated the likely cause. Therefore, SubVESS generated the best dataset for selecting soil management response. However, due to the restricted spatial distribution of SubVESS, it is best reserved for decision making on areas already highlighted as a concern by alternative methods, for example PR and EC_a .

5.7 References

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6 Integrated discussion

The findings of this research show that rotation and cultivation management have the potential to positively influence subsoil compaction, as alternatives to mechanical cultivation. The repeated application of cover crops increased root proliferation of compacted subsoil compared to control treatments under both field and laboratory conditions but a significant benefit to following crop performance was not observed under laboratory conditions. Reducing the depth and intensity of cultivation had a positive impact on subsoil compaction and influenced whether benefits from repeated cover cropping occurred. Visual soil analysis (SubVESS) and non-invasive soil scanning (EC_a via EMI), despite the limitations outlined (Chapter 5), were applicable to characterise subsoil compaction compared to conventional approaches. The alternative characterisation methods explored presented significant advantages in terms of spatial and temporal scales, and the type of data gathered. Appropriate selection of which, depending on the objective, would enhance characterisation compared to the controls.

The repeated application of cover crops and their interaction with cultivation should be further investigated over a wider variety of soil types and agricultural systems to investigate how different cover crop species, with varied above and below ground traits, interact with subsoil compaction and crop performance under field conditions. If successful on a wider variety of soil types and management approaches, these strategies represent a viable alternative to mechanical alleviation in the long-term.

Further work is required to improve interpretation of non-invasive datasets such as EC_a in the characterisation of subsoil compaction. This should focus on the benchmarking of EC_a output for subsoil compactness under a representative range of soil types and management approaches. If the interpretation of measurements is improved through experimental work, application of the non-invasive and invasive alternative methods considered (EC_a and SubVESS) could help to address the spatial and temporal methodological gaps in subsoil compaction characterisation.

This research has met its aims and objectives (Chapter 1, Section 1.4) and confirmed that there are viable alternatives to mechanical subsoil alleviation, and characterisation of subsoil compaction may be improved through alternative methods (Chapters 2 – 5). This chapter discusses the consequences of the results presented, considers their adoption and highlights future research requirements.

6.1 Integrating cover crops into arable rotations for subsoil compaction alleviation

Subsoil compaction had a negative impact on the yield performance components of spring barley. Repeated application of cover crops and reducing the intensity of cultivation had significant benefits to some subsoil physical properties. Both the dicot species tested (field - mustard brassica (*Brassica* spp.); laboratory – SMART radish (*Raphanus sativus*)) and the monocot species (laboratory – black oat (*Avena strigose*)) increased the proliferation of roots in compacted subsoil compared to a cereal cash crop alone (field – winter wheat (*Triticum aestivum*); laboratory – spring barley (*Hordeum vulgare* var. RGT Planet)). SMART radish (*Raphanus sativus* var. SMART Radish) had an additive factor with larger root diameters in response to subsoil compaction. This may represent an additional positive root trait with brassica species, especially those that form taproot structures (Chen and Weil, 2011; Clark et al., 2003; Kautz, 2015). These root differences were not translated into increased crop performance.

Interpreting these results from field and laboratory experiments in context has challenges. Laboratory experiments using intact soil columns were shown to have significant limitations in the representation of field conditions regarding soil temperature over depth, soil weight distribution, root distribution, and the cycle of root decay and pore colonisation by roots in an artificial structure (Burr-Hersey et al., 2017; Gao et al., 2016; Han et al., 2015; Pulido-Moncada et al., 2021). However, the results presented in Chapters 3 (field experiment) and 4 (laboratory experiment) broadly demonstrate agreement in terms of root growth, rotation approach and subsoil compaction. Therefore, the results presented in this thesis

highlight the usefulness of contextualising laboratory studies using long-term field experiments and vice versa.

Yield is commonly used as the benchmark by which management approaches (and to a lesser degree characterisation approaches) are considered. In some ways for agriculture this is a flawed approach, as margin generation is the key metric of profitability, and a focus solely on seasonal yield ignores the wider interactions of soil management approach on long-term profitability (Martinho, 2019) and any tertiary benefits from improved soil functions (e.g. to ecosystem services). Therefore, as highlighted in Pulido-Moncada et al. (2020) (as originally set out by Cresswell and Kirkegaard (1995)) and reflected in this thesis, the most suitable approach may be to first understand the changes caused by roots to compacted subsoil and the impact on soil functions, rather than rely solely on yield as a proxy for better soil function. This is especially pertinent to subsoil compaction where although the effects on yield have been shown to be highly variable, generally the evidence supports that a negative impact really does occur under field conditions long-term (Ishaq et al., 2001; Munkholm et al., 2005; Van Den Akker et al., 2003; Wahlström et al., 2021). Broadening the consideration from solely yield also extends the discussion to allow the economic inclusion of tertiary benefits, such as ecosystem services and public goods, that are likely to grow as influential factors on soil management in the near future (DEFRA, 2021; European Commission, 2006).

