July 2017

Project Report No. PR574

Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments

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This is the final report of a 48-month project (RD-2012-3786) which started in October 2012. The work was funded by James Hutton Limited and a contract for £703,745 from AHDB Cereals & Oilseeds.

CONTENTS

1. Abstract

Three long term and one newer soil management experiments from eastern Britain were used to answer several key questions relevant for cereal growers. The questions focused on soil physical and chemical conditions (including possible carbon accumulation) for crop growth and comparing cultivar, yield and economic performance under different tillage regimes. To respond to these questions, a number of approaches to characterise soil quality were used, particularly in ways relevant to root proliferation.

Based on our results, non-inversion yields were lower than inversion yields but there were no differences between the three inversion tillage treatments. With promotion of, and movement to, reduced (non-inversion) tillage in the UK this suggests a need for breeding programs to consider crop performance under soil conditions created by non-inversion (or no-till) systems.

No strong reason for not advocating reduced (non-inversion) tillage in preference to ploughing was found. In the experiments using farm-scale machinery, yield data under non-inversion tillage was only marginally lower than under ploughed conditions but when decreased costs of labour and fuel were factored in, gross margins under non-inversion tillage were better than under ploughed systems. The hesitation from advocating non-inversion tillage more strongly comes from the plot-scale experiment which ran with no crop rotation (for more than 10 years) and developed severe weed problems. Under these conditions, ploughing helped control weeds and thus delivered better productivity.

Using a range of indexes, our study, consistent with other research, found soil physical condition was well below optimal at the sites studied and in many instances offered very limited opportunity for root proliferation. In soils under non-inversion tillage, we sometimes found large improvements to soil physical conditions over a growing season driven by the growing crop. Under no-till, the pH of the surface soil decreased to an extent where it would contribute to further soil structural deterioration and limit plant productivity. Whether changing soil tillage regimes can alter the total amount of carbon (as organic matter) stored in soil is of wide interest. We assessed carbon storage over the soil profile to a depth of 60 cm and took account of bulk density and stone content. We found no gains in carbon storage under non-inversion tillage (compared with ploughed systems). Where there were large annual additions of carbon as compost, the amount of carbon stored in the soil was increased.

2. Introduction

“Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments” was established with several objectives. For years there has been a shift by farmers towards less intensive tillage systems, driven by decreased costs of fuel and labour, as well as perceived benefits to soil. In the UK the impacts to soil are not well understood, with data drawn from regions with different climates or soils, or from relatively short-term field experiments in the UK. However, shifts in soil management can take many years to reach a new equilibrium before crop productivity benefits can be realised. The UK has lacked information from robust experiments that address the agronomic, environmental and economic impacts of soil management practices. Our overall aim was therefore to provide farmers with robust, UK based data, on the benefits and disadvantages of different soil tillage practices for cereals, with our assays also allowing for key soil indicators of good soil management to be identified.

At the start of this project The James Hutton Institute and NIAB TAG hosted the oldest contemporary tillage experiments, where reduced tillage and conventional ploughing/harrowing were compared robustly. These three medium term field experiments had been running for 4-9 years at the start of this project and are:

- Mid-Pilmore Platform – The James Hutton Institute – Est. 2003. Contrasts 5 different soil management treatments. Perthshire, Scotland. Sandy loam soil
- New Farming Systems – NIAB TAG - Est. 2007. Fields selected contrast 3 soil management treatments. Norfolk, England. Silty loam soil
- STAR Experiment – NIAB TAG – Est. 2005. Fields selected contrast 3 soil management treatments. Suffolk, England. Clay loam soil.

These experiments are complemented by the relatively new (2011) Centre for Sustainable Cropping (CSC) at Hutton's Balruddery farm, investigating organic matter management, rotations and reduced tillage. Sustainable crop production experiments at both institutes are a focal point for science and knowledge exchange activities.

The project aimed to quantify soil properties using state-of-the-art approaches, coupled with an assessment of economic and environmental benefits. Soil physical tests included assessing (i) potential for abiotic stresses from water-logging, drought or mechanical impedance; and (ii) resilience of the soil to weathering and machinery stresses. Carbon storage was assessed for a range of soil management treatments under the platforms, as assessments soon after the Hutton platform was established found no difference in carbon concentrations between reduced tillage and ploughing. Further, the aim was to test the performance of a range of cereal cultivars, including Recommended List entry varieties under different soil management practices. This included analysis of nutrient capture, root system responses and a root phenomics laboratory assay using intact soil cores that provides a rapid assessment of cultivar performance.

The background to the project is based on that over the growing season soil conditions for plant growth are continuously changing due to weather, farm operations and the action of biology (Roger

Estrade et al., 2004). An illustration contrasting hypothetical soil structure changes of a stable grassland and an unstable arable field over a growing season is shown in Figure 2.1.

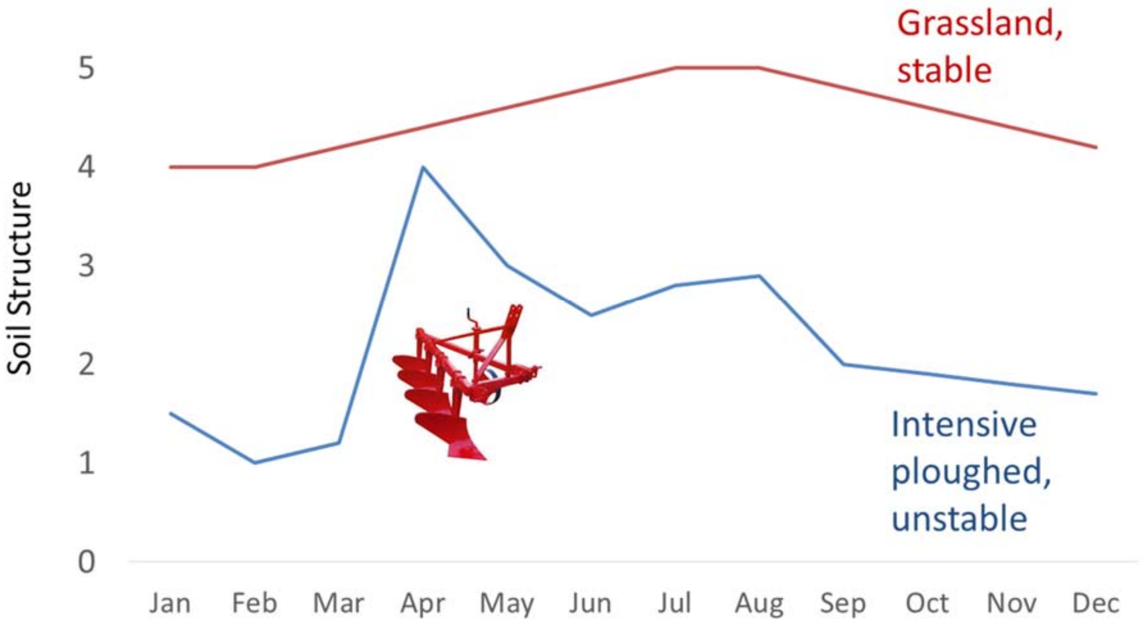


Figure 2.1: Conceptual diagram of how soil structure, rated on a subjective scale from 0 poor to 5 for excellent, can change over a growing season. Declines in soil structure are likely greater if carbon has been depleted from the soil, tillage is used to create a seedbed and vegetation is not present. Figure is based on previous studies that have explored seedbed degradation over time and the impacts of plants on soil physical stability.

Intensive cultivation exists to loosen the soil and create a homogeneous seed-bed for even germination and rapid early root-elongation. However if the soil is unstable, the structure in the seed-bed may quickly degrade. As either the crop or grass grows over time, the action of plant roots, soil fauna and weathering may create aggregation and stabilise the new structure. The ethos of reduced tillage systems is that the mechanical action of the plough can be replaced by biology that will not mechanically disrupt soil. Further, existing channels or biopores will remain intact and pans created by the passage of a plough can be avoided. Traditional ploughing exposes soil to the air and facilitates rapid mineralisation i.e. the breakdown of soil organic matter with the release of plant available nutrients. However this mineralisation is a loss of the soil organic carbon which delivers other important functions such as providing inherent resilience to physical degradation, maintaining stability and perhaps sequestering carbon within the soil. Thus the physical, chemical and biological status and functions of the soil are interlinked.

This project used the 3 existing field experiments which are referred to as platforms since they are used here to build understanding based on a series of questions. With known, comparable tillage systems on different soil types the use of the platforms sought to understand differences in the soil conditions (including structure, stability, resilience and chemistry) and to relate these to cultivar performance and root growth. Importantly because of the commonalities in the platform treatments yield and economic performance could be assessed and compared.

Specifically the project addressed six key questions.

1. To assess differences in soil conditions for plant growth at 3 sites that have been in place for 9 (Hutton), 7 and 4 (NIAB TAG) years;
2. To quantify carbon concentrations under different forms of soil management;
3. To measure the impact of soil management on the performance of contrasting cereal varieties;
4. To determine the broader impacts of the changes in soil management practices to more "sustainable systems";
5. To measure inputs and outputs of production system costs to quantify farm gate impacts of major shifts in soil management practices and;
6. To deliver a combination of in-depth quantitative analysis and practical tools to advisors and the farming community to define favourable soil physical conditions for cereal production.

Because the (field experiments) platforms have common features and are used for all phases of the research in this project they are introduced here (rather than for each subsection). As each of the platforms was established separately prior to this project and, because there are already published data from them, each has legacy terminology. For example, what is now referred to as No-till in Mid-Pilmore has elsewhere in published work (e.g. Newton et al 2012) been termed Zero Tillage. Every effort has been made within this document to be consistent and to cross reference, but where published text or diagrams are used the original terminology may appear.

The Mid-Pilmore platform

The Mid-Pilmore Tillage Experiment was set up in 2003 in Perthshire (Scotland) with support from the Scottish Government Rural and Environment Science and Analytical Services (RESAS) for funding from the Sustainable Agriculture - Plants programme. The Mid-Pilmore experiment is located on a Dystric-Fluvic Cambisol (FAO) soil with a sandy-loam texture (predominantly Carpow association, Carpow series with an incursion of Farfar association, Airntully series in the south-west corner). Five tillage techniques are employed and spring barley has been grown from 2007 (see Table 2.1).

Table 2.1: Summary of Mid-Pilmore project rotation and tillage.

Rotation	2007/08 (Yr 1)	2008/09 (Yr 2)	2009/10 (Yr 3)	2010/11 (Yr 4)	2011/12 (Yr 5)	2012/13 (Yr 6)	2013/14 (Yr 7)	2014/15 (Yr 8)	2015/16 (Yr 9)
Spring Barley	sbr	sbr	sbr	sbr	sbr	sbr	sbr	sbr	sbr

Key – sbr (spring barley).

Cultivation	Reference(s)	Type	Depth	Other notes
Annual plough	Conventional Plough	Inversion	20cm	Followed by power harrowing with a 3 m Kuhn hr3003 machine
Deep annual plough	Deep	Inversion	40cm	Followed by power harrowing with a 3 m Kuhn hr3003 machine
Annual plough, compaction	Compact	Inversion	20cm	After ploughing, compaction induced by wheeling the entire plot with a Massey Ferguson 6270 tractor fitted with 16.9R-38 rear tyres (8.8 M total load, 2.9 Mg wheel load and 110kPa contact pressure)
Shallow tillage	Minimum	Non-inversion	10cm	Sumo Trio cultivator based on a tine and disc system
Zero tillage	No-till	Direct drilling	-	Treatment discontinued after 2014 due to uncontrollable weeds

The experiment is a fully replicated randomised design with three replicates. Each plot is 33m x 33m but within each plot barley is sown (360 seeds/m^2) in sub-plots of 1.55 m wide x 6.0 m long, reduced to 4.8 m harvested length (Figure 2.2). Sowing is with an eight-row Hege plot drill (Newton et al 2012). Each tillage treatment is managed in accordance with the requirements of that approach and all inputs are consistent with local best practice. Nitrogen fertiliser was 350 kg/ha of 22-4-14(7.5SO_3) applied as top dressings. Standard pre- and post-emergence herbicide treatments were applied but no fungicide treatments were used. Straw was removed from all of the plots following harvest. The entire trial grows continuous winter or spring barley every year by dividing each plot in two (but for this platforms project only the spring barley was used). The Deep annual plough treatment is not representative of farm operations and was included in the original design to provide contrast with disturbance exceeding the normal range. For this work supported by AHDB the Deep annual plough treatment was not included in any of the soil measurements (i.e. soil structure and stability, soil chemistry, soil carbon). Where sampling and processing capability allowed, data from the deep annual plough treatment were used to help understand the crop, disease and economic processes associated with extra disturbance.

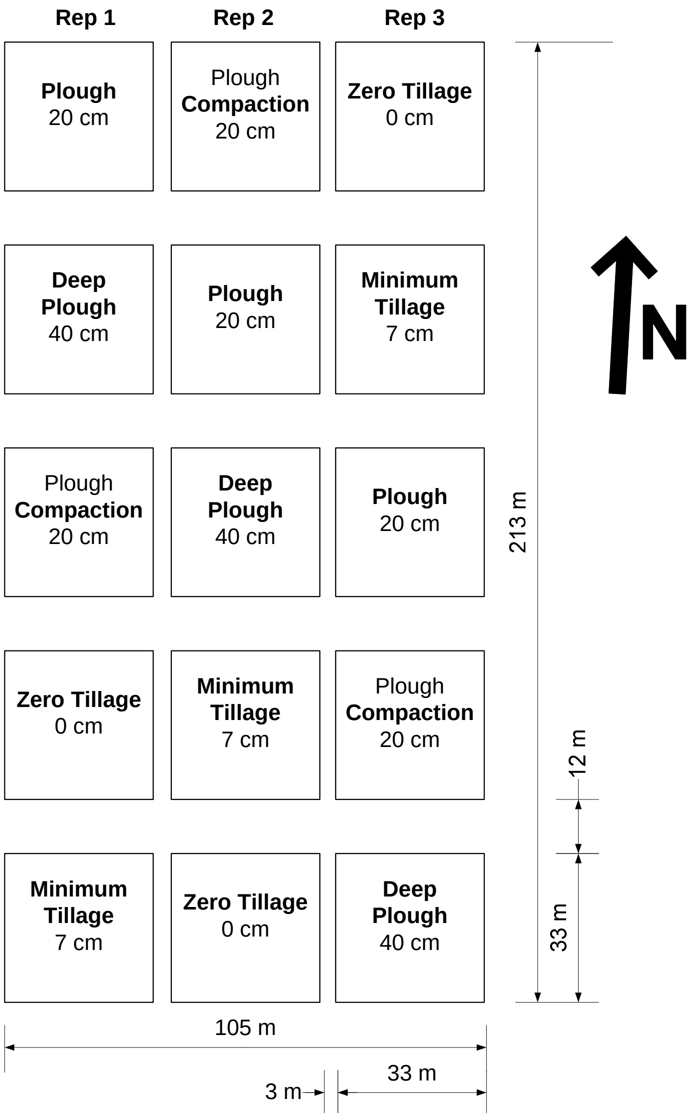


Figure 2.2: Design of the Mid-Pilmore platform.

STAR project (NIAB TAG, Suffolk)

The Sustainability Trial in Arable Rotations (STAR) project was set up in 2005 at Stanaway Farm, with support from the Felix Thornley Cobbold Trust and more latterly the Chadacre Agricultural Trust. The STAR experiment is located in Nelson Field (Otley, Suffolk) on a heavy (Beccles / Hanslope series) clay loam soil. Four cultivation techniques and four rotations are employed, resulting in 16 treatments; these treatments are outlined in Table 2.2. The experiment is a fully replicated factorial design with three replicates. Each plot is 36m x 36m to facilitate the use of farm scale equipment and techniques. Permanent grass pathways on the site allow each plot to be accessed independently. In each plot the outside area is treated as a ‘headland’ and all assessments and samples are taken from the central areas of the plots. Each treatment is managed in accordance with the requirements of that approach and all inputs are consistent with local best practice. All rotations grow wheat every second year, the year between is a break crop/fallow year. Winter cropping has a winter sown break crop, spring cropping a spring sown break crop, continuous wheat grows wheat every year and the alternate fallow grows wheat one year and is left fallow (with cover crop treatment) the next. Cultivation approaches follow an annual plough inversion tillage approach (c. 20-25cm), deep (c. 20-25cm) non-inversion tillage or shallow (c. 10cm) non-inversion tillage approach (typically using tine and disc based systems) or a managed system (decided on an annual basis). Non-inversion treatments used a Sumo Trio cultivator. A full breakdown of the managed approach cultivations can be found in Appendix 2.

Soil samples from the STAR project were collected only from the 'winter cropping' rotation for the plough, deep non-inversion and shallow non-inversion treatments.

Table 2.2: Summary of STAR project rotation and cultivation treatments.

	Cropping										
Rotation / Year	2005/06 (Yr 1)	2006/07 (Yr 2)	2007/08 (Yr 3)	2008/09 (Yr 4)	2009/10 (Yr 5)	2010/11 (Yr 6)	2011/12 (Yr 7)	2012/13 (Yr 8)	2013/14 (Yr 9)	2014/15 (Yr 10)	2015/16 (Yr 11)
Winter cropping	wosr	ww	wbn	ww	wosr	ww	wbn	ww	wosr	ww	wbn
Spring cropping	sbn	ww	so	ww	sbn	ww	sln	ww	so	ww	sbn
Continuous wheat	ww	ww	ww	ww	ww	ww	ww	ww	ww	ww	ww
Alternate fallow	fal	ww	fal	ww	fal	ww	fal	ww	fal	ww	fal

Key – ww (winter wheat), wosr (winter oilseed rape), so (spring oats), sbn (spring bean), wbn (winter bean), sln (spring linseed), fal (fallow).

Cultivation	Reference(s)	Type	Depth	Other notes
Annual plough	plough	inversion	20cm	
Deep tillage	Deep	Non-inversion	20-25cm	
Shallow tillage	Shallow	Non-inversion	10cm	
Managed	-	-	-	Decision on cultivation regime is not decided until much nearer the time, decision is based around soil/weather conditions, previous cropping, weed burden, soil assessments etc.

NFS project (NIAB TAG, Norfolk)

The New Farming Systems (NFS) project was set up in 2007 with support from the Morley Agricultural Foundation (TMAF) and the JC Mann Trust. The NFS experiment is located in Bullswood Field (Morley, Norfolk) on a medium (Ashley series) sandy loam soil. Four cultivation techniques and two rotations are employed, resulting in 8 treatments; these treatments are outlined in Table 2.3. The experiment is a fully replicated factorial design with four replicates. Each plot is 12m x 36m to facilitate the use of farm scale equipment and techniques. Permanent grass pathways on the site allow each plot to be accessed independently. In each plot the outside area is treated as a 'headland' and all assessments and samples are taken from the central areas of the plots. Each treatment is managed in accordance with the requirements of that approach and all inputs are consistent with local best practice. Rotations alternate between winter wheat and ostensibly spring sown combinable crops, and rotations are differentiated further by the presence/absence of an autumn cover crop (radish, *Raphinus sativus*) before spring crops. Cover crops are typically sown in late August / early September and destroyed using glyphosate in the following January / February (the cover crop aspects of this NFS study are not included directly in AHDB project 3786). Cultivation approaches follow an annual plough inversion tillage approach (c. 20-25cm), deep (c. 20-25cm) non-inversion tillage or shallow (c. 10cm) non-inversion tillage approach (typically using tine and disc based systems) or a managed system (decided on an annual basis). Non-inversion treatments used a Sumo Trio cultivator. A full breakdown of the managed approach cultivations can be found in Appendix 2.

Soil samples from the NFS were collected only from 'without cover crop' rotation for the plough, deep non-inversion and shallow non-inversion treatments.

Table 2.3: Summary of NFS project rotation, cultivation and management treatments.

Rotation	2007/08 (Yr 1)	2008/09 (Yr 2)	2009/10 (Yr 3)	2010/11 (Yr 4)	2011/12 (Yr 5)	2012/13 (Yr 6)	2013/14 (Yr 7)	2014/15 (Yr 8)	2015/16 (Yr 9)
Without cover crop	ww	sosr	ww	sbn	ww	sbr	wosr	ww	so
With cover crop	ww	sosr	ww	sbn	ww	sbr	wosr	ww	so

Key – ww (winter wheat), sosr (spring oilseed rape), wosr (winter oilseed rape), so (spring oats), sbn (spring bean), sbr (spring barley). Cover crop: radish cover crop autumn sown and destroyed overwinter ahead of spring sown crops.

Cultivation	Reference(s)	Type	Depth	Other notes
Annual plough	plough	inversion	20-25cm	
Deep tillage	Deep	Non-inversion	20-25cm	
Shallow tillage	Shallow	Non-inversion	10cm	
Managed	-	-	-	Decision on cultivation regime is not decided until much nearer the time, decision is based around soil/weather

				conditions, previous cropping, weed burden, soil assessments etc.

Centre for Sustainable Cropping CSC at Balruddery

The Centre for Sustainable Cropping (CSC), at the James Hutton Institute's Balruddery farm near Dundee, is a long-term experimental platform comprising a 42 ha block of six fields. It was established in 2009 to integrate cross-disciplinary research on sustainability in arable ecosystems. The platform provides an open research facility to test and demonstrate the economic, ecological and environmental trade-offs of sustainable land management over many decades. The Centre uses a six year rotation including potatoes, winter wheat, winter oilseed rape, winter barley, beans and spring barley with each of the six fields split between a conventional management and a sustainable approach. The sustainable cropping system currently includes:

- non-inversion tillage (10cm),
- tied-ridging in potatoes to reduce tramline erosion,
- compost addition pre-sowing (@ 35 t/ha),
- reduced artificial N fertiliser (70% of standard with further reductions as soil fertility improves),
- reduced dose herbicide (50% of the conventional, or alternative chemical to promote a diverse but low abundance dicot weed flora - aiming at 10% cover),
- threshold crop protection applications, and reductions where possible based on AHDB dose response curves,
- clover undersowing of spring barley crops for additional N input to the rotation
- green cover (oil radish) over winter before potato to trap soil N and reduce leaching.

As each split-field is not replicated in a given year statistical analysis of some measurements is not possible until completion of multiple rotations.

3. Materials and methods

Our methods focussed on detailed measurements of soil conditions for crop growth, focussing on physical impacts resulting from different tillage practices. From past research conducted internationally, the production of shallower plough pans, differences in aggregate structure and changes in the storage of carbon at different soil depths is known to have a large impact on crop yield potential. We relate the soil physical measurements to soil nutrients, carbon and crop yield to obtain a more holistic understanding of how soil tillage may influence productivity. These data are then related to farm gate economic costs, to determine if potential yield penalties with a particular practice may be more than off-set by lower input costs. Our physical tests range in complexity from a detailed and expensive analysis of how well the pore structure holds onto water and affects root penetration, to simpler assays that are easier for farmers to implement. By measuring a range of properties we identify key indicators that could be used practically by farmers. Soil physical characterisation was done on samples collected at multiple times during a growing season, as described in section 3.1. New resilience assays are proposed to quickly and cheaply assess the vulnerability of seedbeds to changes over time in section 3.2.

3.1. Soil structure and stability

Soil texture is the relative amounts of primary particles, sand, silt and clay sized, that comprise the soil. Texture is a stable property of the soil and in an agricultural context is largely unchangeable. Soil structure is the arrangement of the primary particles and the assembly of these into larger compound units. The manipulation of soil structure to improve conditions for root growth is fundamental to agriculture, but soil structure is also changed by weather and by loading associated with traffic. The stability of the structure in water, i.e. the structural stability, is an important feature in assessing how the soil will maintain its integrity and thus maintain its condition for root proliferation. Consistent with the aims outlined in the introduction to characterise soil structure we took core samples (55 mm diameter x 40 mm height) of soil from each platform (field experiment) described in the Introduction (section 2) for water retention and related measurements, and bulk soil samples from adjacent locations for aggregate stability. For soil physical characterisation (including water release) at least three (core) samples were taken from each treatment and replication in each platform. Sampling was done on different dates within the developing crop – usually at sowing, around establishment and at harvest. Samples collected on different dates were collected as near spatially as was feasible to earlier samples. Samples were taken at or near the surface (depending on the amount of residue remaining described as 0 – 5 cm or 2 – 7 cm), within the cultivated or main rooting depth (approx. 7 – 12 cm) and around 25 – 30 cm depth (being around any traffic or plough pan but below the normal depth of tillage). For analysis of soil carbon storage additional core samples were collected at greater depths (see section 3.4). Core samples were brought to the laboratory and saturated; then placed on ceramic suction plates (up to -50kPa; ELE Limited, Hemel Hempstead, UK) and pressure plates (up to -1500kPa; ELE Limited) to adjust the water potential through a series of potentials ranging from saturation to permanent wilting. The water potentials used were saturation = 0.01 kPa and 1, 5, 20, 50, 300, and 1500kPa. After equilibration at 1500 kPa and weighing, samples were oven-dried (105 C for 24 h) and weighed. Thus the mass of oven dry soil and the volume of the sample from the core dimensions allowed for bulk density determination. At 20, 50 and 300 kPa water potentials penetration resistance was measured with a needle penetrometer fitted to a mechanical test frame (Instron Model 5544, INSTRON, Massachusetts, United States). A 1 mm diameter needle penetrometer 30 degree semi-angle with a relieved shaft was used. Resistance readings were taken every 0.75 mm and the 8 values range between 4.5 mm and 9.75 mm were averaged to provide a mean resistance.

The data from this characterisation was used to quantify critical thresholds of impeded plant performance through water-logging, drought or mechanical impedance. Several approaches to quantifying soil physical quality, particularly those relating to root proliferation, were employed. We used standard measures such as bulk density (mass of oven dry soil per unit volume) and water release data providing plant available water (PAW) and easily available water (EAW). PAW is the volume of water stored between field capacity (taken as -5 kPa water potential) and wilting point (taken as -1500 kPa water potential) and EAW is the volume of water between field capacity and -300 kPa. The combination of water release data with (micro-)penetration resistance (a.k.a. mechanical impedance) measurements allows the calculation of the Least Limiting Water Range (LLWR) (daSilva & Kay 1996). LLWR characterises soil for root proliferation by including aeration, mechanical resistance and water status into a single measure (McKenzie et al 2011). Valentine et al (2012) related root development to macroporosity (i.e. volume of large pores within the soil). From the water release data of soil collected as core samples, macroporosity (greater than 60 µm equivalent diameter) was taken as the difference in pore volume between saturation and -5kPa water potential. From the complete water retention curve for each sample the van Genuchten water release parameters were determined (van Genuchten 1980) using statistical fitting procedures in "R".

Soils are heterogeneous media providing a range of aggregate sizes and hence a range of pore sizes. These different sizes of aggregates and pores allow soils to provide different environments for roots and the soil biology (e.g. Six et al 2004) and to deliver different functions e.g. different hydraulic conductivities (McKenzie and Dexter 1996). Soils with greater heterogeneity of aggregate and pore sizes are thus seen to have better quality. The slope of the water release curve at the point of inflection is a characterisation of the heterogeneity of the soil structure and this pore scaling behaviour allows the "S" value to be determined. Soils with greater values of "S" are interpreted as having better quality. This measure of soil quality is becoming widely accepted by soil scientists since proposed by Dexter (2004). Sampling of the soil was done soon after cultivation, when the crop has emerged (typically 1 month post sowing for spring crops and early spring for winter sown crops), and post-harvest to assess seasonal shifts (Angers & Caron 1998).

The loose soil collected at the same time as the cores was used to determine aggregate stability in water. Moist soil was gently passed through an 8 mm sieve to remove stones and gravel then air-dried and the water content determined. Four grams (+/- 0.1 g) of the air-dried soil was placed onto the sieves (either 0.5 mm or 2 mm aperture) of a standard Eijkelkamp wet-sieving apparatus. The soil on the sieves was vertically oscillated in water for three minutes and the weight of soil remaining on the sieves determined (and corrected for initial water content). This was done in triplicate for all sampling point and depth combinations. Water stable aggregation (WSA) is expressed as a percentage of the initial dry weight of soil. General statistical analysis was performed in Genstat with data (log) transformed where necessary to achieve normality of the residuals. Analysis was usually by analysis of variance but on the very few occasions where outliers or missing data created imbalance REML was used.

For analysis of the soil structure and stability in the spring cropping platforms, i.e. Mid-Pilmore and NFS, two approaches were taken. The first considered the effect of date for April (4), May (5) and August (8) and covered only surface samples. The second excluded May (5) where only one depth was sampled to consider all depths and assess structural changes resulting from different cultivation approaches from beginning to end of season. The STAR experiment involved winter cropping. Sampling of soil for winter wheat was done soon after crop sowing in October then in May when the crop was established (and for comparison at a similar date to the spring crops used in Mid-Pilmore and NFS) and just prior to harvest in August. Tillage systems were the same as for NFS with a conventional plough and a deep and shallow non-inversion described in Table 2.2.

Hydraulic conductivity measures of the soil under the various treatments in Mid-Pilmore were also determined as part of an AHDB funded student project. A summary of the project conducted by Alastair Robertson from the University of Aberdeen can be found in Appendix 9.6.

3.2. Soil Resilience

Resilience assays were developed to mimic conditions that can cause changes to soil physical structure over time in the field. These built on various laboratory assays that assess how well soils resist and recover from stresses such as compaction and waterlogging (Gregory et al. 2009, Kuan et al., 2007). A novel aspect of the current study is that the resilience assays can be compared to time-dependent measurements of soil physical conditions for crop growth, so their practical value can be better assessed.

Our original intention was to conduct resilience assays on intact soil cores collected shortly after seedbed preparation. After sampling the STAR experiment in October 2012 we abandoned this approach in favour of repacked cores for a number of reasons. Even after a couple of days, seedbed soil structure can change dramatically depending on the weather. We sampled within 1 week of seeding, but found that the soils had already coalesced. By breaking the soil apart and repacking it into soil cores, initial tillage conditions are simulated. The approach may also make it feasible to conduct measurements of seedbed physical resistance and resilience at any time of year.

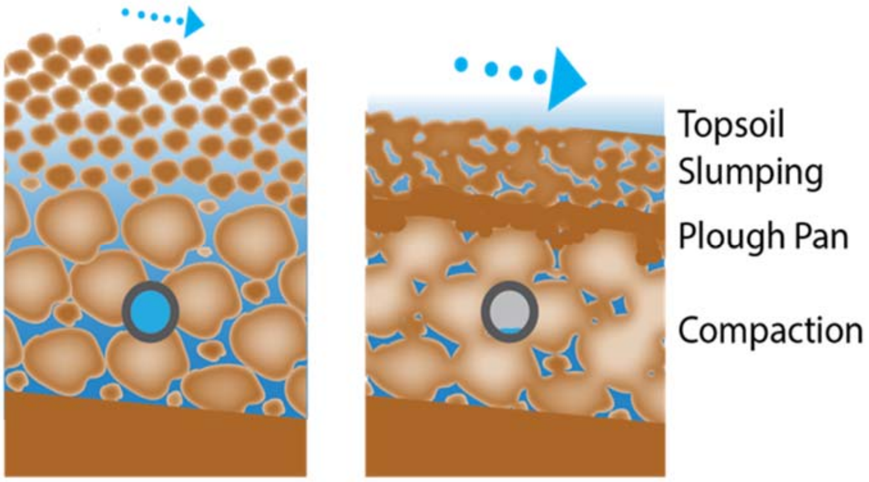


Figure 3.2.1: The physical structure of soil can degrade through inter-linked processes of compaction and slumping during a growing season.

3.2.1. Soil Preparation

Resilience assays were only conducted once during the growing season, shortly after seed sowing when the first sampling for other soil properties also occurred. Field replication and treatments were identical to the intact soil cores described in section 3.1. Bulk soil samples were taken from 2-6 cm depth, placed in sealed plastic bags and transported to the laboratory where they were stored at 4 ˚C until processing. The soil was passed through a 4 mm sieve and then poured into 60 mm diameter x 42 mm height soil cores. These cores had mesh on the base to allow for water equilibration. Gentle tapping was done to settle the soil.

3.2.2. Slumping Assay

These cores had an initial soil depth of 20 mm, which corresponded to about 50 g of soil. They were wet gradually from the base, then drained to -5 kPa water potential and then weighed. The depth of the soil in the core was also measured at three locations to account for any initial settling. Slumping was imposed by wetting the soil to saturation with a 350 g weight placed on the surface. This weight is the equivalent of a 2 kPa overburden stress, as would occur about 15 cm beneath the soil surface. The soils were then drained again to -5 kPa water potential, weighed and measured for soil depth. After the slumping stress, the soils were subjected to two cycles of wetting and drying to measure pore structure resilience. Cores were dried at 40 ˚C until water loss ceased and then rewetting rapidly during each cycle. They were then drained again to -5 kPa water potential, weighed and measured for soil depth.

3.2.3. Compression Assay

A separate set of cores were initially filled to the top of the soil core. They were wet gradually and then equilibrated to -5 kPa water potential. After equilibration the depth of the soil in the core was measured at three locations. A mechanical test frame (Model 5544, INSTRON, 100 Royall St., Canton, MA 02021-1089, USA) was used to impart a compression stress to the soil. It was fitted with a 1 kN load cell that was accurate to 1/250 of its maximum load that had a round platen slightly smaller than the core diameter to prevent friction. The platen compressed the soil at a stress controlled loading rate of 100 kPa/minute. This is much faster than traditional soil compression tests and also previous compression resilience assays (Kuan et al., 2007), but it more closely reflects the speed of farm machinery (Keller et al., 2013) and allows for the rapid processing of samples. The soil was first compressed to 50 kPa, followed by relaxation to 0 kPa. This stress simulates the action of a roller that is used to compress the soil after tillage to improve seed soil contact and seedbed stability. It was then compressed to 200 kPa to simulate compaction from farm machinery, followed by relaxation to 0 kPa. The mechanical test frame recorded the applied stress and crosshead displacement during both loading and unloading, so that the volume change of the soil in the core during cycles of loading and unloading could be calculated.

3.3. Soil Chemistry Analysis

3.3.1. pH

Ten grams (+/- 0.1g) of soil from each sample point were weighed into approximately 100mL glass jars and 20mL of 0.01M CaCl2 was added into each jar. The suspension was swirled and left to equilibrate for 20mins. Prior to measurement of pH with a glass electrode attached to a standard pH meter the suspension was swirled again and pH measured. To express all nutrient concentrations on a per soil dry weight basis, gravimetric water content was determined on all soil samples prior to further analysis.

3.3.2. Olsen P Extraction

Two grams (+/- 0.05g) of each soil sample (including standard soil) was weighed into unskirted 50mL centrifuge tubes and 20ml 0.5 M $NaHCO_3$ was added to each tube plus empty tubes which acted as an extraction control. All tubes where then shaken on a roller bed (75rpm) for 1 hour. Samples were then centrifuged for 5 mins at 4500 rpm and 2ml of the supernatant was transferred to 2ml Eppendorf tube and stored in fridge for P determination later.

Fifteen µL aliquots of the supernatants were pipetted into 96 well plates for phosphorus analysis. These aliquots were diluted 20 times in a malachite green reagent (Irving and McLaughlin, 1990) and the reaction was allowed to proceed for 30 minutes. This reaction caused a change in the colour of the solution which was then measured on a spectrophotometer at a wavelength 620nm. Concentrations of P in the solutions were calculated based on a calibration curve produced with the use of a range of standard concentration P solutions. These concentrations were then converted to a dry soil weight concentration using data from the soil moisture analysis above.

3.3.3. KCl extraction for NH_4 and NO_3

Ten grams (+/- 0.1g) of each soil sample was weighed into 100mL glass jars with screw caps and 40mL 1M KCl was added to each jar plus some empty jars which acted as a extraction control. Sealed jars where shaken on a roller bed (75rpm) for 45 mins. Suspensions were then swirled and poured through a Whatman 1 filter paper and filtrate collected. Filtrates were stored at -20°C until analysis could be performed.

The samples were analysed using the Konelab Aqua 20 Discrete Analyser for NH_4, Total Organic Nitrogen (TON) and NO_2. Ammonium reacts with Salicylate and Dichloroisocyanurate in the presence of sodium nitroprusside to form a blue colour that is proportional to the amount of ammonia present. The colour produced is measured spectrophotometrically at 660nm. For nitrate the sample is acidified and reacts with sulphanilamide to form a diazo compound. This compound couples with N-(1-Naphthyl)ethylenediamine (NEDD) to form a reddish-purple azo dye and the resulting colour change, which is proportional to the concentration of nitrite ions, is measured spectrophotometrically at 550 nm.

Concentrations of NH_4 and NO_3 in the solutions were calculated based on a calibration curve produced with the use of a range of standard concentration NH_4 and NO_3 solutions. These concentrations were then converted to a dry soil weight concentration using data from the soil moisture analysis above.

3.4. Soil Carbon

Soil samples were taken from the STAR, NFS and Mid-Pilmore platforms in August 2013 at 5 depths intervals to a depth of 60 cm (Table 3.4.1). At each position and depth, core samples (see 3.1) were collected for soil bulk density determination. Loose soil was also collected in plastic bags, sieved to 8 mm, dried for 24 h at 105°C in a fan-assisted oven and ball-milled for carbon analyses. Total carbon was determined by the Analytical branch of The James Hutton Institute using a Thermo Flash EA 1112 Elemental Analyser (Thermo Fisher Scientific). Given that the parent material of the STAR site was calcareous, samples were treated with HCl to remove carbonate prior to analysis. Soil from the Mid-Pilmore platform had previously been sampled and analysed in October 2008 at different depths intervals (Sun et al., 2011). In order to make comparisons between the 2013 and 2008 data, a new depth categorical variable was created. This variable consisted of the most similar depths between samples (Table 3.4.1).

Table 3.4.1: Depths of samples in the soil profile in 2008 for Mid-Pilmore and 2013 for Mid-Pilmore, STAR and NFS by treatment. The depth category was created to facilitate comparisons between Mid-Pilmore data from 2008 and 2013. The values in cm correspond to the middle point of the core. Data for 2008 after Sun et al. 2011. P= plough, N= no-till, M= shallow non-inversion.

Depth 2008 – P (cm)	Depth 2008 – N (cm)	Depth 2008 –M (cm)	Depth 2013 (cm)	Depth category
-2.5	-3.5	-5.25	-4.5	1
-7.5	-7.5	-9.5	-9.5	2
-27.5	-25	-27.5	-27.5	3
-35	-35	-35	-37.5	4
-55	-55	-55	-57.5	5

3.5. Cultivar Performance

3.5.1. Trial History

The Mid-Pilmore soil cultivation trial platform was set up in 2003 with the first winter barley harvest in 2004. The first spring barley varieties were sown in 2007 revealing variety interactions with soil tillage treatment. Two cultivars, Optic and Westminster, were grown every year except 2011 from 2007 until 2016. From 2003 to 2014 there were five tillage treatments but the zero tillage treatment was discontinued after 2014 due to weed problems that could no longer be controlled adequately by herbicides.

3.5.2. Cultivars

Each trial had 35 entries and the same 35 were sown in 2013, 2014 and 2015 trials (Table 3.5.1). These were: Optic (referred to as Optic1), Optic2 (a repeat from a different seed batch), Westminster, Waggon, and Concerto as widely-grown standard comparison cultivars; all six 2-component equal proportion mixtures of Optic (Op), Westminster (We), Waggon (Wa) and Concerto (Co) (Op/Wa, Op/We, Op/Co, Wa/We, Wa/Co, We/Co), together with the 4-component equal proportion mixture (Op/We/Wa/Co); three root hair mutants of Optic (T-short root hairs-R, Q-no root hairs-S and V-short root hairs-R); and 20 other cultivars representing a diversity of origins and attributes (Propino, Appaloosa, Riviera, Prestige, Carafe, Scarlett, Tocada, Kennia, Morex, Derkado, Aramir, Bowman, Troon, Vada, Decanter, B83-12/21/5, Golden Promise, Carlsberg, NFC Tipple and Melius). In 2016 11 new cultivars were added (RGT Planet, KWS Sassy, Olympus, Octavia, Sienna, Odyssey, Origin, Fairing, Belgravia, Ovation and Scholar). To make room for these within the trial platform 11 cultivars had to be removed and these were selected either because they were the 2-component mixtures (six entries) or around the middle of the distribution of responses to cultivation treatment in the 2013-15 trials (Prestige, Carafe, Scarlett, Derkado and B83-12/21/5). Pedigree and breeder information on these cultivars is given in Table 3.5.1.

Only cultivars were specified originally in this work; the mixtures and mutants in particular were funded as part of complementary Scottish Government-funded work but are reported here as they provide more useful data in this context. The core cultivars (Optic, Concerto, Westminster, Waggon) are also the core cultivars in the Centre for Sustainable Cropping Platform, Balruddery that is used in part of this project too.

3.5.3. Trial

For Mid-Pilmore the five tillage treatments originally established in autumn 2003 represented different levels of soil disturbance (see Table 2.1). These treatments were selected to provide different physical constraints to root growth and water availability. Within each of the 15 blocks, half of the trial was winter sown (not reported here) and half spring sown with the 35 entries described above

3.5.4. Assessments

Diseases were scored on a 1-9 whole plant severity scale (Newton and Hackett, 1994) when above trace levels, and scored again at approximately two-weekly intervals. Scores were converted to percentage infection and the Area Under the Disease Progress Curve (AUDPC) calculated. Plots were harvested when ripe using a Wintersteiger plot combine and the grain was dried to constant moisture and weighed.

Table 3.5.1: Spring barley cultivars used in Mid-Pilmore soil cultivation trial

Cultivar	**Trials**				**Pedigree**	**Breeder**
	2013	2014	2015	2016		
Optic (Op)	+	+	+	+	(Corniche*Force)*Chad	New Farm Crops Ltd (Syngenta)
Westminster (We)	+	+	+	+	NSL 97-5547*Barke	Nickerson (UK) Ltd (Limagrain)
Waggon (Wa)	+	+	+	+	NFC 499-69*Vortex	Syngenta Netherlands
Concerto (Co)	+	+	+	+	Minstrel*Westminster	Limagrain
Op/Wa	+	+	+	-	(Equal component mixture)	Syngenta
Op/We	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
Op/Co	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
Wa/We	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
Wa/Co	+	+	+	-	(Equal component mixture)	Syngenta/Limagrain
We/Co	+	+	+	-	(Equal component mixture)	Limagrain
Op/We/Wa/Co	+	+	+	+	(Equal component mixture)	Syngenta/Limagrain
T-short root hairs-R[a]	+	+	+	+	EMS mutant	-
Q-no root hairs-S[a]	+	+	+	+	EMS mutant	-
V-short root hairs-R[a]	+	+	+	+	EMS mutant	-
Propino	+	+	+	+	Quench*NFC Tipple[b]	Syngenta
Appaloosa	+	+	+	+	493113-502*Decanter	Nickerson-Advanta Seeds UK Ltd (Limagrain)
Riviera	+	+	+	+	Stanza*Cebeco 8331	PBI Cambridge Ltd
Tocada	+	+	+	+	Henni*Pasadena	KWS
Kenia	+	+	+	+	Binder*Gull	Abed Plant Breeding Stn., Denmark
Morex	+	+	+	+	Cree*Bonanza	Dept Agri, University Minnesota
Aramir	+	+	+	+	Volla*Emir	Cebeco, Netherlands
Bowman	+	+	+	+	((Klages*(Fergus*Nordic))*ND 1156)*Hector	North Dakota Agri Exp Stn
Troon	+	+	+	+	Extract*NSL 95-2949	Nickerson (UK) Ltd (Limagrain)

Vada	+	+	+	+	*H.laevigatum**Gull	Instituut de Haaff, Netherlands
Decanter	+	+	+	+	Heron*Dallas	Limagrain
Golden Promise	+	+	+	+	Maythorpe Gamma-Ray Mutant	Zenica
Carlsberg	+	+	+	+	Prentice*Maja	Carlsberg
NFC Tipple	+	+	+	+	(NFC 497-12*Cork)*Vortex	New Farm Crops Ltd (Syngenta)
Melius	+	+	+	+	Conchita x TamTam	Syngenta
Prestige	+	+	+	-	(Bohemian Wheat*Rye)*(Ble de Domes*Garnet)	PBI Cambridge Ltd
Carafe	+	+	+	-	(Linden x Cooper) x Extract	New Farm Crops Ltd (Syngenta)
Scarlett	+	+	+	-	Amazona (Breun ST 2730e x Kym)	Bruen
Derkado	+	+	+	-	Lada*Salome	VEB Berlin
B83/12/21/5	+	+	+	-	Thurso*Esk	Scottish Crop Research Institute
RGT Planet	-	-	-	+	Concerto*TamTam	RAGT
KWS Sassy	-	-	-	+	Publican*Concerto	KWS
Olympus	-	-	-	+	Genie*Tesla	Limagrain
Octavia	-	-	-	+	Odyssey*SY Universal	Limagrain
Sienna	-	-	-	+	Chronicle*Genie	Limagrain
Odyssey	-	-	-	+	Concerto*Quench	Limagrain
Origin	-	-	-	+	NSL07-8113-B*Tesla	Limagrain
Fairing	-	-	-	+	144-02-4*Titouan	Syngenta
Belgravia	-	-	-	+	Minstrel*Westminster[b]	Limagrain
Ovation	-	-	-	+	Tesla*Odyssey	Limagrain
Scholar	-	-	-	+	Summit*SJ056065	Breeder’s code: SY411-285

[a] Root hair mutants induced by EMS. John Innes Centre Germplasm Resources Unit (GRU) Searchable database for BBSRC Small Grain Cereal Collections (https://www.jic.ac.uk/germplasm/databases.htm) and barley pedigree data excel file. [b] AHDB Recommended List Barley and Oats Pocketbook 2011/12; & 2014/15. Cultivars common to pedigrees of other cultivars are highlighted.

3.6. Root Elongation

3.6.1. Method

Root elongation assays were performed in groups of samples, separated by replicate where necessary. Assays were performed as in Valentine *et al.* (2012). Cores used in this study were the same cores used for the soil physical characterisation (including water release) (Section 3.1). Briefly, cores were saturated, and the water content was gradually decreased to -300kPa or -500kPa matric potential, after which a subsample of the soil was extracted for the drier end of the water release curve. Cores were then resaturated and returned to -20kPa matric potential. Barley seeds (cv Optic) were pre-germinated for 2-3 days using the method in Valentine *et al.* (2012). Two seedlings were placed into two holes approximate 5mm in diameter and 1 cm deep on opposite sides of the cores 1cm from the edge of the core. All roots were placed within the hole and seedlings were secured in place using a 5 cm petri-dish lid and elastic bands. All cores were placed into single sealed plastic bags and were incubated at 15^{o}C for approximately 48hours. Roots were extracted from cores by gently removing the soil from the cores and prising it gently away from the roots. The length of the longest root of each seedling was measured before and after incubation in soil.

3.6.2. Statistical Analysis

All analysis of soil and root elongation for this section was performed using R. Root parameters were calculated per core as an average of the two seedlings prior to further analysis. Starting length between each root growth experiment groups varied considerably, and starting length of roots was found to negatively correlate with elongation rate ($p<0.001$, R^2 0.118, estimate = -0.02), albeit accounting for a small percentage of the variation in elongation rate. However, to account for this, starting length was included in all linear models as a random factor. Cores were designated a Sampling group based on the position within the growing season, i.e. S1 was the first sample after tillage, S2 the middle of the season, and S3 was sampled around harvest. For some analysis subsets of the data were extracted from the complete dataset as the following datasets:

1. Chemistry (First season cores taken at the same time as the samples taken for chemical analysis);
2. Physical_Surface only – All cores taken from the top 2-7cm, including S1,S2 and S3 samplings;
3. Physical_S1S3 – All cores taken at sampling S1 and S3 including all depths (i.e. S2 samples not included as these only included surface sampling).