Results presented in this thesis (Chapters 3 and 4) showed that utilising cover crops as an alternative to mechanical cultivation to generate positive change in subsoil has potential as an alternative to conventional mechanical alleviation. However, this approach has significant differences when compared to mechanical alleviation that, if not considered, may impede adoption. Evidence from this thesis and other experiments (Pulido-Moncada et al., 2021; Wahlström et al., 2021; Williams and Weil, 2004) suggest that alleviation of soil compaction using plant roots takes multiple seasons of repeated application to occur and complete recovery of soil function to a 'pre-compaction treatment' state has not been specifically demonstrated. Lucas et al. (2019a) and Lucas et al. (2019b)

showed that as a network of root biopores develop through compacted soils, subsequent root growth preferentially uses and furthers the biopore network until an equilibrium is reached, in their case after 12 years. These results provide strong support for the factors of time and repetition acting as significant factors in alternative biological methods. This is significantly different to, for example, a subsoiling operation that produces immediate, measurable results (Spoor et al., 2003). Given that Chamen et al. (2015) reported that end-users had poor perception of the effectiveness of mechanical cultivation to alleviate underlying subsoil compaction issues, the results of that work, the work presented in this thesis and the ongoing investigation into biological methods should be used to provide improved information for alleviation method choice. Findings presented in Chapters 3 and 4 suggest that alleviation of subsoil compaction using plant roots does not replace mechanical cultivation in the short-term. Instead, this alternative approach is probably best suited as part of a long-term proactive strategy for subsoil compaction. Further investigation is required to explore this on a variety of soil types and management histories long term.

Although there is evidence to show the instability of the soil structure created by mechanical subsoiling (as summarised in: Alakukku et al., 2003; Chamen et al., 2003; Spoor et al., 2003), there is little evidence to support the comparable stability of biopores created in compacted subsoil to resist recompaction. Circumstantial evidence has suggested that bioporosity may be more resilient compared to cultivated soil structure (Koch et al., 2008). Biopores have been shown to be persistent in undisturbed soils and support increased soil biology (e.g. increased microbial activity) in comparison to those mechanically created (Kautz, 2015), which may confer higher resilience. However, evidence to quantify the resilience of mechanically cultivated vs biologically created structure at field-scale in compacted subsoil would be a significant addition to the literature. Much of the experimental investigation into direct drilling could be used as a proxy for this research if it is found that biopores are more resilient to compaction and it is assumed that direct drilling favours increased subsoil biopore formation. However, a systematic review of available literature and experimental research to address this would be required.

The maximum depth of observations in this thesis was 800 mm in the field (Chapter 3) and 1000 mm in the controlled experiment (Chapter 4). Significant positive differences between control treatments and experimental treatments were observed for both. This represented a significant depth advantage for the alternative methods compared to mechanical cultivation, where the deepest cultivation operations are limited to c. 500 mm (Chamen et al., 2015). Given that the root depth of arable crops may exceed 1000 mm and that biopore utilisation is increasingly important for root growth as depth increases (Atkinson et al., 2020; Kautz et al., 2013), this represents a potentially substantial advantage over mechanical cultivation. This benefit may also apply equally to naturally compacted subsoil as in anthropogenic subsoil compaction, however as far as the author is aware, similar research work on naturally occurring compact subsoils has not been carried out.

The results of this thesis (Chapters 3 and 4) suggest that increased plant residence (i.e. the addition of a cover crop and/or variation in species in a rotation) had a positive impact on subsoil properties compared to the controls of continuous winter wheat and a winter fallow period. Consequently, it is relevant to consider whether the concept of a cover crop is appropriate given that perhaps increasing any living cover of the soil surface may have yielded similar results. The advantages of growing a specific cover crop, compared to for example allowing natural regrowth to occur, may be agronomic, environmental, to include a specific desirable trait, or to provide a tertiary income (e.g. livestock feed) (Adetunji et al., 2020; Blanco-Canqui and Ruis, 2020). In this thesis, both cover crop species increased total root length and biomass in compacted subsoil compared to a control. Therefore, the main difference between the cover crop species was the difference in root diameter between brassica species and grass species. As previously discussed, despite evidence that root thickness may be important for compaction alleviation, the relative importance of different root traits is an active research question (e.g. Ogilvie et al., 2021; Pulido-Moncada et al., 2020; Wahlström et al., 2021). Based on previous root thickness evidence, it is likely that one or a combination of root traits will be more important for a given soil issue (i.e. subsoil compaction) compared to those most important when

considering another soil problem (e.g. surface erosion). Therefore, the concept of a specific species cover crop (or mixture thereof (Chapagain et al., 2020)) remains relevant for the subsoil, as the ability to choose agronomic, environmental or economic advantages, through specific species traits may be a significant advantage over and above natural regrowth. Again, given that a high proportion of roots in the subsoil are associated with biopores (Kautz et al., 2013; Perkons et al., 2014) the implications of appropriate root trait choice may be high. In practice, the choice of cover crop for a subsoil compaction issue will need to be considered in light of the impact to the topsoil (Bergtold et al., 2019; Wittwer et al., 2017). Future research should segregate root species during this type of research in order to more accurately attribute root traits and avoid this significant drawback of the work presented in this thesis.