These datasets were extracted to improve the balance of the datasets used to model the effects of trial, tillage, depth and sampling time. A mixed linear models approach was used to assess the impact of Trial (MP, NFS, STAR, CSC), Tillage (No-till, Shallow non inversion, Deep non inversion, Plough, Compaction), within season sampling time (S1,S2,S3) and sampling depth (either Sampling Depth in cm or Sampling Depth Category (Surface, Middle, Deep) on the soil parameters and on root elongation. Further correlations between the individual soil characteristics or principle components of the soil characteristics and root elongation rates were investigated. Mixed linear modelling was performed initially using lmerTest::lmer function with fixed effects selected from, the field parameters “Trial, Tillage, Trial_Tillage, Sampling_Time, Sampling_Depth, Sampling_Category”. Random factors were selected from Replicate within the trial (Trial_Plot_Rep), Replicate taken from within plots (Trial_Plot_Rep_Within), Root Growth experiment batch (RootGrowthExpt), RootGrowthExpt :Individual root starting length (RootStartingLength) and the season during which the soil was sampled (Sampling Season). After initial model analysis, models were transformed to lm (i.e. random factors, were added to the front of the fixed terms of the model). The car::boxCox function was used to find the likely lambda for transforming the response variable., after which the initial lmer model was reconstructed, with the transformed response variable. The transformed and untransformed models were compared using the lmerTEST::anova, function. The model was then exposed to fixed effects and random term reduction using the fitLMER.fnc to remove terms that did not have a significant impact on the model. The mcp.fnc was used to evaluate model fit. The final model was re-assessed using LMERTest::anova to compare it with previous no reduced models, and then finally with the same function using Kenward-Roger to estimate ddf and type 2 settings to produce F estimates of p values.

3.7. Yield and Economic Performance

Table 3.7.1 outlines the initiation dates for STAR, NFS and Mid-Pilmore and the seasons of study included directly in AHDB project RD-2012-3786. Yield and margin output data from these seasons are presented in section 4.7; these include both findings from the seasons of study in AHDB project RD-2012-3786 directly, and output from longer term datasets from each study. Margins are based on gross output less the cost of all direct inputs and machinery usage for prices relevant to each production season. All crop prices and input costs are determined annually through market bulletin publications and in agreement with the advisory committee. Further details of costs used are presented in the relevant tables and in Appendices 3-5. Platform descriptions for STAR, NFS and Mid-Pilmore were provided in section 2 (Introduction).

Table 3.7.1 Project initiation date and seasons included directly within project RD-2012-3786.

Platform	Initiated	Seasons included for analysis in this report
STAR	2005/06	Season 8 (2012/13) to season 11 (2015/16)
NFS	2007/08	Season 6 (2012/13) to season 9 (2015/16)
Mid-Pilmore	2007/08	Season 1 (2007/08) to season 9 (2015/16)
Mid-Pilmore	2007/08	Season 6 (2012/13) to season 9 (2015/16)

4. Results

4.1. Soil structure and stability

4.1.1. Mid-Pilmore Surface data – Bulk Density, EAW, LLWR, and S

There is a significant 2-way interaction between treatment and date (Figure 4.1.1) for bulk density. In April the No-till (Zero-Till) had the highest bulk density followed by plough and compaction (not significantly different) and the least dense was the Min-Till (non-inversion). Over the season following drilling there was a major decrease in the density of the Zero-Till, while the by the end of the season the ploughed treatments had greatest bulk density. The surface soil of the non-inversion tillage treatment remained least dense throughout the season.

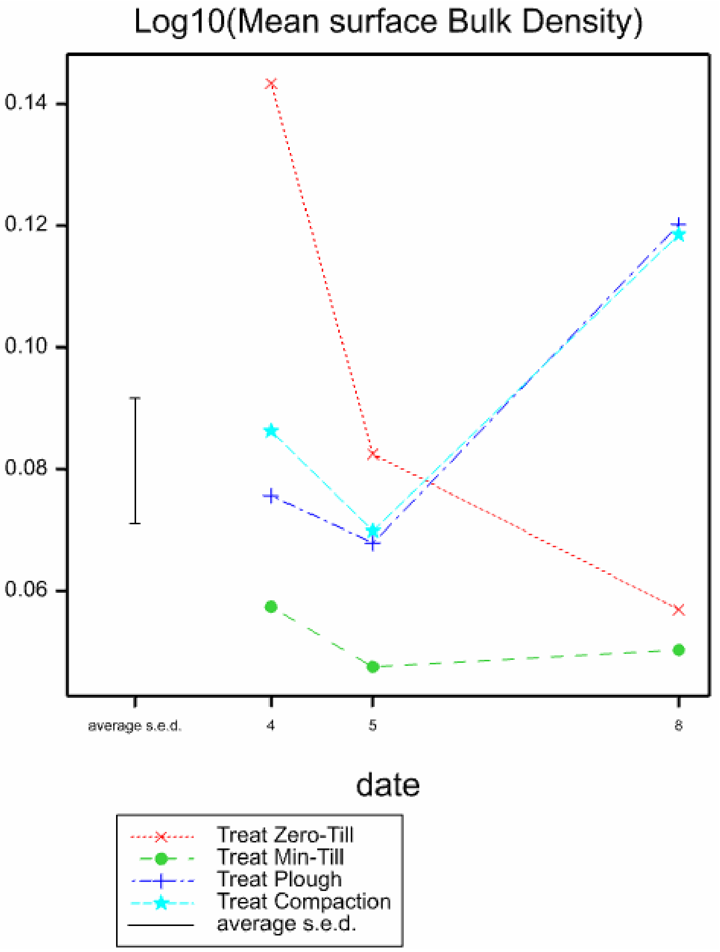


Figure 4.1.1: shows the log transformed mean surface bulk density on three dates April (4), May (5) and August (8) for the different tillage treatments in Mid-Pilmore.

Easily Available Water (EAW) of the surface soil from Mid-Pilmore also showed a significant 2-way interaction between tillage treatment and date (Figure 4.1.2). The No-till (Zero-Till) treatment shows a significant increase during the season which is in the opposite direction to the Min-Till (non-inversion) which has a decrease in EAW. The plough and compaction treatments while initially different become almost identical after sowing through to harvest and showed the lowest easily available water in the surface soil of the treatments at around harvest.

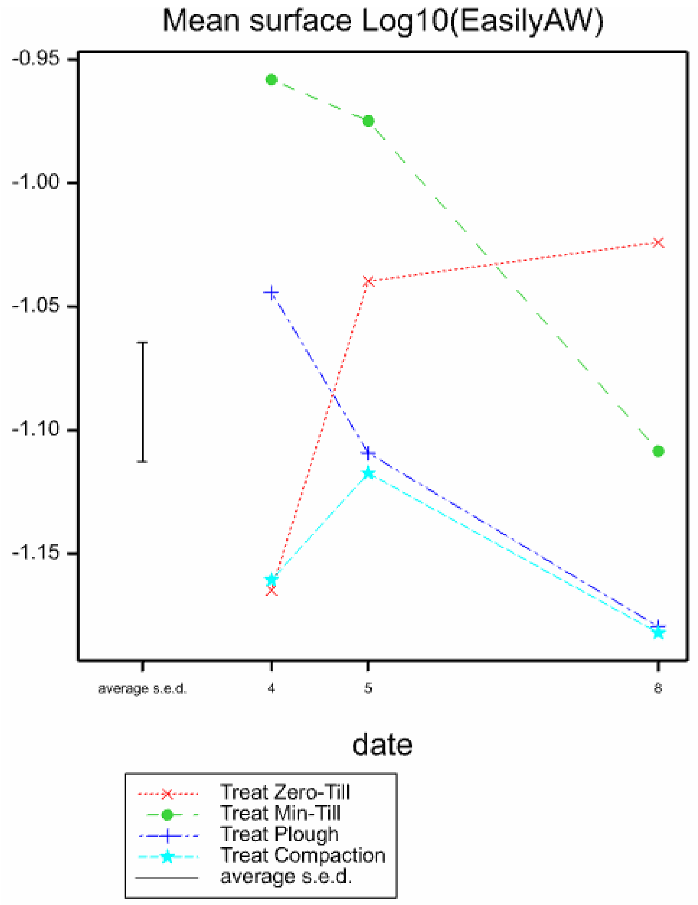


Figure 4.1.2: shows the log transformed mean surface Easily Available Water on three dates April (4), May (5) and August (8) for the different tillage treatments in Mid-Pilmore.

For the least limiting water range (LLWR) there is also a significant 2-way interaction between tillage treatment and date for the surface soil from Mid-Pilmore (Figure 4.1.3). However unlike the other indexes of soil quality this is due almost entirely to the changes in the No-till (Zero-Till) treatment for which the LLWR is initially very low (indicating limited opportunity for root proliferation in the surface soil) but then with slit created at sowing the LLWR increases and at harvest the surface soil has the greatest LLWR. This is consistent with the decrease in bulk density shown above.

As with most of the other soil quality variables for the surface soil from Mid-Pilmore the "S" values needed to be log transformed for analysis. As described in section 3.1 an increase in the value for "S" can be interpreted as an improvement in soil quality as this represents greater heterogeneity of pore and aggregate sizes. Similarly consistent with the other soil quality data there was a significant 2-way interaction between treatment and date (Figure 4.1.4). The "S" values for all treatments increased between April (4) and May (5), however the compaction treatment decreased between May (5) and around post-harvest in August (8), while the trends in other treatments were for "S" to remain constant or to increase.

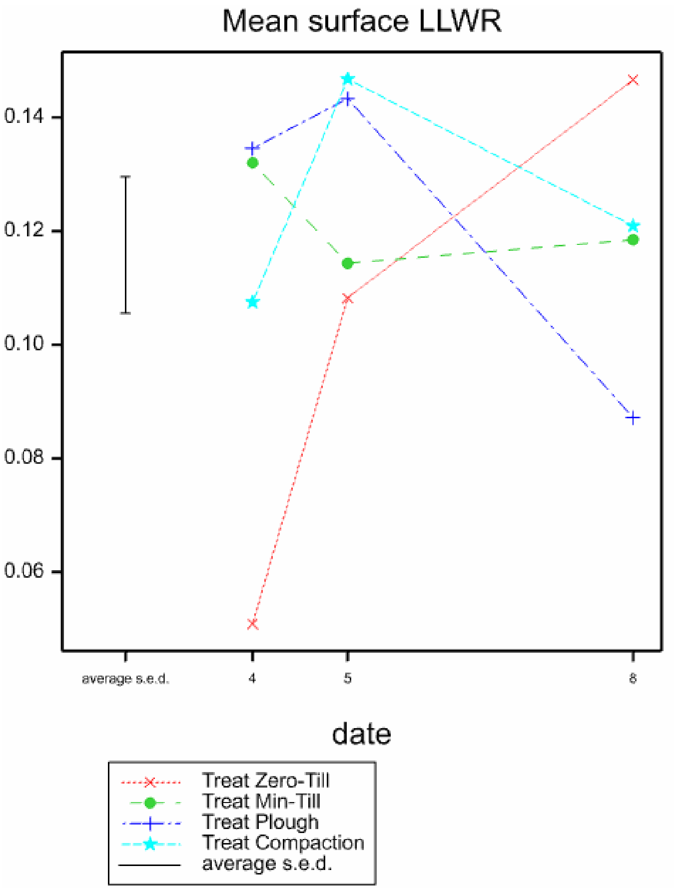


Figure 4.1.3: log transformed mean surface least limiting water range (LLWR) on three dates April (4), May (5) and August (8) for the different tillage treatments in Mid-Pilmore.

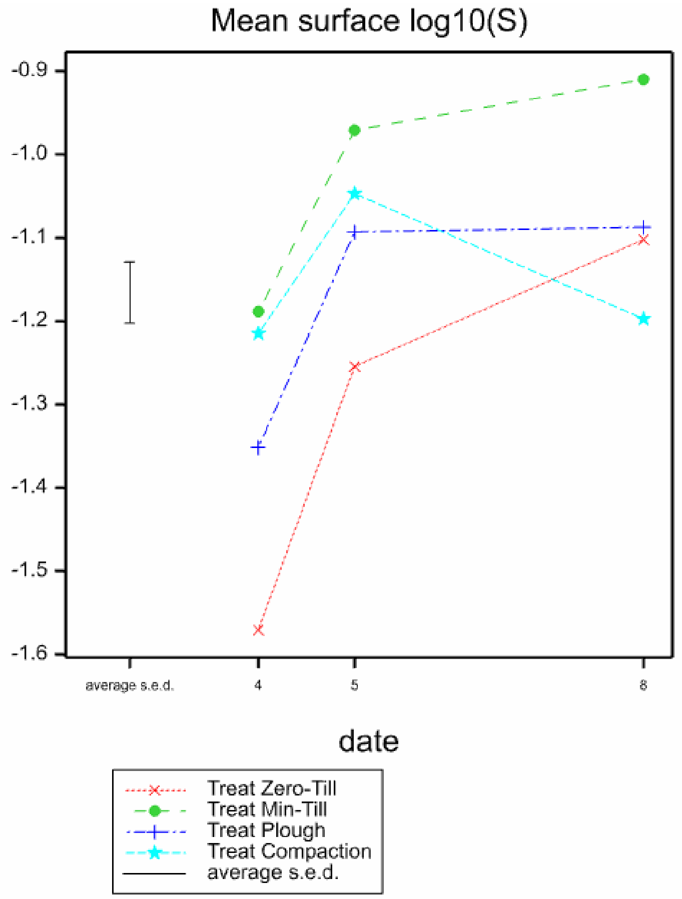


Figure 4.1.4: log transformed mean "S" values on three dates April (4), May (5) and August (8) for the different tillage treatments in Mid-Pilmore.

4.1.2. Mid-Pilmore Depth data – Bulk Density, EAW, LLWR, and S

For the soil quality analysis including depth we focussed on the changes from soon after cultivation to post-harvest. As the treatments had all been in place for more than 7 years the soil conditions had sufficient time to reach a stable state (Horn 2004).

For bulk density there is a significant 3-way interaction: treatment x depth x date (Figure 4.1.5). The plough and compaction treatments were similar with little change in bulk density with depth and date, except that bulk density at the surface in April (soon after tillage) was lower than at other times or depths. The bulk density of the No-till (Zero-Till) treatment does not change with depth in April, but in August the bulk density at 0 and 7 cm depth is much lower while there is no change at 30 cm. The Min-Till (non-inversion) shows increasing bulk density with depth but little difference between April and August apart from being marginally greater at 7 cm in April than in August.

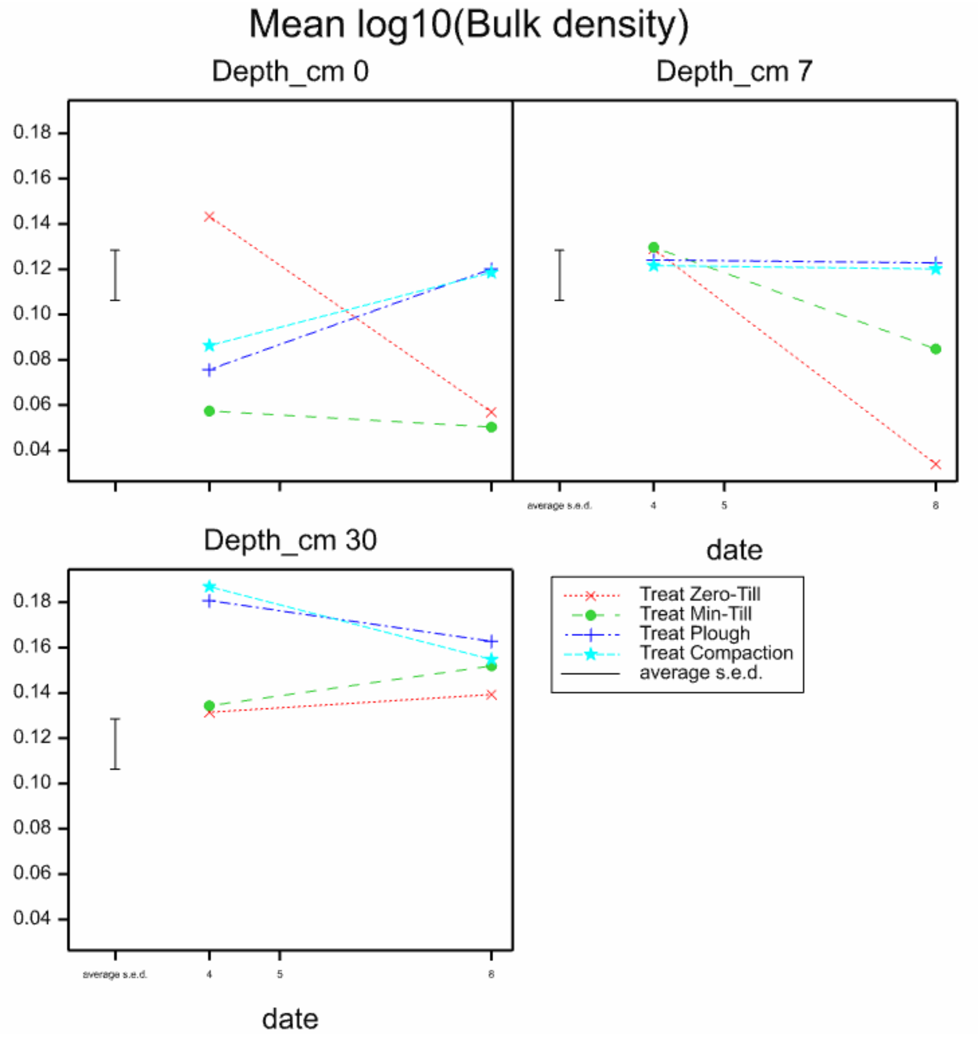


Figure 4.1.5: log transformed bulk density values in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in Mid-Pilmore.

For Easily Available Water (EAW) the main effects tillage and date were significant as was the two-way interaction. Because there was no depth effect the data can be presented as a single figure (Figure 4.1.6). With the exception of the Zero-Till (No-Till) there was no real change between April (4) and August (8) with the ploughed and compacted treatments having the greatest easily available water. Unlike the other treatments the Zero-Till exhibited a significant decrease in EAW over the year. A decrease in bulk density (i.e. an increase in total porosity) in the surface and at 7 cm and a decrease in EAW indicate that there was an increase in macroporosity over the growing season in the Zero-Till (No-Till).

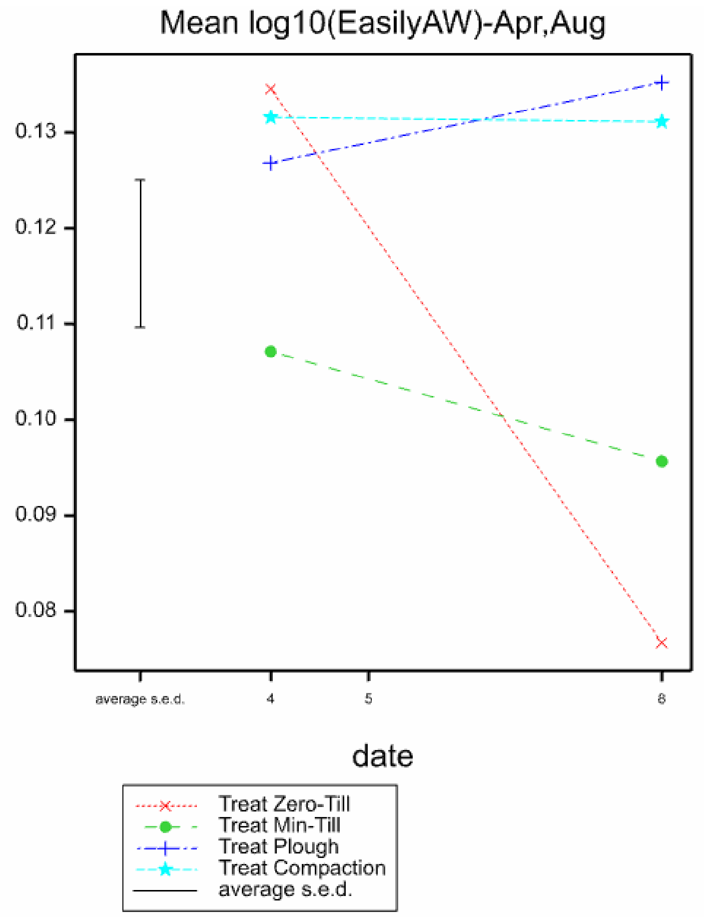


Figure 4.1.6: log transformed Easily Available Water (EAW) values in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in Mid-Pilmore.

Interestingly for LLWR the data did not need to be transformed and because there was no effect of depth the data can be presented as a single figure (Figure 4.1.7). There are two points of interest. First the LLWR decreases during the year in the compaction treatment and similar to the Easily Available Water pattern there is a major change in LLWR for Zero-Till (No-Till). Unlike the EAW pattern it is a significant increase in LLWR (rather than a decrease). Unlike EAW the LLWR includes a mechanical impedance (penetrometer resistance) component so the difference in behaviour is likely to be linked to differences in soil strength. Such changes have also been linked to increases in soil macroporosity (Valentine et al 2012).

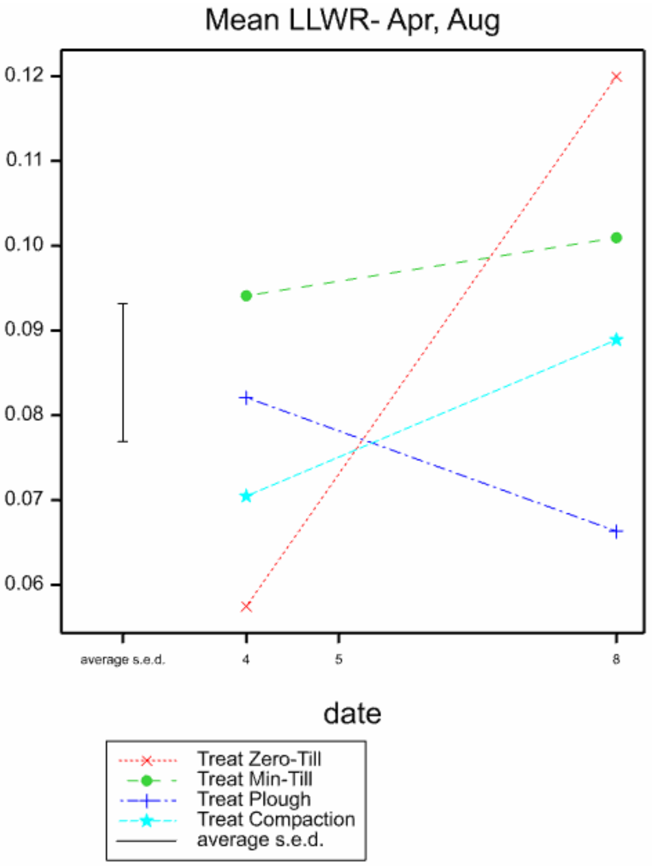


Figure 4.1.7: LLWR soil quality index in April (4) and August (8) for all sampling depths (0, 7 and 30 cm) as there was no interaction. Data are for the different tillage treatments in Mid-Pilmore.

There is a 3-way interaction: treatment x depth x date for "S" that is significant ($p<0.05$). In all cases with one exception "S" is lower in April (4) than in August (8) (Figure 4.1.8). The exception is the surface of the compacted soil where there is no difference between the 2 dates. In all cases except the No-Till (Zero-Till) in April (4) and the compaction in August (8), "S" decreases with depth. With the two exceptions, there is no discernible change with depth.

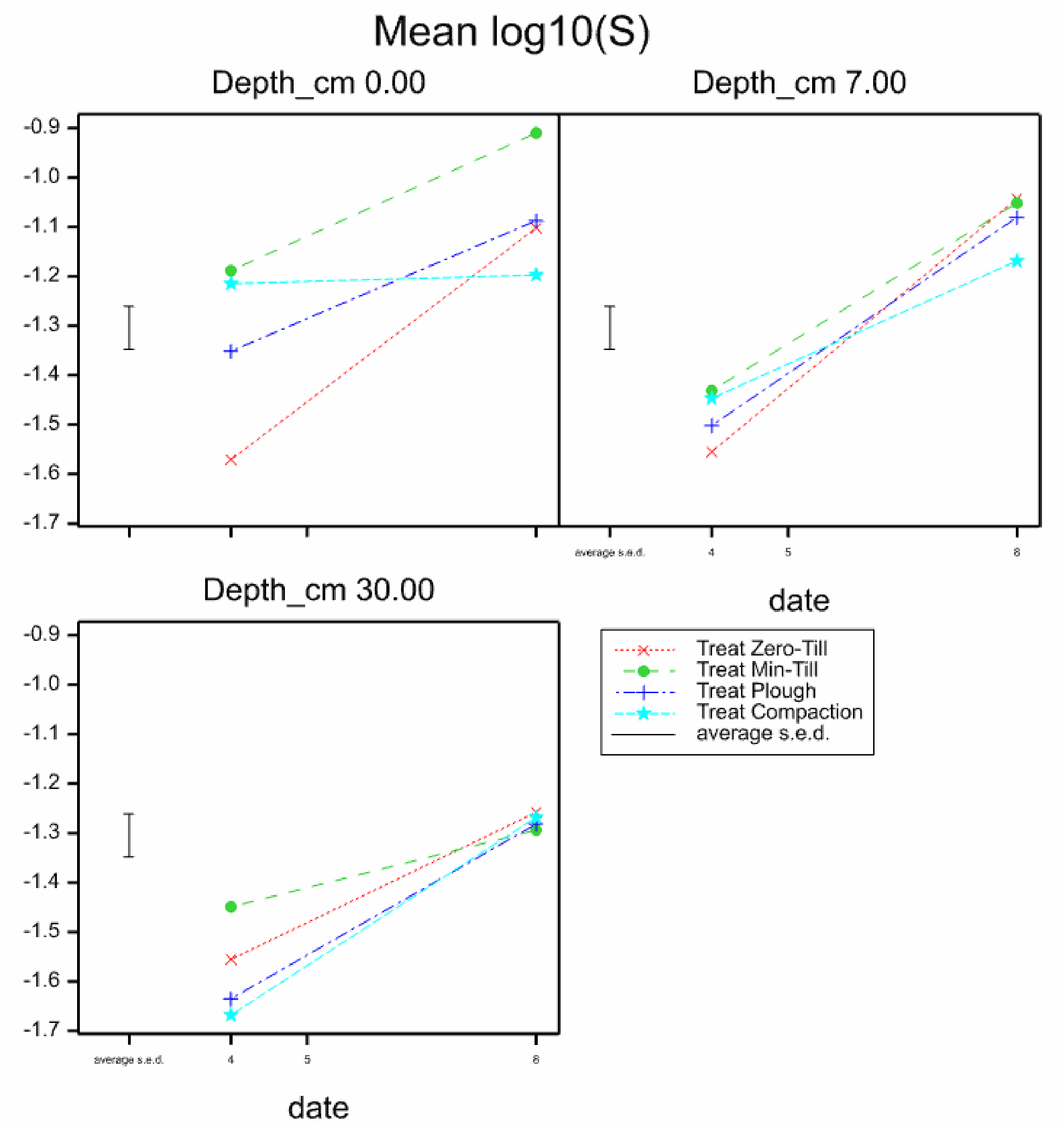


Figure 4.1.8: log transformed "S" soil quality index in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in Mid-Pilmore. Greater values of "S" indicate more heterogeneity of aggregate and pore sizes within the soil.

The "S" values for Min-Till (non-inversion) are consistently as good or greater than the other treatments, indicating better soil quality by this measure. At 7 cm, and at 30 cm in August there is no distinguishable differences between the treatments. At 30cm in April the No-Till (Zero-Till) and the Min-Till have higher S values than plough or compaction. However the results from the surface are more complicated. In April Min-Till and compaction have the largest "S" values with the No-Till (Zero-Till) the lowest. In August minimum till does best followed by plough and Zero-till because these "S" values have all increased, whilst compaction has not changed and is lowest.

4.1.3. Mid-Pilmore Soil Stability – WSA 2 mm and 0.25 mm

For WSA 2 mm from soil sampled at the surface of Mid-Pilmore both date and treatment are statistically significant as is the interaction between them (Figure 4.1.9). With the exception of the ploughed soil all treatments show large increases between April (4) and May (5) and further increases by August (8). The slight decrease between April (4) and May (5) for the plough treatment is marginal and is followed by a large increase by August (8).

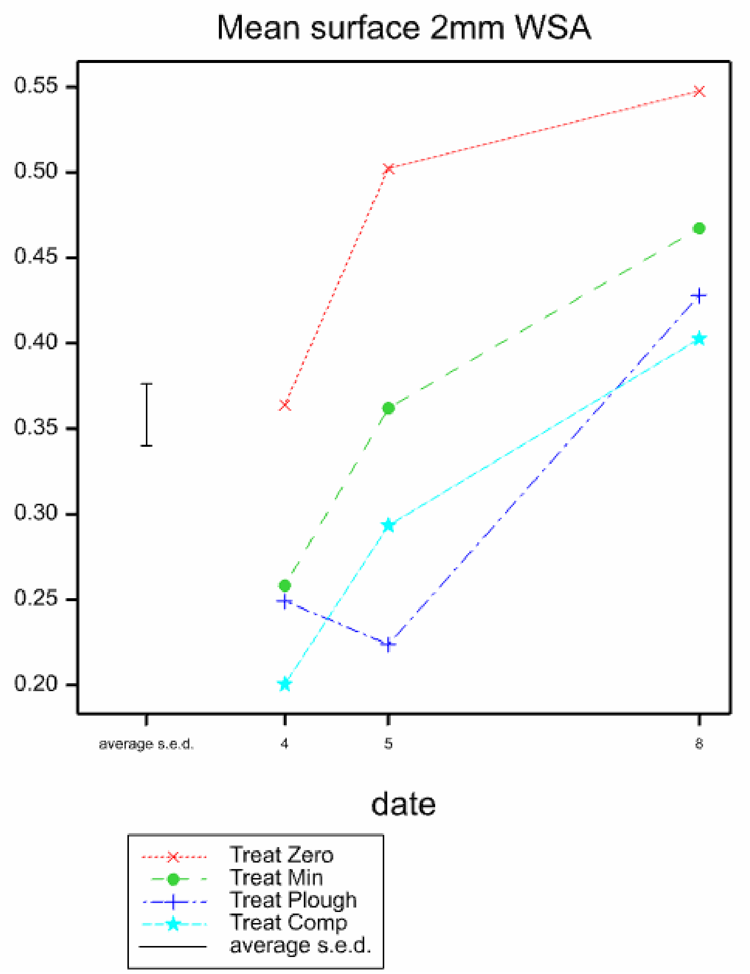


Figure 4.1.9: the percentage of stable soil > 2 mm from the surface of Mid-Pilmore for three dates April (4), May (5) and August (8) for the different tillage treatments.

For the depth response of soil stability (WSA > 2 mm) there are two significant two-way interactions; tillage x depth and depth x date, but tillage x date is not significant nor is there are significant three way interaction (Figure 4.1.10 a,b). Soil stability is always greater in August, but decreases with depth whilst it increases with depth in April. Separating WSA by tillage treatment (Figure 4.1.10b) shows that stability is greater at all depths with less soil disturbance, although the response to depth varies between the No-till (Zero) and the non-inversion Min-Till with no difference at 30 cm. The ploughed treatment (Plough) becomes less stable with depth while the compaction treatment becomes marginally more stable with depth.

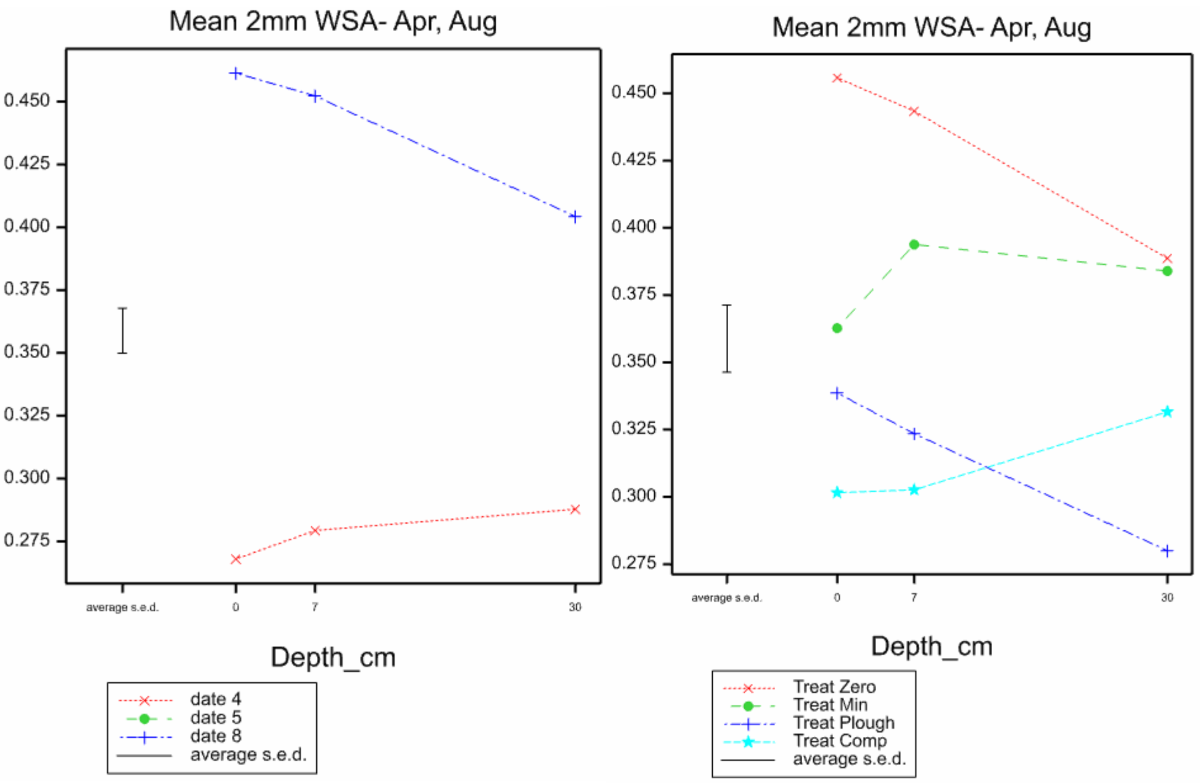


Figure 4.1.10 a,b: the percentage of stable soil > 2mm from Mid-Pilmore with a) showing the combined data from all tillage treatments by depth for April (4) and August (8), and b) for the three dates April (4), May (5) and August (8) for the different tillage treatments.

The WSA > 0.25 mm show no interaction between treatment and date, but as with WSA > 2 mm soil from the Zero-till (No-till) was most stable followed by soil from the Min-till. There was a decrease in stability in May (5) not only for the plough treatment as occurred for WSA > 2 mm but for all tillage treatments (Figure 4.1.11) followed by a recovery by August (8).

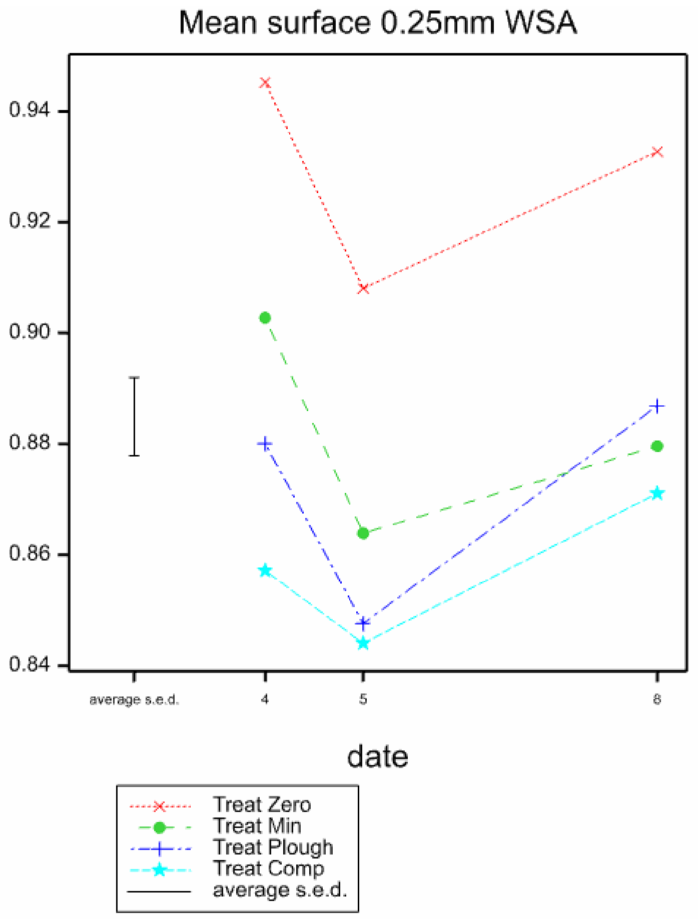


Figure 4.1.11 the percentage of stable soil > 0.25 mm from the surface of Mid-Pilmore on three dates April (4), May (5) and August (8) for the different tillage treatments.

For the depth response of soil stability (WSA > 0.25 mm), tillage x depth and depth x date were significant interactions. Figure 4.1.12a shows that in April (4) there is little difference in the soil stability with depth. Later in the year in August (8) the stability in the surface is not significantly changed but there is a marked decrease in stability at 7 cm depth and an even greater decrease in stability at 30 cm depth. Figure 4.1.12b for WSA > 0.25 mm shows a similar response to the data for WSA > 2 mm: at the surface (0 depth) the Zero-till (No-till) is most stable followed by the Min-Till and no discernible difference between Plough and Compaction treatments.

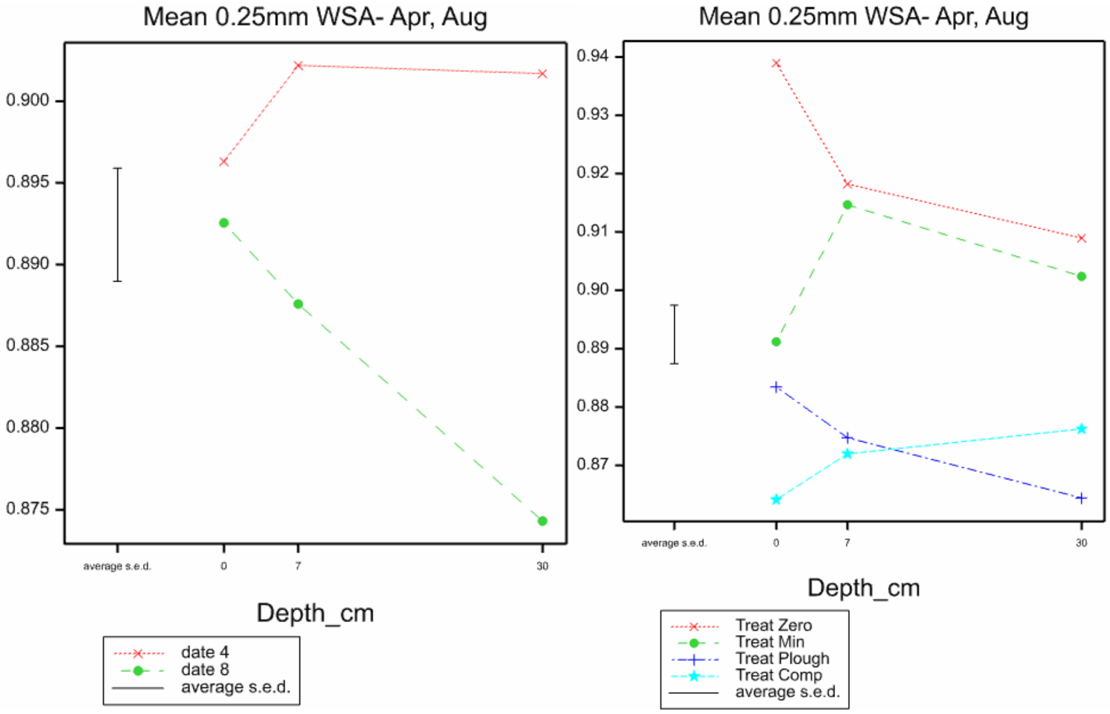


Figure 4.1.12 : the percentage of stable soil > 0.25 mm from Mid-Pilmore with a) showing all data by depth for April (4) and August (8); and b) for the three dates April (4), May (5) and August (8) for the different tillage treatments.

4.1.4. NFS Surface data – Bulk Density, EAW, LLWR, and S

For bulk density as with several other soil physical characteristics from the New Farming Systems (NFS) the statistical residuals were approximately normally distributed indicating there was no need to transform the data for analysis. The bulk density in the surface soil was not different in April (4) (Figure 4.1.13) and was decreased by tillage in all systems in May (5). There is a significant interaction date x tillage resulting from the different soil conditions in August (8) with the ploughed system having greater bulk density than both non-inversion systems.

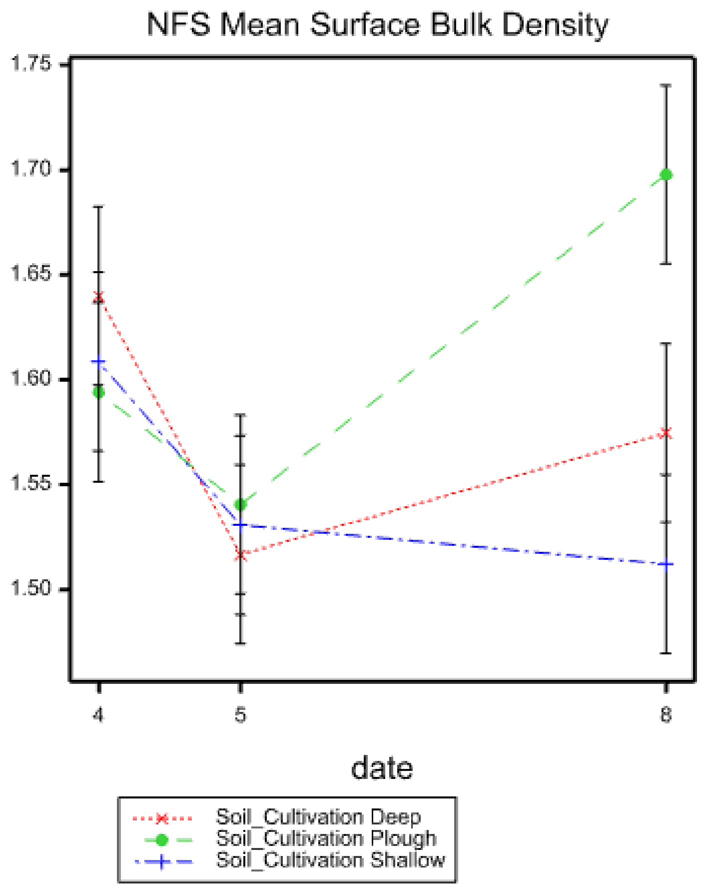


Figure 4.1.13: the mean surface bulk density (mass of soil per unit volume) on three dates April (4), May (5) and August (8) for the different tillage treatments in the New Farming Systems.

Easily Available Water (EAW) of the surface soil from NFS (Figure 4.1.14) shows no difference between tillage treatments on any date. EAW significantly increased between April (4) and May (5) with then only minor (not significant) changes at harvest in August (8).

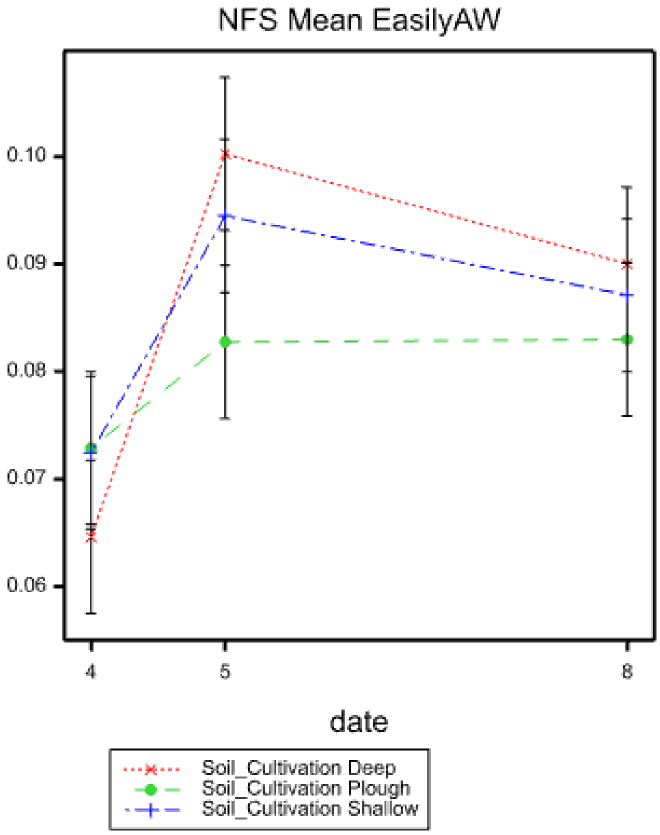


Figure 4.1.14: the mean surface Easily Available Water on three dates April (4), May (5) and August (8) for the different tillage treatments in the New Farming Systems.

For the least limiting water range (LLWR) of the surface soil from NFS there was a time but not a tillage effect. Figure 4.1.15 shows all treatments had similar values in April (4) and these increased with tillage by May (5). While the LLWR decreases in all treatments by August (8) the change is greatest for the ploughed treatment creating a significant two way intereaction of treatment x time.

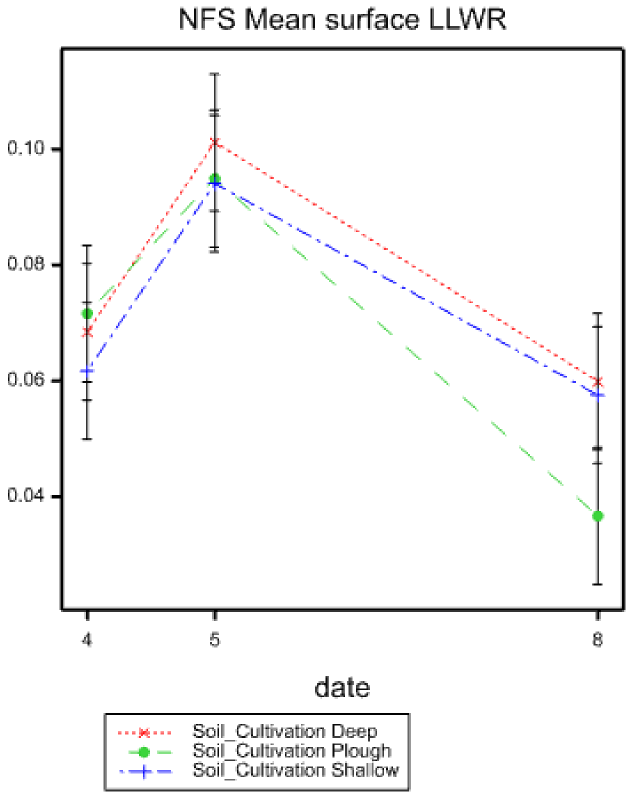


Figure 4.1.15: the mean surface least limiting water range (LLWR) on three dates April (4), May (5) and August (8) for the different tillage treatments in the New Farming Systems.

The index “S” was the one soil physical character from NFS that needed to be log transformed for statistical analysis. However the pattern of the results (Figure 4.1.16) is consistent with the other properties in that the initial states are very similar at the start of the season in April (4), show a similar increase response to tillage by May (5) and a decrease by August (8). The decrease in the ploughed treatment is greatest creating a significant tillage x date interaction.

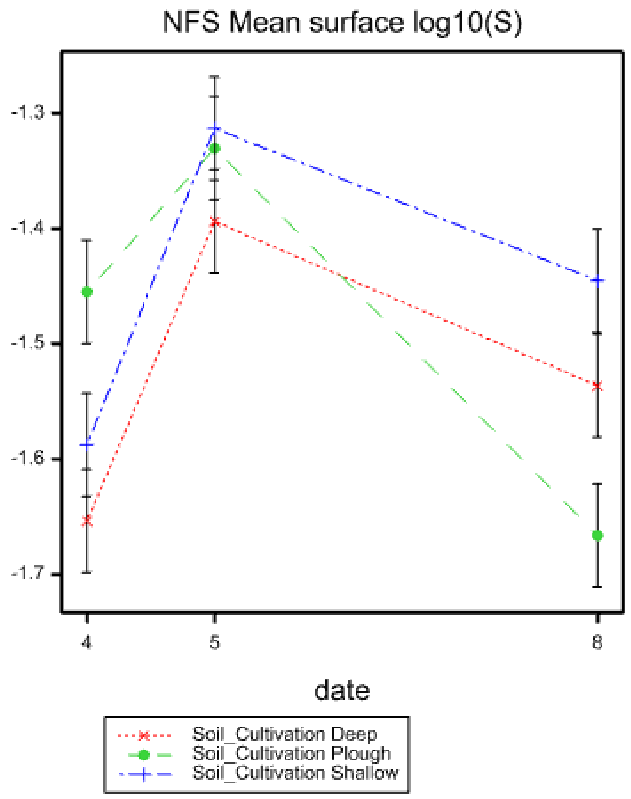


Figure 4.1.16: the log transformed mean "S" values on three dates April (4), May (5) and August (8) for the different tillage treatments in the New Farming Systems. Greater values of "S" indicate more heterogeneity of aggregate and pore sizes within the soil.

4.1.5. NFS Depth data – Bulk Density, EAW, LLWR, and S

Transformation of the data was needed only for the "S" soil quality index. For bulk density tillage was not by itself a significant factor, but date and depth were. There was also a significant two way interaction between date (April (4) and August (8)) and depth. Figure 4.1.7 shows the responses for each of the tillage systems. Apart from the surface soil of the plough treatment the bulk density is less after harvest than the initial condition.

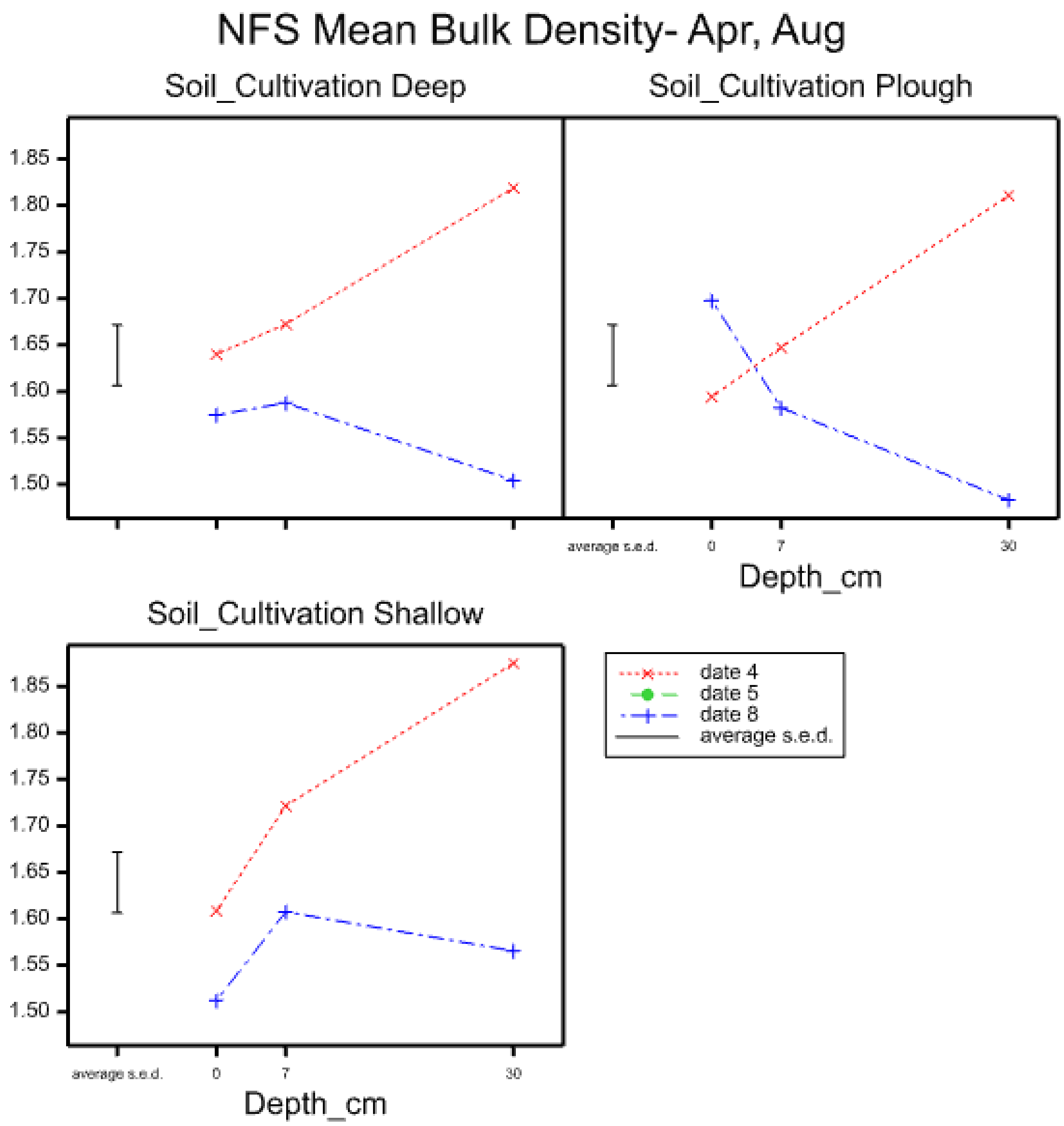


Figure 4.1.17: the mean bulk density in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in the New Farming Systems.

Similar to bulk density there was no direct significant tillage effect on (EAW) Easily Available Water (Figure 4.1.18). Date and depth were significant effects and there were significant two way interactions between tillage x depth and date x depth and a significant three way interaction tillage x depth x date. The noticeable rebound in EAW at 30 cm depth in the plough treatment may indicate some recovery from compaction associated with the plough passing just above that depth in April.

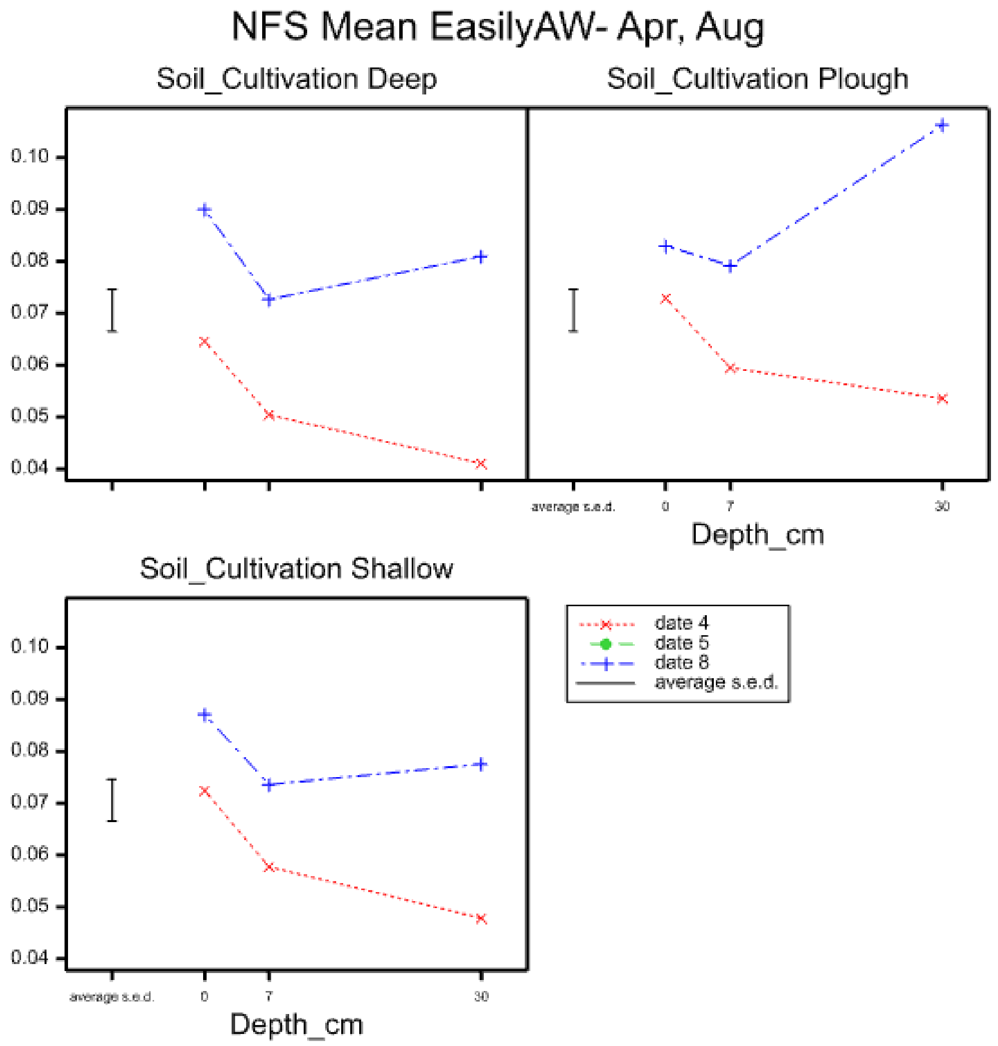


Figure 4.1.18: the mean Easily Available Water (EAW) in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in the New Farming Systems.

As with the other soil physical indexes there was no direct, significant tillage effect on LLWR for soil in the NFS experiment (Figure 4.1.19). Unlike the other indexes there was only a trend (P = 0.06) for date to significantly affect LLWR. Depth and the two way interaction depth x date were significant factors for LLWR. As with bulk density and EAW the LLWR index is generally better (in suitability for root proliferation) at harvest than soon after planting.

The mean values for the LLWR (grand mean 0.05) are of similar magnitude but slightly less than the value of EAW (grand mean 0.08). The drier limit for EAW is at 300kPa matric suction. That the overall LLWR is less than the overall EAW is strong evidence that even when the soil contains water that should be available to the plant the soil strength is sufficient to prevent roots elongating into that soil.

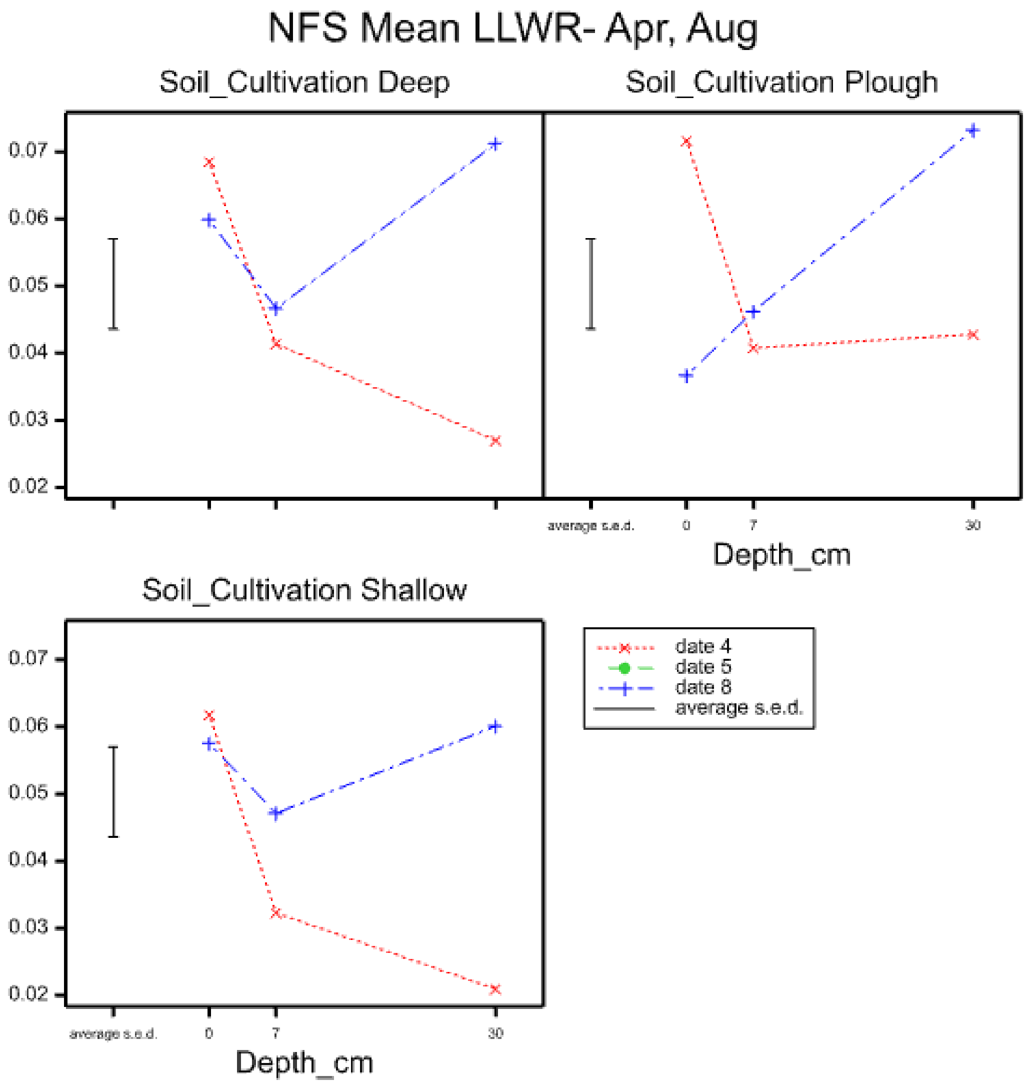


Figure 4.1.19: the mean Least Limiting Water Range (LLWR) in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in the New Farming Systems.

While tillage was not a significant effect on “S”, individually both date and depth were (Figure 4.1.20). The two way interaction date x depth and the three way interaction tillage x date x depth were also significant. Apart from the surface soil of the ploughed treatment the “S” values were greater after harvest than soon after planting. While no cause and effect is attributable, the improvement in conditions throughout the year is possibly associated with the presence of an active root system at the end of the season which was not present in April for spring sown crops.

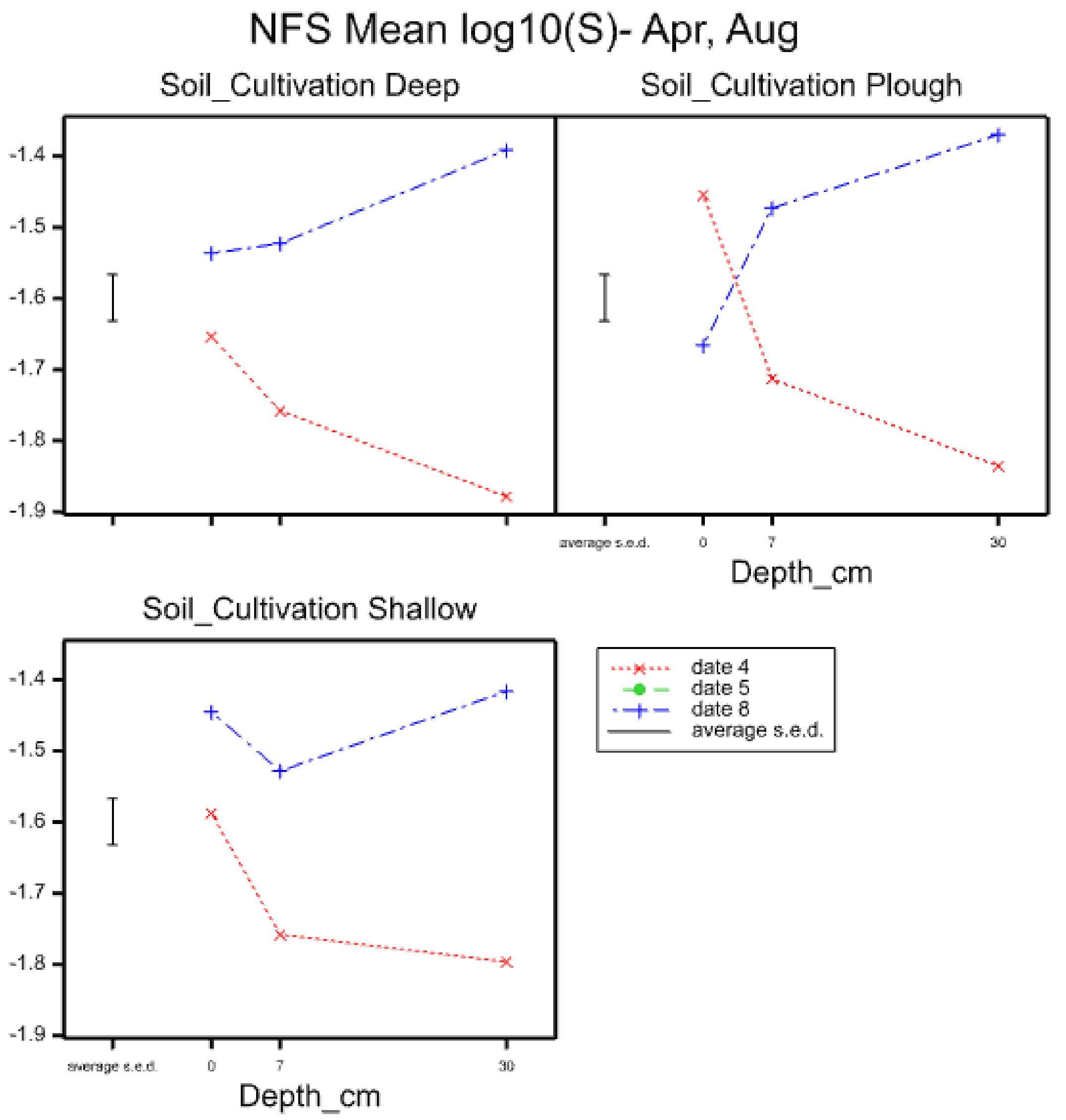


Figure 4.1.20: the mean log transformed “S” in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in the New Farming Systems.

4.1.6. STAR Surface data – Bulk Density, EAW, LLWR, and S

For soil physical quality data from the STAR site it was possible to conduct the statistical analysis on all the indexes, apart from "S" without needing to transform the data. There are no significant differences in bulk density of the surface soil in the STAR experiment (Figure 4.1.21).

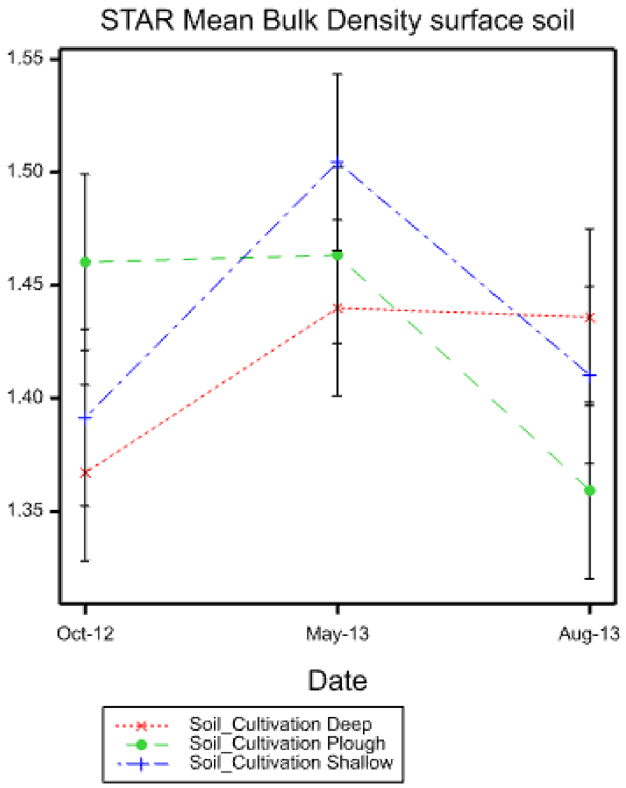


Figure 4.1.21: the mean surface bulk density (mass of soil per unit volume) on three dates October 2012, May 2013 and August 2013 for the different tillage treatments in the STAR experiment.

The results for Easily Available Water (EAW) show a non-significant trend (P = 0.079) for the plough treatment to have a lower EAW driven by the conditions soon after sowing (Figure 4.1.22). There is both a significant difference with time of sampling and a significant interaction between tillage and sampling date. Similar to the NFS experiment EAW was generally highest soon after sowing, decreased during early crop growth and showed some variable recovery at harvest.

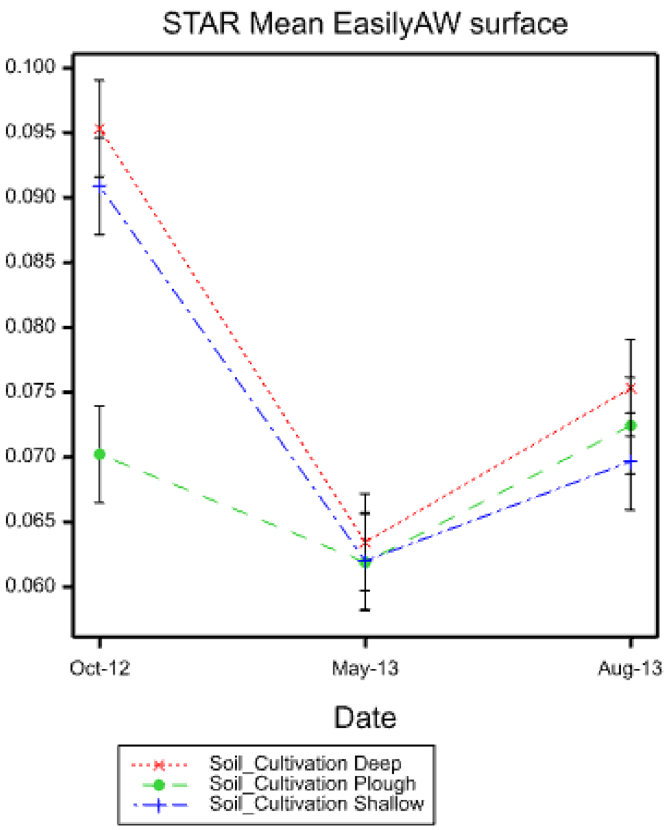


Figure 4.1.22: the mean Easily Available Water on three dates October 2012, May 2013 and August 2013 for the different tillage treatments in the STAR experiment.

The results for the LLWR of the surface soil shown in Figure 4.1.23 have a similar pattern to those for EAW in that there is a significant date effect ($P < 0.001$) with decrease from the initial state and then a trend ($P = 0.076$) for a small, variable rebound by harvest.

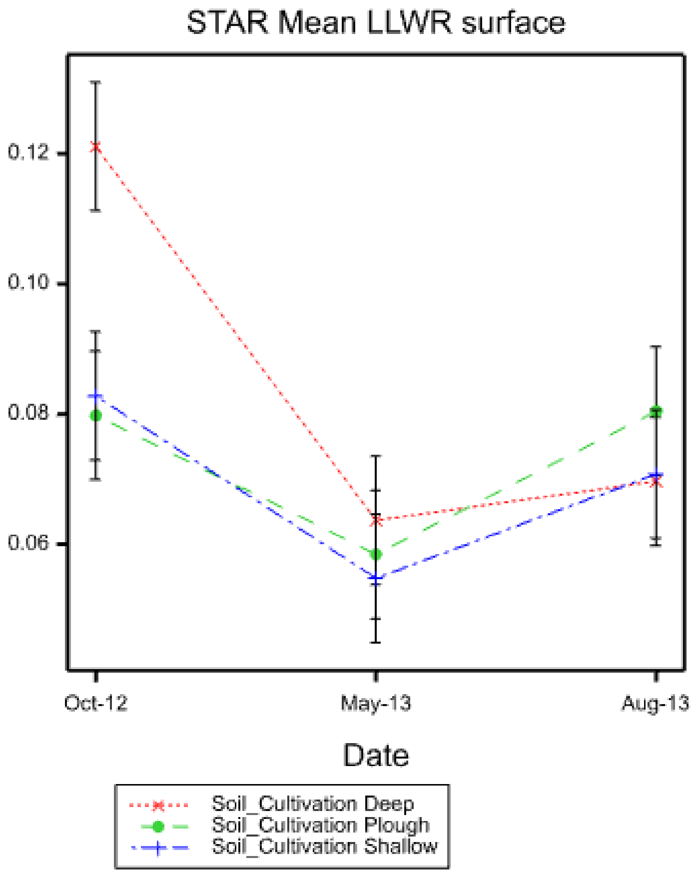


Figure 4.1.23: the mean least limiting water range (LLWR) on three dates October 2012, May 2013 and August 2013 for the different tillage treatments in the STAR experiment.

The results for “S” of the surface soil shown in Figure 4.1.24 are not different for tillage treatment and there is no tillage by date interaction. There is a significant response to date, however it is only the plough treatment that shows an increase in “S” from the initial value (i.e. the “S” values for the non-inversion treatments remain unchanged through the season). The increase in “S” for the plough treatment is opposite to the result for the NFS platform where surface soil had the greatest “S” values in May and then decreased. STAR is a winter rotation and so the increase may be associated with recovery after winter although why this did not happen for the non-inversion treatments remains unclear.

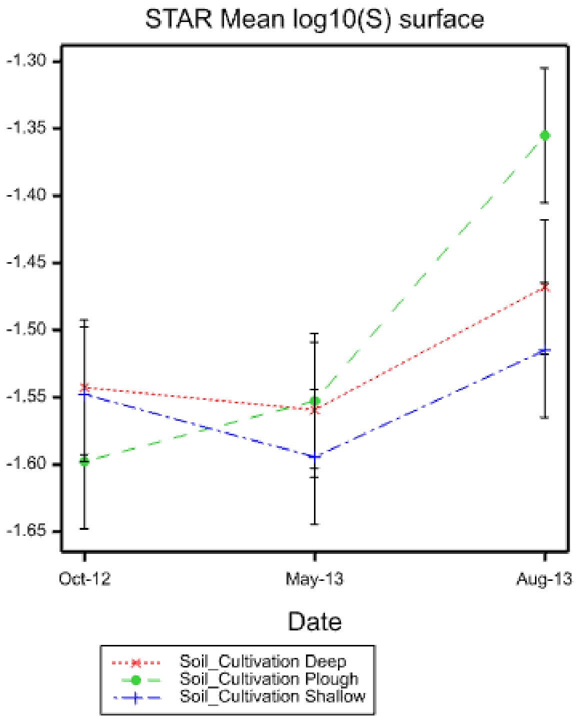


Figure 4.1.24: the mean “S” on three dates October 2012, May 2013 and August 2013 for the different tillage treatments in the STAR experiment.

4.1.7. STAR Depth data – Bulk Density, EAW, LLWR, and S

There was no significant overall effect of tillage on bulk density for the STAR experiment (Figure 4.1.25). There was a significant effect of date and of depth and a significant two-way interaction between date and depth. The final bulk densities for each depth are not different between treatments. Soil bulk density increases with depth in the profile. The interaction between date and depth is a result of rebound in the subsoil for all treatments (i.e. a decrease in bulk density).

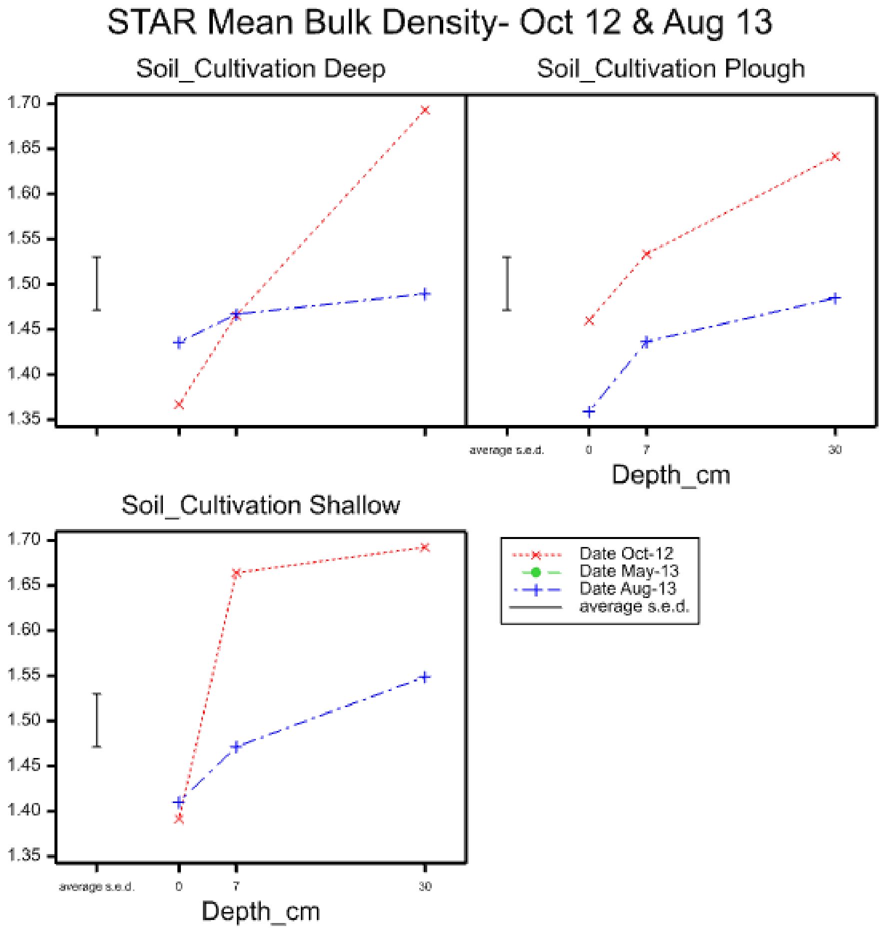


Figure 4.1.25: the bulk density values in October 2012, May 2013 and August 2013 for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in the STAR experiment.

For EAW in the STAR experiment (Figure 4.1.26) the soil responses to imposed treatments are generally consistent with other indexes and the other experiments. There is no statistically significant effect of tillage but there are effects of date and depth and several interactions. The interactions include two way interactions tillage x depth and date x depth and a significant three way interaction tillage x date x depth. While the evidence is not direct, it is worth noting that unlike the spring cropped systems (i.e. Mid-Pilmore and NFS) the surface soil at sowing in the deep and shallow non-inversion tillage had greater EAW values than later at harvest and the values in the surface of the ploughed treatment were almost identical.

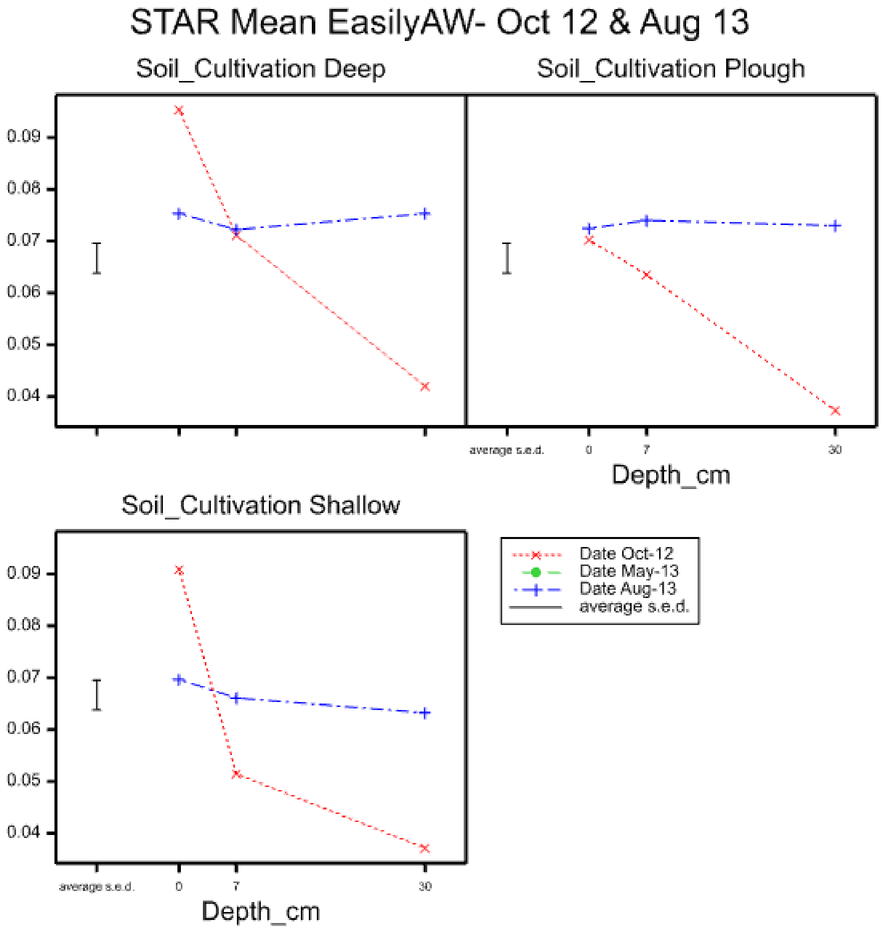


Figure 4.1.26: the log transformed Easily Available Water (EAW) values in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in the New Farming Systems.

For LLWR only depth and the two way interaction date x depth are significant (Figure 4.1.27). The magnitudes of the LLWR values (grand mean 0.064) are similar to the values for EAW (grand mean 0.067). As with other sites this indicates that at a matric suction of 300 kPa, despite the soil still holding water that should be available to the crops, the soil is sufficiently hard to restrict root proliferation. At 30 cm depth irrespective of tillage treatment the soil will impede root proliferation unless the soil is at near optimal water conditions i.e. close to field capacity.

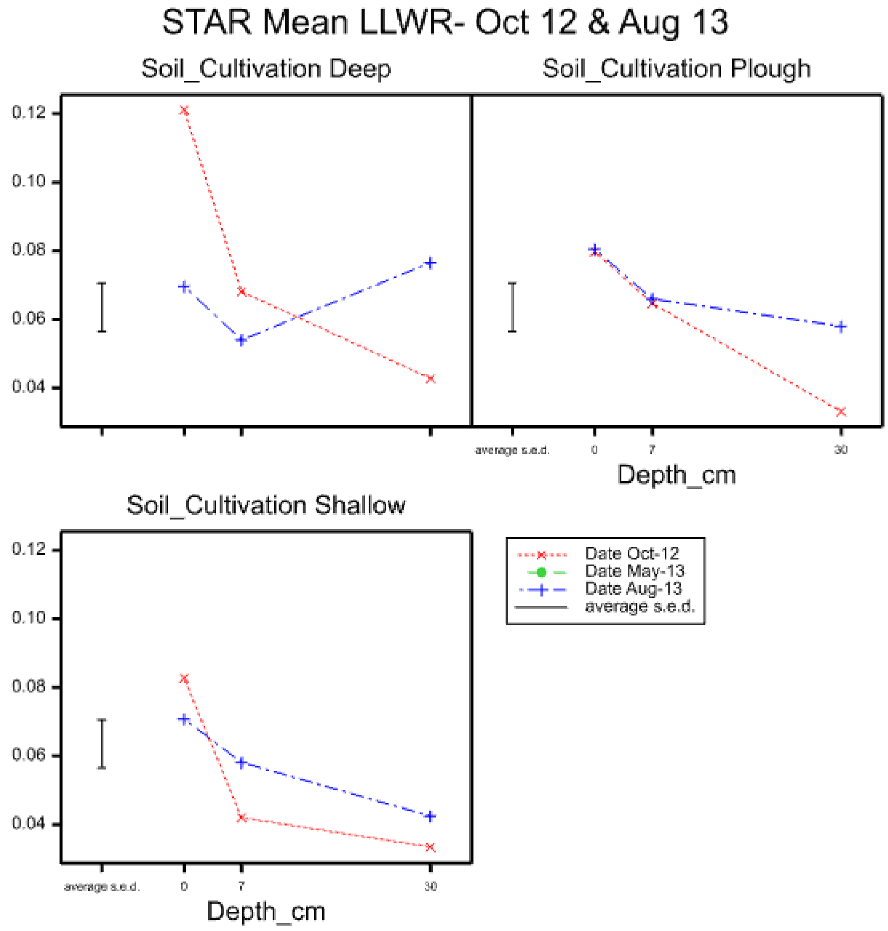


Figure 4.1.27: the LLWR soil quality index in April (4) and August (8) for all sampling depths (0, 7 and 30 cm). Data are for the different tillage treatments in the New Farming Systems.

The grand mean of the log values of “S” for the STAR soils is -1.606. Taking the antilog of -1.606 gives an “S” value of 0.0245. While clay soils tend to have lower “S” values than loams or sandy-loam soils Dexter (2004) suggested a boundary of around 0.035 between soils of good and poor structural state. Further he identified soils with “S” < 0.02 (i.e. log values more negative than -1.7) as being associated with very poor soil physical condition. Consistent with other soil physical indexes the statistical analysis again shows no effect of tillage but an effect of date, depth and a two way interaction date x depth (Figure 4.1.28). Clearly there is improvement in the “S” values throughout the growing season and that the soil nearer the surface is in better condition than at depth.

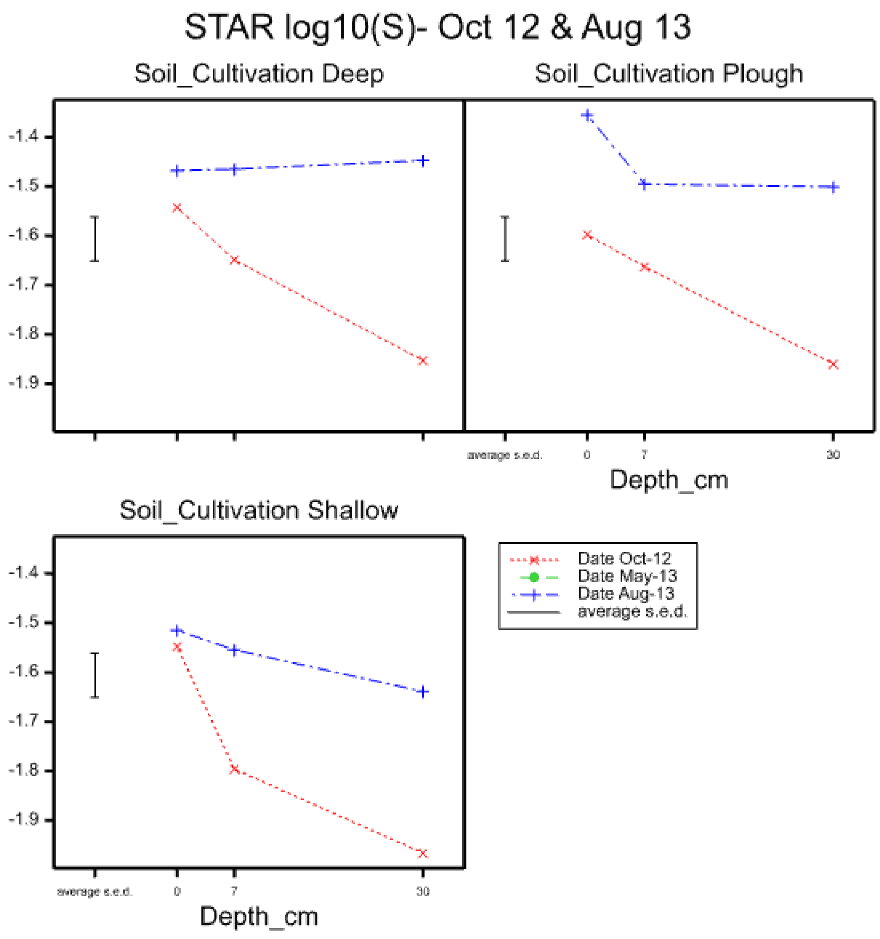


Figure 4.1.28: the log transformed "S" soil quality index in April (4) and August (8) for each of the sampling depths (0, 7 and 30 cm) for the different tillage treatments in Mid-Pilmore.

4.1.8. STAR Soil Stability – WSA 2 mm and 0.25 mm

For the STAR platform we were able to take and analyse multiple samples for aggregate stability (WSA). Samples were collected from three depths (i.e. surface, 7 cm and 30 cm) in October 2012, August 2013, April 2014, October 2014, March 2015, August 2015 and October 2015. In addition samples were collected from the surface only in May 2013 and September 2013. Samples were analysed for WSA > 2 mm and > 0.25 mm as described in section 3.1. Data were statistically analysed using a linear mixed model with tillage, depth and date treated as fixed factors.

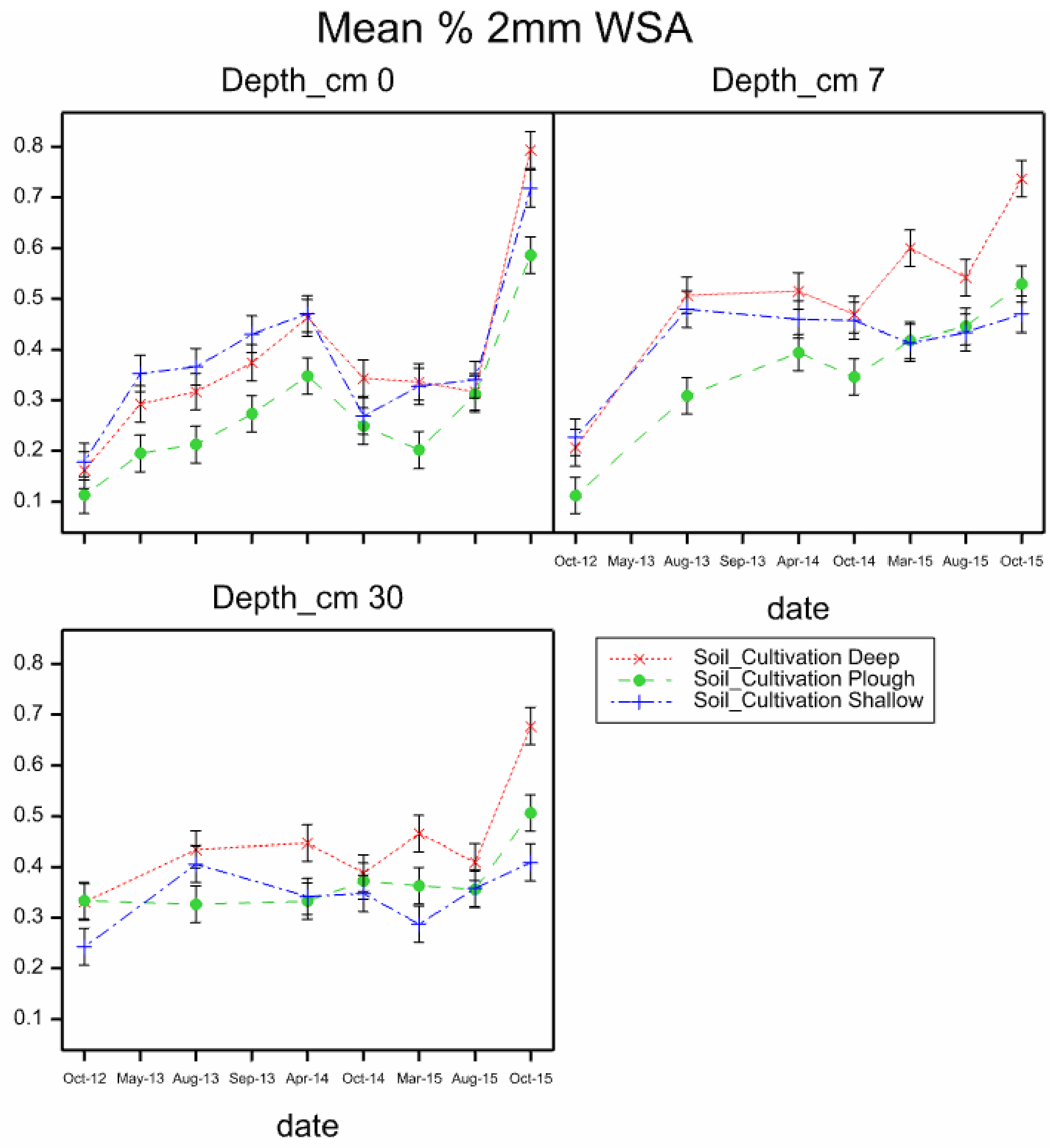


Figure 4.1.29 the percentage of stable soil > 2 mm from each of the three depths of the STAR platform for the three tillage treatments by date of sampling.

Across all depths tillage, date and depth were all significant as were the three two-way interactions for both > 2 mm and > 0.25 mm (Figure 4.1.29 and 4.1.30). The three way interaction tillage x date x depth was not significant. As expected, there is a strong positive correlation between the two sieve sizes.

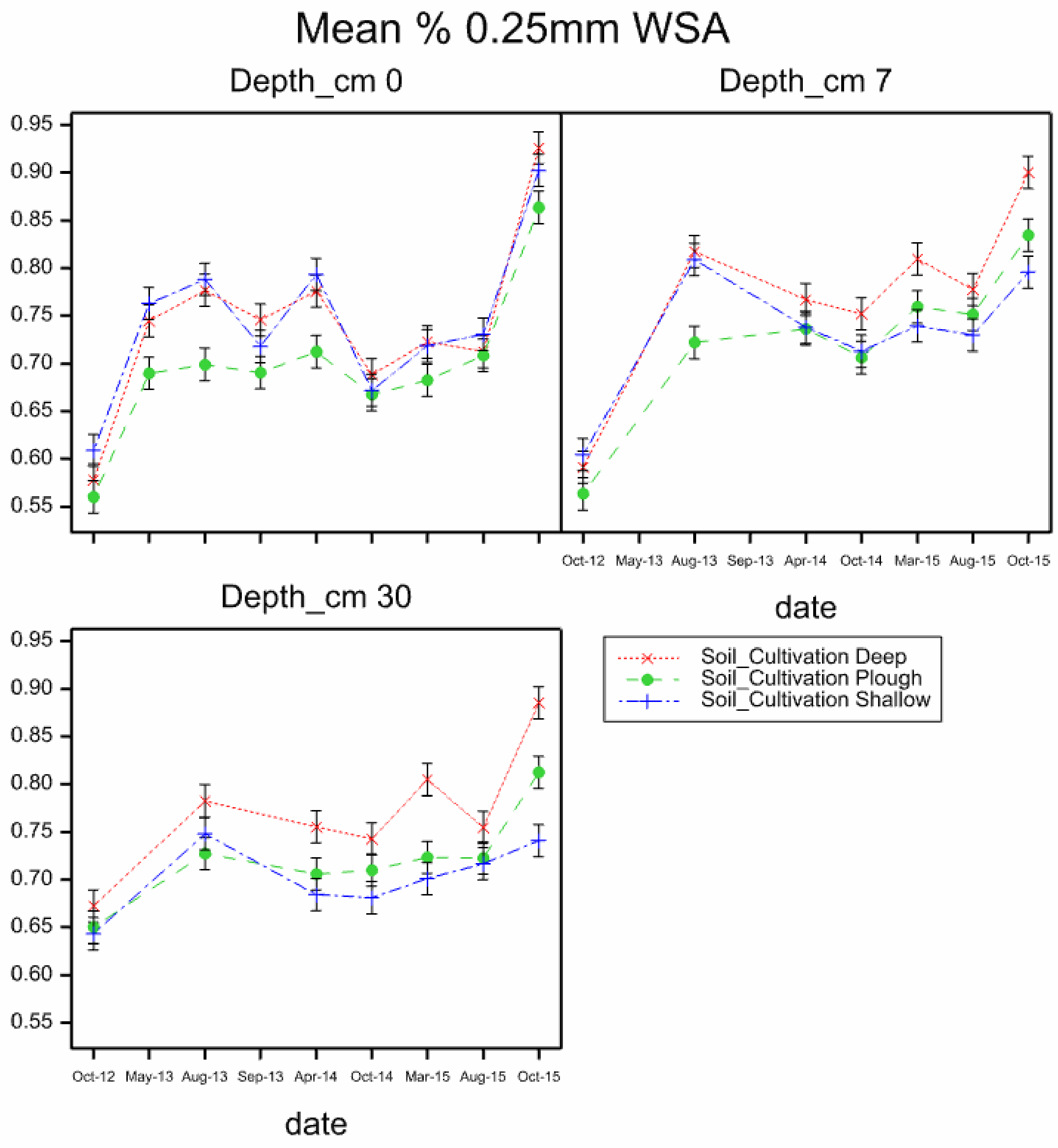


Figure 4.1.30 the percentage of stable soil > 0.25 mm from each of the three depths of the STAR platform for the three tillage treatments by date of sampling.

At the surface, soil from the ploughing treatment is consistently less stable than either non-inversion cultivations. This is not the case at 7 cm or at 30 cm depth. For the WSA > 0.25 mm assay at 7 cm ploughing creates less stable soil in October 2012 and August 2013 but from April 2014 onwards ploughing and shallow non-inversion are indistinguishable, whilst the deep non-inversion has more stable soil. At 30 cm depth, soil from the deep non-inversion cultivation is consistently more stable. For WSA > 2 mm the trends are the same but shallow non-inversion remains similar to deep non-inversion at 7 cm depth until October 2014 then becomes similar to the ploughed soil in March 2015. At no stage is there evidence of within season trends. The very low stability in October 2012 and the high stability in October 2015 are less evident as the depths become deeper. The winter of 2012-13 is generally regarded as difficult for farm operations. In Dundee it was in the wettest decile for the 52 years recorded. Long periods of wet or water logged conditions are detrimental to soil structure and stability (White 1987). It is possible that the changes in soil stability documented here are a gradual recovery following waterlogging. A future opportunity may be to test options to increase the rate of recovery in soil stability following waterlogging.