Although the evidence presented in this thesis supports the literature on integrating cover crops and reducing cultivation intensity as an alternative mitigation approach for subsoil compaction alleviation, there are practical and economic considerations for adoption. Survey work has suggested that a lack of information regarding cover crop economics, their expected effects and appropriate ways to measure them are significant barriers to adoption in the UK (Storr et al., 2019). A lack of technical guidance on the application of cover crop principles to specific farm situations (e.g. varied soil series, different crop rotations) has been shown to limit uptake and success. Those farmers who had a higher level of knowledge on soil processes were more likely to recognise and have realistic expectations of results (Ingram et al., 2010; Mills et al., 2017; Prager and Curfs, 2016). However, even farmers who have a relatively high level of soil knowledge were constrained in adoption by economic and workload pressures that meant they felt unable to consider trying alternative alleviation approaches to subsoiling, despite recognising mechanical cultivation was not the best choice, and was likely to have less long-term and tertiary benefits (Frelih-Larsen et al., 2018). The results of this thesis (Chapters 3 and 4) have provided technical information to help address this knowledge gap (as identified in Blanco-Canqui and Ruis, 2020; Vincent-Caboud et al., 2017), and further research should focus on continuing to refine species selection and long-term applicability

of different ‘biosubsoilers’ (Pulido-Moncada et al., 2021) to provide guidance for use as widely as possible.

Relatively few studies have considered the economics of integrating cover crops into a rotation, especially concerning subsoil compaction. However, as mentioned previously, economic concerns have been implicated in limitations to adoption of alternative alleviation approaches (Blanco-Canqui et al., 2015; Storr et al., 2019). Generation of a positive economic margin from application of cover crops has been shown to be highly site specific, dependent on factors both within control (e.g. management approach, species selection), those outside control (e.g. weather, soil texture) and a realistic expectation of the time required for results to be measurable (Bergtold et al., 2017). The establishment and management costs of a cover crop vary widely but are mainly dependent on the cost of seed and the cost of management (i.e. the type and frequency of field operations). As an example, rough approximation of costs in the UK may vary from c. £47 ha⁻¹ (£29 ha⁻¹ seed cost, £7 ha⁻¹ broadcast establishment and £11 ha⁻¹ rolling) to c. £98 ha⁻¹ (£29 ha⁻¹ seed cost, £25 ha⁻¹ shallow cultivation, £33 ha⁻¹ direct drill and £11 ha⁻¹ rolling) (Morris, personal communication, June 10th 2021). Bhogal et al. (2020) reported that margin generation from cover cropping across a comparison of 20 experiments from seven sites were mainly dependent on yield and resulted in an average margin reduction of £150 ha⁻¹ from two consecutive arable crops that could be offset by a variety of variable and fixed cost saving approaches. Margin estimations vary widely with Cooper et al. (2017) reporting the cost of cover crop establishment was offset by a £13 ha⁻¹ positive yield margin, White et al. (2016) reported a £43 ha⁻¹ positive yield margin, and Stobart and Morris (2014) recorded a typical margin increase of £50 – 75 ha⁻¹.

It is clear then, that an economic benefit may be derived from the integration of a cover crop provided yield is increased and/or an appropriate offset measure(s) are included. This is problematic for the results presented in this thesis because the effect on crop yield components was not significant (supplementary yield information for the NIAB STAR project (Chapter 3) not included in this thesis is available in Stobart and Morris (2011)). Placing a monetary value on any benefit

to subsoil structure or function is challenging (Brady et al., 2019; DEFRA, 2021). Subsidisation of alternative approaches that address a soil issue but have inconsistent yield/margin benefits, yet do have evidence of a positive impact on wider ecosystem services aligned with aspirations of third parties, has been identified as a solution to this (Bergtold et al., 2017; Storr et al., 2019) (e.g. 'Environmental Land Management Scheme' (DEFRA, 2021) or 'EU Thematic Soil Strategy' (European Commission, 2006)). Subsidisation has been shown to aid the adoption of alternative management approaches that have inconsistent economic benefits but subsidisation has also been shown to suffer drawbacks with the definition of approaches, participation and administration (Franks, 2019; Whitby, 2000). The results presented in this thesis (Chapters 3 and 4) provide contributory technical information of alternative alleviation approaches for subsoil compaction in this case.

6.2 Characterising subsoil compaction and measuring the impact of alleviation approaches

Reliable and accurate characterisation is a critical component in both understanding the extent of subsoil compaction in agriculture, and appraising alternative alleviation approaches (Ogilvie et al., 2021). Demands on characterisation are diverse, from understanding subsoil issues within a single field, through to national and international scale assessments.