4.2. Soil Resilience

Based on physical characterisation of the intact soil cores described in Section 3.1, we selected the simplest physical measurements possible to describe the resistance and resilience properties. This is to allow for easier interpretation by a wide range of end-users. For the slumping test air filled porosity was used. This allowed for a direct comparison to the critical cut-off of 0.10 m^3 m^{-3} air filled porosity often used in LLWR assessment as a critical threshold for hypoxia risk. The compression test resulted in a large decrease in soil porosity, with water exuded from many samples at 200 kPa. This prevented using air filled porosity because values were often negative and water loss during compression introduced error. Compression was therefore described by the soil porosity.

4.2.1. Slumping Resilience

Figure 4.2.1a and 4.2.1b illustrate the slumping resilience at different times for the four different experimental platforms used in this project.

Whereas all treatments of Pilmore and CSC Balruddery retained an air-filled porosity >0.10 m^3 m^{-3} following the slumping stress, NFS dropped below this threshold. Both shallow and deep non-inversion tillage resulted in recovery above this threshold, whereas plough recovered less. In Mid-Pilmore, Zero-till was much more resistant to slumping than the other treatments ($P<0.05$). This soil was not responsive to recovery through cycles of wetting and drying, with the pore structure further degrading for the ploughed soil ($P<0.001$). CSC Balruddery only recovered through cycles of wetting and drying for the Sustainable field in 2014 ($P<0.01$). Although CSC Balruddery between the two sampling years had statistically different results ($P<0.05$), differences were within 0.03 m^3 m^{-3} porosity for Slumped and Recovery.

More marked differences between sampling times were found for STAR. The tillage system used did not influence the slumping or recovery of soils from this site. However, between sampling dates the initial conditions varied markedly, and the air-filled porosity following slumping and recovery varied from 0.10 to 0.28 m^3 m^{-3}.

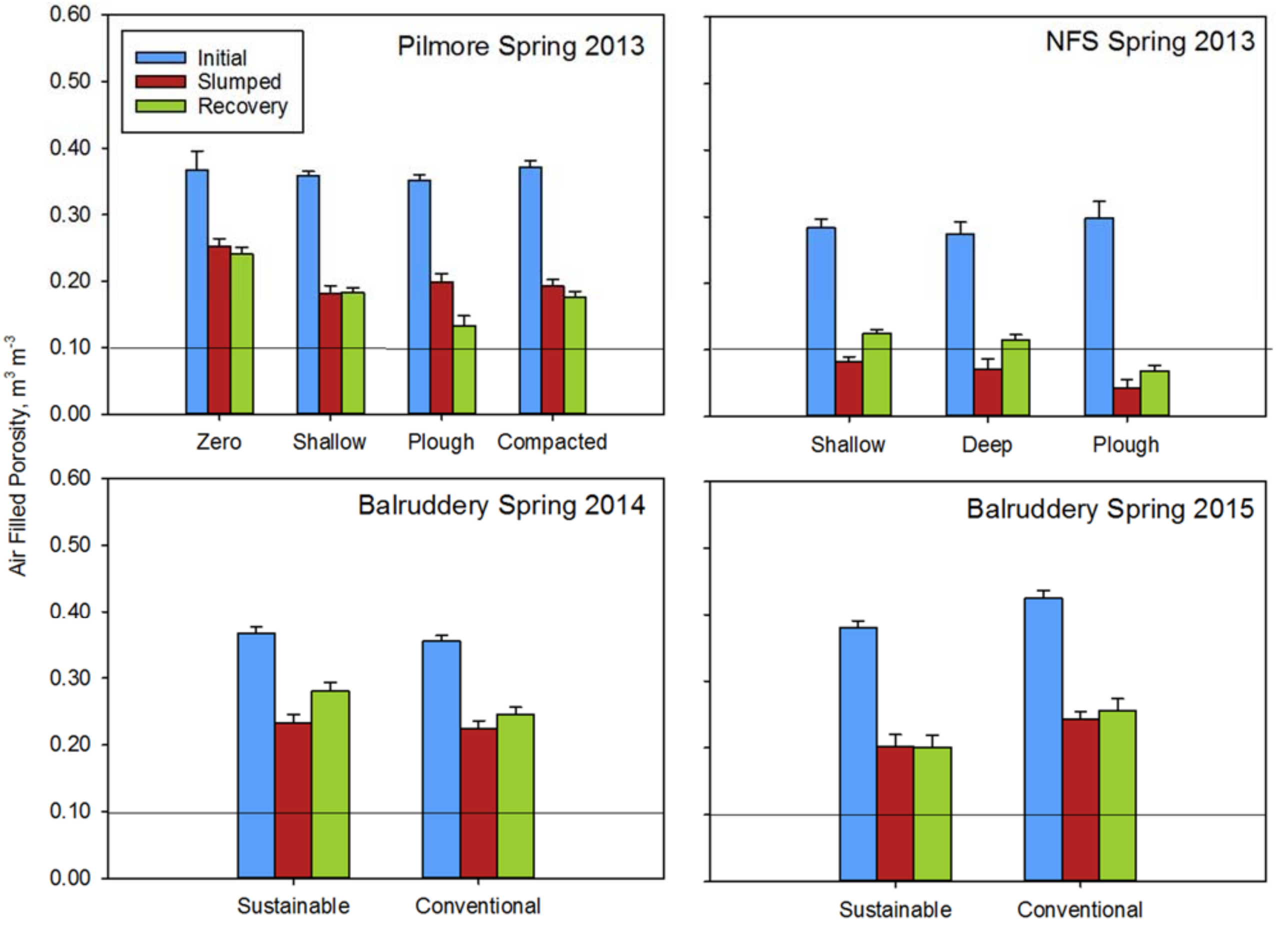


Figure 4.2.1a: Slumping and recovery of surface soil. Shallow and Deep refer to non-inversion tillage depths. Zero refers to zero-tillage (No-Till). CSC Balruddery Sustainable is a combination of shallow non-inversion tillage and compost addition, whereas Conventional is ploughing to 20 cm with no compost added (See Table 2.2)

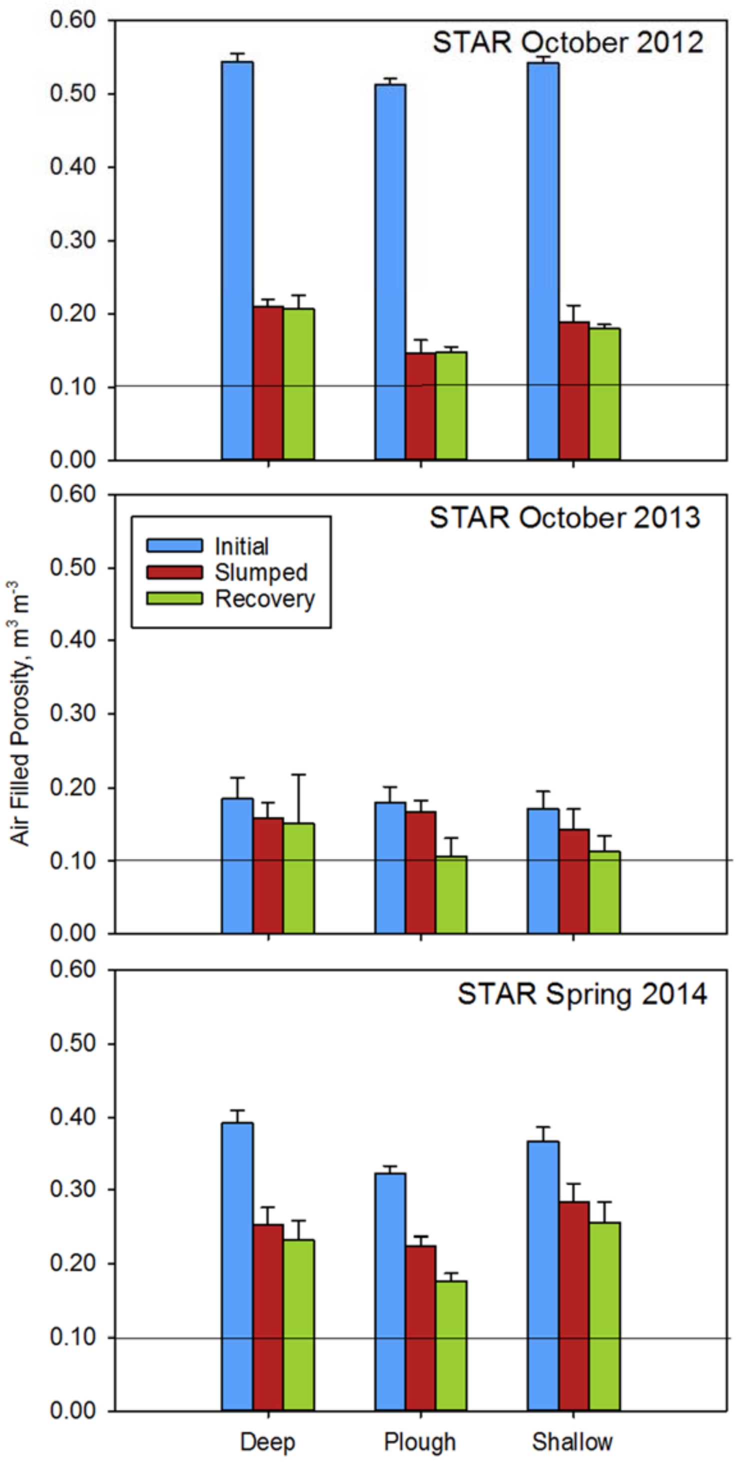


Figure 4.2.1b: Slumping and recovery of surface soil. Shallow and Deep refer to non-inversion tillage depths.

4.2.2. Compression Resilience

Figure 4.2.2a and 4.2.2b illustrate the compression resilience at different times for the four different experimental platforms used in this project. The wavy lines simulate the action of a roller at 50 kPa stress, followed by the action of a tractor at 200 kPa stress. When either of these stresses are removed, the soil bounces back slightly, recovering porosity. Between the stress of a roller and the stress of a tractor, >0.15 $m^3 m^{-3}$ can be lost, which was enough to fully fill pores with water so that no air was present for plant roots and microorganisms.

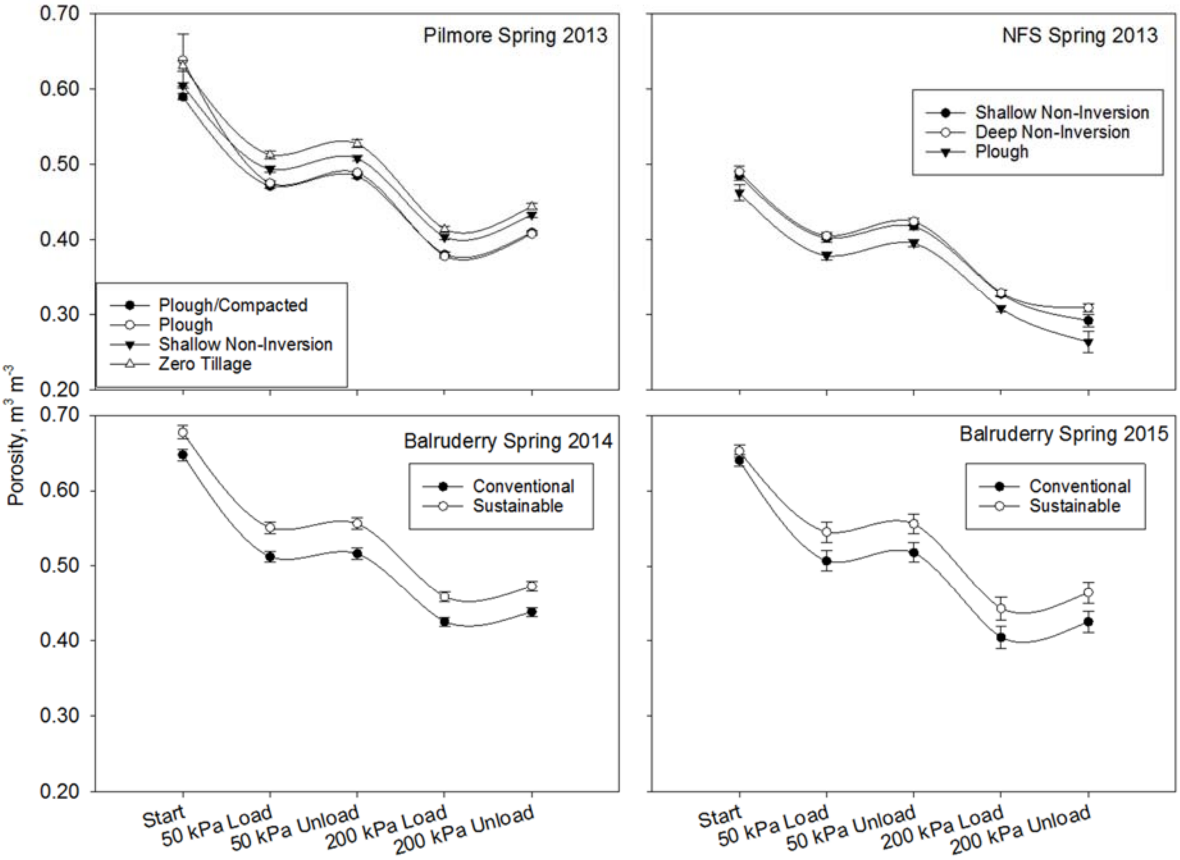


Figure 4.2.2a: Compression and rebound of surface soil for Mid-Pilmore, NFS and CSC Balruddery Platforms. CSC Balruddery Sustainable is a combination of shallow non-inversion tillage and compost addition, whereas Conventional is ploughing to 20 cm with no compost added.

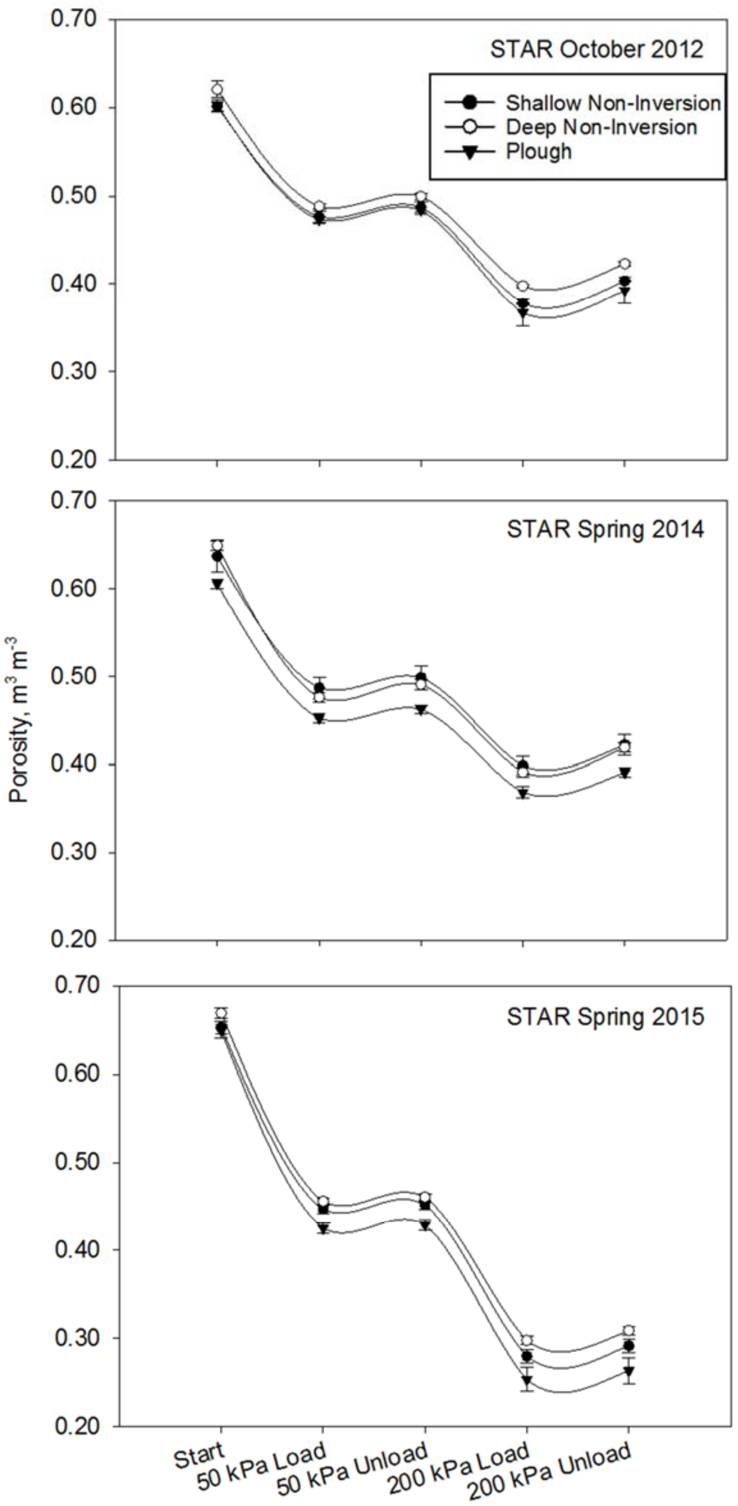


Figure 4.2.2b: Compression and rebound of surface soil for the STAR Platform at multiple dates

For Mid-Pilmore, NFS, CSC Balruddery and STAR in Spring 2014, non-inversion tillage resulted in greater resistance and resilience to compaction ($P<0.05$). As with the slumping tests, STAR varies between sampling times.

4.3. Soil Chemistry

4.3.1. pH

At the Mid-Pilmore site cultivation techniques had had a significant ($p<0.05$) main effect on pH at the start of the observation period in 2012 in that the compaction treatment with inversion was less acidic (pH 5.3) compared to non-inversion tillage treatments no-till and shallow non-inversion (both pH 5.1), plough treatments (pH 5.2) were between the two (Figure 4.3.1). By 2016 these main effects on pH had remained, but all treatments had a slightly increased pH, compaction (pH 5.5) and non-inversion tillage treatments (pH 5.3). At the beginning of the experiments pH also increased significantly ($p<0.001$) with depth, being more acidic at the surface 2-7cm (pH 4.8) and less so at 7-12cm (pH 5.3) and 25-30 cm (pH 5.5). Again this was maintained through to 2016 but all pH's were raised: 5.2 at 2-7cm, 5.3 at 7-12cm and 5.6 at 25-30cm (Figure 4.3.2).

When considering the interactions between treatment and depth at the start of the experiment it was apparent that the depth effect was more pronounced ($p<0.001$) in the non-inversion tillage treatments, No-till (4.5, 5.2, 5.6) and shallow non-inversion tillage (4.7, 5.1, 5.5) than in the plough treatments, compaction (5.1, 5.3, 5.3) and plough (5.0, 5.4, 5.3). This effect ($p<0.01$) was maintained through to the end of the experiment in 2016 (Figure 4.3.3).

At the STAR site at the start of the experimental period there were significant ($p<0.001$) differences in pH with depth, becoming more alkaline with depth: at the surface and at 7-12cm the pH was 6.1, whereas at 25-30cm it increased slightly to 6.4 (Figure 4.3.4). This difference ($p<0.001$) became more pronounced by the end of the observation period in 2016, with the surface becoming more acidic down to pH 5.8. There were no significant differences in the pH between tillage treatments at the start of the experiment in 2012 and none developed by the end of the observation period in 2016. Likewise there were no significant interactions between depth and treatment.

A similar set of results were found at NFS as observed at STAR. There were no significant effects of tillage treatment on pH throughout the experiment and no interactions between this and depth. However, there were statistically significant ($p<0.05$) differences with depth at the start of the observation period in that the surface pH (5.7) was more acidic than that at 30cm depth (5.8) (Figure 4.3.5) although these differences are likely to be insignificant from a practical perspective. This difference became more extreme ($p<0.001$) over the observation period such that in 2016 the pH at the surface (5.6) was significantly lower than at 7-12cm (pH

5.8) and at 25-30cm (pH 6.1). The surface soils had become more acidic and those at depth more alkaline.

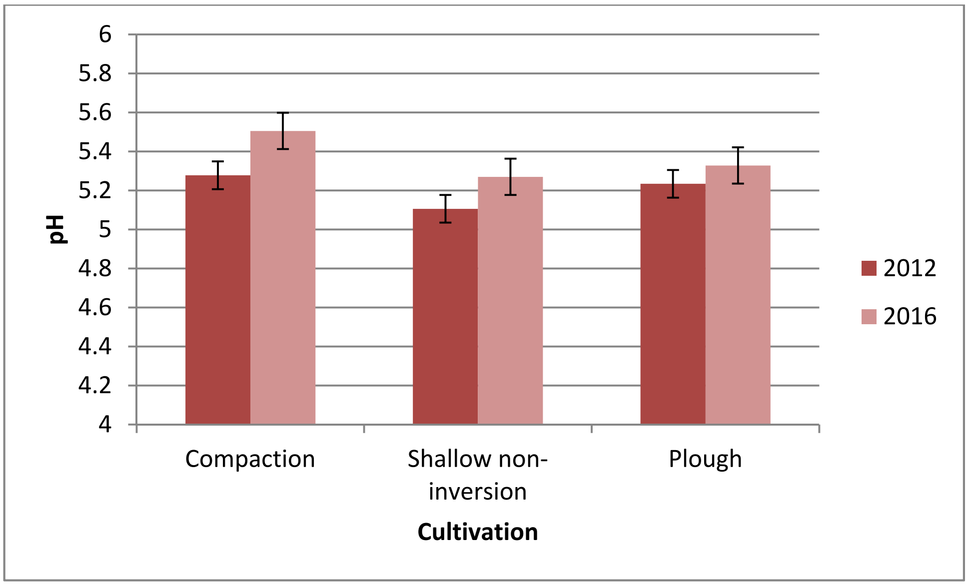


Figure 4.3.1 pH in soils taken from different tillage treatments (see Table 2.2) at the Mid-Pilmore site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates at 3 depths and the error bars represent the LSD.

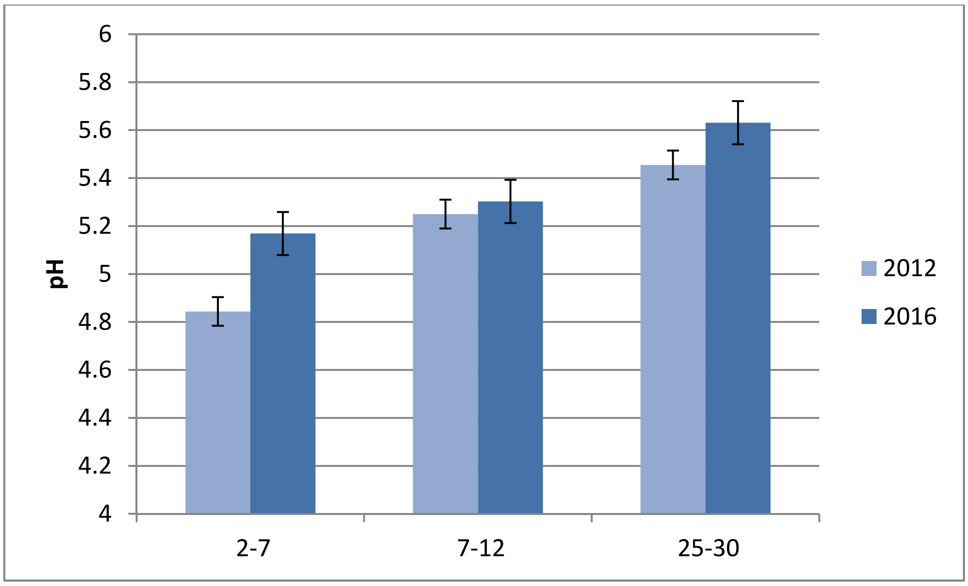


Figure 4.3.2 pH in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the Mid-Pilmore site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

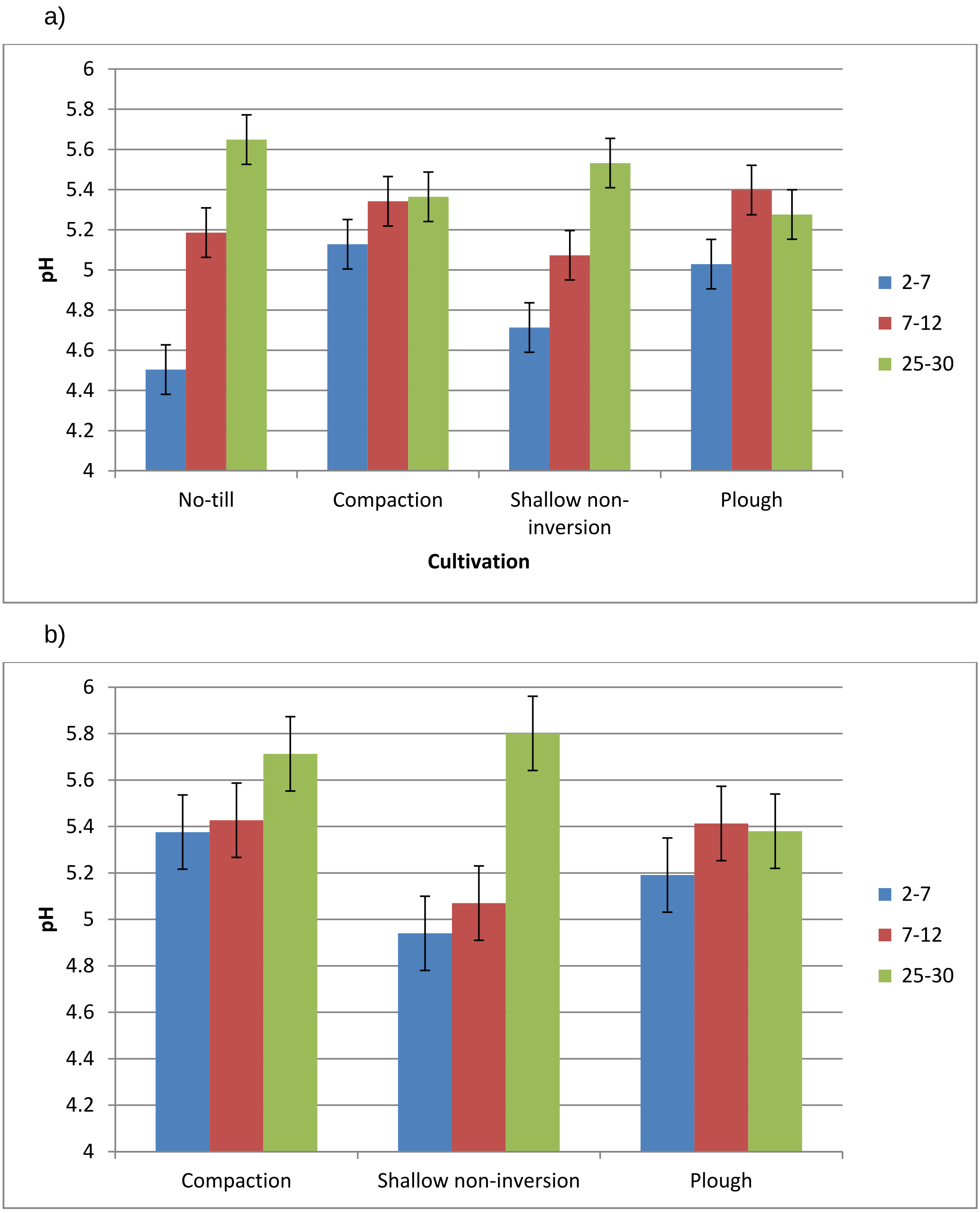


Figure 4.3.3 a,b: The interaction between depth and different tillage treatments with inversion (compaction and plough) and without inversion (No-till; shallow non-inversion) on pH at the Mid-Pilmore site a) in 2012 and b) in 2016 at the end of the observation period. Data represents the mean of 3 replicates and the error bars represent the LSD.

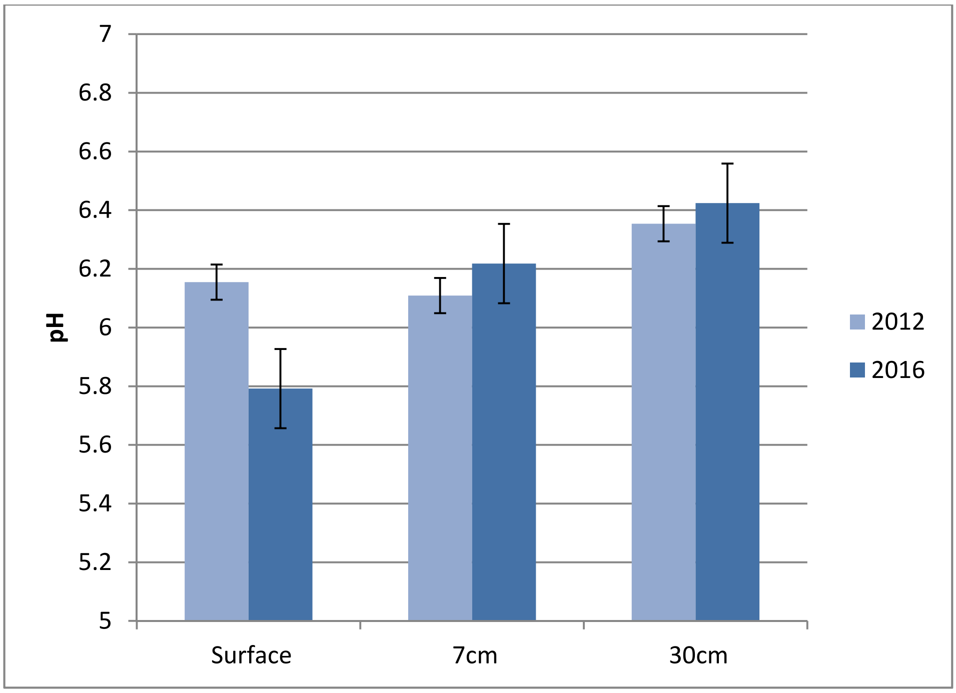


Figure 4.3.4 pH in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the STAR site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

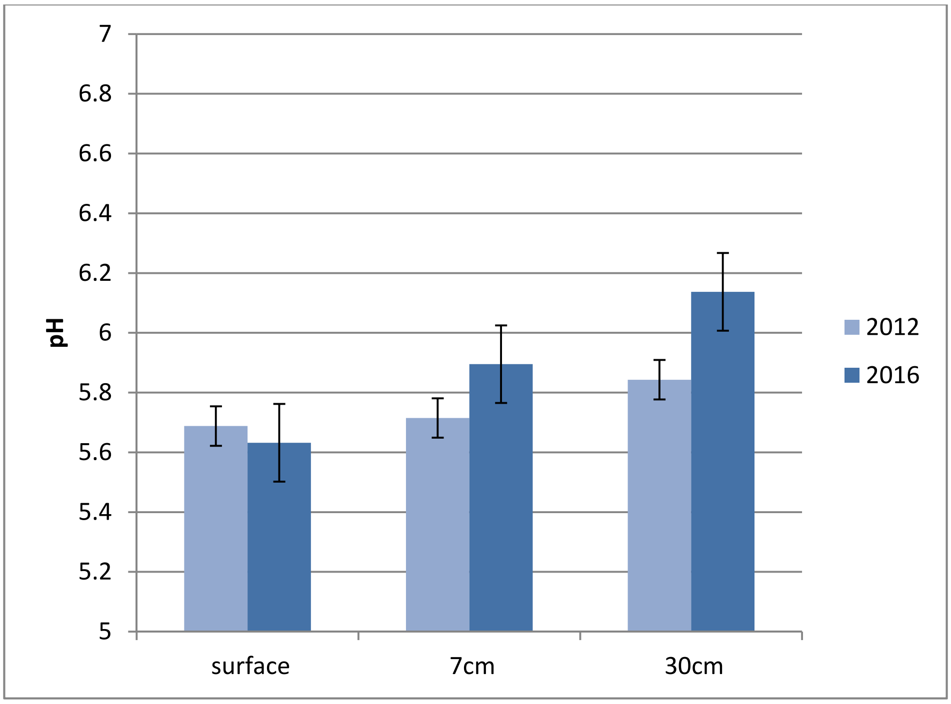


Figure 4.3.5 pH in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the NFS site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

4.3.2. Olsen P

In general, Mid-Pilmore has an adequate Olsen P and would be considered replete for P regarding plant growth. At this site cultivation techniques had had a significant ($p<0.001$) main effect on the Olsen P at the start of the observation period in 2012 in that the treatments with inversion had less available P (compaction38.3 mg P kg^{-1}; plough 40.3 mg P kg^{-1}) compared to non-inversion tillage treatments No-till (48.2 mg P kg^{-1}) and Shallow non-inversion (49.1 mg P kg^{-1}) (Figure 4.3.6). By 2016 these main effects on Olsen P remained ($p<0.05$), but P availability had increased in all treatments particularly in the plough treatment which now had more available P than the compaction treatment and statistically the same as the shallow non-inversion tillage treatment. At the beginning of the observation period Olsen P also declined significantly ($p<0.05$) with depth being more available at the surface 2.7cm (47.0 mg P kg^{-1}) and less so at 7-12cm (43.4 mg P kg $^{-1}$) and 25-30 cm (41.6 mg P kg^{-1}), again this was maintained ($p<0.05$) through to 2016 but all Olsen P were raised (Figure 4.3.7). There were no significant interactions between depth and cultivation treatment at Mid-Pilmore at any point in the observation period.

At the STAR site the Olsen P level was much less than at Mid-Pilmore and would be considered limiting to plant growth. At the start of the experimental period there were significant ($p<0.001$) differences in Olsen P with depth, becoming less available with depth in that at the surface and at 7-12cm the Olsen P was statistically the same (11.4 and 9.5 mg P kg^{-1}, respectively), whereas at 25-30cm it was less available at 2.7 mg P kg^{-1}, which would be considered extremely limiting (Figure 4.3.8). This difference ($p<0.001$) became more pronounced by the end of the observation period in 2016, with the surface becoming more replete in available P (21.8 mg P kg^{-1}) and differentiating itself from the lower depths, which remained virtually unchanged. There were no significant difference in the Olsen-P between treatments at the start of the experiment in 2012 and none developed by the end of the observation period in 2016. Likewise there were no significant interactions between depth and treatment.

A similar set of results for depth were found at NFS as observed at STAR and again this site would be considered deficient in P, based on the Olsen-P level. There were no significant effects of tillage treatment or depth on the Olsen P at the start of the observation period, but they did develop such that significant ($p<0.001$) differences with depth and treatment existed in 2016. By the end of the observation period there was a significant decline in P availability with depth such that the surface (17.7 mg P kg^{-1}) was more replete than at both 7-12cm (11.5 mg P kg^{-}1) and 25-30cm (9.1 mg P kg^{-1}), which were statistically similar (Figure 4.3.9). A significant ($p<0.01$) impact of the cultivation treatment also developed over the observation period (Figure 4.3.10) in that the Olsen P became significantly greater in the shallow non-inversion tillage treatment (16.3 mg P kg^{-1}) compared to the other treatments (10.5-11.6 mg P kg^{-1}).

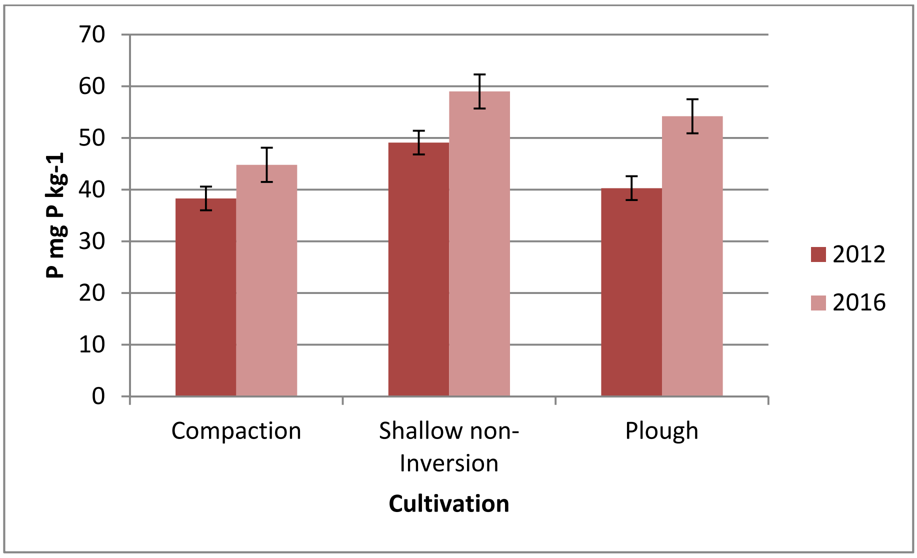


Figure 4.3.6 Olsen P (mg P kg^{-1}) in soils taken from different tillage treatments with inversion (compaction and plough) and without inversion (shallow non-inversion) at the Mid-Pilmore site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates at 3 depths and the error bars represent the LSD.

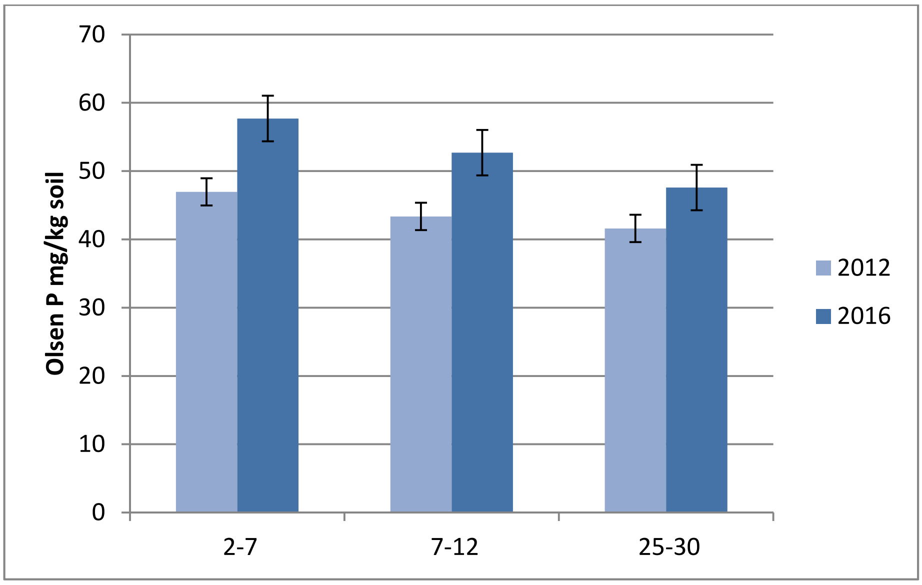


Figure 4.3.7 Olsen P (mg P kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the Mid-Pilmore site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

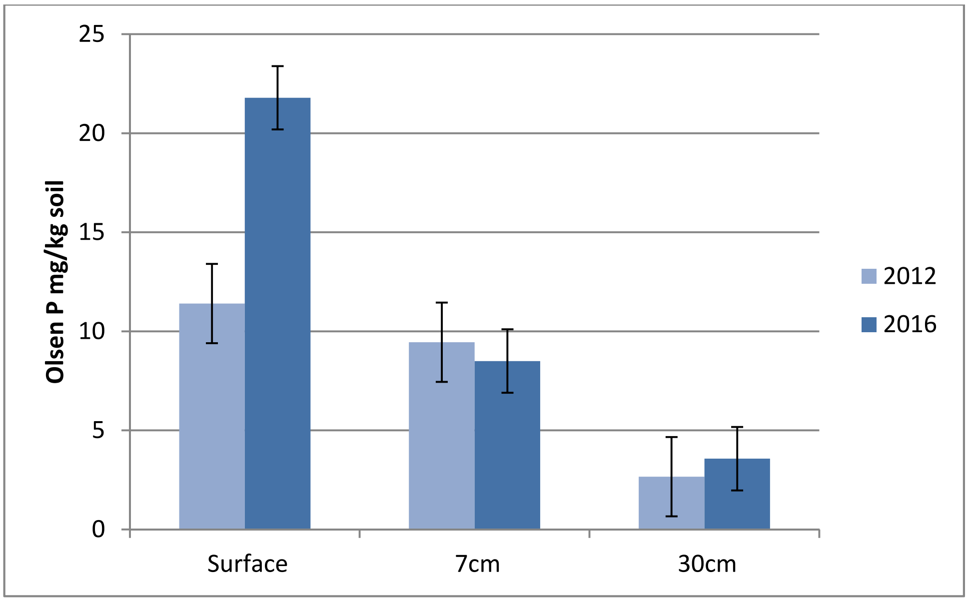


Figure 4.3.8 Olsen P (mg P kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the STAR site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

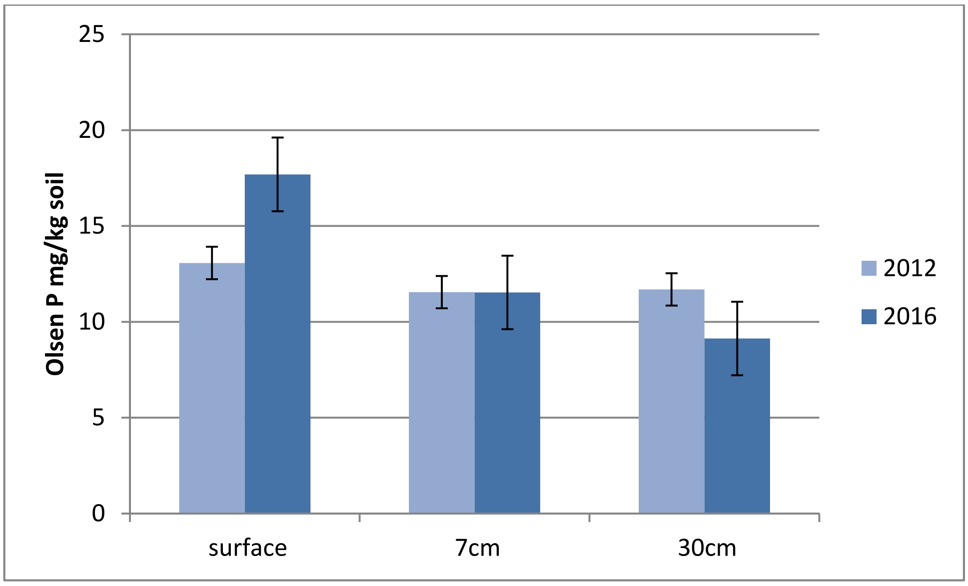


Figure 4.3.9: Olsen P (mg P kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the NFS site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

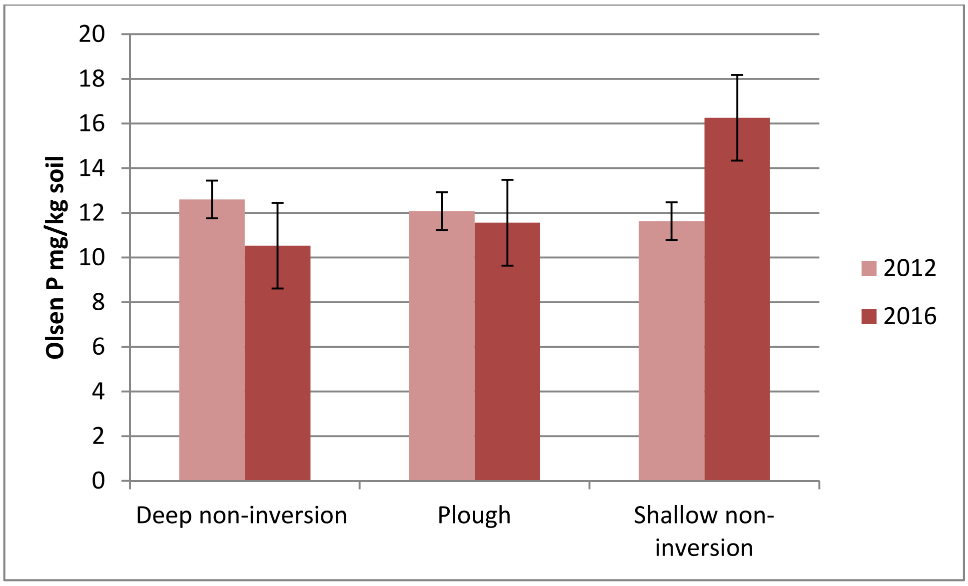


Figure 4.3.10: Olsen P (mg P kg^{-1}) in soils taken from different tillage treatments with inversion (plough) and without inversion (deep non-inversion; shallow non-inversion) at the NFS site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates at 3 depths and the error bars represent the LSD.

4.3.3. NH_4

At the Mid-Pilmore site there were no significant effects of depth or cultivation treatment on the NH_4 concentration at the start of the observation period in 2012. There were also no interactions between depth and cultivation. By the end of the observation period in 2016 the concentrations of NH_4 were below detection.

At the STAR site at the start of the experimental period there were significant ($p<0.001$) differences in NH_4 with depth, with the concentration declining with depth, in that at the surface and at 7-12cm the concentration was statistically the same (1.6 and 1.4 mg kg^{-1}), whereas at 25-30cm it less (1.1 mg kg^{-1}) (Figure 4.3.11). By the end of the observation period in 2016 the concentrations of NH_4 were below detection.

A similar set of results were found at NFS as observed at STAR. There were no significant effects of tillage treatment on NH_4 and no interactions between this and depth. There were significant ($p<0.05$) differences with depth at the start of the observation period in that the surface NH_4 (0.5 mg kg^{-1}) was greater than that at both 7-12cm and 25-30cm depth (0.4 and 0.3 mg kg^{-1}, respectively) (Figure 4.3.12). Again, by the end of the observation period in 2016 the concentrations of NH_4 were below detection.

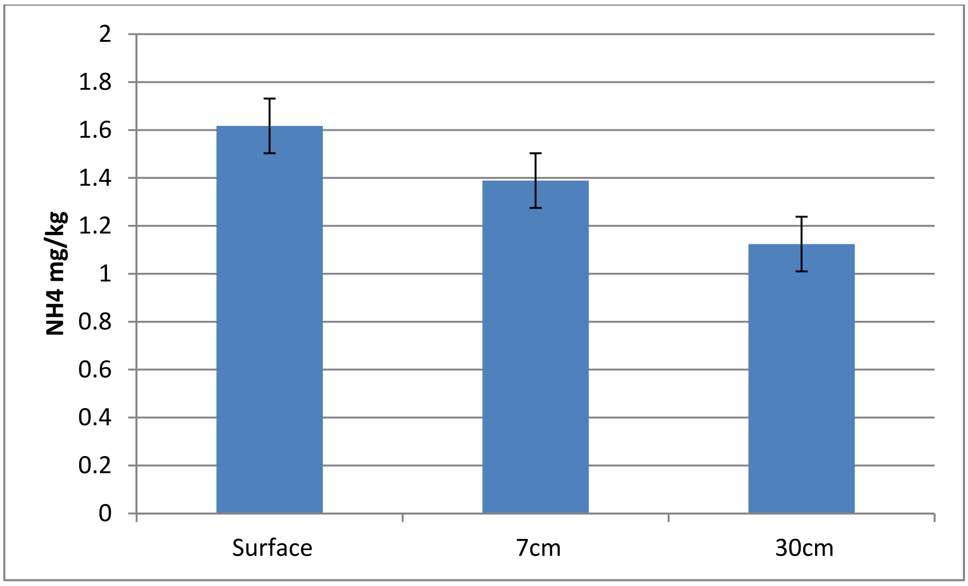


Figure 4.3.11: NH_4 (mg kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the STAR site in 2012. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

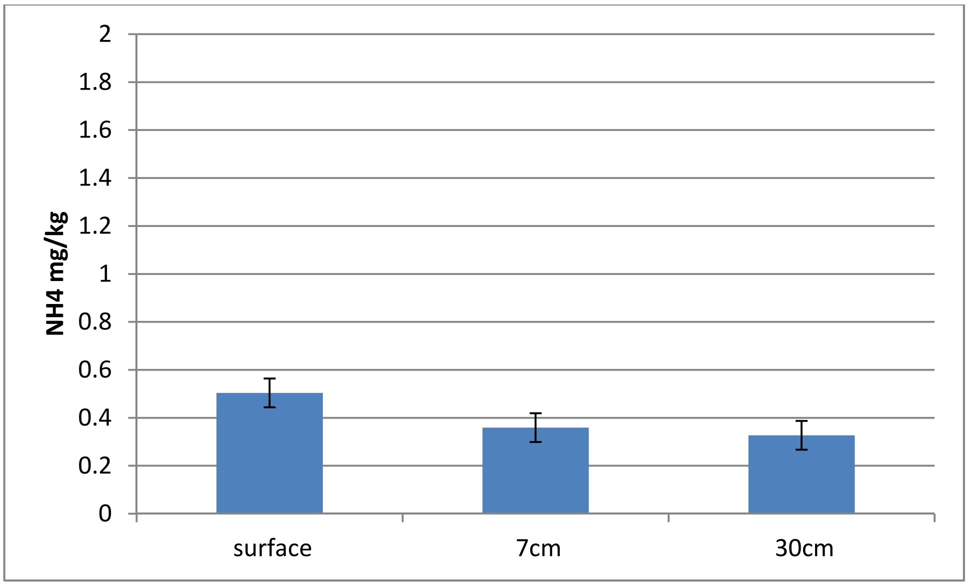


Figure 4.3.12: NH_4 (mg kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the NFS site in 2012. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

4.3.4. NO_3

There were no significant effects of tillage treatment or depth on the NO_3 at the Mid-Pilmore site at the start of the observation period, but they did develop such that significant ($p<0.001$) differences with depth existed in 2016. By the end of the observation period there was a significant ($p<0.001$) decline in NO_3 availability with depth such that at the surface 2-7cm (29.9 mg kg^{-1}) and 7-12 cm depth (23.2 mg kg^{-1}) the NO_3 was more replete than at 25-30cm (14.3 mg kg^{-1}) (Figure 4.3.13).

At the STAR site at the start of the observation period there were significant ($p<0.01$) differences in NO_3 with depth, becoming more available with depth in that at the surface NO_3 had a concentration of 4.9 mg kg^{-1}, which was less than at both 7-12cm (7.5 mg kg^{-1}) and 25-30cm (7.5 mg kg^{-1}) depth (Figure 4.3.14). This difference with depth ($p<0.001$) changed by the end of the observation period in 2016, with the surface (16.2 mg kg^{-1}) and 25-30cm depth (24.5 mg kg^{-1}) becoming more concentrated and the intermediate depth (7.3 mg kg^{-1}) remaining unchanged. There were no significant difference in the NO_3 between treatments at the start of the experiment in 2012 and none developed by the end of the observation period in 2016. Likewise there were no significant interactions between depth and treatment.

At the NFS site cultivation techniques had no significant effect on NO_3 concentration at the start of the experiment in 2012 and there was no interaction between depth and cultivation treatment. However, by 2016 cultivation treatment effects had emerged, with the non-inversion treatments (deep non-inversion 11.8 mg kg^{-1}; shallow non-inversion 11.0 mg kg^{-1}) having greater ($p<0.05$) NO_3 concentrations than the plough treatment (7.3 mg kg^{-1}) (Figure 4.3.15), At the beginning of the observation period NO_3 concentration declined significantly ($p<0.01$) with depth, being more concentrated at the surface 2-7cm (22.9 mg kg^{-1}) and 7-12cm depth (22.7 mg kg^{-1}) than at the 25-30cm depth (13.6 mg kg^{-1}). The distribution with depth of NO_3 remained significant ($p<0.001$) through to 2016, but the surface (15.8 mg kg^{-1}) became more concentrated than deeper in the profile, where NO_3 declined with depth at 7-12cm (8.0 mg kg^{-1}) and 25-30cm (6.3 mg kg^{-1}), which were not different from one another (Figure 4.3.16). When considering the interactions between treatment and depth there was no significant interaction at the start of the experiment. However, an interaction developed over the period of observation such that it was apparent that the depth effect was most pronounced ($p<0.05$) in the non-inversion tillage treatments (2016) (Figure 4.3.17). This was particularly apparent in the shallow non-inversion (20.2, 7.3, 5.4 mg kg^{-1}) then the deep non-inversion (17.7, 11.0, 6.7 mg kg^{-1}). There was no depth effect in the plough treatment (9.5, 5.7. 6.7 mg kg^{-1}).

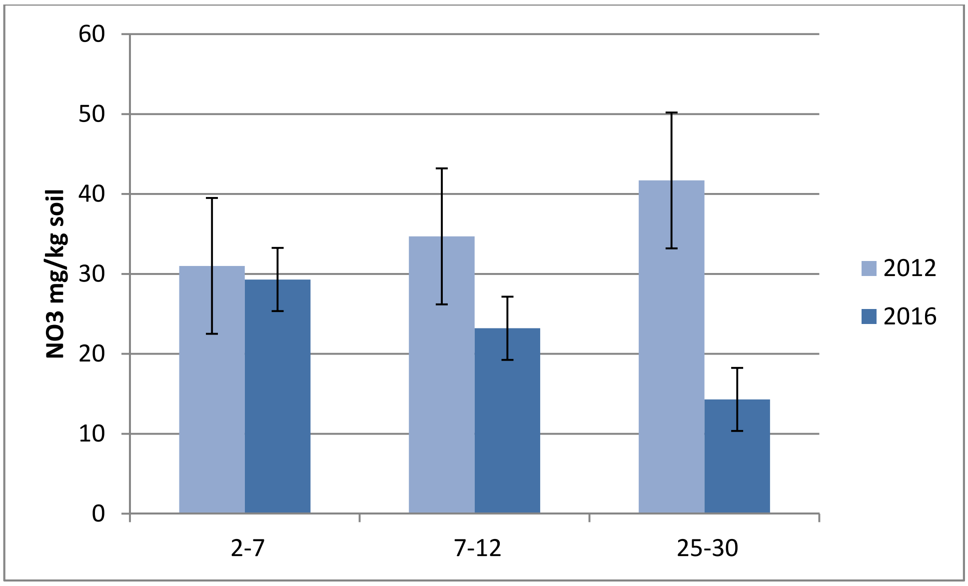


Figure 4.3.13: NO_3 (mg kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the Mid-Pilmore site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

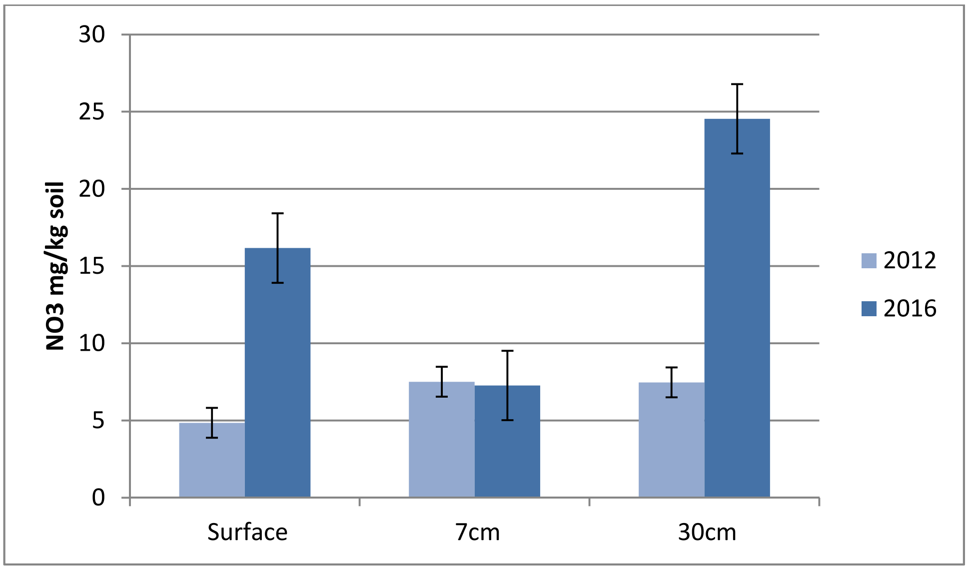


Figure 4.3.14: NO_3 (mg kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the STAR site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

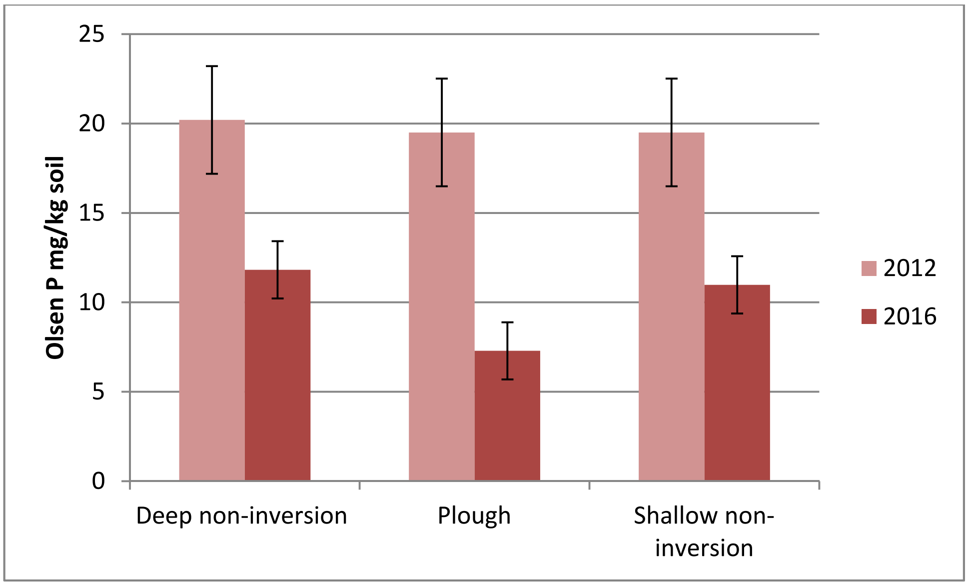


Figure 4.3.15: NO_3 (mg kg^{-1}) in soils taken from different tillage treatments with inversion (plough) and without inversion (deep non-inversion; shallow non-inversion) at the NFS site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates at 3 depths and the error bars represent the LSD.

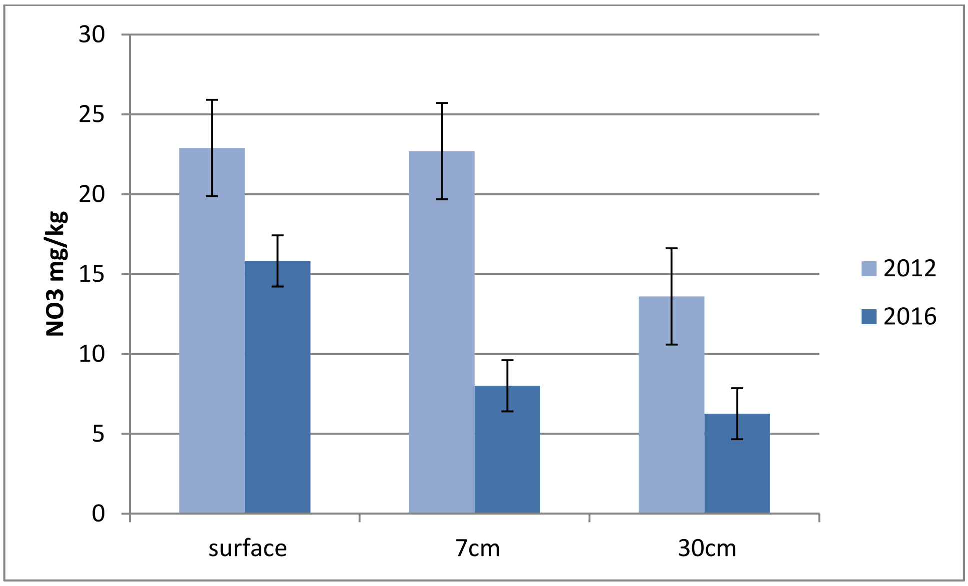
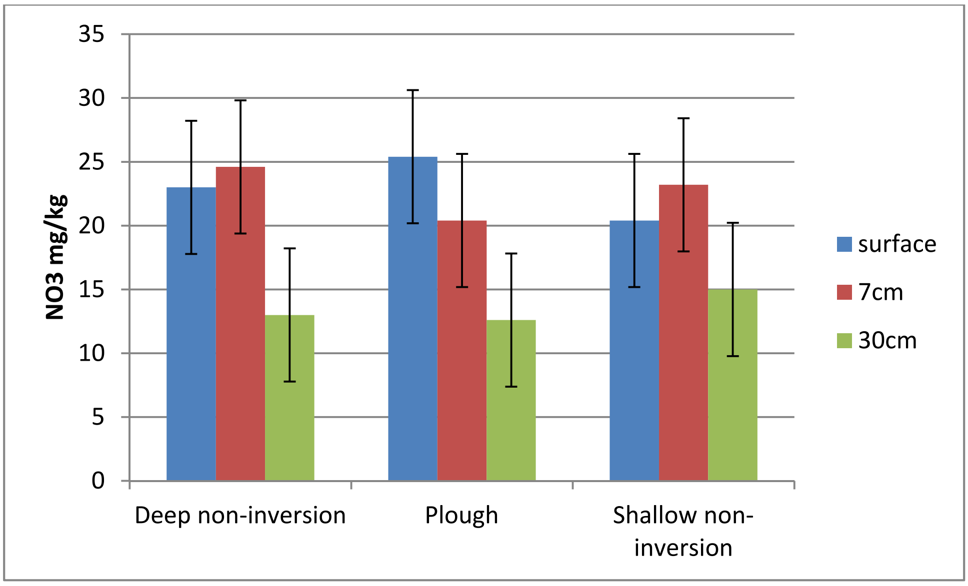


Figure 4.3.16: NO_3 (mg kg^{-1}) in soils taken from different depths (2-7, 7-12 and 25-30cm) of a range of tillage treatments at the NFS site in 2012 and 2016 at the end of the observation period. Data represents the mean of 3 replicates for cultivation treatments and the error bars represent the LSD.

a)



b)

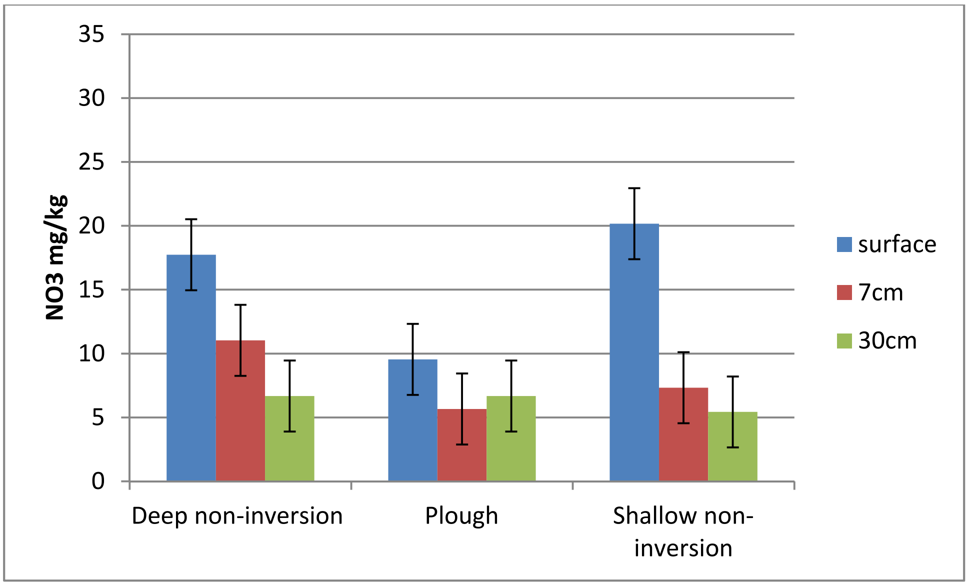


Figure 4.3.17 a,b: The interaction between depth and different tillage treatments with inversion (plough) and without inversion (deep non-inversion; shallow non-inversion) on NO_3 concentration in soil at the NFS site a) in 2012 and b) in 2016 at the end of the observation period. Data represents the mean of 3 replicates and the error bars represent the LSD.

4.4. Soil Bulk Density and Carbon Distribution

Table 4.1.1 summarises the results on the effects of tillage treatment on bulk density and soil carbon distribution amongst the sites. It shows the main effect of tillage treatment on bulk density was not statistically significant in all of the study sites. It also shows very similar results for the English sites.

Table 4.1.1: Summary of results on the effects of tillage treatment on depth and soil carbon distribution at four study sites. BD= bulk density, D=deep non-inversion, M=shallow non-inversion, N= no-till, P= plough, C= compaction.

	Bulk Density			**Carbon Content**		
Site	**Treatment main effect**	**Depth main effect**	**Effect of interaction treatment x depth**	**Treatment main effect**	**Depth main effect**	**Effect of interaction treatment x depth**
English sites						
STAR	Not significant	Higher BD below the plough layer	Not significant	Not significant	Greater above 25-30 cm layer	Not significant
NFS	Not significant	Higher BD below the plough layer	Not significant	Not significant	Gradually decreasing from surface to subsoil	Surface: D>M>P 7-12 cm: D>P
Scottish sites						
Mid-Pilmore	Not significant	Increasing BD from the surface up to 25-30 cm then decrease at 35-40 cm and increase at 55-60 cm	Surface: P>M 25-30 cm: C>N 35-40 cm: no differences 55-60 cm: M,N >P; M,N>C	P > C, N	Greater above 25-30 cm layer. Greater at 25-30 cm than surface and below 35 cm. 35-40 cm > 55-60 cm.	Not significant
Mid-Pilmore with adjustment for stone content	Not significant	Increasing BD from the surface up to 25-30 cm then decrease at 35-40 cm and increase at 55-60 cm.	Surface: P>M 25-30 cm: C>M,N 55-60 cm: M>P; M,N>C	P > C, N, M	Greater above 25-30 cm layer. Greater at 25-30 cm than surface.	Surface: P>C 25-30 cm: P> M,N C>M 35-40 cm: P>C 55-60 cm: P,N,M>C
CSC Balruddery	Not significant	Not significant	Not significant	Sust. > Conv.	Greater above 25-30 cm layer	Not significant

4.4.1. Mid-Pilmore

In Mid-Pilmore the bulk density ranged from 0.95 to 1.74 g/cm^3 and it differed significantly between depths in the soil profile (DF=4; F=20.24; P<0.001). The 25-30 and 55-60 cm layers had a significantly greater bulk density than all other soil layers. The interaction between treatment and depth was significant (DF=12; F=3.57; P<0.001). Figure 4.4.1 illustrates bulk density and the interactions between treatment and depth. In the surface layer the maximum bulk density occurred in the plough treatment. The maximum bulk density overall occurred below the plough depth (25-30 cm) in the compaction treatment. Statistically, bulk density was greater in the compaction treatment than in the no-till treatment at this depth but there were no significant differences between other treatments. In the deepest soil layer (55-60 cm) the bulk densities of the shallow non-inversion and no-till treatments were significantly greater than that of the compaction and plough treatments.

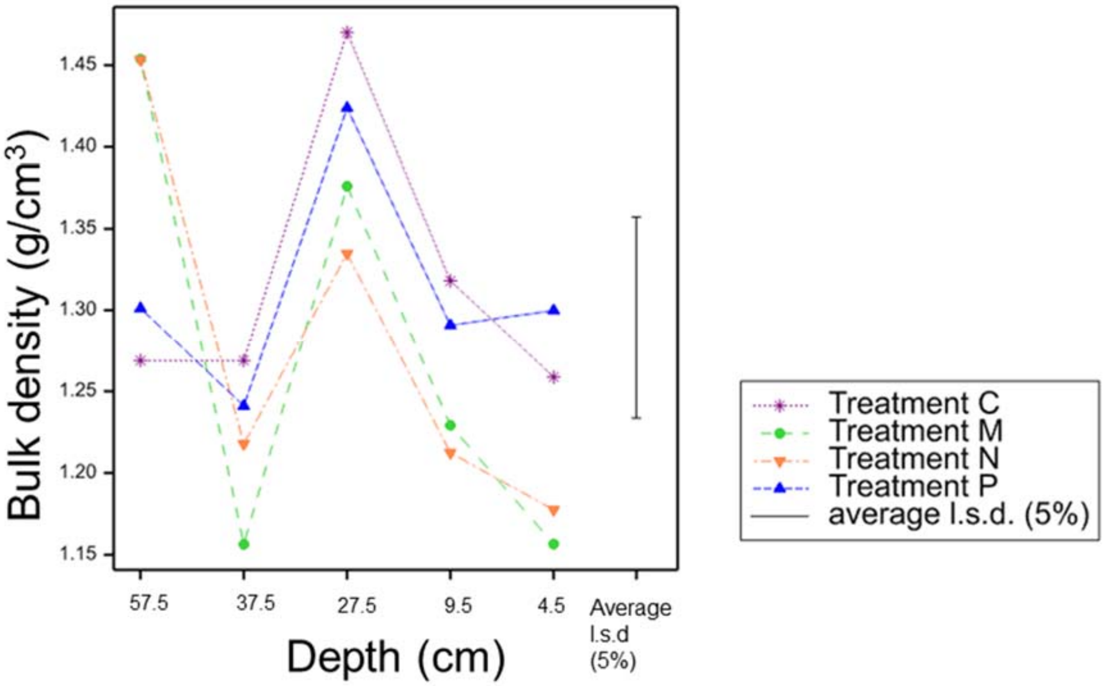


Figure 4.4.1: Bulk density distribution by depth and tillage treatment in Mid-Pilmore. C= compaction treatment, M= shallow non-inversion tillage, N= no-till, P= plough.

Figure 4.4.2 shows the carbon content, expressed as weight per volume, between treatments and depths in Mid-Pilmore. The main effect of treatment on soil carbon content was statistically significant in Mid-Pilmore (DF=3; F=7.27; P=0.020). LSD showed that the plough treatment had significantly greater carbon content than the compaction and no-till treatments, although it showed no significant differences with the shallow non-inversion treatment. Carbon content differed significantly between depths (DF=4; F=42.11; P<0.001). The greatest carbon content occurred below the plough layer at a depth of 25-30 cm. Carbon content was greater above the plough layer than in the deeper layers. The interaction between treatment and depth was not statistically significant (DF=12; F=1.49; P=0.135).

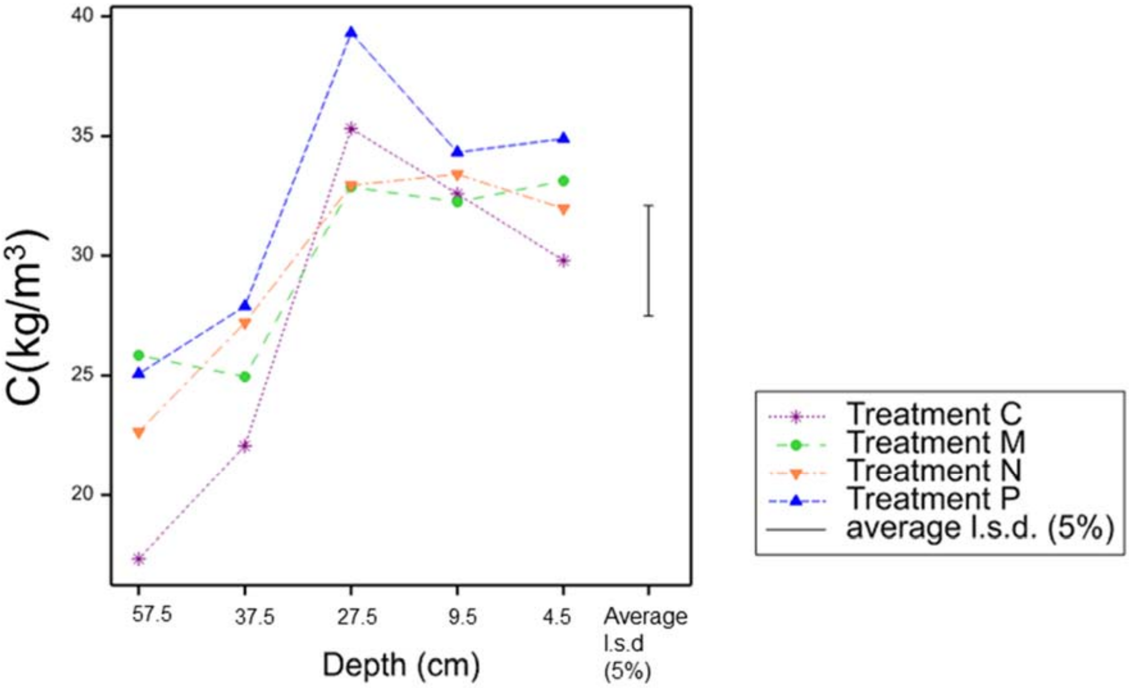


Figure 4.4.2: Soil carbon distribution by depth and tillage treatment in Mid-Pilmore. C= compaction treatment, M= shallow non-inversion tillage, N= no-till, P= plough.

Comparing the datasets with ANOVA for plots with winter barley in 2008 and plots with spring barley in 2013, produced significant results for differences between depths (df=4; F=94.62; p<0.001) and year (df=1; F=6.19; p=0.014). The interactions treatment x year (df=2; F=6.08; P=0.003) and depth x year (df=4; F=6.77; p<0.001) were also significant but not the main effect of treatment (df=2; F=1.06; p=0.429) or the interactions treatment x depth (df=8; F=1.95; p=0.061) and treatment x depth x year (df=8; F=1.67; p=0.113). Although significantly different statistically, the overall differences in carbon content (taking into account the three treatments) for 2013 was only 5% higher than in 2008.The l.s.d test showed that the differences in carbon content between years were only significant for the P treatment (Figure 4.4.3). The P treatment plots in 2013 had approximately 15% more carbon content than the 2008 plots.

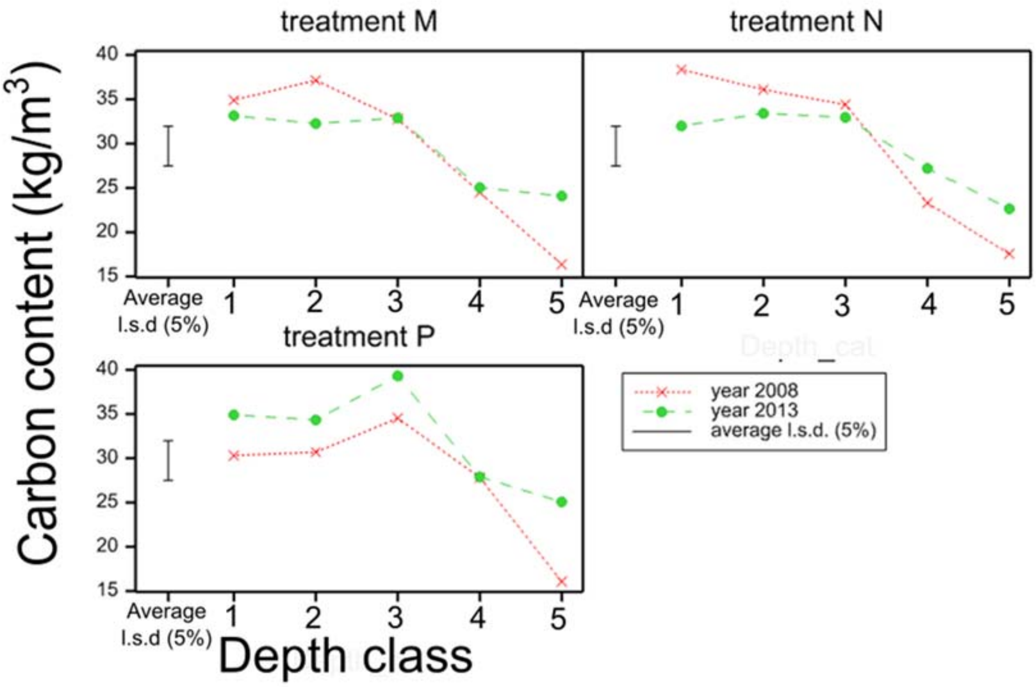


Figure 4.4.3: Carbon content in winter barley plots in 2008 and spring barley plots in 2013 for shallow non-inversion tillage (M), no-till (N) and plough (P) treatments in Mid-Pilmore.

The main effect of adjusting the bulk density of the soil according to the stone content was an overall reduction of density values. This adjustment was used here to calculate the carbon per unit volume of soil and to ensure that differences in stone content were not confounding results. The decrease in density was seen in particular in the deepest soil layers (Figure 4.4.4). Bulk density in the 35-40 cm depth went from a mean value of 1.22 to 0.97 g/cm3 and in the 55-60 cm depth from 1.37 to 1.10 g/cm^3. This resulted in changing the significance of the interaction term of depth and treatment on carbon content to a significant one (DF=12; F=2.00; P=0.029). At the surface and 55-60 cm layers the P treatment had greater carbon content than the C treatment but showed no differences between the reduced tillage treatments. At the plough layer the P treatment had greater carbon content than the reduced tillage treatments. However the overall conclusion of main effect significance remained true.

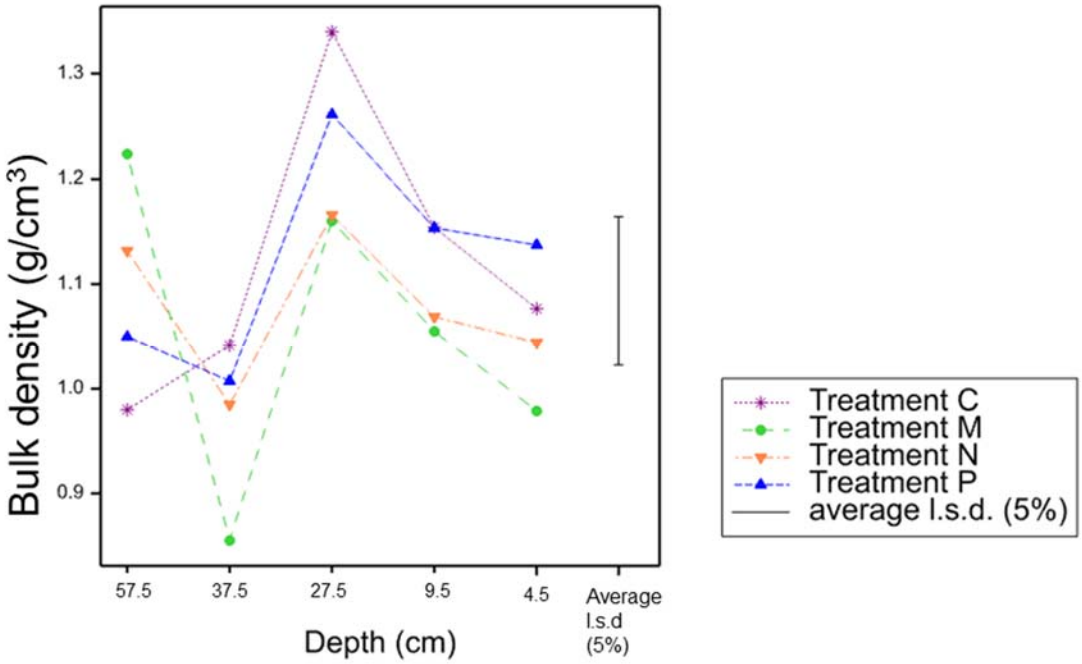


Figure 4.4.4: Bulk density values after adjusting for stone content in Mid-Pilmore. C= compaction treatment, M= shallow non-inversion tillage, N= no-till, P= plough.

4.4.2. NFS

Bulk density in NFS ranged from 1.04 to 1.70 g/cm^3. It was not significantly affected by the tillage treatments (DF=2; F=3.03; P=0.158) but it differed by depth (DF=4; F=6.05; P<0.001). The interaction of tillage treatment by depth was not statistically significant (DF=8; F=1.66; P=0.117).

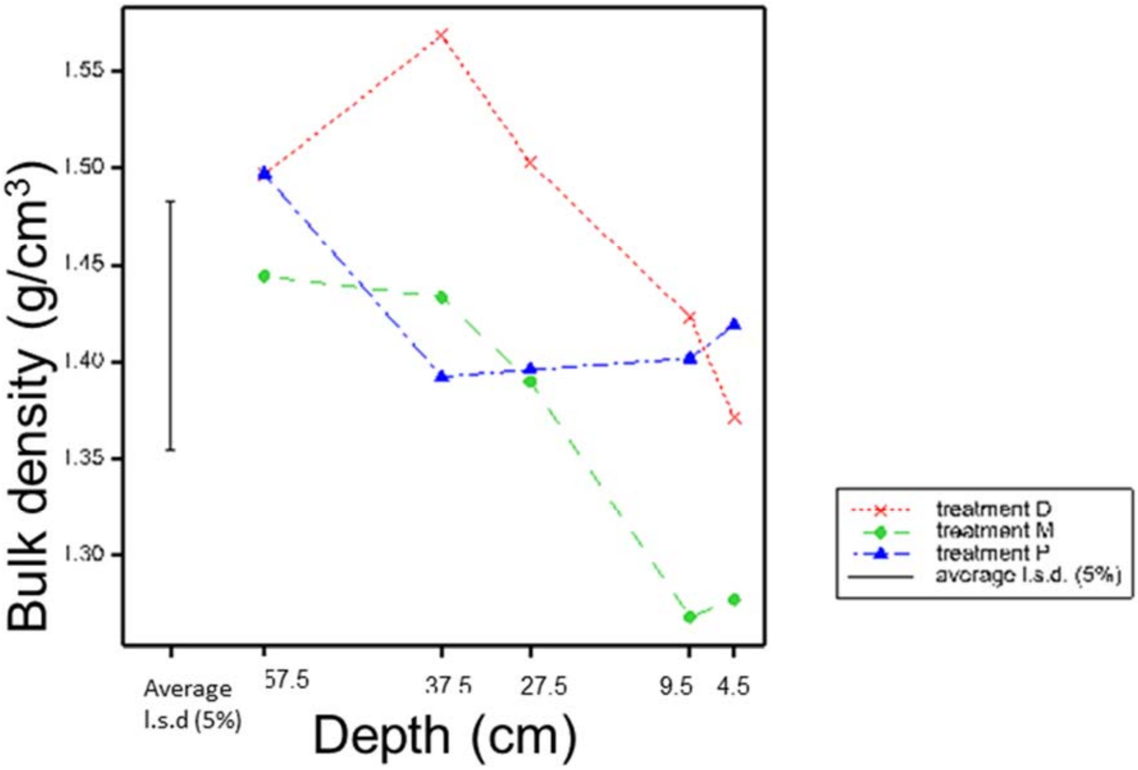


Figure 4.4.5: Soil bulk density by depth in three tillage treatments in NFS. D= deep non-inversion tillage, M= shallow non-inversion tillage, P= plough.

The results from an ANOVA showed there were significant differences in carbon content by depth (DF=4; F=157.68; P<0.001) and the interaction of treatment by depth was significant (DF=8; F=3.53; P=0.001) (Figure 4.4.6). This illustrates the differences by depth resulting from a l.s.d test. Samples from the deep non-inversion treatment had a greater content of carbon than those from the shallow non-inversion tillage and the plough treatments in the surface samples. At this surface level, samples from shallow non-inversion had greater carbon content than those from the plough. In the 7-12 cm depth, the deep non-inversion treatment samples had greater carbon content than the plough but were no different from those from the shallow non-inversion treatment. At the deepest depths, below the plough layer, there were no significant differences in carbon content between treatments. Despite these differences, the main effect of tillage treatment when the whole soil profile is taken into account was not significant (DF=2; F=3.56; P=0.129).

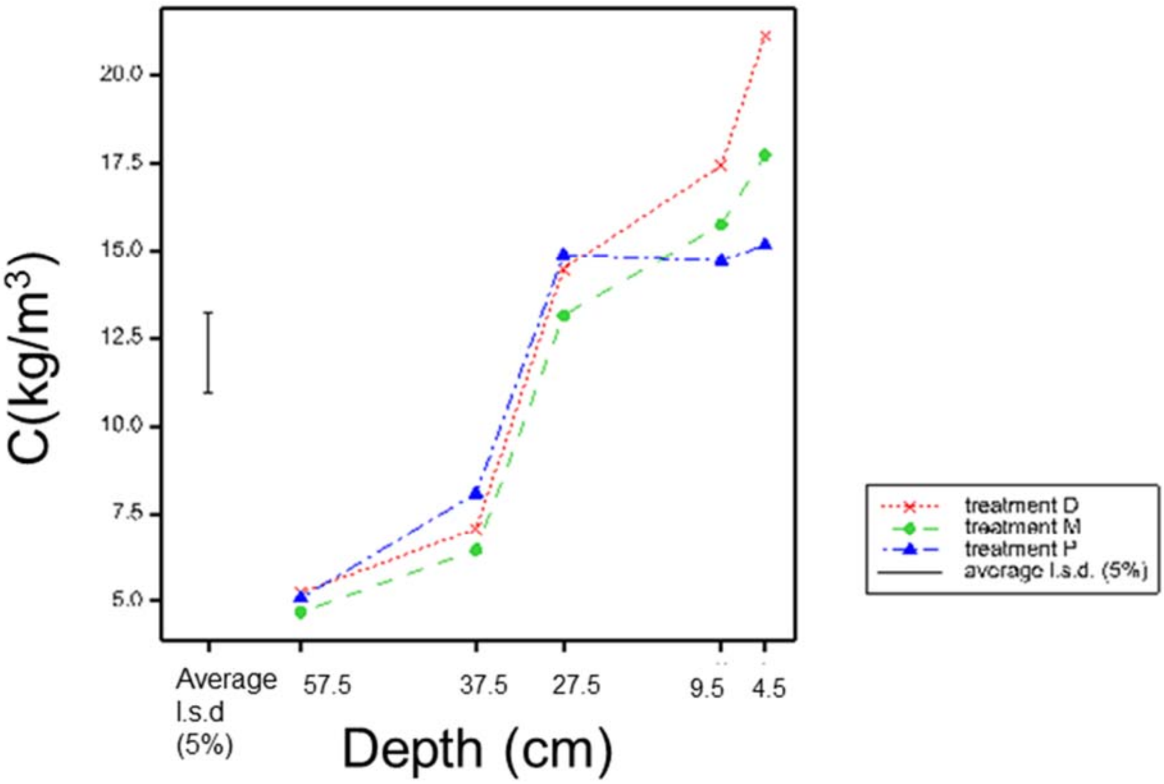


Figure 4.4.6: Soil carbon distribution by depth and tillage treatment in the NFS site. D= deep non-inversion tillage, M= shallow non-inversion tillage, P= plough.

4.4.3. STAR

Bulk density in STAR ranged from 1.03 to 1.60 g/cm^3. It was not significantly affected by the tillage treatments (DF=2; F=0.05; P=0.956) but it differed by depth (DF=4; F=28.86; P<0.001). The interaction of tillage treatment by depth was not statistically significant (DF=8; F=1.52; P=0.162). Figure 4.4.5 illustrates the bulk density in the soil profile by treatment, showing that the higher bulk densities occurred in the deepest samples in all the tillage treatments.

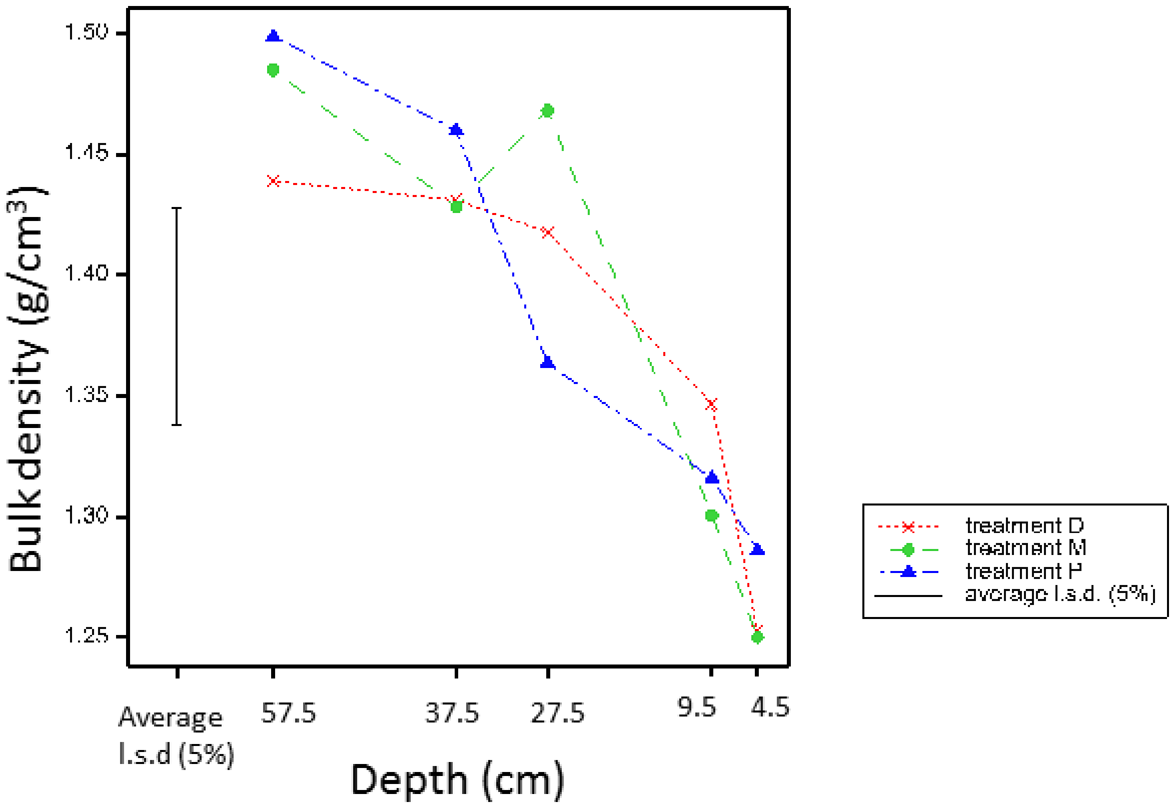


Figure 4.4.7: Soil bulk density by depth in three tillage treatments at STAR in August 2013. D= deep non-inversion tillage, M= shallow non-inversion tillage , P= plough.

The results from an ANOVA showed no significant differences at the 5% level in carbon content between treatments (DF=2; F=3.17; P=0.150) or the interaction of treatment by depth (DF=8; F=1.78; P=0.090). The main effect of depth on carbon content was highly significant (DF=4; F=629.21; P<0.001). Figure 4.2.6 shows soil carbon by tillage treatment and depth. The figure illustrates the results from the Least Significant Differences test (l.s.d) showing no significant differences in carbon content between the three most superficial samples (2-5 cm, 7-12 and 25-30 cm) but around four times less carbon content in the subsoil samples.

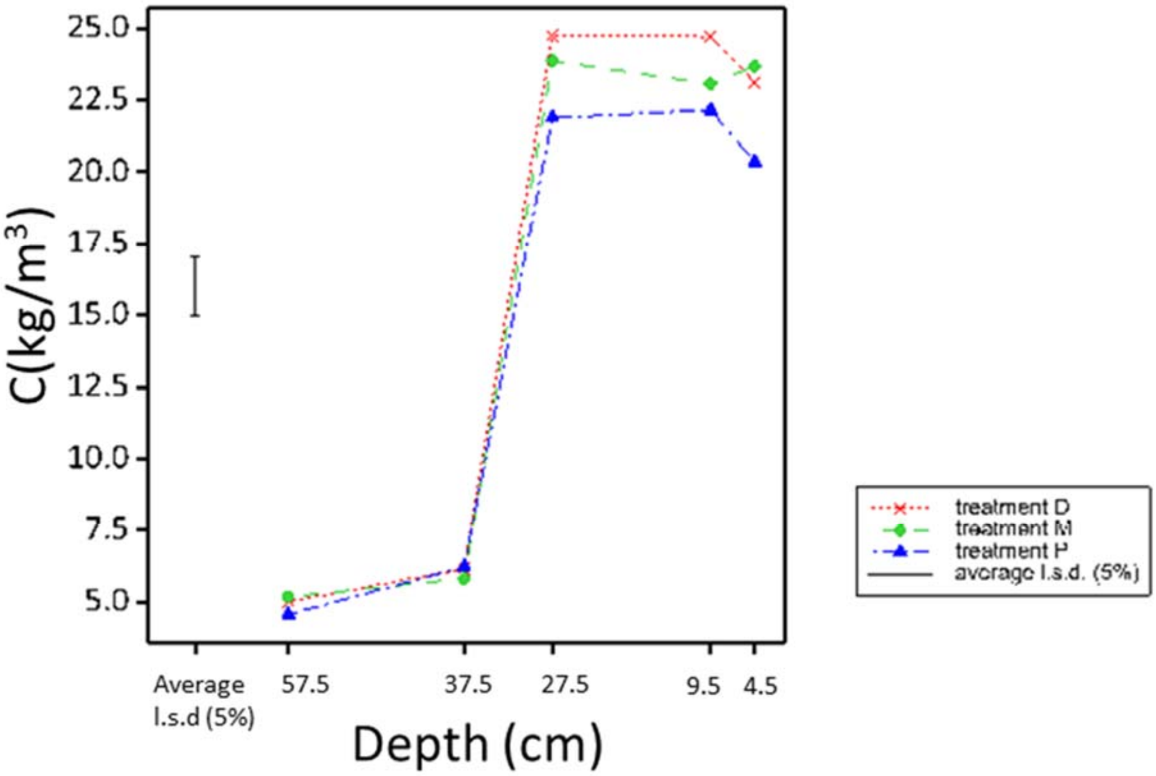


Figure 4.4.8: Soil organic carbon by tillage treatment and depth in STAR. D= deep non-inversion tillage, M= shallow, non-inversion tillage, P= plough.

4.4.4. CSC Balruddery

Figure 4.4.9 shows bulk density by treatment and depth in the CSC Balruddery. The figure shows the conventional treatment had higher bulk density in the deeper layers (35-40 and 55-60 cm) but these differences were not statistically significant (treatment x depth interaction term: df=4; F=0.75; p=0.568). The main effect of treatment on bulk density was not statistically significant (df=1; F= 0.24; p=0.637), nor was the main effect of depth on bulk density (df=4; F=2.20; p=0.092). Figure 4.4.1010 shows carbon content in Balurddery by treatment and depth. There were significant differences in the main effects of treatment (df= 1; F= 113.30; p<0.001) and depth (df=4; F= 17.26; p<0.001) on soil carbon but no significant differences in their interaction (df=4; F=0.66; p=0.625). Carbon content in the sustainable treatment was significantly greater than in the conventional treatment by approximately 6 kg of carbon more per m^3 on average. According to depth, carbon content was significantly greater in the soil layers from 25-30 cm and above than in the deeper soil layers.

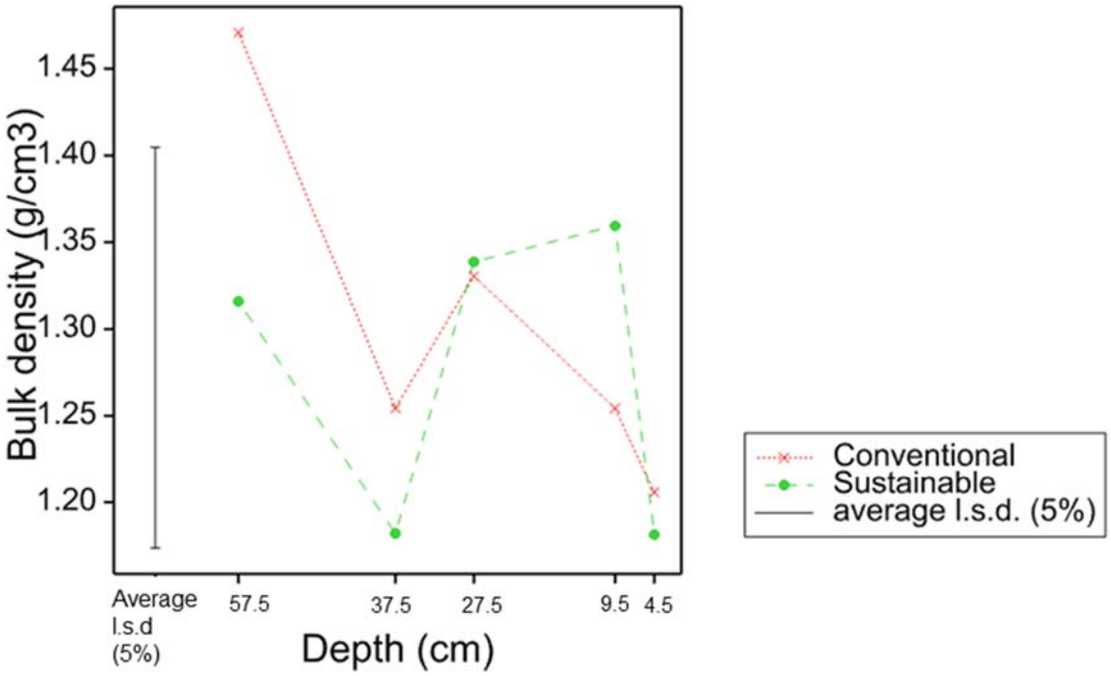


Figure 4.4.9 : Bulk density by depth in sustainable and conventional treatments in CSC Balruddery in 2004.