The results presented in Chapter 5 represent a single snapshot for the characterisation of subsoil compaction with supporting measurements to help contextualise the results. To varying degrees, all the methods tested provided information on subsoil compactness and would act as a guide for soil management. The experimental situation included control treatments against which the results of the characterisation work can be compared. In reality, it is highly unlikely that the same frequency of sampling for characterisation or supporting measurements would be used by practitioners in the field and therefore, defining the context in which these methods are applied will be crucial, especially where there is no representative control. The most applicable method(s), using previous literature and the results presented in this thesis on

the strengths and weaknesses of characterisation approaches, may then be chosen to characterise the subsoil compaction in context and determine whether subsoil compactness is problematic (Bunemann et al., 2018). As discussed in Chapters 2 and 5, supporting measurements on key confounding variables are required for reliable interpretation, and this definition of context is suggested to complement not replace this.

Application of the characterisation methods to 'real-world' situations mean that setting out a set of critical values for subsoil compaction on measurable soil properties is not feasible, given the large range of soil, management and environmental situations in which they are and will be applied (Sojka et al., 2003), and the lack of reference measurements for each. Therefore, Stockdale et al. (2021) suggest that setting the minimum set of acceptable values to judge whether soil degradation (e.g. subsoil compaction) is problematic to land use would be a way forward. Based on the reviewed literature (Chapter 2) and the experimental work conducted in this thesis (Chapter 5), for subsoil compaction this minimum set of information should include: the location and depth(s) of subsoil layers, more than one characterisation method of compactness, horizontal extent of subsoil layers, and change through time. This, in combination with contextual site information and supporting measurements on key confounding variables, would provide sufficient information to characterise whether subsoil compaction is detrimental for a particular situation, to inform alleviation, and to set out the likely boundaries achievable by alleviation, dependent on inherent soil characteristics (Bunemann et al., 2018; Moebius-Clune et al., 2016; Stockdale et al., 2021). The addition of repeated measurement through time refines this approach further (Karlen et al., 2001).

The results presented in Chapter 5 highlighted that interpretation was of high importance to relate the different measures or inferences of subsoil compaction to subsoil compaction and function. Chapter 2 discussed the possible pitfalls of the definition of subsoil (i.e. where it occurs in the soil profile) in the interpretation (and selection) of characterisation results. The historic plough-based definition is probably not fit for purpose going forward, given the direction of soil management

practices towards less soil movement (Kassam et al., 2009) and therefore a very different stratification of the soil profile (Martínez et al., 2016). Work to apply the characterisation methods tested in this thesis not only to a wider variety of soil types but also to a variety of long-term rotation and cultivation systems would produce useful results to aid the interpretation in the context of different soil management approaches.

Evidence shows that adequate training is required to address sample collection, subjectivity and misinterpretation (Ball et al., 2017; van Leeuwen et al., 2018). The sampling method should be suitable to meet the aim/objective, otherwise the characterisation undertaken may not generate appropriate results (Batey, 2000). This agrees with the findings of survey work that suggest greater knowledge of the suitable application of characterisation methods generated more applicable data for soil management (Frelih-Larsen et al., 2018; Storr et al., 2019). The data and discussion in Chapter 5 contributes to that knowledge gap by demonstrating the positives and negatives of the applicability for each method.

Historically, the usefulness of characterisation methods have been extended through understanding how results may be used to predict other subsoil properties related to compaction (McBratney et al., 2002; Wosten et al., 2001). Models have previously relied on historical soil survey datasets that were not necessarily collected with this end use in mind to provide proxy measurements in the absence of more relevant subsoil compaction data, which has limited subsoil characterisation especially at large spatial scales (Brus and van den Akker, 2018a; van den Akker and Hoogland, 2011b). Results discussed in Chapter 5 demonstrated potential to characterise subsoil compaction at a variety of spatial and temporal scales that may be useful depending on the modelling/transfer function question at hand. As highlighted in the discussion (Chapter 5), utilising more than one characterisation method is a general trend in the literature to offset respective weaknesses (André et al., 2012; Hemmat and Adamchuk, 2008) and therefore a combination of BD, PR, SubVESS or EC_a may be most useful. Further to the extension of subsoil compaction characterisation, VSE methods (e.g. SubVESS) have been linked as proxies for soil carbon flux, greenhouse gas

emission and nutrient loss (Cloy et al., 2015; Guimaraes et al., 2017). This demonstrates the potentially broad application of the methods assessed in Chapter 5, to meet a diverse set of aims and objectives related to the characterisation of subsoil compaction.

It has been argued that VSE methods such as SubVESS have an additional social value over and above scanning or sample based techniques, in that they put the operator in direct contact with soil in the field (Ball et al., 2017; Wahlhutter et al., 2016). This does agree logically with the notion that greater soil knowledge increases the acknowledgement and perception of soil issues (Ingram et al., 2010; Mills et al., 2017; Posthumus et al., 2011). However, in terms of the applicability of characterisation approach, the most significant factor must be the selection of appropriate characterisation method(s) to address a suspected subsoil compaction issue, whether or not the chosen methods have a greater tertiary value.