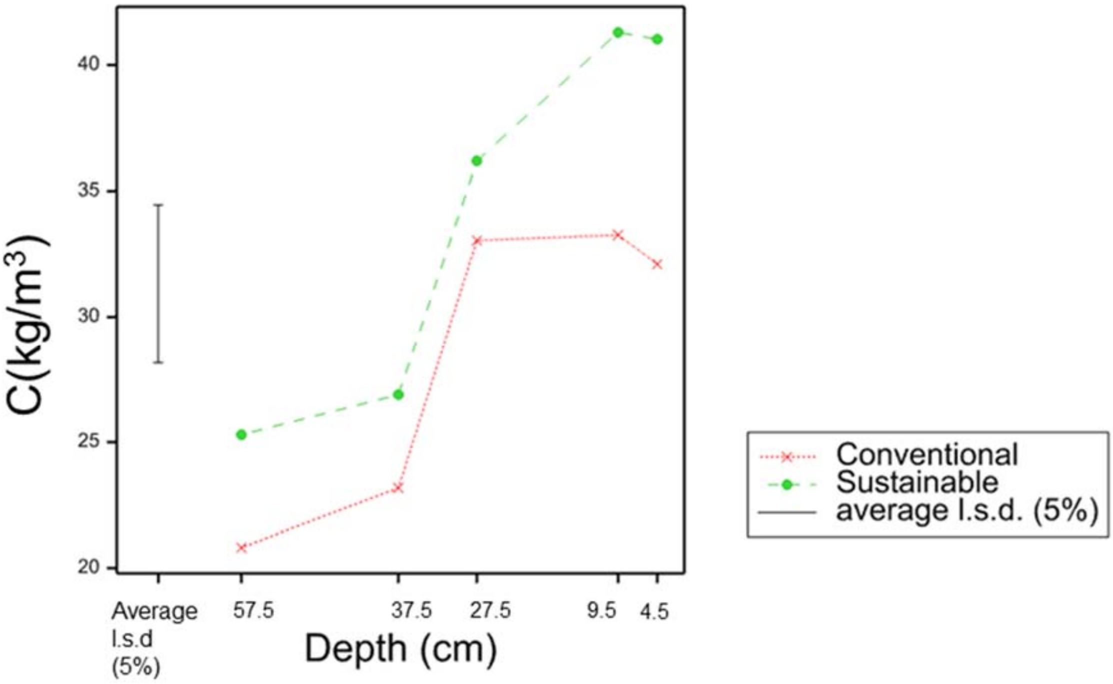


Figure 4.4.10: Soil carbon by depth in sustainable and conventional treatments in Balruddery in 2004.

4.5. Cultivar Performance

4.5.1. Disease

The trials all established well (with the exception of zero tillage where weeds were becoming too problematic and so the treatment was discontinued for 2014). Powdery mildew occurred only at low levels occasionally. Rhynchosporium occurred as the main disease every year but levels were never high and unlikely to have much impact on yield directly. Numbers of scores varied from year to year so the most appropriate comparison was made using the mean of the raw scores. Conversion of the scores to percentage then required transformation to restore a normal distribution of residuals and comparison of subsequent AUDPC calculations potentially compounded differences in epidemics between years.

Differences in the mean rhynchosporium score were significant for year, treatment, cultivar, year*treatment and year*cultivar but neither treatment*cultivar nor treatment*year were anywhere near significant at any level. Figure 4.5.1 illustrates the similarity of responses of the three inversion tillage treatments in all years except 2013 and the trend towards increased infection with minimum tillage in some years (2014 and 2016).

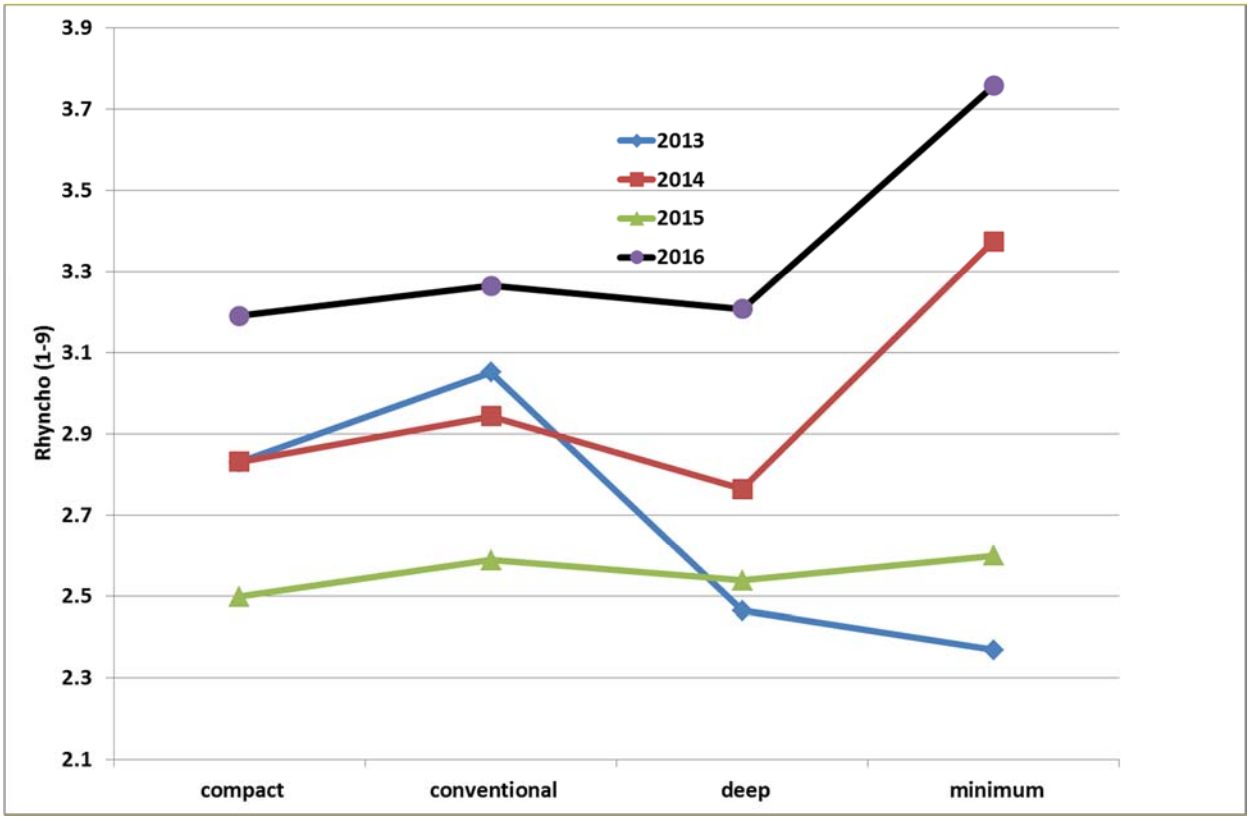


Figure 4.5.1: Significant interaction between cultivation treatment and year for rhynchosporium score where 1 is no score and 9 is 100% symptoms. (The scoring system is referenced and described in 3.5.3).

4.5.2. Yield

The 2013, 2014 and 2015 trials were identical in terms of cultivars and agronomy and therefore these were analysed together for yield. As would be expected there were highly significant interactions ($p<0.001$) for year, cultivation treatment and cultivar. Year x treatment, year x cultivar and treatment x cultivar interactions were also all highly significant ($p<0.001$) though not year*treatment*cultivar. Year x treatment clearly shows the lower yield effect of the minimum tillage treatment and the overall difference between years (Figure 4.5.2). The yield x cultivar relationship ordered by overall cultivar yield shows the gross similarity in cultivar yield performance between years but some contrasting behaviours too (Figure 4.5.3).

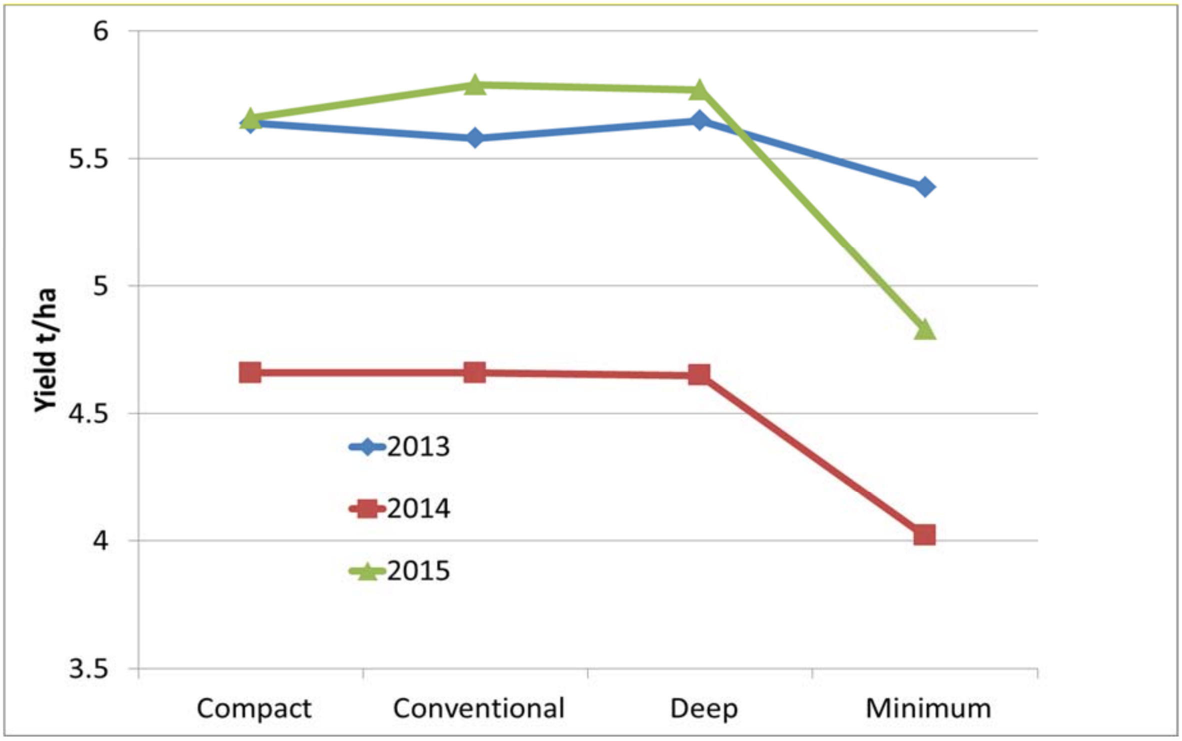


Figure 4.5.2: Mean yield response to soil cultivation treatment in each year.

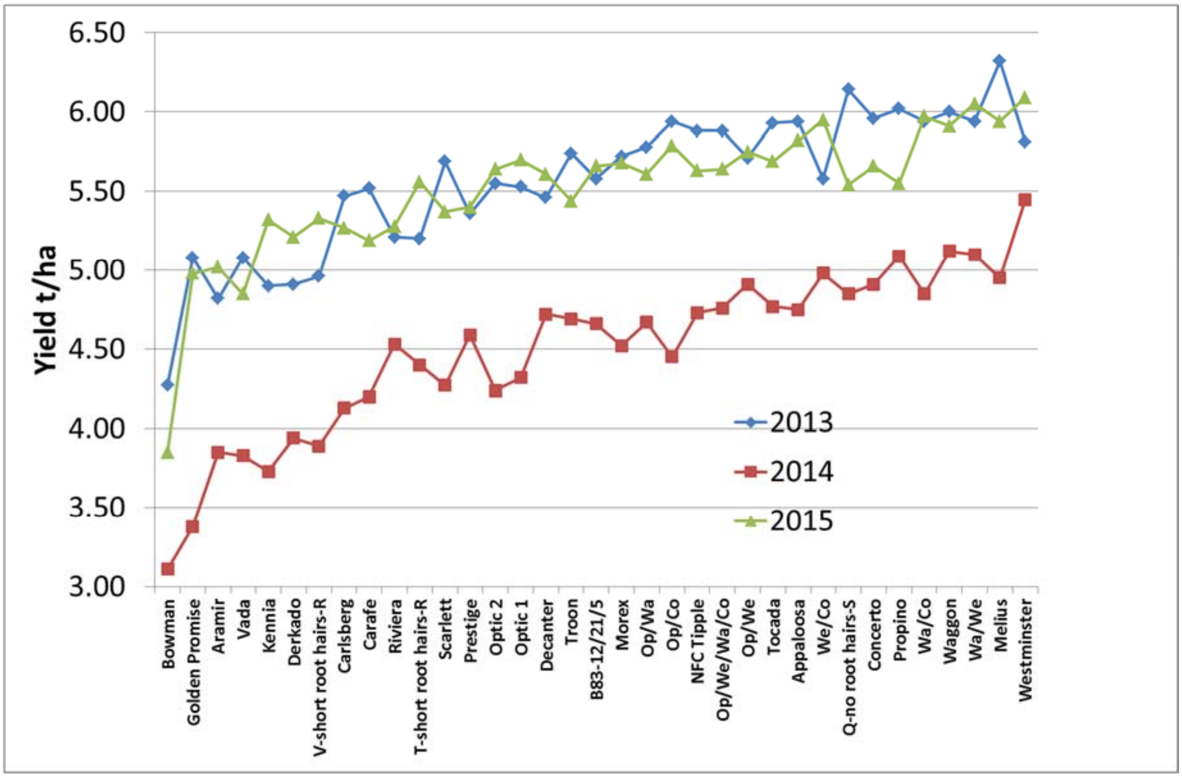


Figure 4.5.3: Mean cultivar yield response differences between years.

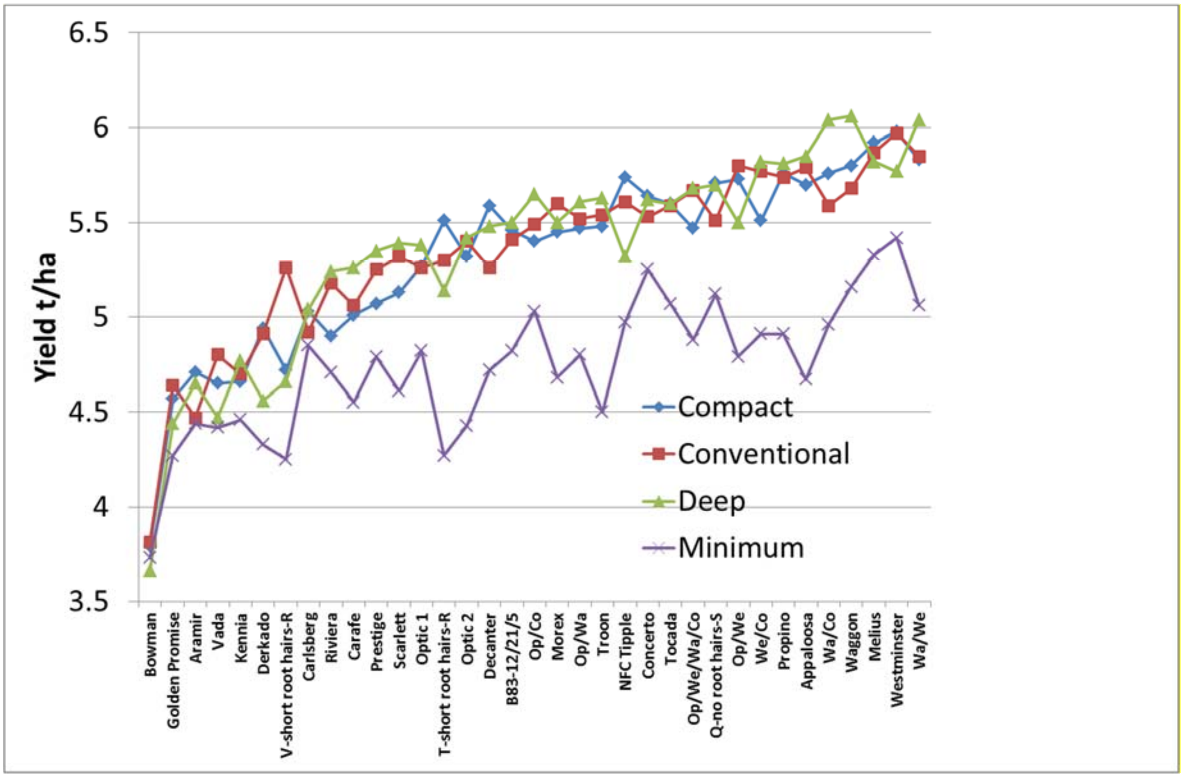


Figure 4.5.4: Mean cultivar yield response differences between cultivation treatment.

The yield*cultivation treatment differences ordered by the mean of the inversion tillage treatments show the marked similarity in performance between the three inversion tillage treatments (Figure 4.5.4). They show also not only the contrasting yield performance of the non-inversion minimum tillage treatment but also the variation in non-inversion tillage yield with respect to the inversion tillage yields. Although there is still an increasing trend overall, the gap between the inversion and non-inversion tillage treatments tends to increase with overall or inversion tillage yield. The lowest yield cultivars tend to differ little in yield response between tillage treatments whereas high-yielding cultivars such as Appoloosa, Waggon and Concerto, show relatively poor non-inversion tillage yield.

Ordering the cultivars by the <u>difference between</u> the mean of the inversion tillage treatments and the non-inversion tillage treatment (Figure 4.5.5) shows more clearly that whilst small difference between treatments is correlated with low overall yield, high yield is not correlated with a large difference between tillage treatments. Here we identify Appoloosa, Troon, Optic and Propino as cultivars showing the greatest differences and Bowman, Carlsberg, Aramir and Vada the least. However, to identify cultivars with the best minimum tillage performance (Figure 4.5.6) Westminster, Melius, Concerto and Waggon are the best performers whilst Bowman (again), Golden Promise Derkado and Vada (again) are the worst four and Aramir (again) fifth.

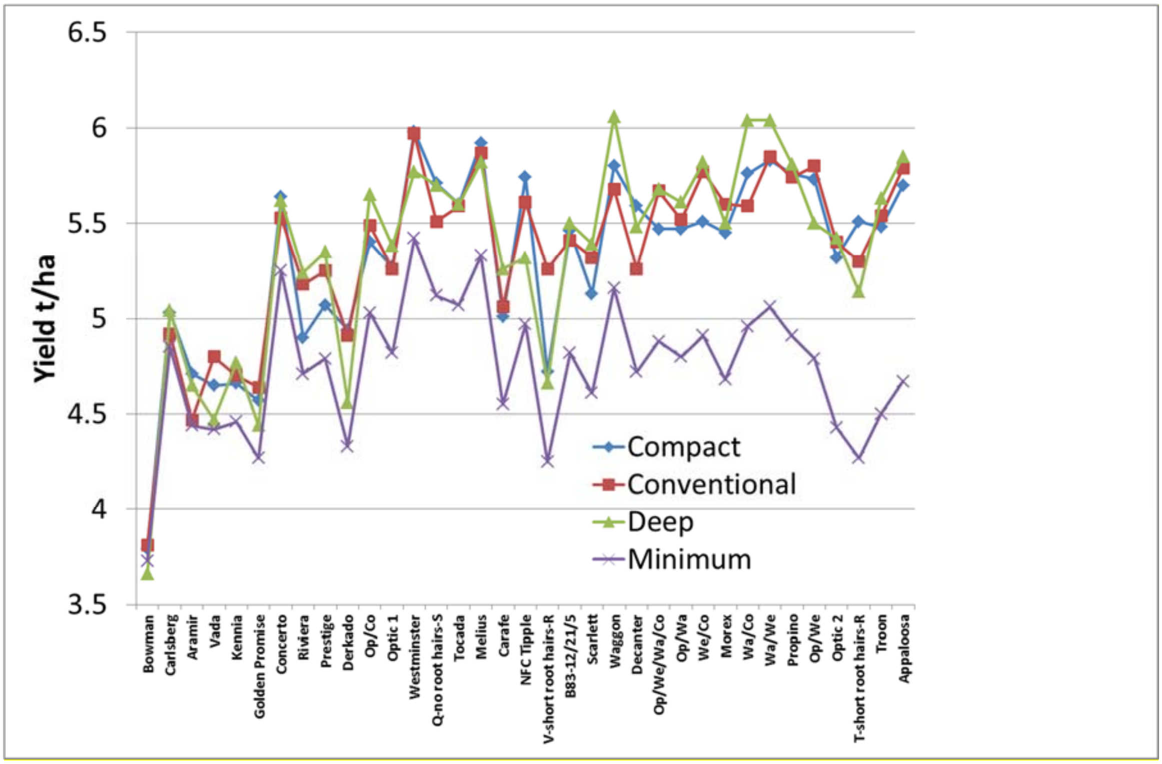


Figure 4.5.5: Mean cultivar yields ranked by difference between non-inversion and inversion tillage treatment.

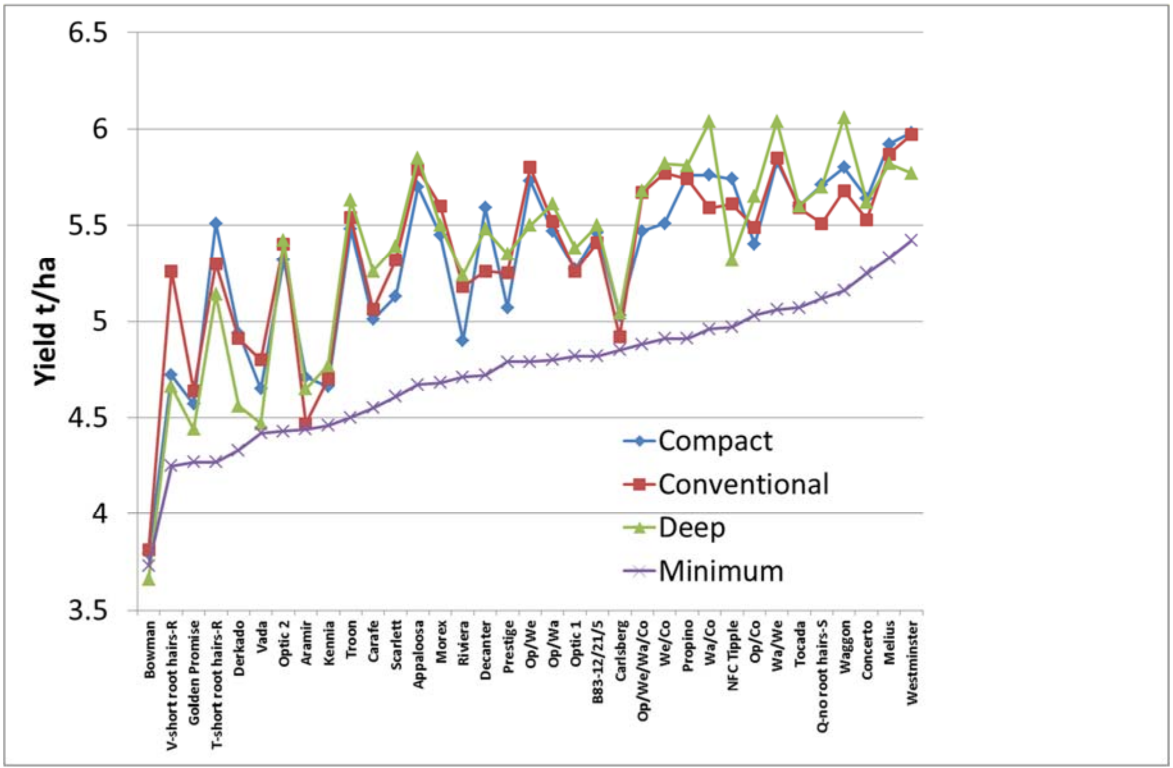


Figure 4.5.6: Mean cultivar yields ranked by non-inversion tillage treatment yields.

Selecting the top third non-inversion and inversion tillage yields, Westminster is ranked 1 and 2 respectively, Melius 2 and 3, Waggon 4 and 4 respectively so higher inversion tillage yields are often reflected in higher non-inversion tillage yields (Table 4.5.1). However, cultivars such as Appaloosa ranks 6 in inversion but 23 in minimum (19% yield reduction) and Troon drops from 15 to 26 (19% yield reduction). Conversely, Concerto goes from 13 in inversion to 3 in non-inversion (6% yield reduction) and Carlsberg from 14 to 28 (3% yield reduction).

Table 4.5.1: Relative (rank) performance of cultivars under ploughing and non-inversion tillage treatments. Highlight colours emphasise ranking changes.

Rank	Cultivar	Non-inv.	Rank	Cultivar	Inversion	Diff.	% yield red.
35	Bowman	3.73	35	Bowman	3.75	0.02	0.6
33	Golden Prom	4.27	34	Golden Prom	4.55	0.28	6.2
31	Derkado	4.33	32	Vada	4.64	0.22	4.7
30	Vada	4.42	30	Derkado	4.80	0.47	9.9
26	Troon	4.50	28	Carlsberg	5.00	0.15	2.9
23	Appaloosa	4.67	15	Troon	5.55	1.05	18.9
14	Carlsberg	4.85	13	Concerto	5.60	0.35	6.2
4	Waggon	5.16	6	Appaloosa	5.78	1.11	19.2
3	Concerto	5.25	4	Waggon	5.85	0.69	11.7
2	Melius	5.33	3	Melius	5.87	0.54	9.2
1	Westminster	5.42	2	Westminster	5.91	0.49	8.2

Several of the replacement new cultivars trialled in 2016 showed good non-inversion tillage yield, notably KWS Sassy, RGT Planet, Fairing, Sienna, Origin and Olympus (Figure 4.5.7). Figure 4.5.8 shows these cultivars ranked by yield difference between non-inversion and inversion tillage but these are again summarised in Table 4.5.2 where the rank changes and yield differences of certain cultivars are apparent. Westminster and Melius still rank 3 and 6 respectively amongst these new entries. Scholar is notable as having good inversion tillage yield but its non-inversion tillage yield is 36% lower dropping from 3 to 16 in the cultivar rankings.In contrast Fairing and KWS Sassy only lose 17% of their yield in non-inversion tillage, changing from 14 to 4 and 7 to 1 in the rankings respectively.

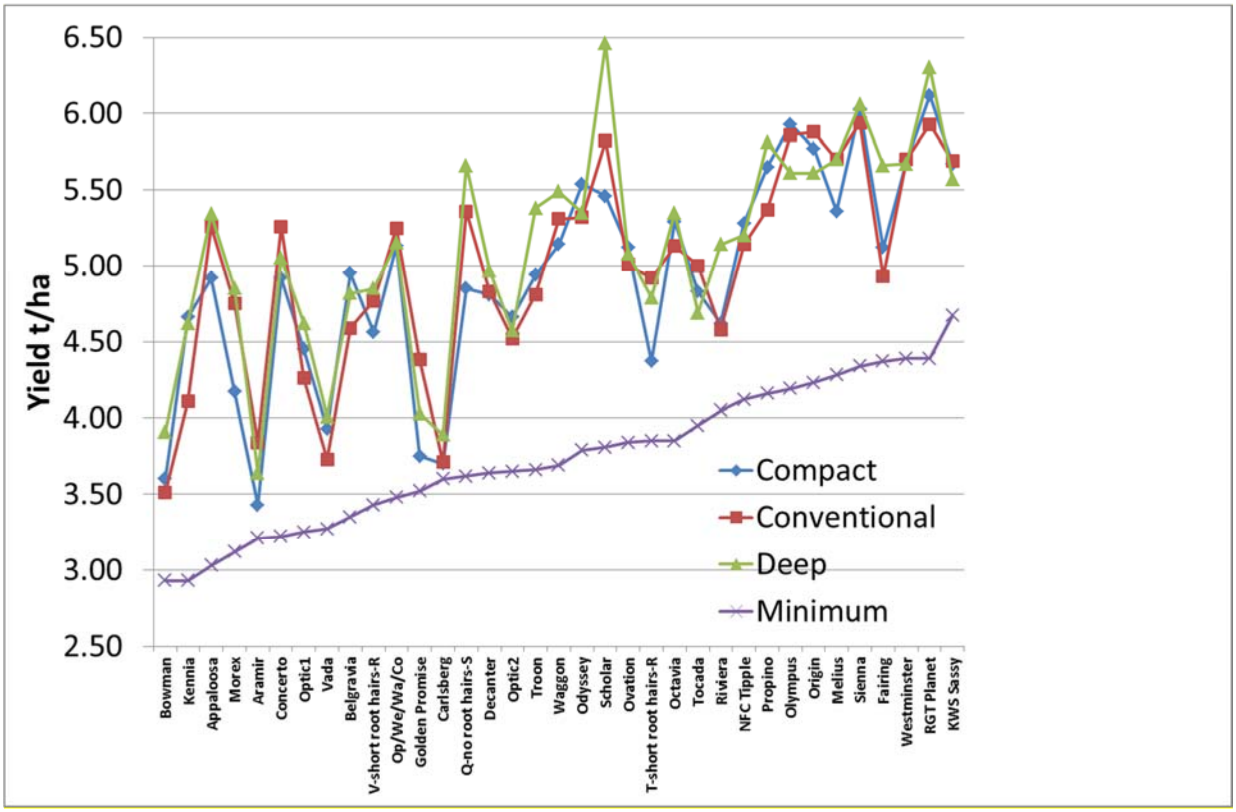


Figure 4.5.7: 2016 trial ordered by non-inversion tillage treatment yield.

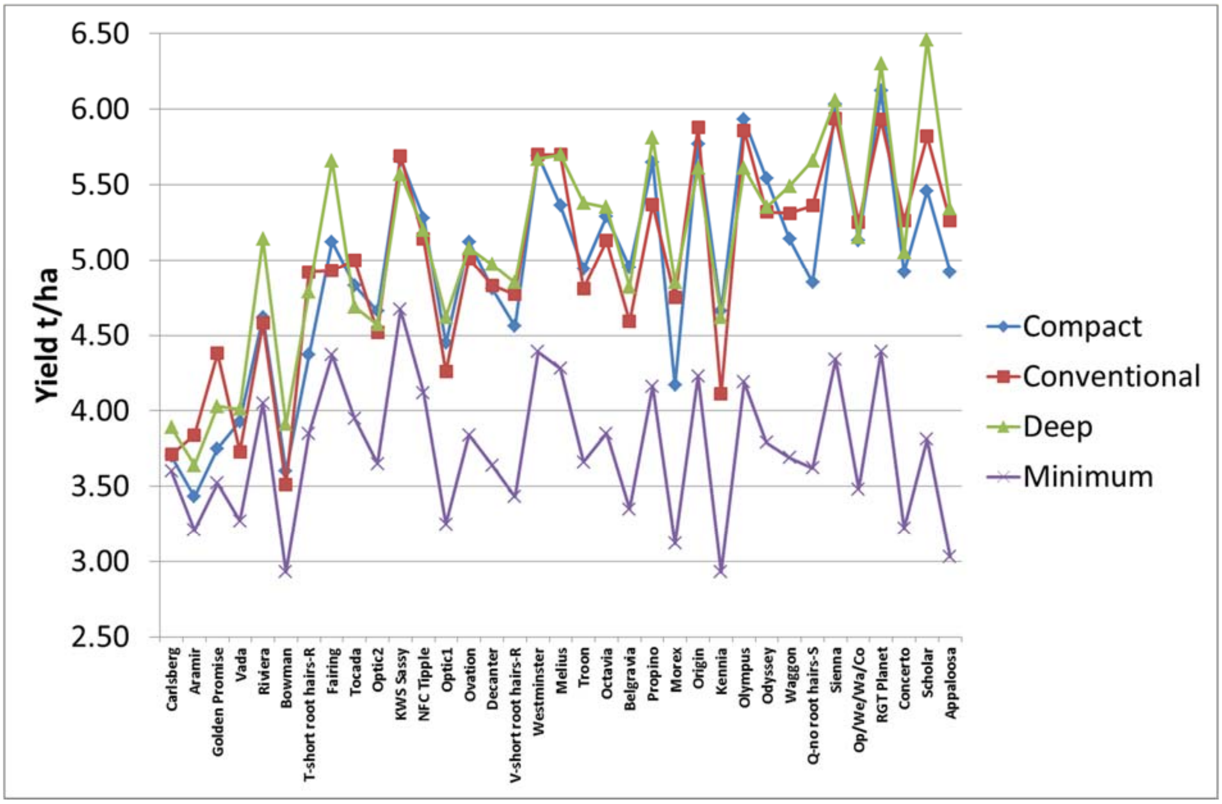


Figure 4.5.8: 2016 trial ranked by yield difference between inversion and non-inversion tillage.

Table 4.5.2: Relative (rank) performance of 2016 cultivars under inversion and non-inversion tillage treatments. Highlight colours emphasise ranking changes.

Rank	Cultivar	Non-inv.	Rank	Cultivar	Inversion	Diff.	% yield red.
16	Scholar	3.81	14	Fairing	5.24	0.87	16.5
8	Olympus	4.19	9	Melius	5.59	1.31	23.4
7	Origin	4.23	7	KWS Sassy	5.64	0.97	17.2
6	Melius	4.28	6	Westminster	5.69	1.30	22.8
5	Sienna	4.34	5	Origin	5.75	1.52	26.5
4	Fairing	4.37	4	Olympus	5.80	1.61	27.8
3	Westminster	4.39	3	Scholar	5.91	2.10	35.6
2	RGT Planet	4.39	2	Sienna	6.01	1.67	27.8
1	KWS Sassy	4.67	1	RGT Planet	6.12	1.73	28.2

4.6. Root Elongation

Root elongation assays were performed on all soil cores at a matric potential of -20kPa. For analysis purposes data was analysed as the full dataset (Dataset_All), and also split into datasets including only the baseline chemistry from year 1 across all trials (Chem_Dataset), the physical properties from the surface cores only across all trials and at three different time points (Physical_Dataset_Surface) and a dataset including the physical data from all depths at two different time points in the growing season (Physical_Dataset_S1S3). For some analyses depth samples were pooled into Surface (2-7 cm), Middle (7-12 cm) and Deep (All other sample below 12cm).

Initial assessment of the entire dataset showed that root elongation within the cores measured at -20kPa across the entire dataset varied considerably across and within trials (Figure 4.6.1).

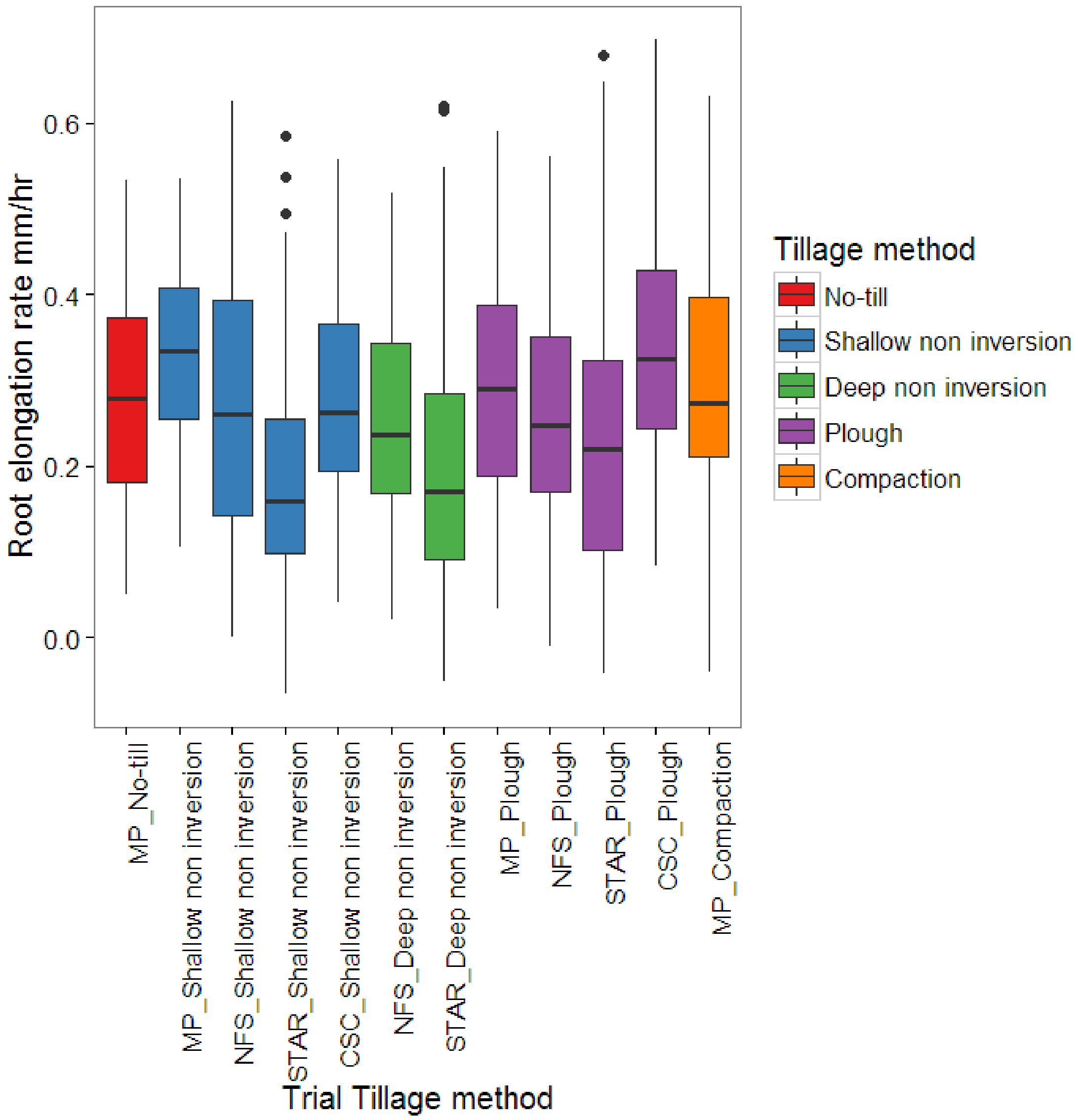


Figure 4.6.1 Overall root elongation at -20kPa in soil cores from all Trials, Treatments and Samplings. Dots illustrate where significant outliers appear in the dataset.

Linear mixed model assessment of the full dataset suggested significant effects of Trial (p=0.003), Tillage (P<001), Sampled Depth (P<0.001) and interaction effects of Trial x Sampling Time (P<0.001), Trial x Sampled Depth (P=0.002) and Sampling Time x Sampling Depth (P<0.001), where Trial_Plot_Rep, Within_Plot_Rep, Root_Elongation_Assay_Grouping, Root_Elongation_Assay_Grouping/Starting_Root_length and Sampling season were treated as random factors. The model captured 48% of the variation in root elongation within the cores, with 32% of the variation explained by the Fixed effects.

4.6.1. Effects of Trial and Tillage on root elongation rates

Figure 4.6.2 shows the average root elongation rates recorded for the different trials, tillage treatments, sampling stages and sampling depth in the ex-situ root elongation assay. Overall there were significant differences in root elongation across the difference Trials (P=0.003). Root elongation was lowest in cores sampled from STAR trial at 0.19 mm / hr compared with the root elongation average in cores sampled from the CSC at 0.29 mm/hr. After repacking the soils from each Trial, Tillage, Sampling time (grouped by rep or plot where necessary), no significant effects of Trial, Tillage, Sampling time or Sampling depth were found. The Overall elongation rate in these repacked soils were found to range from NFC (0.38mm/ hour) to CSC (0.48 mm / hour) but there was no statistical difference between them.

This suggested a reduction in root elongation due to soil structure being in the region of 36.9 % (NFS) and 54.7 % (STAR) between the different Trials.

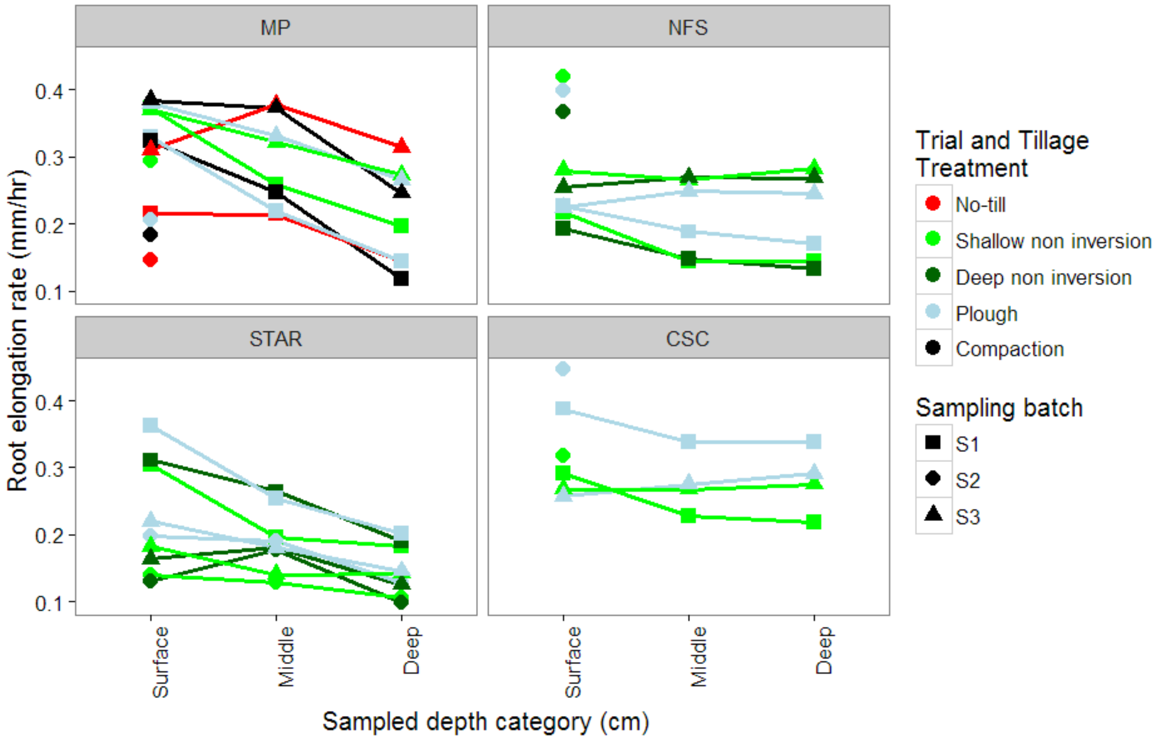
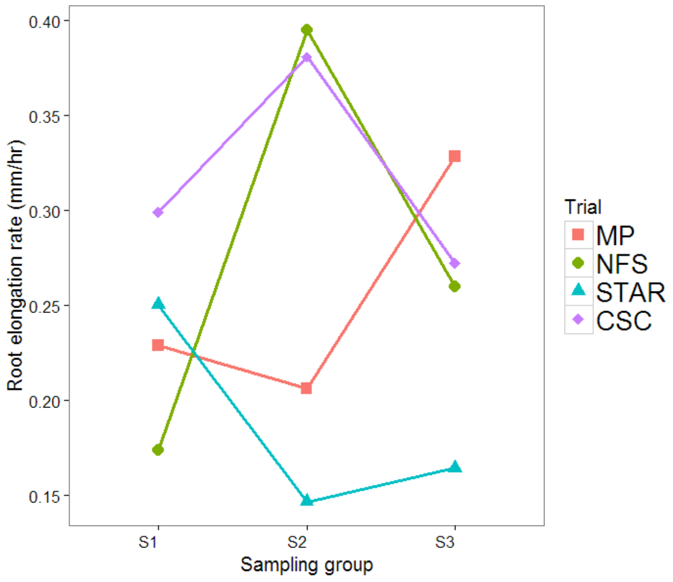


Figure 4.6.2 Average root elongation rates separated by trial, tillage treatment within trials, sampling stages and sampled depths. Sampling stages (S1 first sampling of the growth season (Autumn or April depending on rotation), S2 middle of the growth season (May), S3 (End of growth season (August).

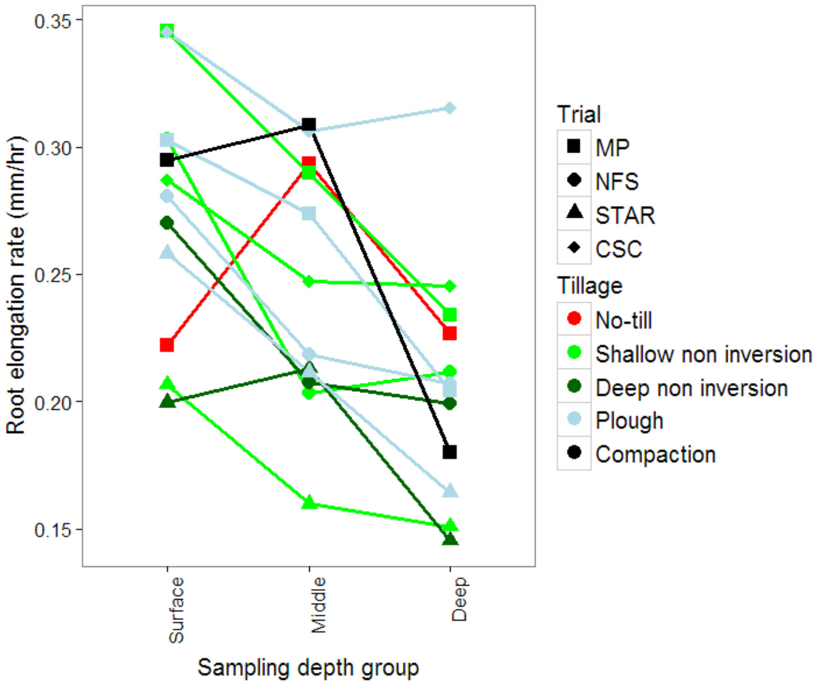
Average root elongation rates between tillage treatments across all Trials ranged from 0.19 mm / hr in the non-inversion shallow plots through to 0.25 mm/ hour in cores taken from the Inversion plough plots through to 0.3 mm / hour in the non-inversion minimum tillage plots. When Trial and Tillage categories were combined, this suggested that within Trials the major differences in root elongation rates between the tillage treatments were found between the Inversion plough and Non inversion sustainable treatment within the CSC (0.34 vs 0.27 mm/hr respectively) and between the Inversion plough and Non inversion shallow treatment for the STAR trial (0.21 vs 0.18 mm / hour respectively), See also Figure 4.6.1.

4.6.2. Effects of Sampling time and Depth across trials

Analysis across the complete dataset showed a significant interaction of trial and sampling time with respect to the rate at which roots elongated in the soil cores (p<0.001 Figure 4.6.3 A). Whereas the root elongation increased in the CSC and NFS Trials between samplings S1 and S2 , returning back down for Sampling S3, the opposite effect occurred for the soil from Mid-Pilmore and the STAR Trial. There were also effects of sampled depth on the rate of root elongation. Root elongation across all trials and treatment drops from an average of 0.28 mm / hr in the surface cores down to 0.21 mm/ hr in the cores sampled from the deeper soil profiles. Evidence of interaction with Trial and Tillage was also present (P<0.002 Trial x Soil Depth, and P=0.004 Trial x Soil Depth Cat, P =0.02 Tillage x Soil Depth). Figure 4.6.3 B shows the variation in the root elongation rates averaged over Trial_Tillage combinations.