As with the alternative alleviation approaches, it is relevant to consider the economic return on investment of characterising subsoil compaction using the methods explored in Chapter 5 (Stevens, 2018). However, the costs vary widely from effectively free assessments carried out with minimal equipment using freely available tools (e.g. SubVESS) through to a contracted service from a specialist provider (e.g. common for EC_a measurement). The marketplace for characterisation is complicated by the specialist apparatus required to collect data such as EC_a and that many commercial organisations perform multiple soil measurements on a cost per area basis, which makes it all but impossible to determine a representative figure for characterisation performed by a third party. Similarly to the discussion in the previous section on the suitability of yield for appraising alternative alleviation approaches, economic justification for characterisation approaches may too be judged on the basis of improved crop yield. At the farm scale post-assessment, an uplift in yield, the alleviation of visual cues (e.g. persistent waterlogging), or the conclusion that subsoil compaction is not problematic, may be sufficient to justify cost. However, this may depend on the level of soil knowledge possessed by the user and the subsequent value they

place on accurate characterisation, or whether as Frelüh-Larsen et al. (2018) found, alleviation is attempted first based on assumption of subsoil compaction instead of accurate characterisation. Users who possessed a more holistic, long-term view of soil management were more likely to pursue appropriate characterisation and to choose alleviation based on the results (Frelüh-Larsen et al., 2018; Thorsoe et al., 2019). Thereby justifying the cost of characterisation, even if this is not immediately obvious from a crop yield improvement. The methods considered in Chapter 5 were shown to have positives and negatives dependent on the research question at hand, and therefore return on investment both financially, and more holistically, is dependent on correct choice to achieve the desired outcome of measurement. The results and the suggestions for further research presented in Chapter 5 provide evidence to address this.

The one-off costs of purchasing EC_a apparatus are high but 'serviced' options are available through specialist businesses that may greatly reduce the cost to the individual. In contrast, SubVESS was developed to be a freely available, mainly qualitative approach (Ball et al., 2017, Ball et al., 2015) that puts the economic control in the farmer's hand and provides methodological guidance. That said, as previously highlighted VSE approaches require training for consistency (Emmet-Booth et al., 2016) whereas for example PR equipment is moderately expensive and has a long lifespan. Engagement with soil characterisation amongst UK farmers has been shown to be relatively low but increasing (DEFRA, 2019, DEFRA 2013), although subsoil compaction is rarely specifically addressed and is instead combined with soil compaction as a whole. The results presented in this thesis show that specific focus on subsoil compaction would be worthwhile in the future, as increased specificity better informed applicability. Policy developments and political aspirations in the UK have resulted in the characterisation of 'soil health' to be included in the recently published 'Sustainable Farming Incentive' (DEFRA, 2021). In this example, farmers will be rewarded with a subsidy of up to £59 ha⁻¹ for soil management, which specifically includes requirements to characterise as part of the soil management planning process. The results presented in this thesis show that all three methods would

be suitable to address this requirement from the point of view of subsoil compaction, depending on the spatial and temporal consideration.

6.3 Recommendations for future research

The applicability of the alternative alleviation work presented in this thesis was aided by the opportunity to observe the effects of repeated experimental treatments, long-term using a field scale experiment. However, it was limited by our results being collected from this one site, which therefore poorly represents the large variety in soil series and agricultural production employed in the UK and further afield. Replicated, long-term repeated cover cropping experiments on a wider range of soil types and management approaches would help to better define the potential of the alleviation approaches investigated here and generate technical guidance for end-users, with as much specificity to their particular circumstances as possible. Additionally, it was not possible due the history of the long-term field experiment used, to define the amount of field traffic applied and variables in terms of axle load, inflation pressures and pass frequency over time. In future, the combination of long-term rotation and cultivation experiments with relevant measurements of field traffic (for example the long-term experiment used by Millington et al. (2018)) would better inform discussion on subsoil compaction.

The root morphology work presented in this thesis was limited by two main factors. Firstly, roots were not separated by species and secondly, the understanding of the relative importance of different root traits is not well understood for the subsoil, both of which limit interpretation of the results. Although we assume that a variation in root morphology may be attributed to including different species in a rotation compared to a control, without separating root material by species, definite conclusions are not possible. Root thickness has traditionally been suggested as the most important trait where compaction alleviation was concerned (Chen and Weil, 2010; Clark et al., 2003) but authors have openly acknowledged that improved evidence is required. Recent publications (for example: Hudek et al., 2019; Pulido-Moncada et al., 2021; Wahlström et al., 2021) question the relative importance of root thickness. Future research should focus on addressing both of these knowledge gaps to improve

the information available on biological approaches to subsoil compaction alleviation.

Accurate characterisation of subsoil compaction looks set to remain on the agenda both from a production-led perspective of improving the profitability and sustainability of agricultural systems, but also from the policy-led approach of quantifying the wider services of agricultural systems and the way sustainable soil management practices should be rewarded. Non-invasive approaches such as EC_a are widely sold and used to characterise subsoils but the evidence presented in this thesis and the research literature suggests the interpretation of data requires improvement to inform subsoil compaction management decisions. Application of EC_a to a wider range of soil series and management systems, with the specific objective of defining how the data collected relates to subsoil compaction and alleviation, would address these knowledge gaps and improve the management and understanding of subsoil compaction more generally. The characterisation method applicability work presented was conducted at a single snapshot in time. Given the evidence of temporal variability of subsoil properties significantly affecting the methods considered, repetition of characterisation through time would further aid interpretation.

6.4 References

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7 Conclusions

The aim of this thesis was to determine the suitability of alternative methods to quantify and alleviate subsoil compaction in arable soils. The following objectives were addressed to meet this aim:

Objective 1: To evaluate whether current subsoil compaction alleviation and characterisation approaches may be improved by alternative methods.

Objective 2: To determine whether long-term rotation and cultivation management have an impact on subsoil compaction at field-scale.

Objective 3: To determine the potential of two cover crop species to alleviate subsoil compaction and provide a benefit to a following arable crop, and if this effect increases over two consecutive seasons.

Objective 4: To determine the applicability of subsoil visual evaluation of soil structure (SubVESS) and electromagnetic conductivity (EC_a) in characterising subsoil compaction as a result of experimental treatments, in comparison to penetration resistance (PR) and bulk density (BD).

7.1 Research outcomes in relation to research objectives

7.1.1 Objective 1

The available literature was critically reviewed to determine the status of subsoil compaction characterisation and alleviation, and to identify and evaluate potential alternatives (Chapter 2). The following key outcomes were:

- There are potential alternative methods for the characterisation of subsoil compaction in the field, which have the potential to address spatial and temporal methodological challenges associated with the current conventional approach. However, the published literature indicated that further examination of alternative approaches was required for subsoil compaction in a heterogeneous field situation.
- Biological alternative approaches to the alleviation of subsoil compaction compared to mechanical cultivation have demonstrated positive results in

meeting the requirements of subsoil compaction alleviation and avoiding some of the drawbacks associated with mechanical cultivation. However, further experimentation was identified as a requirement to define the role of plant species, associated root traits and the application of the alternative biological methods long-term at field-scale.

7.1.2 Objective 2

Review work highlighted the potential for alternative rotation and cultivation alleviation approaches for subsoil compaction (Chapter 2). Field monitoring and laboratory analyses determined the impact of long-term repeated cover cropping and cultivation approach on subsoil compaction (Chapter 3). The following key conclusions were drawn:

- Long-term repeated cover cropping and a reduction in the intensity of cultivation, reduced subsoil compaction compared to continuous winter wheat and/or intensive cultivation.
- Rotation and cultivation treatments interacted, where reducing the intensity of cultivation resulted in the greatest subsoil benefits associated with repeated cover cropping.

7.1.3 Objective 3

Review work highlighted potential cover crop species suitable for alternative alleviation of subsoil compaction (Chapter 2). Experimental work determined the effect of two cover crop species on subsoil compaction and arable crop performance over two consecutive seasons (Chapter 4). The following key conclusions were drawn:

- Subsoil compaction had a negative impact on spring barley yield components and neither cover crop significantly improved this after two repeated seasons.
- Cover crop treatments increased the root proliferation in compacted subsoil compared to a control and repetition over multiple seasons demonstrated some limited additional improvement.

7.1.4 Objective 4

Review work highlighted two potential alternative methods applicable to characterise subsoil compaction in the field (Chapter 2). Experimental work characterised subsoil compaction at field-scale to compare the conclusions drawn by each method compared to controls (Chapter 5). The following key conclusions were drawn:

- Methods were applicable to characterise subsoil compaction compared to the controls, provided there was sufficient contextual information for accurate interpretation.
- Each method has both spatial and temporal advantages and disadvantages, appropriate selection in light of which serve to address some of the characterisation knowledge gaps identified.

7.2 Contribution to knowledge

The key novel contributions produced by the research project were:

- This research demonstrated that repeated cover crop rotation and reduced intensity cultivation had a positive impact on the formation and/or persistence of subsoil compactness in the field under an arable production system, and the interaction of these two factors.
- This research demonstrated the potential of specific species to have a positive effect in compacted subsoil but showed that a significant benefit to crop yield components is not realistic short-term.
- This research demonstrated the potential of alternative characterisation methods to meet the spatial and temporal methodological knowledge gaps identified in the literature.

7.3 Concluding statements

Repeated application of cover crops increased the root proliferation of compacted subsoil compared to control treatments under both field and laboratory conditions but a significant benefit to crop performance was not observed. Reducing the intensity and depth of cultivation approach had a positive impact on subsoil

compaction and influenced whether the benefits from repeated covering cropping were observed. Results suggested that repeated cover cropping and reducing the intensity of cultivations were not a direct replacement for mechanical cultivations. Instead, they form a wider proactive not reactive approach to alleviate subsoil compaction as part of a wider systems change towards increasing living soil cover and minimising soil disruption.