A

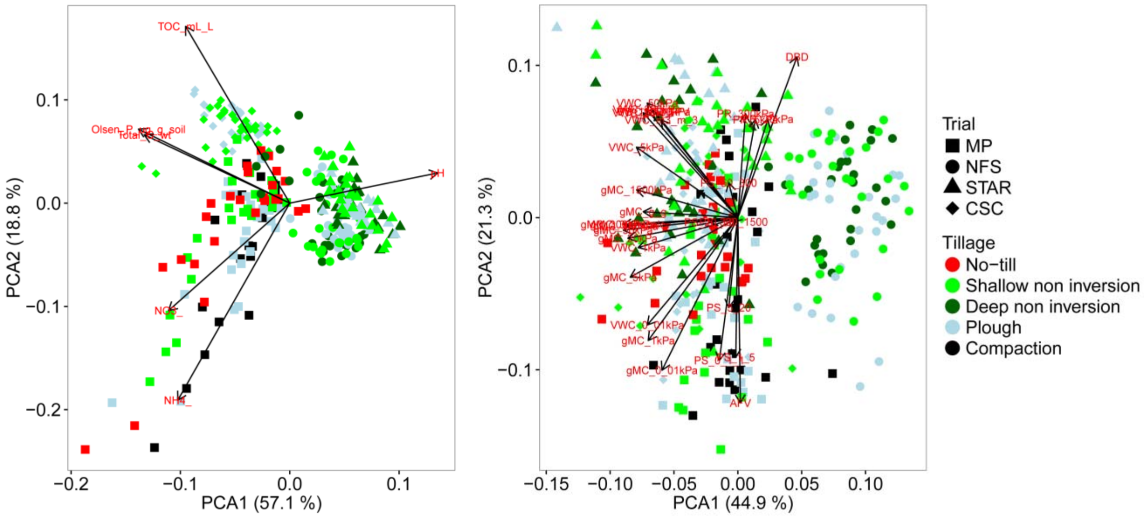


B

Figure 4.6.3 Sampling time and depth effects across Trials in complete dataset, using barley (cv. Optic) averaged across all replicates.

4.6.3. Chemistry data and its relationship with growing season, trials, tillage, sampling time, sampling depth

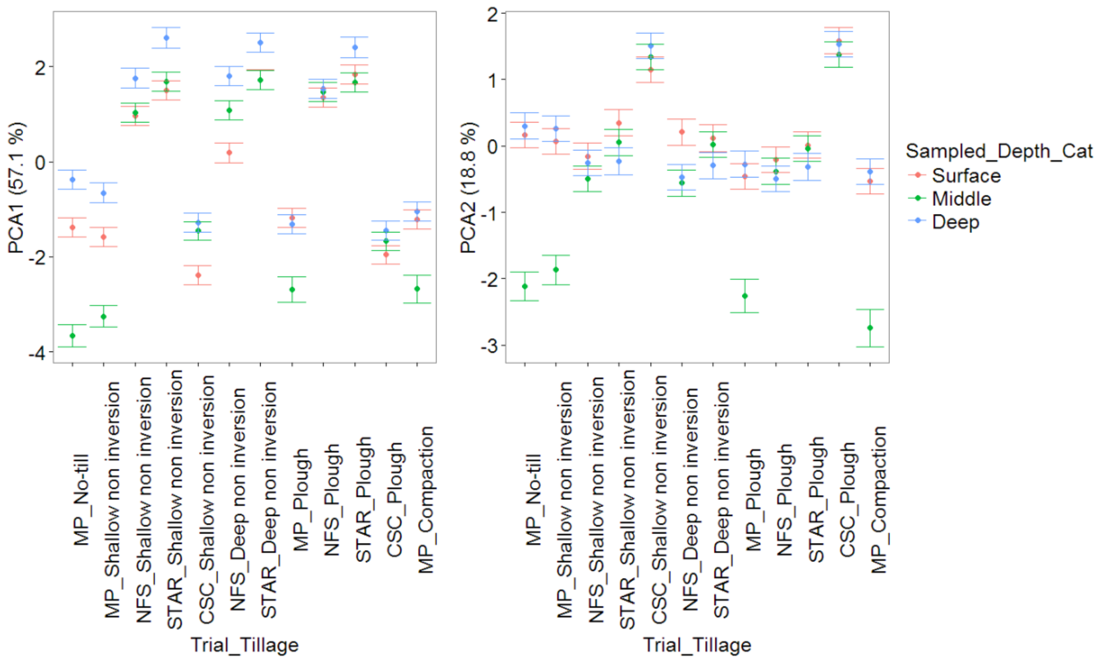
Principal components analysis captures the variation in many measurements into fewer parameters/components. Analysis of the baseline Y1 chemistry (Chem Dataset) subset of the soils data showed that 57.1 and 18.8% of the variation in the chemistry parameters were accounted for by two principal components suggesting a levels of correlation between the different chemical parameters measured. In comparison 44.9 and 21.3% of the variation in physical parameters of this subset dataset of samples were accounted for by the first two components. (Figure 4.6.4).



A B

Figure 4.6.4 Principal component analysis of initial chemical properties (A) and physical properties (B), using only the samples taken at the same time as the chemical sampling.

Principal component 1 of the chemistry data split the data based on sites, with the Scottish sites having more negative values ($p<0.001$ F = 44.573). PC1 was driven mainly by differences in pH, Total C (by weight) and Olsen P. There were also significant differences in chemistry overall for the difference depths sampled ($P<0.001$ F = 94.028), with a significant interaction between site/management and depth. Within each site the only significant difference in PCA1 for the chemistry was found between tillage treatments deep non-inversion and inversion plough systems at the NFS site. Similarly, PCA2 separated CSC samples from the samples from the other three sites. These differences were driven mainly by total organic carbon vs nitrogen parameters. Mid-Pilmore showed a large interaction with sampling depth for the chemistry first and second principal components (Figure 4.6.5).



A B

Figure 4.6.5 Variation in chemical characteristics across the trials in relation to treatment.

The combined effect of the chemical and physical parameters of the soil cores as captured by the first and second principal components on root elongation is illustrated in Figure 4.6.6. For the chemical parameters PCA1 and PCA2 explained approximately 19% and 0.5% of the variation in root growth found in the cores. This appeared to be linked mainly due to the differences in the chemistry between Scottish and English sites. Therefore 19% of the variation in the root elongation was correlated to the 57% of the chemistry variation. Within this subset of the data, PCA1 of the physical parameters only accounted for 1% of the root elongation rate in the cores, however PCA2 which explained 21.3% of the soil physical variation accounted for 37% of the variation in the root elongation in the cores.

PCA1 of the chemistry was mainly driven by differences in total carbon, Olsen P vs pH, whereas PCA2 of the physical PCA analysis was mainly driven by differences in large macropores, airfilled volume vs dry bulk density and high soil strength.

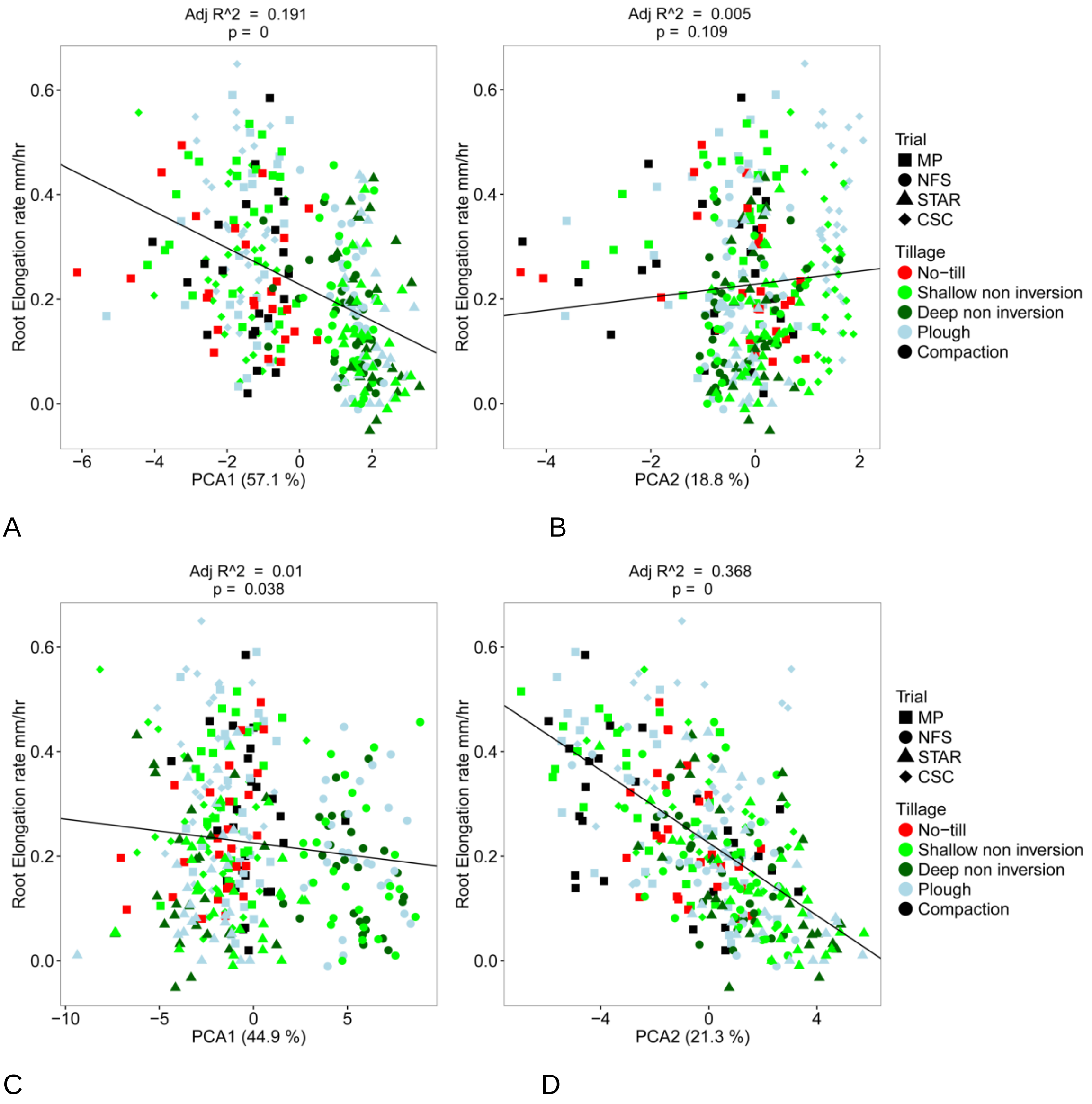
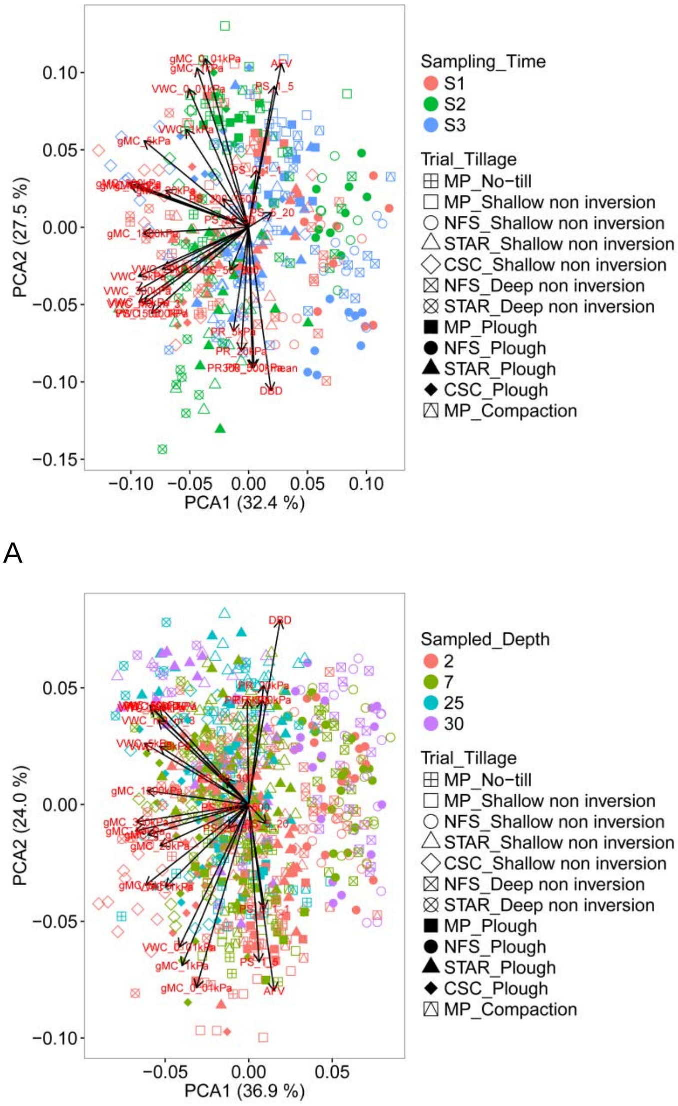


Figure 4.6.6 Correlation between soil physical and chemical properties and root elongation rates in the season 1 soil cores taken at the same time as the samples used for chemical analysis. Root elongation in soil cores vs A) PCA1 and B) PCA2 of the chemistry parameters, vs C) PCA1 and D) PCA2 of physical parameters.

4.6.4. Effects of Soil physical properties on root elongation across growth season and due to depth

Principal components analysis of the surface only cores or the sampling S1_S3 cores captured (32.4%, 27.5% Figure 4.6.7 A) and (36.9%, 24.0% Figure 4.6.7 B) in each of the first two principal components repsectively. Both first component separated the distribution of cores based mainly on their gravimetric and volumetric water content properties. In contrast the second components mainly separated cores based on their soil strength or air filled volume / Pore structural characteristics.



A

B

Figure 4.6.7 Principal components analysis of soil cores analysis (A) included only surface cores, but included samplings S1,S2 and S3 for all years, analysis (B) included only samplings S1 and S3 cores, included all sampled depths.

To assess the impact of the difference in physical properties on root elongation, correlations between the components and root elongation in the individual cores were assessed (Figure 4.6.8). The first components of the surface only cores only accounted for 5% of the root elongation rate in those cores (P<0.001) and the first component of the S1_S3 analysis did not have a signicant correlation with the root elognation. Both components were driven mainly by differences in the cores' gravimetric and volumetric water content properties. In contrast the second component of each of the analysis explained a much larger proportion of the variation in root elongation rates in the soil cores, with the surface only cores principal component accounting for 17.7% of the variation in the root elongation rates (P<0.001) and the second component of the S1_S3 analysis accounting for 31.3% of the variation in the root elongation in the cores. The more positive the second principal component the higher the soil strength and the lower the Air filled volume and pore volume properties.

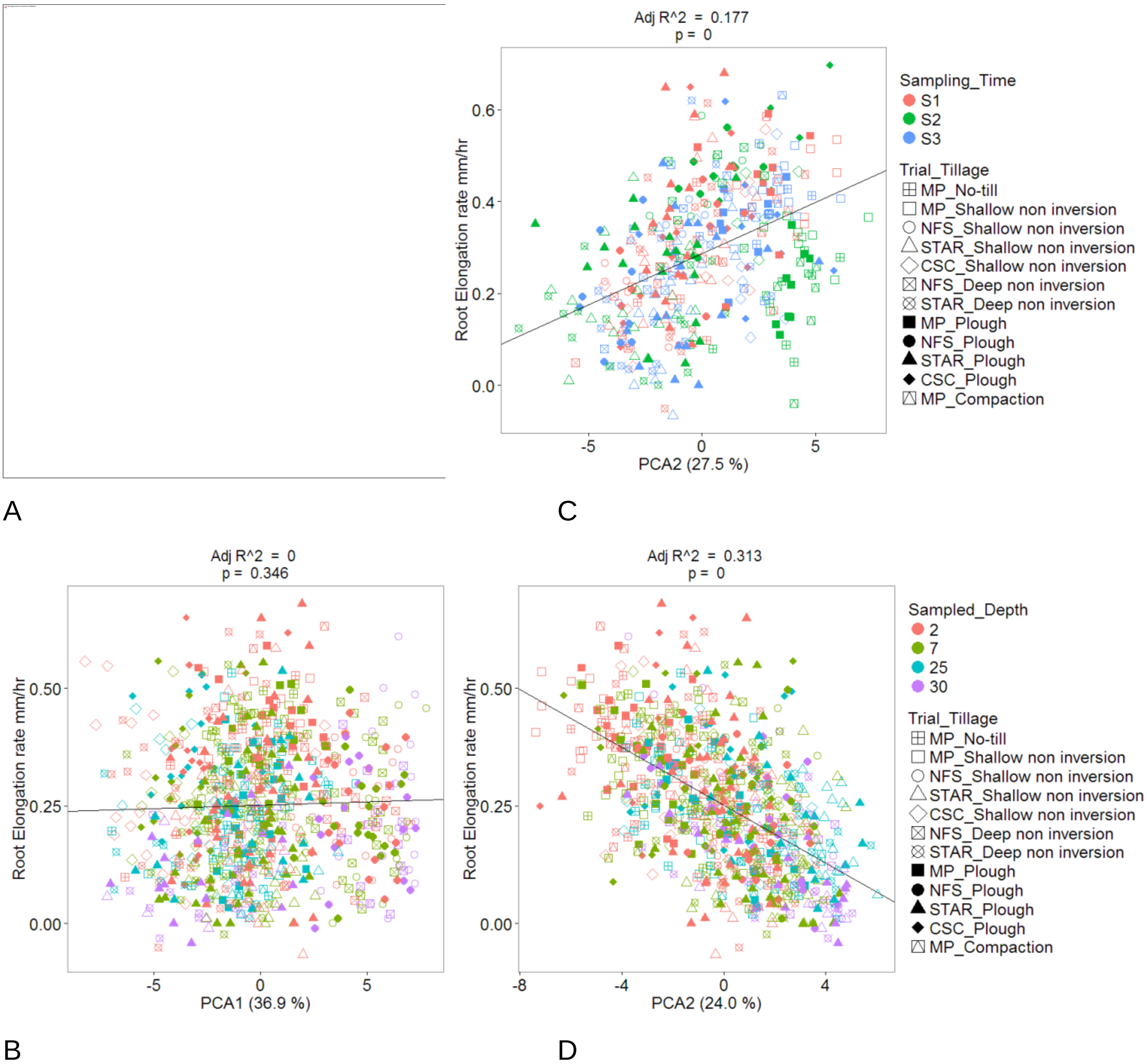


Figure 4.6.8 Correlation analysis linking the root elongation rates in individual cores to principal components of soil physical properties. A, C Surface only cores, B, D Samples from S1 and S3 only. A, B First component, C,D second component.

To assess the relationships between soil physical properties in individual Trials further, datasets were split into each individual trials and the properties were assessed for effects of Tillage, Sampling Time and Depth Category (Table 4.6.1). The properties were also individually correlated against the root elongation rates. The table shows that some soil properties change in response to Tillage and/ or sampling time or sampling depth. However within a specific trial not all of these properties correlate with the root elongation rates, an example is the gravimetric water content. This parameter only correlated with root elongation rates in the CSC, but not in the other trials. However some parameters change with some or all of Tillage, Sampling time and depth and are also highly correlated to the root elongation rate in that trial e.g. Air filled porosity or PCA2. Relationships between soil tillage, soil parameters and root elongation rates are complex, for example the PCA2 parameter accounted for 16, 49, 23 and 18 % of the root elongation rates in each of the individual trials (MP, NFS, STAR, CSC respectively). In the Mid-Pilmore and STAR Trials this parameter was significantly affected by the Tillage treatments, Sampling time and Sampling depth categories; however in the CSC the parameter was not affected by the tillage treatments, and in the NFS while there was no main effect of tillage treatment there was a three way interaction with Sampling Time and Depth. The highest correlation between a single parameter was found in the NFS dataset where the pore space PS_1_5 parameter accounted for 46% of the variation in root elongation. This parameter was affected by Tillage, Sampling time, with Sampling time:Depth and Tillage:Sampling_Time:Depth interactions. The large datasets created by this analysis will be further investigated for consistent relationships across Trials and tillage methods.

Table 4.6.1. Analysis of individual trial datasets for effects of tillage, sampling time, and depth category for each of the soil physical characteristics. Root column - Relationship between individual soil property and root elongation showing marginal (fixed effects) and conditional (whole model) R^2. Bold highlights indicate where soil parameter was significantly affected by tillage either alone or as an interaction with time or depth and there is a significant relationship between the soil parameter and the root elongation rate.

	MP					**NFS**					**STAR**					**CSC**				
Soil Parameter	**Tillage (T)**	**Time (S)**	**Depth (D)**	**Interactions**	**Root (R^{2}m, R^{2}c)**	**Tillage(T)**	**Time(S)**	**Depth(D)**	**Interactions**	**Root (R^{2}m, R^{2}c)**	**Tillage(T)**	**Time(S)**	**Depth(D)**	**Interactions**	**Root (R^{2}m, R^{2}c)**	**Tillage (T)**	**Time (S)**	**Depth (D)**	**Interactions**	**Root (R^{2}m, R^{2}c)**
Root elongation rate	*	***	***	T:D *		ns-r	***	ns-r	S:D ***		**	***	***	S:D ***		**	**	-ns-r	T:S *	
AFV	***	***	***	T:S ns T:S *** S:D ns T:S:D *	*** **0.24** 0.29	ns-r	***	ns-r	S:D ***	*** 0.35 0.35	***	***	***	S:D **	*** **0.22** 0.48	-ns-r	**	***	-ns-r	*** **0.14** 0.16
gMC	**	*	ns-r	ns-r	ns	***	ns-r	***	T:D ***	ns	ns-r	ns-r	ns-r	ns-r	ns	ns	***	ns	T:S T:D	** **0.07** 0.13
VWC	***	***	***	T:S * T:D **	*** **0.23** 0.29	**	***	ns-r	S:D **	*** **0.12** 0.14	ns-r	ns-r	***	ns-r	*** 0.16 0.39	ns	***	-ns-r	T:S *	ns
DBD	***	***	***	T:S ns T:D ** S:D ns T:S:D **	*** **0.21** 0.25	ns-r	***	**	S:D ***	*** 0.36 0.36	***	***	***	S:D *	*** **0.20** 0.48	-ns-r	-ns-r	***	-ns-r	*** **0.20** 0.24
PAW	**	*	**	T:S ***	* **0.02** 0.10	*	ns	***	T:S * T:D *** S:D *** T:S:D *	ns	**	ns	***	T:D * S:D ***	* **0.01** 0.27	ns	**	*	T:D *** S:D*	ns
PR_5	ns	***	ns-r	T:S **	* 0.02 0.10	ns-r	***	ns	S:D **	*** 0.23 0.23	***	***	***	ns-r	*** **0.12** 0.44	-ns-r	ns	**	S:D **	ns
PR_20	*	***	***	T:D ***	*** **0.11** 0.19	ns-r	***	ns	S:D **	*** 0.23 0.23	***	***	***	ns-r	*** **0.06** 0.35	-ns-r	-ns-r	***	-ns-r	*** 0.09 0.19
PR_300	ns	***	***	T:S **	*** **0.12** 0.17	ns	***	ns	T:S ** S:D ***	*** **0.08** 0.10	ns-r	***	***	ns-r	*** 0.08 0.33	-ns-r	ns	ns	S:D **	** 0.07 0.11
PS_0.1_1	*	***	***	T:S **	*** **0.14** 0.23	ns-r	***	ns-r		ns	ns-r	***	***	ns-r	*** 0.13 0.35	ns	***	**	T:S **	*** **0.24** 0.24

PS_1_5	***	***	***	T:S *** T:D *	** **0.04** 0.12	***	*	ns	T:S ns T:D ns S:D *** T:S:D ***	*** **0.46** 0.46	***	***	***	T:S **	*** **0.09** 0.42	-ns-r	***	-ns-r	-ns-r	** 0.09 0.18
PS_5_20	***	**	ns-r	ns-r	ns	***	***	***	T:S ns T:D * S:D *** T:S:D ***	*** **0.29** 0.29	ns-r	***	***	ns-r	*** 0.10 0.38	-ns-r	***	-ns-r	-ns-r	ns
PS_20_50	ns	*	ns-r	T:S **	ns	ns-r	ns-r	*	ns-r	ns	ns-r	**	***	S:D *	*** 0.06 0.34	**	**	ns	T:S ** S:D *	** **0.16** 0.16
PS_50_300	**	*	*	T:S ***	** 0.03 0.12	*	ns	***	T:S * T:D *** S:D *** T:S:D *	ns	***	ns	***	T:S ** T:D * S:D ***	NS	*	***	***	T:S *** T:D ***	ns
PS_300_1500	*	***	ns-r	T:S *	*** **0.10** 0.13	**	***	**	T:S **	* 0.04 0.04	ns-r	ns-r	***	ns-r	ns	***	ns	-ns-r	-ns-r	ns
PS_1500_TPV	ns-r	***	***		*** **0.12** 0.16	*	*	ns-r	ns-r	*** 0.09 0.15	***	***	***	ns-r	*** **0.14** 0.44	***	***	*		*** **0.19** 0.22
Phys_PCA_1	***	***	***	ns-r	*** **0.19** 0.25	*	***	***	T:S ** T:D ***	ns	***	***	**	ns-r	*** 0.05 0.28	**	**	ns	T:D **	ns
Phys_PCA_2	***	***	***	T:S * T:D *** S:D ns T:S:D **	*** **0.16** 0.26	ns-r	***	***	T:S ns T:D ns S:D *** T:S:D *	*** **0.49** 0.50	***	***	***	T:D *	*** **0.23** 0.56	-ns-r	**	**	-ns-r	*** **0.18** 0.24
Phys_PCA_3	ns	***	*	T:S **	*** **0.12** 0.20	ns-r	***	**	S:D ***	** 0.06 0.06	*	***	ns-r	ns-r	*** 0.09 0.29	**	**	*	-ns-r	ns
Phys_PCA_4	*	***	**	T:S **	*** **0.17** 0.23	ns	***	**	T:S * S:D ***	** 0.06 0.06	ns-r	**	***	ns-r	* 0.01 0.24	***	-ns-r	-ns-r	-ns-r	ns

R2m <- proportion of variation explained by fixed effects alone. R2c <- proportion of variation explained by fixed and random.

ns-r parameter removed during model fitting process based on AIC i.e. not present in final fitted model, ns included in final model but not significant at the 95% level. * p<0.05, ** p<0.01, *** p<0.001

Abbreviations -

Air filled volume (AFV – cm^3 air / cm^3 core volume), Gravimetric moisture content (gMC g water / g dry soil), Volumetric water content (VWC cm^3 water / cm^3 core volume), Dry Bulk density (DBD g dry soil / cm^3 core volume), Plant Available water (PAW), Soil strength as penetrometer resistance at -5kPa (PR_5 MPa), at -20kPa (PR_20 MPa), at -300kPa (PR_300 MPa),

Volume occupied by pores of diameter >300µm (PS_0.1_1), between 300 µm and 60 µm (PS_1_5), between 60 µm and 15 µm (PS_5_20), between 15 µm and 6 µm (PS_20_50), between 6 µm and 1 µm (PS_50_300), between 1 µm and 0.2 µm (PS_300_1500) and less than 0.2 µm (PS_1500_TPV).

Principle components 1:4 of the physical properties only Dataset (Phys_PCA_1,Phys_PCA_2,Phys_PCA_3 Phys_PCA_4)

4.6.5. Effects of trial, sampling, depth and link to root elongation.

1. Chemical properties of the soil accounted for a higher proportion of the variation in root elongation in this dataset than reported in Valentine et al (2012), however the physical properties still accounted for a higher proportion of the root elongation rates than the chemical properties.
2. After reducing the differences in physical properties by repacking the soil cores no differences were found between the root elongation rates linked to Trial, Tillage, sampling time or depth. Suggesting the differences in the physical properties were the main drivers in differences at this early rooting stage.
3. Evidence of effects of Trial, Tillage both within and across sites, Sampling time and sampling depth has been found in terms of the rates of root elongation achieved and in terms of changes in soil physical properties.
4. Soil pore structure and AFV were important parameters that were linked to changes in Tillage, sampling time and sampling depth across the different Trials, with these properties having high correlation with the root elongation rates.

4.7. Yield and Economic Performance

Within the STAR and NFS projects the plough (inversion), deep non-inversion and shallow non-inversion (as described in the Introduction) are ‘consistent systems’ and remain the same across seasons, however, the managed approach is a ‘variable system’ and changes with season and crop; this needs to be considered within the interpretation of the results presented. Within the Mid-Pilmore project the plough (inversion), deep plough (deep inversion) and shallow non-inversion (see Introduction) are ‘consistent systems’ and remain the same across seasons. Yield and margin data for individual seasons are presented in the following sections and then considered collectively across the rotation. Where cover crops, or fallow periods, have featured costs are presented in individual seasons for clarity, but not included in the financial analysis for the given season. Cover crop impacts / benefits are accrued rotationally (rather than solely in the season of cropping) and costs should therefore be treated similarly: inclusion of these costs is addressed in section 4.7.5 considering rotational responses. The full cost and margin breakdown can be found in Appendices 3-5.

4.7.1. STAR project:

For the 2012/13 season, STAR project year 8, winter wheat (cv. Santiago) was sown. Due to wet field conditions the first replicate was sown on the 06/10/12 and replicates 2 and 3 were sown on the 16/10/12. Yield and margin data are presented in Table 4.7.1; with statistically significant differences apparent for yield. Regarding cultivation systems (irrespective of rotation), the highest mean yield and margin was associated with the managed system. Considering the consistent systems, while the highest mean yield was achieved with the plough, the mean margins for the plough and deep non-inversion systems were within £1/ha of each other. With respect to the impact of rotation irrespective of cultivation system, the mean continuous wheat yield was c. 1.9 – 2.4 t/ha less than other approaches and also resulted in the lowest margin.

Table 4.7.1: Yield and margin summary information from winter wheat in STAR year 8 (2012/2013).

	Yield (t/ha)						Margin (£/ha)				
	Winter	Spring	Cont	Alt Fallow	Mean		Winter	Spring	Cont	Alt Fallow	Mean
Plough	9.39	9.04	7.08	8.91	8.61		768	716	422	696	651
Managed	8.92	9.50	7.84	8.23	8.62		743	830	581	652	702
Shallow	8.62	8.92	5.85	8.65	8.01		711	756	295	715	619
Deep	8.66	9.16	6.48	8.91	8.30		704	779	377	741	650
Average	8.90	9.16	6.81	8.68			732	770	419	701	
P value	P=0.0001										
LSD t/ha	1.14										
CV %	8.2										

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 68ppl; N at 80p/kg N and wheat at £150/t.

In the 2013/14 season, STAR project year 9, the study was in a ‘break crop year’ (see Table 2.2) and sown with winter oilseed rape (cv. Incentive, sown 06/09/13; winter cropping), spring oats (cv. Conway, sown 27/03/14; spring cropping) and winter wheat (cv. Santiago, sown 09/10/13; continuous wheat). Yield and margin data are presented in Table 4.7.2; statistically significant yield differences were only apparent in the spring oats. The good yields e.g. for winter wheat are possibly due to the very good environmental conditions at grainfill. The fallow cost was c. £120/ha (including input, management and additional machinery costs) and is not included in the margin data presented. Considering yield data with respect to cultivation systems, in the winter oilseed rape and spring oats the highest yields were associated with the plough based system, whereas in the continuous winter wheat the highest yields were associated with the shallow tillage system. The cultivation system giving the highest margin varied with crop; for the winter oilseed rape the highest margin arose from the deep non-inversion system and in the continuous wheat and spring oats the shallow non-inversion system. Mean margins achieved from spring oats were notably lower than those achieved for either winter oilseed rape or continuous wheat.

Table 4.7.2: Yield and margin summary information from break crops in STAR year 9 (2013/2014).

	Yield (t/ha)					Margin (£/ha)				
	Winter (OSR)	Spring (oats)	Cont (WW)	Alt Fallow		Winter	Spring	Cont	Alt Fallow	Mean
Plough	4.68	6.47	10.66	-		774	250	664	-	563
Managed	4.12	6.21	10.54	-		719	284	693	-	565
Shallow	3.78	6.27	10.73	-		624	302	728	-	551
Deep	4.67	5.22	10.38	-		861	185	674	-	573
Average	4.31	6.04	10.58	-		745	255	690	-	
P value	NS	P<0.05	NS	-						
LSD t/ha	0.58	0.71	0.96	-						
CV %	6.4	5.9	4.5	-						

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 68ppl; N at 72p/kg N; wheat (£120/t); OSR (£280/t); oats (£100/t).

An additional cost of c. £120/ha could be applied to the delivery of the fallow treatments in 2013/14.

The 2014/15 season, STAR project year 10, was sown with winter wheat (cv. Skyfall) on the 02/10/14. Yield and margin data are presented in Table 4.7.3; with statistically significant differences apparent for yield. Regarding cultivation systems (irrespective of rotation), the highest mean yield and margin was associated with the managed system. Considering the consistent systems, the highest mean yield was achieved with the deep non-inversion system, although there was little difference between plough, deep non-inversion or shallow non-inversion approaches. The mean margins across rotations for the managed, deep non-inversion or shallow non-inversion approaches were all within £5/ha of each other and c. £70/ha above the mean ploughed margin. With respect to the impact of rotation irrespective of cultivation system, the mean continuous wheat yield was c. 0.6 – 1.0 t/ha less than other approaches and also resulted in the lowest margin.

Table 4.7.3: Yield and margin summary information from winter wheat in STAR year 10 (2014/2015).

	Yield (t/ha)		Margin (£/ha)	

	Winter	Spring	Cont	Alt Fallow	Mean		Winter	Spring	Cont	Alt Fallow	Mean
Plough	12.14	11.67	10.84	11.93	11.65		850	771	694	825	785
Managed	11.56	11.77	11.44	12.24	11.75		851	821	824	920	854
Shallow	11.74	11.61	11.04	12.11	11.63		872	834	788	917	853
Deep	11.89	11.68	10.98	12.23	11.70		878	830	769	919	849
Average	11.83	11.68	11.08	12.13			863	814	769	895	
P value	P=0.0001										
LSD t/ha	0.47										
CV %	2.5										

Margins represent a gross output minus direct input and machinery costs. Margins use on diesel at 58ppl; nitrogen at 70p/kg N and wheat at £120/t.

In the 2015/16 season, STAR project year 11, the study was in a ‘break crop year’ (see Table 2.2) and sown with winter beans (cv. Tundra, sown 20/10/15; winter cropping), spring beans (cv. Vertigo, sown 24/03/16; spring cropping) and winter wheat (cv. Zulu, sown 04/10/15; continuous wheat). Yield and margin data are presented in Table 4.7.4; statistically significant yield differences were apparent in the spring beans and differences were close to significance (P=0.08) in the continuous wheat. Seasonal study related issues caused by wet conditions at drilling in combination with pest problems (notably rook damage on plots) resulted in poor and patchy establishment in the winter bean deep non-inversion tillage and generally across the spring bean crop. The fallow cost was c. £140/ha (including input, management and additional machinery costs) and is not included in the margin data presented. Regarding the spring cropping field conditions impacted particularly on spring bean shallow non-inversion tillage treatment, however, all spring bean yields should be treated with some caution. Given this was an artefact of the study, the winter bean deep non-inversion tillage and spring bean shallow non-inversion treatments results were considered unrepresentative for these treatments and yields have been removed from the presented analysis. This limits the yield and margin comparisons that can be drawn; however, regarding the winter bean crops, the highest yield and margins were associated with the shallow non-inversion tillage treatment. Considering spring beans, as indicated, all yields were poor and resulting margins were negative, however, the highest yields were associated with the managed approach. With respect to the continuous wheat, while the highest yields resulted from the managed approach, the highest margins were associated with the shallow tillage treatments.

Table 4.7.4: Yield and margin summary information from break crops in STAR year 11 (2015/2016).

	Yield (t/ha)		Margin (£/ha)	

	Winter (W bean)	Spring (S bean)	Cont (WW)	Alt Fallow		Winter	Spring	Cont	Alt Fallow	Mean
Plough	2.89	1.46	7.05	-		48	-238	227	-	12
Managed	2.96	2.83	7.88	-		32	-72	376	-	112
Shallow	3.22	-	7.08	-		127	-	290	-	209
Deep	-	1.26	7.05	-		-	-186	276	-	45
Average	3.02	1.85	7.27	-						
P value	NS	P<0.05	NS (P=0.08)	-						
LSD t/ha	1.02	2.68	0.75	-						
CV %	14.9	41.3	4.9	-						

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 42ppl; N at 58p/kg N; wheat at £120/t and beans at £140/t.

An additional cost of c. £140/ha could be applied to the delivery of the fallow treatments in 2013/14.

Note: the deep non-inversion tillage winter beans and shallow non-inversion tillage spring beans were both crop failures.

NFS cultivations project:

For the 2012/13 season, NFS cultivations project year 6, the study was sown with spring barley (cv. Propino) on the 03/04/13. Yield and margin data are presented in Table 4.7.5; statistically significant differences in yield were not apparent (a P value of 0.15 was recorded). The cover crop cost was c. £80/ha (including input, management and additional machinery costs) and is not included in the margin data presented for the cover crop based rotation; the cover crop was sown on the 14/09/12. Regarding cultivation systems, in both the non-cover cropped approach and the mean across systems, the highest mean yield was associated with the plough system and the lowest with shallow non-inversion tillage. In the non-cover cropped approach and the mean across systems, the margins for plough, managed and deep non-inversion systems were similar and the lowest margin was associated with the shallow non-inversion tillage approach.

Table 4.7.5: Yield and margin summary information from spring barley in NFS year 6 (2012/2013).

	Yield (t/ha)				Margin (£/ha)		
	No cover crop	Cover crop	Mean		No cover crop	Cover crop	Mean
Plough	5.28	5.27	5.28		391	389	390

Managed	5.09	5.31	5.20		384	417	401
Shallow	4.70	4.85	4.78		336	359	348
Deep	5.17	5.13	5.15		396	389	393
Average	5.06	5.14	-		377	389	
P value	NS (P=0.15)						
LSD t/ha	0.48						
CV %	6.4						

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 68ppl; N at 80p/kg N and spring barley at £155/t.

For the 2013/14 season, NFS cultivations project year 7, the study was in a winter cropping year and no cover crop was grown in this season. The study was sown with winter oilseed rape (cv. PR46W21) on the 26/08/13. Yield and margin data are presented in Table 4.7.6; statistically significant differences in yield were apparent. Regarding cultivation systems in both the non-cover cropped approach and the mean across systems, the highest yield and margin were recorded with the managed approach and the lowest mean yield and margin with the plough. Further crop performance data relating to plant populations and ear counts are reported in Appendix 1. In general, increased crop performance was reflected in higher yields and margins.

Table 4.7.6: Yield and margin summary information from winter oilseed rape in NFS year 7 (2013/2014).

	Yield (t/ha)				Margin (£/ha)		
	No cover crop	Cover crop	Mean		No cover crop	Cover crop	Mean
Plough	3.63	3.30	3.47		563	470	517
Managed	4.42	4.12	4.27		806	722	764
Shallow	4.19	4.00	4.10		755	701	728
Deep	3.96	3.72	3.84		677	610	644
Average	4.05	3.79	-		700	626	
P value	P<0.01						
LSD t/ha	0.48						
CV %	8.3						

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 68p/l, nitrogen at 70p/kg N and oilseed rape at £280/t.

The 2014/15 season, NFS project year 8, the study was in a winter cropping year and no cover crop was grown in this season. The study was sown with winter wheat (cv. Relay) on the 30/09/14. Yield and margin data are presented in Table 4.7.8; statistically significant differences were not apparent for yield. Yield differences with respect to system were generally small, but regarding cultivation systems in both the non-cover cropped approach and the mean across systems, the highest mean yield and margin across was associated with the deep non-inversion system.

Table 4.7.8: Yield and margin summary information from winter wheat in NFS year 8 (2014/2015).

	Yield (t/ha)				Margin (£/ha)		
	No cover crop	Cover crop	Mean		No cover crop	Cover crop	Mean
Plough	10.61	10.78	10.70		741	761	751
Managed	10.72	10.50	10.61		787	761	774
Shallow	10.26	10.65	10.46		732	779	756
Deep	11.33	11.21	11.27		848	834	841
Average	10.73	10.79	-		777	784	
P value	NS						
LSD t/ha	0.96						
CV %	6.1						

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 64p/l, nitrogen at 67p/kg N and wheat at £120/t.

For the 2015/16 season, NFS cultivations project year 9, the study was sown with spring oats (cv. Canyon) on the 11/04/16. Yield and margin data are presented in Table 4.7.9; statistically significant differences in yield were not apparent. The cover crop cost was c. £52/ha (including input, management and additional machinery costs) and is not included in the margin data presented for the cover crop based rotation; due to late harvest and field conditions the cover crop was not sown until the 04/09/15. Yield differences with respect to system were small, but regarding cultivation systems in both the non-cover cropped approach and the mean across systems the highest mean yield was recorded in the deep non-inversion system. With regard to margin, the lowest margin in both cover cropped and non-cover cropped systems was associated with the ploughed approach and highest mean margins with the shallow non-inversion systems.

Table 4.7.9: Yield and margin summary information from spring oats in NFS year 9 (2015/2016).

	Yield (t/ha)				Margin (£/ha)		
	No cover crop	Cover crop	Mean		No cover crop	Cover crop	Mean
Plough	8.11	8.03	8.07		600	590	595
Managed	8.06	8.11	8.09		627	633	630
Shallow	8.12	8.17	8.15		634	640	637
Deep	8.22	8.15	8.19		636	628	632
Average	8.13	8.12	-		624	623	
P value	NS						
LSD t/ha	0.43						
CV %	3.6						

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 40p/l, nitrogen at 50p/kg N and oats at £120/t.

4.7.2. Mid-Pilmore cultivations project:

For the 2012/13 season, Mid-Pilmore project year 6, the study was sown with 34 spring barley cultivars; of these 23 cultivars were common in seasons 6 (2012/13) though to 9 (2015/16). Yield and margin data are presented in Table 4.7.10; and are the mean yield figures for the 23 common cultivars grown under each cultivation approach across the seasons. This allowed for a comparison of cultivation approaches that were common across all sites. The zero tillage approach was not included in the yield and margin analysis due to the high weed burden that occurred as a result of this treatment. It was considered that this would have been unrepresentative of the performance potential of this approach. No significant differences between cultivation approaches were apparent for yield. Considering the cultivation approaches, while the highest mean yield was achieved with the deep plough, the margin for the plough and deep plough approaches were within £10/ha of each other.

Table 4.7.10: Yield and margin summary information from spring barley in Mid Pilmore year 6 (2012/2013).

	Yield (t/ha)		Margin (£/ha)
Deep Plough	5.60		500
Plough	5.55		510
Shallow	5.37		496
Average	5.51		502
P value	NS		
LSD t/ha	0.41		
CV %	3.3		

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 68ppl; N at 80p/kg N and barley at £155/t.

For the 2013/14 season, Mid-Pilmore project year 7, the study was sown with 23 common cultivars (as described previously). Yield and margin data are presented in Table 4.7.11; and are the mean yield figures for the 23 common cultivars grown under each cultivation approach. Statistically significant differences between cultivation approaches were apparent for yield. Considering the cultivation approaches, the highest mean yield of 4.6 t/ha was achieved with either plough or deep plough approaches, with the shallow non-inversion approach achieving a notably lower yield of 4.0 t/ha. The highest margin was associated with the plough approach (£298/ha) with the shallow non-inversion tillage approach resulting in the lowest margin of £250/ha.

Table 4.7.11: Yield and margin summary information from spring barley in Mid-Pilmore year 7 (2013/2014).

	Yield (t/ha)		Margin (£/ha)
Deep Plough	4.58		278
Plough	4.58		298
Shallow	4.00		250
Average	*4.39*		*275*
P value	P<0.05		
LSD t/ha	0.41		
CV %	4.1		

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 68ppl; N at 72p/kg N and barley at £140/t.

For the 2014/15 season, Mid-Pilmore project year 8, the study was sown with 23 common cultivars (as described previously). Yield and margin data are presented in Table 4.7.12; and are the mean yield figures for the 23 common cultivars grown under each cultivation approach. Statistically significant differences between cultivation approaches were apparent for yield. Considering the cultivation approaches, the highest mean yield of 5.8 t/ha was achieved with the plough approach, with the shallow non-inversion approach achieving a notably lower yield of 4.8 t/ha. The highest margin was associated with the plough approach (£442/ha) with the shallow non-inversion tillage approach resulting a reduction in margin of £96/ha *cf*. plough approach.

Table 4.7.12: Yield and margin summary information from spring barley in Mid-Pilmore year 8 (2014/2015).

	Yield (t/ha)		Margin (£/ha)
Deep Plough	5.65		406
Plough	5.76		442
Shallow	4.80		346
Average	*5.40*		*398*
P value	P<0.001		
LSD t/ha	0.26		
CV %	2.2		

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 64ppl; N at 70p/kg N and barley at £135/t.

For the 2015/16 season, Mid-Pilmore project year 9, the study was sown with 23 common cultivars (as described previously). Yield and margin data are presented in Table 4.7.13; and are the mean yield figures for the 23 common cultivars grown under each cultivation approach. Statistically significant differences between cultivation approaches were apparent for yield. Considering the cultivation approaches, the highest mean yield of 4.9 t/ha was achieved with the deep plough approach, with a similar yield in the plough approach of 4.8 t/ha. The shallow non-inversion approach achieved a notably lower yield of 3.6 t/ha. The highest margin was associated with the plough approach (£280/ha) with the shallow non-inversion tillage approach resulting a reduction in margin of £118/ha *cf*. plough approach.

Table 4.7.13: Yield and margin summary information from spring barley in Mid-Pilmore year 9 (2015/2016).

	Yield (t/ha)		Margin (£/ha)
Deep Plough	4.88		273
Plough	4.75		280
Shallow	3.59		162
Average	*4.41*		*238*
P value	P<0.01		
LSD t/ha	0.53		
CV %	5.3		

Margins represent a gross output minus direct input and machinery costs. Margins use diesel at 40ppl; N at 58p/kg N and barley at £130/t.

4.7.3. Long term responses in winter wheat in STAR and NFS

Within both STAR and NFS rotations the regular use of winter wheat enables the impact of cultivation method to be evaluated on this crop within the context of longer term data sets. Winter wheat yield data for the ‘consistent systems’ (where treatments have remained the same over this time period) from harvest years 2, 4, 6, 8 and 10 of the STAR project are presented in Table 4.7.14; this depicts the mean data for ‘all rotations’. Yield differences are significant in two of the five seasons with P values of around 0.1 apparent in two further seasons. Winter wheat yield from the ‘consistent systems’ (where treatments have remained the same over this time period) in harvest years 1, 3, 5 and 8 of the NFS Cultivations study is presented in Table 4.7.15. This shows the mean data for the ‘with and without’ cover crop rotational approaches. Yield differences presented for individual seasons are not statistically significant, although P values of around 0.1 in three of the four seasons were apparent. In both studies year had a statistically significant impact on yield and cross season differences were statistically significant in NFS but not in STAR. Further data for individual seasons not presented in the report can be found in Morris *et al*., 2014, Stobart *et al*. 2015 and Stobart *et al*. 2016.

Table 4.7.14: Yield (t/ha) and margin (£/ha) data for winter wheat and tillage in STAR in years 2 (2006/07), 4 (2008/09), 6 (2010/11), 8 (2012/13) and 10 (2014/15). Cross season analysis for tillage is as presented in the table; ‘year’ was significant at P<0.001 and ‘treatment x year’ interaction was NS.

	Seasonal yield data (t/ha)					Mean yield and margin data			
Tillage	Year 2	Year 4	Year 6	Year 8	Year 10	Mean yield (t/ha)	Yield (% of plough)	Margin (£/ha)	Margin (% of plough)
Plough	8.64	8.51	6.83	8.61	11.64	8.85	100	547	100
Deep	7.78	9.00	7.40	8.30	11.69	8.82	100	584	107
Shallow	7.52	8.80	7.32	8.01	11.62	8.66	98	571	104
Mean	7.98	8.77	7.18	8.31	11.65	-			
P value	*P*<0.0001	NS (*P*=0.14)	*P*<0.05	NS (*P*=0.11)	NS	NS			
LSD (t/ha)	0.45	0.42	0.49	0.57	0.24	1.02			

Table 4.7.15: Yield (t/ha) and margin (£/ha) data for winter wheat and tillage in NFS in years 1 (2007/08), 3 (2009/10) and 5 (2011/12) and 8 (2014/15). Cross season analysis for tillage is as presented in the table; ‘year’ was significant at P<0.001 and ‘treatment x year’ interaction at P<0.01.