The characterisation of subsoil compaction is critical to address the knowledge gaps regarding the extent and occurrence of subsoil compaction, and aid the selection of an appropriate alleviation method. Visual soil assessment (SubVESS) and non-invasive scanning (EC_a), despite the limitations outlined, were applicable to characterise subsoil compaction compared to conventional approaches. The alternative methods explored presented significant advantages in terms of spatial and temporal scales, and the type of data collected. Appropriate selection of which, depending on the question at hand, would enhance characterisation compared to the control.

Appendix A

Rotation treatment herbal ley (HL) establishment operations and species mixture

(1) HL establishment operations; 2) HL pre-drilling herbicide treatment; 3) HL species mixture).

1) HL establishment operations:

Previous cultivation method	HL establishment cultivation method	HL establishment cultivation date	HL drilling method	HL drilling date
Plough	Sumo Trio ~10cm (legs off) Power Harrow	31/08/2018 01/09/2018	Weaving tine drill Cambridge Roll	03/09/2018
Shallow	Sumo Trio ~10cm (legs off) Power Harrow	31/08/2018 01/09/2018	Weaving tine drill Cambridge Roll	03/09/2018
Deep	Sumo Trio ~10cm (legs off) Power Harrow	31/08/2018 01/09/2018	Weaving tine drill Cambridge Roll	03/09/2018

2) HL pre-drilling herbicide treatment:

Input type	Product	Product rate (l or kg)	Date
Herbicide:	Glyphosate 360	3.0	30/08/2018

3) HL species mixture:

Group	Species/Variety	%	kg/ha
Grasses	Tified FEDORO festulolium	11.5	3.7

	DONATA cocksfoot	11.5	3.7
	NIFTY perennial ryegrass	9.2	3.0
	Winnetou timothy	4.6	1.5
	PARDUS meadow fescue	3.9	1.2
	KORA tall fescue	3.9	1.2
Legumes	GLOBAL red clover	5.4	1.7
	ABERDAI white clover	1.5	0.5
	ABERHERALD white clover	2.3	0.7
	LOMIAI alsike clover	1.5	0.5
	LEO birdsfoot trefoil	1.5	0.5
	Luzelle lucerne - Rhizobium Inoculated	2.3	0.7
	Sainfoin	19.2	6.2
	Sweet clover	7.7	2.5
Herb	PUNA II chicory	4.6	1.5
	ENDURANCE ribgrass	1.5	0.5
	Burnet forage herb	5.4	1.7
	Yarrow forage herb	0.8	0.2
	Sheeps Parsley forage herb	1.5	0.5
Total	19	100	32

Appendix B

NIAB STAR experiment soil texture over depth a) 0 – 200 mm, b) 200 – 400 mm, c) 400 – 600 mm, d) 600 – 800 mm (SL - sandy loam, SCL - sandy clay loam, SC - sandy clay, C - clay, CL – clay loam, LS - loamy sand, CH - chalk) (blank spaces represent plots not considered during this experiment).

	Block 1				Block 2				Block 3			
	1	2	3	4	5	6	7	8	9	10	11	12
a)												
A		SL	SL	SCL		SCL				SCL		SCL
B		SL			SL	SCL		SCL				
C				SCL			SCL	SCL		SL	SL	
D				SCL					SL	SL		
b)												
A		SCL	SC	CL		SC				SCL/C		SCL
B		SCL/C(CH)			SCL/C(CH)	SCL/C		C(CH)				
C				SCL/SC			C(CH)	SCL/C(CH)		SCL	SCL	
D				SCL/C					SCL/SC	SC		
c)												
A		SL	SCL	C(CH)		SC				C(CH)		C(CH)
B		C(CH)			SC	C(CH)		C(CH)				
C				C			C(CH)	C(CH)		C(CH)	C(CH)	
D				SCL					C(CH)	SC		
d)												
A		C(CH)	C(CH)	C(CH)		SC				C(CH)		C(CH)/LS
B		SC			C(CH)	C(CH)		C(CH)				
C				C(CH)			C(CH)	C(CH)		C(CH)	C(CH)	
D				SCL					C(CH)	C(CH)		

Appendix C

Apparent electromagnetic conductivity (EC_a) ($mS\ m^{-1}$) by individual plot and data points (n). Rotation treatments: CWW – continuous winter wheat and ALTCC – alternative cover crop. Cultivation treatments: PLOUGH, DEEP and SHALLOW.

Plot	Data points (n)	Rotation treatment	Cultivation treatment	Mean EC ($mS\ m^{-1}$) (500 mm)	Mean EC ($mS\ m^{-1}$) (1500 mm)
A2	117	ALTCC	SHALLOW	17.9	41.4
A3	120	ALTCC	PLOUGH	17.9	41.2
A4	136	ALTCC	DEEP	17.1	39.9
B2	120	CWW	PLOUGH	19.5	44.8
C4	125	CWW	SHALLOW	17.9	41.8
D4	129	CWW	DEEP	17.3	40.5
A6	114	ALTCC	DEEP	16.8	39.0
B5	116	ALTCC	PLOUGH	18.0	41.1
B6	131	CWW	SHALLOW	18.4	42.9
B8	113	CWW	DEEP	18.8	43.2
C7	122	ALTCC	SHALLOW	15.0	36.0
C8	118	CWW	PLOUGH	17.0	40.0
A10	128	CWW	SHALLOW	18.6	42.4
A12	145	ALTCC	SHALLOW	17.1	39.1
C10	135	CWW	DEEP	17.0	41.1
C11	125	ALTCC	DEEP	17.6	41.4
D9	127	ALTCC	PLOUGH	17.2	41.1
D10	125	CWW	PLOUGH	16.6	40.4

Appendix D

Replicate block results for quantitative datasets (letters indicate a significant difference within column).

Block	PR	BD (g cm ⁻³)	VSM (cm cm ⁻³)	Probe (%)	Mean EC (mS m ⁻¹) (500 mm)	Mean EC (mS m ⁻¹) (1500 mm)
1	1.73	1.44	0.21	35.4	17.9 ^a	41.6 ^a
2	1.75	1.40	0.20	34.2	17.5 ^b	40.7 ^b
3	1.66	1.44	0.20	33.6	17.5 ^b	41.1 ^c

Replicate blocks results for SubVESS dataset (letters indicate a significant difference within a column).

Block	Depth	SubVESS											
		Mottling	H	Strength	H	Porosity	H	Roots	H	Aggregate	H	Ssq	H
1		1.5		2.7		2.3		1.8		3.2		2.7	
2		1.3	2.42	2.8	0.02	2.7	0.29	1.8	0.01	2.8	5.03	2.5	0.44
3	1	1.0		2.8		2.5		1.8		2.5		2.7	
1		2.8 ^a		3.1		2.8 ^a		1.9		2.8		3.0	
2		2.3	7.66	3.0	<0.01	3.5 ^b	6.65	2.6	1.58	3.2	5.03	3.3	3.66
3	2	1.7 ^b		3.0		3.0		2.0		3.5		3.5	

Appendix E

SubVESS scores by individual plots by rotation and cultivation treatments.

Block	Plot	Rotation	Cultivation	Layer depth (cm)	Mottling	Strength	Porosity	Roots	Aggregates	SsQ
1	A2	ALTCC	SHALLOW	24 - 30	1	3	1	1	3	2
				30 - 50	3	3	2	1	3	3
1	A3	ALTCC	PLOUGH	26 - 31	1	3	3	2	4	3
				31 - 40	2	3	3	1	3	3
				40 - 50	3	3	3	2	3	3
1	A4	ALTCC	DEEP	25 - 33	2	3	2	2	3	3
				33 - 50	3	4	3	3	3	3
1	B2	CWW	PLOUGH	25 - 32	1	3	3	3	3	3
				32 - 50	3	3	3	3	3	3
1	C4	CWW	SHALLOW	20 - 40	3	3	3	2	3	3
				40 - 50	2	3	3	1	2	3
1	D4	CWW	DEEP	22 - 30	1	1	2	1	3	2
				30 - 40	3	3	3	2	3	3
				40 - 50	3	2	3	2	3	3
2	A6	ALTCC	DEEP	27 - 35	2	3	3	1	3	2
				35 - 50	3	3	3	2	3	3
2	B5	ALTCC	PLOUGH	27 - 32	2	2	2	1	3	2
				32 - 50	2	3	3	2	3	3
2	B6	CWW	SHALLOW	27 - 36	1	3	4	3	3	3

				36 - 50	1	3	4	3	3	3
2	B8	CWW	DEEP	27 - 34	1	3	3	2	3	3
				34 - 50	3	3	4	3	4	4
2	C7	ALTCC	SHALLOW	26 - 30	1	3	2	1	2	2
				30 - 37	2	3	3	2	3	3
				37 - 50	3	3	3	3	3	3
2	C8	CWW	PLOUGH	23 - 28	1	3	2	3	3	3
				28 - 50	2	3	4	3	3	4
3	A10	CWW	SHALLOW	27 - 50	1	3	3	1	3	3
3	A12	ALTCC	SHALLOW	20 - 40	1	3	2	1	2	2
				40 - 50	1	3	3	1	3	3
3	C10	CWW	DEEP	23 - 31	1	2	3	3	3	3
				31 - 50	2	3	3	3	4	4
3	C11	ALTCC	DEEP	25 - 31	1	2	2	1	2	2
				31 - 50	2	3	3	1	3	3
3	D9	ALTCC	PLOUGH	22 - 32	1	3	3	2	3	3
				32 - 50	2	3	3	3	4	4
3	D10	CWW	PLOUGH	20 - 25	1	4	2	3	2	3
				25 - 50	2	3	3	3	4	4