	Seasonal yield data (t/ha)				Mean yield and margin data			
Tillage	Year 1	Year 3	Year 5	Year 8	Mean yield (t/ha)	Yield (% of plough)	Margin (£/ha)	Margin (% of plough)
Plough	12.75	8.26	10.41	10.70	10.53	100	921	100
Deep	12.55	8.17	10.54	11.27	10.63	101	978	106
Shallow	12.30	7.42	10.48	10.45	10.17	96	930	101
Mean	12.53	7.95	10.47	10.81	-			
P value	NS (*P*=0.16)	NS (*P*=0.11)	NS	NS (P= 0.10)	P<0.001			
LSD (t/ha)	0.30	0.77	0.21	0.68	0.16			

4.7.4. Long term responses in spring barley in Mid-Pilmore

Within Mid-Pilmore rotations the continuous use of spring barley enables the impact of cultivation method to be evaluated on this crop within the context of longer term data sets. Spring barley yield data for the ‘consistent systems’, using two commercial, Recommended List, cultivars of spring barley (cv Optic and Westminster) that were commonly grown across the full time period (seasons 1 (2008/09) through to season 9 (2015/16) with the exception of 2010/11 where only Optic was grown) are presented in Table 4.7.16 (other cultivars were not included either because they were breeding lines or other material associated with wider studies). Yield differences are significant in five of the nine seasons. Tillage and year had a statistically significant impact on yield and cross season differences were statistically significant in Mid-Pilmore. Relative mean yield across all seasons (based % of plough tillage) for the three tillage approaches indicated no difference between deep plough and plough (100%) but a drop in yield performance (89%) when using shallow non-inversion tillage.

Table 4.7.16: Yield (t/ha) data for spring barley and tillage in Mid-Pilmore in years 1 (2007/08), 2 (2008/09), 3 (2009/10), 5 (2011/12), 6 (2012/13), 7 (2013/14), 8 (2014/15) and 9 (2015/16). Cross season analysis for tillage is as presented in the table; ‘year’ was significant at P<0.001 and ‘treatment’ was significant at P<0.001.

	Seasonal yield data (t/ha)									Mean yield
Tillage	Year 1	Year 2	Year 3	Year 5	Year 6	Year 7	Year 8	Year 9	Mean yield (t/ha)	Yield (% of plough)
Deep Plough	4.91	5.49	6.49	4.36	5.61	5.11	6.02	5.13	5.39	100
Plough	4.73	5.50	6.48	4.44	5.56	5.08	6.31	5.05	5.39	100
Shallow	4.83	5.05	5.83	3.88	5.61	4.22	5.23	3.92	4.82	89
Mean	*4.82*	*5.34*	*6.26*	*4.22*	*5.60*	*4.80*	*5.86*	*4.70*	-	
P value	NS	NS	P<0.01	P<0.05	NS	P<0.01	P<0.01	P<0.01	P<0.01	
LSD (t/ha)	1.23	0.95	0.54	0.52	0.60	0.46	0.43	0.63	0.28	

4.7.5. Relative margin and variability in STAR and NFS

As well as considering margin data for STAR and NFS within seasons, the collective responses across seasons can also be evaluated; providing an indication of cumulative productivity and variability over seasons.

Cumulative yield and margin data from STAR over cropping seasons 8-10 of the study (i.e. those included in project RD-2012-3786) are presented in Table 4.7.17; results from year 11 have been excluded (due to field issues outlined previously) as have the additional costs associated with the alternate fallow treatment. Should the alternative fallow treatment be of interest an additional total cost of £120/ha was incurred over this period, although in practice the actual costs would vary with season and the fallowing approach used. Within STAR, with respect to cultivation the plough system resulted in the highest cumulative yields and the shallow non-inversion tillage the lowest. Considering margin, irrespective of cultivation approach, the winter cropping rotation resulted in the highest margin (this rotation was used for soil assessment work undertaken in this study). Within the winter cropping rotation the lowest cumulative margin was found in the shallow non-inversion system and the highest with the deep non-inversion system; a difference of £236/ha over three seasons. This latter treatment gives the highest cumulative output recorded in the study. Considered across all STAR rotations, the managed approach resulted in the highest cumulative margin and the plough system the lowest (difference of £122/ha over three seasons).

Table 4.7.17: Cumulative margin (£/ha) within season for STAR years 8 (2012/13) to 10 (2014/15).

	Cumulative yield over seasons 8-10 (t/ha)					Cumulative margin over seasons 8-10 (£/ha)				
Tillage	Winter	Spring	Cont	Alt Fallow	Mean	Winter	Spring	Cont	Alt Fallow	Mean
Plough	26.21	27.18	28.58	20.84	25.70	2392	1737	1780	1521	1858
Managed	24.60	27.48	29.82	20.47	25.59	2313	1935	2098	1572	1980
Shallow	24.14	26.80	27.62	20.76	24.83	2207	1892	1811	1632	1886
Deep	25.22	26.06	27.84	21.14	25.07	2443	1794	1820	1660	1929
Mean	25.04	26.88	28.47	20.80	-	*2339*	*1840*	*1877*	*1596*	-

Cumulative margin data from NFS over seasons 6-9 of the study (i.e. those included in project RD-2012-3786) are presented in Table 4.7.18. Margin data are presented with and without the cost of the cover crop (£132/ha cumulatively across this period). Cover crops were included in NFS in the first and last seasons of AHDB project RD-2012-3786 (2012/13 and 2015/16). Longer term findings from the NFS project, presented by Stobart *et al.* (2016), demonstrate that cover crop yield benefits are being accrued not only in the season of use but also rotationally in the NFS shallow tillage system. Consequently, the yield response and cover crop costs / returns (particularly those from the final project season) may not be fully expressed in the dataset presented. This should be considered when evaluating the returns including cover crop costs and, unless otherwise stated, comparisons made in the text refer to comparisons excluding cover crop costs.

Within NFS, with respect to cultivation the deep non-inversion tillage system resulted in the highest cumulative yields, while the lowest cumulative yield varied with approach: in the non-cover cropped systems this was associated with shallow non-inversion tillage while in the cover crop based approach the plough based system resulted in a lower cumulative yield. Regarding margin, whether considering the non-cover cropped systems within NFS (the rotation was used for the soil assessment work undertaken in this study) or the mean over both cover cropped and non-cover cropped systems, the plough resulted in the lowest cumulative margin and the managed approach the highest (difference of £309/ha over four seasons in the non cover cropped system and £316/ha over both approaches). Of the consistent systems the deep non-inversion systems was similar to the managed approach.

Table 4.7.18: Cumulative yield (t/ha) margin (£/ha) for NFS years 6 (2012/13) to 9 (2014/15).

	Cumulative yield over seasons 6-9 (t/ha)		
Tillage	No cover crop	Cover crop	Mean
Plough	27.63	27.38	27.51
Managed	28.29	28.04	28.17
Shallow	27.27	27.67	27.47
Deep	28.68	28.21	28.45
Mean	27.97	27.83	-
	Cumulative margin over seasons 6-9 (£/ha) (excluding the cost of the cover crop)		
Plough	2295	2210	2253
Managed	2604	2533	2569
Shallow	2457	2479	2468
Deep	2557	2461	2509
Mean	*2478*	*2421*	-
	Cumulative margin over seasons 6-9 (£/ha) (including the cost of the cover crop)		
Plough	2295	2078	2187
Managed	2604	2401	2503
Shallow	2457	2347	2402
Deep	2557	2329	2443
Mean	2478	2289	-

To consider variability in margin over seasons, the margins from each individual season can be considered and expressed as a percentage of the mean margin for the study that season. This output can then be averaged over a number of seasons. Table 4.7.19 presents this appraisal from STAR, considering mean responses across all rotations over cropping seasons 8-10 with respect to cultivation practice. The table also includes a standard error of the mean over this time to provide an indication of variability around the mean. Within STAR over this period the highest relative responses were recorded against the managed approach and deep non-inversion systems although the deep non-inversion system was subject to lower variability (Table 4.7.19). Within the NFS study an analogous appraisal based on season 6-9 is presented in Table 4.7.20. Within the non-cover cropped rotation, similarly, the highest relative responses were recorded against the managed approach and deep non-inversion systems, although the deep non-inversion system was again subject to lower variability (Table 4.7.20). The greatest degree of variability, on this medium soil site, was associated with the shallow non-inversion system. Considering mean response ranking over both NFS systems, impacts on variability were similar to those described for the non-cover cropped system. Comparing between the cover crop and non-cover crops systems a notable drop in variability was noted with the shallow tillage approach; suggesting that cover cropping reduced variability (improved resilience) in this approach.

Table 4.7.19: Margin (± SEM) expressed as a percentage of mean margin in a given season averaged over STAR years 8 (2012/13) to 10 (2014/15).

Tillage	Mean
Plough	*98 (± 1.9)*
Managed	*103 (± 2.0)*
Shallow	*98 (± 2.2)*
Deep	*101 (± 0.8)*

Table 4.7.20: Margin (± SEM) expressed as a percentage of mean margin in a given season averaged over NFS years 6 (2012/13) to 9 (2014/15).

Tillage	No cover crop	Cover crop	Mean
Plough	95 (± 3.6)	91 (± 6.9)	*93 (± 5.2)*
Managed	106 (± 5.2)	104 (± 2.8)	*105 (± 3.6)*
Shallow	99 (± 5.6)	101 (± 2.5)	*100 (± 4.0)*
Deep	104 (± 1.6)	100 (± 3.1)	*102 (± 2.2)*
Mean	*101 (± 1.6)*	*99 (± 1.6)*	

4.7.6. Relative margin and variability in Mid-Pilmore

As well as considering margin data for Mid-Pilmore within seasons, the collective responses across seasons can also be evaluated; providing an indication of cumulative productivity and variability over seasons.

Cumulative yield and margin data from Mid-Pilmore over seasons 6-9 of the study (i.e. those included in project RD-2012-3786) are presented in Table 4.7.21. With respect to cultivation, the deep plough approach resulted in the highest cumulative yields and the shallow non-inversion approach the lowest. The plough approach resulted in the highest cumulative margin and the shallow non-inversion approach the lowest (difference of £276/ha over four seasons).

Table 4.7.21: Cumulative margin (£/ha) within season for Mid-Pilmore years 6 (2012/13) to 9 (2015/16).

	Cumulative yield over seasons 6-9 (t/ha)	Cumulative margin over seasons 6-9 (£/ha)
Tillage		
Deep Plough	20.71	1457
Plough	20.64	1530
Shallow	17.76	1254
Mean	19.70	*1414*

To consider variability in margin over seasons, the margins from each individual season can be considered and expressed as a percentage of the mean margin for the study that season. This output can then be averaged over a number of seasons. Table 4.7.22 presents this appraisal from Mid-Pilmore, considering mean responses over cropping seasons 6-9 with respect to cultivation practice. The table also includes a standard error of the mean over this time to provide an indication of variability around the mean. Within Mid-Pilmore, over this period the highest relative responses were recorded against the plough and deep plough approaches, although the plough approach was subject to slightly lower variability (Table 4.7.22). The greatest degree of variability, on this sandy-loam textured (predominantly Carpow association) site, was associated with the shallow non-inversion system.

Table 4.7.22: Margin (± SEM) expressed as a percentage of mean margin in a given season averaged over Mid-Pilmore years 6 (2012/13) to 9 (2015/16).

Tillage	Mean
Deep Plough	*104 (± 3.5)*
Plough	*110 (± 3.3)*
Shallow	*86 (± 6.5)*
Mean	*100 (± 4.4)*

5. Discussion

5.1.1. Soil structure and stability

The methods employed in this research quantify multiple aspects of the soil structure. The water retention data provides a complete pore size distribution. For example how much of the total porosity was in pores so small that water held in them is unavailable to the plant, or how much of the total porosity was able to hold water that was easily available (EAW) to the plant roots. Apart from access to water the other main feature of the soil that influences root proliferation is the soil hardness. The least limiting water range (LLWR) index combines the limits of water availability with a controlled measure of soil strength to characterise the soil in terms of a window of opportunity for root proliferation. A soil with a larger window is better for plant production. We also used a measure of the stability of the soil in water (water stable aggregation – WSA), which is influenced by the soil chemistry and in particular the amount and nature of the soil organic matter, as an indicator of the soil's ability to maintain function under stress.

WSA is a very commonly measured (Bartoli et al, 2015) parameter to predict how soils may change over time. Soil aggregate stability, like most physical parameters, is affected by the amount of carbon stored in soils (Six et al., 2004). When carbon is more concentrated near the soil surface, as is commonly found for No-Till and shallow non-inversion tillage systems, greater aggregate stability and less erosion risk occurs. Deeper in the rooting zone of soil other processes cause soil structure to change over the growing season as illustrated earlier in Figure 3.2.1. Wetting through rainfall can cause soil to slump and coalesce (Augeard et al., 2008), so the initial aggregated structure formed by tillage collapses and provides poorer conditions for crop growth (Hakanson et al., 2014). The potential impacts are dramatic. Bresson & Moran (2004) found that under prolonged wetting, coalescence was the dominant process affecting porosity and likely infiltration degradation. A growing evidence base is linking structural degradation of seedbeds during prolonged wetting in the winter to flood risk (Holman et al., 2003). Farm operations may also compact areas of soil (Chamen et al., 2015). These are worst at times of tillage or harvesting, but the effects are evident in subsequent seedbeds and will persist for long periods of time, particularly in the subsoil. Our data from all sites demonstrated large changes in soil structure over a growing season, driven by the weathering processes described above.

Non-inversion tillage has positive impacts on measures such as soil bulk density and EAW compared with ploughing in Mid-Pilmore and NFS. These and the other measures of soil structure often show improvements over the (spring) growing season. The causes associated with soil structural improvement over the season may be attributed to several things. The opportunity for the soil condition to improve may in part result from a poor condition at the start of the season. Both NFS and Mid-Pilmore are spring cropped sites. Over winter there is little or no plant cover (and root growth) to provide organic matter to support the soil biology. Long periods of wet (but not frozen) conditions are associated with changes to the soil chemistry, denaturing of organic matter, breakdown of aggregation and loss of aggregate stability. The improvement from an initial poor condition is likely to be driven by root proliferation acting to provide exudates that stimulate the soil biology and act to dry the soil as water is used for crop development. Exposing soil to cycles of wetting and drying will improve aggregation and soil structure in general.

Slump Resilience is intended to mimic time dependent changes in soil structure over the growing season induced by weather. It captures some similar trends to field behaviour, such as the more marked degradation over time for Plough in Mid Pilmore and NFS, and for all tillage treatments in STAR. However, the rapid laboratory assay did not simulate the physical recovery that occurred in the field, probably because biophysical drivers such as the action of plant roots were absent (Gregory *et al.*, 2013; Hallett and Bengough, 2013).

Compaction resilience mimics the light stress of a roller followed by the larger stress of a tractor wheel, with recovery induced after each stress by exposing the soil to cycles of wetting and drying to simulate weather. For a given field platform, there is some agreement between the soil structure measurements on field cores over time versus the rapid laboratory resilience assay. In Mid-Pilmore and NFS, plough had the worst resistance and recovery to compaction in the lab, and it also had the greatest deterioration of pore structure in the field over time. The opposite was shown for zero tillage in Mid-Pilmore, which recovered in the field and was the most resistant and resilient to compaction.

The trends we observed are somewhat supported by Gregory *et al.* (2009) who used a similar assay to measure compression resilience of long-term grassland and arable soils. They argued that greater carbon in a grassland soil acted like a spring that increased compression resilience and porosity. For a larger field experiment across Scotland, that incorporated a wide range of soils under different land use, Kuan *et al.* (2007) found a good relationship between soil carbon and compression resilience. However, rerunning their analysis for carbon contents <5%, which is more realistic for the arable soils we examined, resulted in a poor relationship. In our field experiments greater surface carbon in NFS for non-inversion tillage, corresponded to greater resistance and resilience to compaction. This was not supported for Mid-Pilmore, where reduced tillage resulted in less carbon but greater compression resilience, or for STAR, where compression resilience was not affected by tillage. Carbon alone can therefore not act as a surrogate measurement of soil physical quality across a range of soil types and management practices.

There is promise in applying these resilience assays to assess soil physical conditions without the need for time-consuming and expensive sampling and analysis over a growing season. The rapid assays identified clear differences in soil behaviour driven by tillage practices at a given location. The non-responsive soil at STAR was insensitive to tillage practice both in the field and the laboratory. For the other soils, the rapid laboratory assays and field data over time had some similar trends, but more work is needed to mimic field conditions that restructure soil. For compression resilience, simple field based measures such as rebound of wheel-tracks following compaction offer another promising approach that could be explored for responsiveness to tillage (Tobias *et al.*, 2001).

A key observation from the Mid-Pilmore data in 2013 is the condition of the No-Till (Zero-Till) treatment at the start of the season. Compared with the other tillage treatments the surface soil from the No-Till was in the worst condition based on most of the indicators (including the LLWR). However the surface soil from the No-Till was the most stable (i.e. had the greatest values of WSA). By harvest the soil quality indicators for the surface soil had all improved and were on a par with the other tillage treatments. The surface soil of the No-Till treatment had been undisturbed for many years and as such the pH had become increasingly acidic to a stage where cementing of the soil into stable but hard structural units may have occurred. Crop performance in the No-Till treatment became so bad that these plots were eventually abandoned. This identifies a risk to the long-term use of No-till systems and suggests that if pH decreases and the soil quality at the surface deteriorates it may be necessary to consider some level of soil disturbance in these systems.

5.1.2. pH

pH at the Mid-Pilmore site was more acidic than at the STAR and NFS sites, but pH increased with depth in soil profiles at all sites. This more acidic pH in the surface soil has been seen in other studies of reduced tillage systems (White, 1994; Franzleubers and Hons, 1996), but the opposite distribution has also been seen (Grant and Bailey, 1994). This acidification of the surface soil suggests that cultivation and crop growth at all sites tended to lead to acidification in this top horizon. The increase in pH with depth became more apparent over the observation period, particularly at the NFS and STAR sites where a pH gradient developed over the project lifetime. By the end of the observation period there was a 0.3 to 0.6 unit pH difference between the surface and 30cm depth at all sites.

There were no significant effects of cultivation treatments or the interaction of this with depth at the STAR or NFS sites, but these were apparent at the Mid-Pilmore site. Both at the start and end of the observation period the compaction treatment at Mid-Pilmore had a greater pH than the non-inversion treatments at this site, although this difference was less the 0.2 pH units which was similar to that seen by White (1994) in Western Australia. Regarding the interaction between cultivation treatment and depth at Mid-Pilmore it was clear that the non-inversion treatments had a strong gradient of pH with depth (0.9 to 1.2 pH units surface to 30cm depth) both at the beginning and end of the observation period, while the plough treatments had no significant gradient in pH down the profile.

Taken together these results suggest that agricultural production at all sites leads to a gradual acidification of the surface horizons where the biological activity (roots and microorganisms) and fertilizer dissolution activity is concentrated (Franzleubers and Hons, 1996). In other studies it was demonstrated that this acidification effect was only present in soils that were fertilised (Thomas et al. 2007; Grant and Bailey, 1994). Inverting the soil appears to mitigate this effect, while non-inversion management of the soil appears to lead to greater pH gradients and therefore more hostile surface horizons where much of the crop biological activity will take place.

5.1.3. Phosphorus

Olsen-P measures indicated that the P status of the soil at Mid-Pilmore was high, moderate at NFS and low at STAR. Changes in P status at Mid-Pilmore are unlikely to have a detrimental effect on crop growth, but declines at STAR and NFS would likely lead to increase P-deficiency stress. At all sites Olsen-P declined with depth and the strength of this gradient tended to increase over the observation period, such that the gradient became significant at the NFS site over the period.

There were no significant impacts of the cultivation treatment on Olsen P at the STAR site and there were no interactions between cultivation treatment and depth at any of the sites. However, there were impacts of cultivation treatment on P status at the Mid-Pilmore and NFS sites. In both cases the least disruptive cultivation process (non-inversion treatments at Mid-Pilmore and the shallow non-inversion treatment at NFS) tended to have a greater P status than the treatments which involved ploughing or deep non-inversion. This effect on P, and a range of other nutrients, has been seen in other studies (White, 1994). At Mid-Pilmore this change in P status is unlikely to make any difference to production as all treatments were replete for P, however at NFS the increased P status of the shallow non-inversion treatment is likely to alleviate some of the P-deficiency stress, so could have practical impact.

Taken together these results suggest that, as has been shown in numerous studies from North America, South America, Europe and Australia, P tends to accumulate in the surface of the profile (Follett and Peterson, 1988; Holanda, 1998; Franzleubers and Hons, 1996; Selles et al. 1997; Thomas et al 2007; Salinas-Garcia, 2002, De Gryze et al. 2008; Martin-Rueda, 2007) and that less disturbance from cultivation will lead to greater accumulation of P. Such a distribution of P in the surface has been shown to be associated with stimulation of root growth in this horizon leading to better P accumulation to the crop (Holanda, 1998). However, in contrast some studies have demonstrated that soil nutrients don’t accumulate in the surface of reduced tillage field treatments (Unger, 1991).

5.1.4. Nitrogen

In general, the NH_4 concentrations at all the sites were very small and became undetectable over the period of the project. While there were gradients of decline in concentration in the profile at both the NFS and STAR sites at the beginning of the project, the lack of detectable concentration in 2016 meant it was impossible to establish what impact the various cultivation treatments had on the dynamics of NH_4 over the period of observation. The highly dynamic nature of the conversion from NH_4 to NO_3 in soil, which can be affected by many factors including time since fertilization, temperature, soil moisture content and pH, mean that it is difficult to explain why NH_4 levels decline to below detection over the period of the project.

The NO_3 concentration changed with depth in the profile at all the sites, although there were no real consistent patterns to either the gradients in the profile or how these changed over time. At the Mid-Pilmore site a gradient of NO_3 concentration declining with depth developed over the period of the experiment and the concentration in the surface remained similar through the period of observation. Whereas at the STAR site the profile developed from equal concentrations of NO_3 down the profile at the start of observation, to a distribution that saw levels of NO_3 largest at 30cm depth and the surface and smallest half way down the profile. Also at STAR, the concentration of NO_3 increased 3-fold over the period of observation. An accumulation of NO_3 at the surface and at depth in soil was also seen in Canadian soils under zero tillage systems (Grant and Bailey, 1994) Different again was the pattern at NFS where the NO_3 concentration tended to decline with depth with this being maintained throughout the observation period, although the concentration declined substantially through the observation period.

There were no significant impacts of the cultivation treatments or interactions between these and depth at either the Mid-Pilmore or STAR sites. However, there were impacts at NFS. Over the period of the project, effects of the cultivation treatments developed such that the non-inversion treatments had greater NO_3 concentrations than the plough treatment and it was clear from the interactions that there tended to be an accumulation of NO_3 in the surface horizons of the non-inversion treatments, while it was evenly distributed down the profile of the plough treatments. Such even distribution of NO_3 with ploughing has been demonstrated in other studies (Salinas-Garcia, 2002).

Taken together these results suggest that sampling strategy was not adequate to capture the dynamism of the conversion of nitrogen in space and time in these field experiments. But, it is apparent that the non-inversion treatments have the ability to increase the availability of NO_3 in the surface of soils under specific circumstances, as has been shown elsewhere (Franzleubers and Hons, 1996).

5.1.5. Chemistry summary

Overall, the data generated here on soil chemistry in a range of long-term cultivation treatments suggest that non-inversion tillage is beneficial in promoting the availability of key nutrients such as P and NO_3 in the surface of the soils where most of the roots and biological activity of the crop will be. Due to the change in a range of properties in this zone it could be questioned whether the standard methods for assessing nutrient status are comparable with conventional cultivation systems (White, 1994), but this would need to be verified with further study. It is also clear from our results that the lack of disturbance of the soil leads to concentration of acidification in the surface of the profile which may render this zone more hostile to plant growth and microbial activity in the long-term. These data suggest that non-inversion tillage treatments will be beneficial to the availability of nutrients to the crop, but the land manager should be mindful of the impact on pH and take precautions through the addition of lime to manage this under certain circumstances.

5.1.6. Soil Carbon

The carbon results were similar for both English sites . As expected, bulk density was higher below the plough layer in both NFS and STAR . When the whole soil profile was taken into account, both sites showed no significant differences in carbon content between tillage treatments. The main differences between the two sites were that in NFS, the deep non-inversion treatment showed greater carbon content than the conventional plough in the depths above 12 cm and greater carbon content than the minimum till in the most superficial layer. In the surface layer, the minimum till treatment had also greater carbon content than the conventional plough. The outcome of greater carbon content in the soil surface in non-inversion treatments compared to inversion treatments is consistent with other studies (West and Post, 2002; Sun, et al., 2011; Singh et al., 2015). This advantage extended in the deep non-inversion system to the 7-12 cm depth layer. These differences in carbon distribution in the soil profile between non-inversion and inversion treatments could lead to wrong conclusions if soils are not sampled to a sufficient depth.

Unlike the English sites, bulk density responses differed according to tillage treatment and depth in Mid-Pilmore. In the surface layer, the bulk density of the conventional plough was significantly higher than in the minimum till treatment. The highest bulk density occurred below the plough layer (25-30 cm) in the compact treatment but statistically it was only significantly different to the no-till treatment. At this depth there were no differences in bulk density between the reduced tillage systems and the conventional plough. At the deepest layer sampled, both reduced tillage systems showed higher bulk density than the compact and the conventional plough. The increased bulk density in deep layers for no-till and minimum till systems compared to conventional plough has been reported before (Cavalierie, 2009). However, very few studies have reported lower bulk densities in no-till and minimum till systems compared to conventional plough in the soil surface. A possible explanation for this outcome might be a reduction of bulk density in the non-inversion treatments due to higher root density and biological activity (Ballcoelho, 1998; Holanda, et al., 1998).

Carbon content in Mid-Pilmore was significantly greater in the conventional plough treatment than in the compact and no-till treatments. In terms of depth, carbon content was greater at the plough layer. The comparisons made with data from the same site in 2008 showed differences in the distribution of carbon in the soil profile between 2008 and 2013. These differences were more marked in the no till treatment which had less carbon in the soil surface and more in the deep layers in 2013 compared to 2008, showing a more even distribution. The results need to be taken with caution since the samples were taken at different times of the year and in different plots (but adjacent to those sampled in 2013). However, it is possible that changes in carbon distribution in the soil profile occurred over the years which may, in part, explain the differences in results between the studies.

When bulk density was adjusted by stone content the greater carbon content in the conventional plough treatment compared to the minimum till became statistically significant too. The adjustment for stone content also affected the significance of the treatment*depth interaction term. This resulted in the conventional plough and the compact treatments showing greater carbon content in particular at the plough layer compared to the non-inversion tillage treatments.

The scientific literature is very variable regarding the effects of tillage practices on bulk density and carbon distribution. This is understandable since studies are carried out in a variety of soil types, climates and moisture regimes and with different crops and rotation systems. Due to the range of differences caution needs to be taken when comparing studies. In general, with regard to bulk density, some studies report an increase in bulk density with no till or minimum tillage practices (e.g. Dam et al. 2005; Afzalinia and Zabihi, 2014). Other studies are consistent with the results presented in this report of no significant difference in bulk density when considering the entire soil profile (Jabro et al., 2016; Martínez et al, 2008).

To summarise, carbon content was either not affected by conventional plough (in the English sites) or was greater than in the reduced tillage systems (Mid-Pilmore). Therefore, the results suggest there are no advantages from the point of view of carbon sequestration, in the use of reduced tillage practices in the long term when a soil profile of 60 cm in taken into account.

In CSC Balruddery the tillage systems were shallow non-inversion for the sustainable treatment and ploughing for the conventional treatment. The results are discussed separately from the other sites because the CSC Balruddery, in addition to different tillage systems, had other management differences (i.e. compost input and reduction of chemical fertilizers in the sustainable treatment) and for logistical reasons the sampling was done a year later than the other sites (in 2014). The results showed no significant differences in bulk density between treatments, depths or their interaction. Carbon content was around 18% greater in the sustainable treatment than in the conventional treatment, presumably due to the compost additions. The crop in the sustainable treatment was reported to look better and more advanced than the conventional during the season. However, yields under the sustainable treatment averaged 6.5 tha^{-1}, substantially less than conventional yields of 10 t ha^{-1}. The reasons for this discrepancy are not known (Hawes, 2015).

5.1.7. Cultivar and Root Performance

The decline in Rhynchosporium in 2013 under plough treatment at Mid-Pilmore might be explained by better burying of inoculum, also suggested by the trend in 2014. The similar decline in minimum tillage in the same year could be explained by increased activity of competitor microbes reducing inoculum but no data were collected to support this. Overall there does appear to be an effect of cultivation treatment on rhynchosporium symptoms that is likely to be attributable to inoculum survival differences on crop debris. However, to draw more specific conclusions more data from different seasons is required along with an analysis of key epidemiological parameters perhaps in particular rain events at critical stages of development.

Overall non-inversion yields were lower than inversion yields in every year but there were no differences between the three inversion tillage treatments. Yield variation in different years was as expected and the significant year*cultivar interaction was most likely partially a reflection of the normal variation in cultivar*environment interaction including favourable epidemic conditions from year to year.

In the first three trials (2013, 2014 and 2015) the lowest yield cultivars also tended to have a smaller difference between inversion and non-inversion tillage yield, shown most clearly in the lowest yielding cultivar Bowman. The highest yield cultivars under non-inversion tillage tended to have the highest yield under inversion tillage too but the yield difference between inversion and non-inversion was not correlated with cultivar yield overall. Amongst the middle-ranking cultivars there were some contrasting yield trends with respect to tillage treatment interactions. Both Appaloosa and Troon showed 19% yield reductions comparing inversion tillage with non-inversion tillage but Concerto only loses 6% and Carlsberg only 3% of their yield under non-inversion tillage. Amongst the 11 new cultivars trialled in 2016 both KWS Sassy and Fairing showed 17% yield reduction under non-inversion tillage but KWS Sassy was also the top yield cultivar under non-inversion tillage whereas Fairing was fourth and lower ranking still under inversion tillage (14th). However, the two highest yielding cultivars under inversion tillage, RGT Planet and Sienna, both showed a much larger yield reduction under non-inversion tillage of 28%. Furthermore, the third highest yielding cultivar under inversion tillage, Scholar, gave a 36% reduction in yield under non-inversion tillage. Thus these newer cultivars do suggest that the yield gains in some recent cultivars shown in RL trials and our inversion tillage treatments may not be realised under non-inversion tillage. Put more generally and equating non-inversion tillage to sub-optimal or some on-farm conditions and inversion tillage to high input, optimum conditions, there is evidence that choice of cultivars should consider the level of inputs and agronomic treatments, at least for cultivations. These ranking changes and corresponding treatment yield differences are being statistically validated to determine which cultivar performance is most robust and therefore amenable to further investigation of the traits responsible.

We previously observed that soil tillage treatment differences have most impact on yield in years of environmental stress, particularly drought, and it is under such conditions that cultivar differences are most likely to be expressed. None of these trials were subject to strong stress conditions but we were still able to identify cultivars with differential responses to tillage treatments. Although we may identify cultivars more suitable to non-inversion tillage, the transient commercial life of cultivars means that by the time these trials have been completed these data may be of limited on-farm application. More valuable will be to use these differential response cultivars to identify the traits responsible. Previous work (Adrian Newton & Glyn Bengough, unpublished data) has suggested that rooting structure physical traits are some of the most likely candidates. Many of the varieties included in these studies have been included in previous and current root phenotyping studies investigating micro root traits (root hair, root width) and macro root traits (overall root distribution in response to soil properties), with the potential of linking root trait responses to responses to soil properties (Valentine et al unpublished data).

The root elongation assay gives an indication of the relative importance of the chemical vs physical properties of the soils sampled, as related to root elongation particularly in relation to the early stages of the seedling growth. Root elongation is necessary for plants to access the high levels of water and nutrients necessary for the high yields in modern crops. Physical properties were found to have a larger influence on the elongation rate than chemical properties. Overall there were significant differences in root elongation between the different platform/ tillage treatments, over depth and across the sampling times and this may mean that roots have significant difficulties accessing nutrient pools in those soils which restrict root elongation. The majority of the differences in root elongation were related to the platform, with the root elongation rates in soil cores taken from the STAR trial being approximately 1/3 less than those in the CSC at Balruddery.

The highest root elongation rates in Mid-Pilmore at the first two samplings were obtained in the minimum (non-inversion) tillage. However, this treatment did not produce the highest final crop yields indicating that other factors may have overpowered root performance. In contrast, the general trends of yield in the STAR trial, with highest accumulated yields in the plough, deep then shallow reflected the root elongations assay results. Differences in yields in the NFS trial were often not significant and this was reflected in the similar root elongation rates found, both across time and space. It may be that in the Mid-Pilmore – minimum (non-inversion) treatments, more root than necessary is being produced, or roots are expanding in areas in the profile that does not benefit the crops later in the season. This later effect may be linked to the crop breeding where the majority of lines have been screened and bred under inversion plough systems. Therefore, while extrapolation to later growth stages is difficult, the root elongation assay gives an indication of the ability of roots to elongate in the different layers of the soil profile, and an analysis of the “optimum” rooting rates and volume and position in the soil profile under different tillage systems may now be timely.

5.1.8. Yield and margins in STAR, NFS and Mid-Pilmore

The long running, large scale STAR, NFS and Mid-Pilmore farming systems projects provide a platform to determine the impact of tillage and rotational practice on soil condition and ultimately the influence of these parameters on yield, margin and crop performance. As indicated in the results section within the four study seasons of AHDB project 3786 in addition to these variables, season has also had an influence and need to be considered within any interpretation.

The impact of tillage practice on yield varied both with season and between STAR, NFS and Mid-Pilmore. For the heavy land STAR site results indicate that the highest cumulative yields were associated with the plough system; notably in STAR year 8 and year 9 the plough resulted in the highest mean yields and in year 10 the plough was only 0.1 t/ha less than the peak mean yield across rotations. However, with the NFS cultivations study, on a medium soil, the highest cumulative yields were associated with the deep non-inversion tillage system and there was greater variability over the four seasons regarding the performance of individual approaches. At Mid-Pilmore, on a light soil, results indicate that the highest cumulative yields were associated with either deep plough or plough approaches. At Mid-Pilmore despite the cost saving associated with the shallow non-inversion tillage system, compared to the plough based approaches, the lower yields obtained with this system did not result in total margins being comparable to the plough based approaches and yields within the shallow non-inversion approach were more variable across seasons. With regard to the impact of system on rotational margins: in STAR despite the high yields associated with the plough based system, in three of the four rotational approaches, ploughing resulted in the lowest cumulative margins. Interestingly though in STAR the cost saving associated with the shallow non-inversion tillage system, compared to the plough based approach, to an extent balanced up with lower yields obtained with this system and meant that the shallow non-inversion tillage system and the plough system resulted in similar total margins. In the NFS study ploughing also resulted in the lowest cumulative margin over the rotation and in both STAR and NFS ploughing would have also resulted in slower speeds of working (*cf*. non-inversion tillage systems); potentially impacting on timeliness of operation as well over a total farm area. In both STAR and NFS the managed approach resulted in the highest mean margin, but of the consistent systems the deep non-inversion system had the highest margin and the least variability.

5.1.9. The effect of tillage on winter wheat yields

While differences in crop rotations between STAR and NFS restrict comparisons for some crop types, the regular use of winter wheat in both studies enables a longer term evaluation of the impact of tillage on the performance of first wheat crops. For both studies, in most individual seasons, the lowest winter wheat yields tended to arise from the use of shallow non-inversion tillage systems. With respect to mean yields across seasons, both STAR and NFS demonstrated similar yields for plough and deep non-inversion systems, but lower wheat yields for shallow non-inversion tillage systems. While ‘year’ was a statistically significant effect, the cross season differences were a 2% reduction in yield compared to plough based approaches for STAR and a 4% reduction compared to the plough in the NFS study for the shallow non-inversion system; this difference was statistically significant in NFS but not in STAR. Regardless of the statistical significance, findings suggest only small percentage yield reductions with shallow tillage (*cf*. plough systems) indicating that wheat yields are relatively robust with respect to the tillage approach assessed. In addition it should be noted that speed of working and timeliness of operation to ensure good field conditions should also be considered when looking at relatively small differences in yield or margin. With regard to margins, the deep non-inversion treatment resulted in the highest margins in both studies, but in both STAR and NFS shallow and deep non-inversion treatments resulted in greater margins compared to the plough. For deep non-inversion systems this benefit was 6-7% and for shallow non-inversion treatments gain was 1-4%.

5.1.10. The effect of tillage on spring barley yields

The root elongation assay showed that the root elongation of spring Barley cv Optic was significantly affected by the soil conditions produced in the different trials and in response to different tillage systems. The assay utilised seedlings and care should be taken in extrapolating results to plants at a more mature physiological stages of growth. However it does demonstrate that roots have increasing difficulties in penetrating soils deeper in the soil profile and that the root:soil relationship may rapidly change throughout the early stage of plant development. Plants will reach different depths in the profile depending on their initial growth rates, thus will be exposed to the stronger soil under different plough system at different relative rates. The continuous cropping of spring barley at Mid-Pilmore enables a longer term evaluation of the impact of tillage on the performance of barley crops. In most individual seasons, the lowest spring barley yields tended to arise from the use of shallow non-inversion tillage systems. With respect to mean yields across seasons, Mid-Pilmore demonstrated similar yields for plough and deep plough approaches, but lower barley yields for the shallow non-inversion tillage approach. In the root elongation assay, these were the samples with the highest root elongation rates on average across the entire depth profile (although the growth rates were similar in the middle depth samples). While ‘year’ was a statistically significant effect, the cross season differences were an 11% reduction in yield compared to plough based approaches for the shallow non-inversion system; this difference was statistically significant in Mid-Pilmore. The findings suggest that percentage yield reductions in barley with shallow tillage (*cf*. plough systems) are more sensitive with respect to the tillage approaches assessed. In addition it should be noted that speed of working and timeliness of operation to ensure good field conditions should also be considered when looking at yield or margin performance. With regard to margins, the plough approach resulted in the highest margins.

5.1.11. The impact of cultivation on speed of working and timeliness of operation

The choice of cultivation operation can have a significant bearing on the working days available for specific soil types. Workability of the soil depends on interactions between climate and soil physical properties. For example, good working conditions on clayey soils are commonly restricted to brief periods when the soil is neither too wet nor too dry for a good tilth to be obtained.

Expected working days vary according to soil type and whether the year is a wet or dry season; a wet season is assumed to occur with a frequency of one year in four (Hodge *et al*., 1984). The expected working days required on a range of soil types (Table 5.1.2) for a specific cultivation technique can be calculated. As an example, a 400 ha arable unit with 80 % of the land down to winter cropping cultivating 320 ha using a 5-furrow plough would take approximately 50 working days and for using a shallow non-inversion tillage (10 cm depth) approximately 10 working days (assuming an 8-hour working day). This equates to a five-fold increase in the expected working days if all cultivations were based on a plough approach compared to a shallow non-inversion approach. It should be noted that the expected working days are calculated for primary cultivation operations only and do not include secondary cultivations or drilling operations. Work rates taken from Table 5.1.3 would be typical of many soil types across East Anglia (UK). On clay loams (Hanslope series) the expected working days during the autumn are well within the good machinery work days (M.W.D's) for these soil types. However, the expected working days in a wet spring (assuming 20 % of the land down to spring cropping) to work the land would greatly reduce. In these situations, the timeliness of using non-inversion tillage would potentially offer more flexibility allowing tillage operations to be completed with less risk of working the soil when it is too wet or too dry.

Table 5.1.2: Typical primary cultivation costs and work rates (Adapted from Morris *et al*., 2014). Costs revised to Autumn 2016 prices.

Establishment approach	Typical cost (£/ha)	Work rate (ha/hr)	Fuel consumption (litres/ha)	Fuel cost £/ha @ 40 p/litre
5-furrow plough	70-105	0.8	40	16
3 m Sumo Trio (Depth 250 mm)	35-45	2.0	30	12
3 m Sumo Trio (Depth 100 mm)	30-40	4.0	27	11
4 m Cultivator drill	30-35	3.0	26	10
Broadcasting / direct drilling	15-30	2.5	18	7

Table 5.1.3. Example of the number of good machinery work days (M.W.D's) during the autumn and spring for a range of soil types (taken from Hodge *et al*., 1984) and expected working days required for plough and non-inversion tillage (figures based on eastern England).

		Autumn				**Spring**			
Soil series	**Type of year**	**M.W.D's**	**Expected working days required for primary cultivations on 80 % of 400 ha arable farm** *[1]			**M.W.D's**	**Expected working days required for primary cultivations on 20 % of 400 ha arable farm** *[2]		
			5-furrow plough	Deep non-inversion	Shallow non-inversion		5-furrow plough	Deep non-inversion	Shallow non-inversion
Newmarket (Sandy loam)	Normal	106	50	20	10	27	13	5	3
	Wet	90				10			
Ashley (Loamy clay)	Normal	89				27			
	Wet	70				7			
Hanslope (Clay loam)	Normal	101				33			
	Wet	79				12			
Windsor (Heavy clay)	Normal	69				20			
	Wet	50				0			

M.W.D's = Number of good machinery work days during the period.

*[1] Assumes a typical 8 hr working day and 80 % of land down to winter cropping.
*[2] Assumes a typical 8 hr working day and 20 % of land down to spring cropping.

5.1.12. Further context / detail for STAR

Wider findings from the STAR project (Morris *et al.* 2014), indicate that long term tillage practice has also resulted in wider agronomic considerations; notably around grass-weed management and mycotoxin risks. The long term trends coming out of the STAR project in terms of grass weed management indicate that in the continuous wheat rotation non-inversion approaches have exacerbated grass-weed issues (particularly around meadow brome (*Bromus commutatus*), sterile brome (*Bromus sterilis*) and black-grass (*Alopecurus myosuroides*) problems). However, in break crops based rotations and in the continuous wheat plough and managed systems (using rotational ploughing) grass-weeds have remained manageable (typically <10 heads per m^2 in wheat crops). It is noteworthy that the grass weed problem in specific treatments developed over a relatively short period of around only 5 years. While mycotoxin problems have been sporadic, findings from the STAR project have also demonstrated an interaction of cultivation and rotation systems on grain mycotoxin risks. This probably associated with the retention and mixing of surface residues associated with the specific cultivation practices. In STAR year 2, mycotoxin analysis was carried out on all plots by Harper Adams University College and significant differences were found. The highest levels of DON (deoxynivalenol) were seen in the continuous wheat shallow non-inversion tillage treatments. While mean DON levels did not surpass those classed as unsafe for human consumption, levels ranged from c. 1000 ppb in shallow non inversion tillage treatments, down to c. 250 ppb in plough based approaches; demonstrating a clear impact of tillage strategy. In all other treatments DON levels were typically in the range 50-250 ppb.

5.1.13. Further context / detail for NFS

Wider findings from the NFS project have also indicated a number of system interactions and outcomes that are relevant when considering the findings from the 4 cropping seasons presented in this project report. When considering the full programme, it should be noted that longer term responses to cover crops have not just been recorded in the crop immediately following the cover crop, but also in subsequent crops in the rotation (Stobart and Morris 2014); consequently rotational yield and margin responses from the NFS cultivations study are not all fully captured with AHDB project 3786.

Key interactions include longer term relationships between cover crop use and primary tillage system in NFS studies (Stobart *et al.,* 2016). Specifically, findings are suggesting different patterns of yield response associated with the interaction of cover crop use and tillage practice. Specifically shallow non-inversion systems have been shown to be more likely to give a positive yield response than plough systems (Figure 5.1.1). Figure 5.1.1 is from work done as part of a separate project and is presented here for comparison. It has been proposed that this is associated with changes to soil structure that potentially lessen the need for further cultivation in some scenarios. This would suggest that low disturbance establishment techniques and cover crop use may be well aligned; recent work by Abdollahi and Munkholm (2014) has also proposed similar relationships.

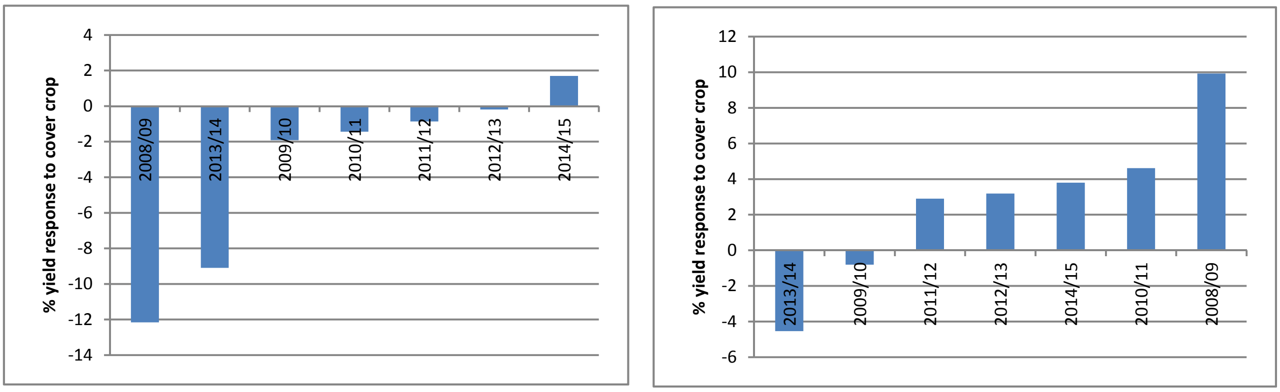


Figure 1a: Plough based system

Figure 1b: Shallow non-inversion tillage system

Figure 5.1.1: The effect of tillage and brassica cover crop (before spring sown break crops in the rotation) on crop yield (t/ha). Figure a) plough based systems and b) shallow non-inversion tillage. Crops in specific harvest years were: 2009 (spring oilseed rape), 2011 (spring beans), 2013 (spring barley), 2014 (winter oilseed rape) and 2010, 2012 and 2015 (winter wheat).

In addition the NFS cultivation study 'cover crop' rotation has utilised brassica cover crops (oil radish, *Raphinus sativus*) on five occasions over the nine year period. In the 2013/14 season (year 7) all NFS treatments grew winter oilseed rape for the first time. This facilitated a comparison between rotations with a short (four brassicas in an 8 year period) or long (two brassicas in an 8 year period) inclusion. Findings demonstrated a reduction in oilseed rape yield associated with the short rotations of brassica cover crops (c. 6%) (Stobart and Morris, 2015), although this was to a to a lesser degree than would be expected from a short (alternate) oilseed rape rotations (c. 12%) (Stobart and Bingham, 2013). The research also suggests some interaction between the yield reduction and cultivation system; with greater reductions being associated with plough based (inversion) tillage; possibly through better management of cover crop volunteers. Understanding the likely risks and potential mitigation is important for farmers growing cover crops and the comparison was undertaken to determine the impact on oilseed rape crop performance, but clearly also impacts on the longer term responses to cover crop use recorded in this study.

6. Final Overall Conclusions

The platforms project has provided robust data to support several important conclusions. Our soil analysis involved the collection of intact soil cores and loose soil at sowing, at crop establishment (one month from sowing for spring crops) and harvest, and at multiple soil depths during the growing season. Laboratory physical assays of these cores evaluated total pore space and its stability (inexpensive), water availability to crops (moderately expensive), and combined water, oxygen and soil strength limitations to crops (expensive). Regardless of soil tillage system, the soils at all field experiments had poor physical structure, which was exacerbated after wet winters and reflected in crop yields. At Mid-Pilmore, zero-tillage (No-till) followed by shallow non-inversion tillage, had the worst surface soil physical conditions at the start of the growing season, but over time the conditions improved, whereas they degraded over time for ploughed soil. At NFS the surface soil physical conditions were unaffected by tillage early on, but plough degraded more over time than shallow or deep non-inversion tillage. In STAR, soil tillage did not influence the poor surface soil structure that was found, with the soil developing improved conditions from the beginning to the end of the growing season. Combined measurements of soil strength and pore structure (or water availability) were essential to characterise limiting conditions for crops. The deterioration of soil physical condition over the growing season for plough, versus improvement for some of the reduced tillage plots, was captured to some extent by rapid, inexpensive soil resilience assays. Reduced tillage soils resisted and rebounded more from compaction at all sites, and were less susceptible to slumping for Mid-Pilmore and NFS.

Our study and other assessments of soil physical condition suggests that UK soils are degraded, but that reduced tillage can lead to improvements in both soils and farm gate income. A desire for 0.4% increases in soil carbon per annum will be difficult to achieve with current practice. In soils under reduced tillage, we sometimes found large improvements to soil physical conditions over a growing season driven by the growing crop. Rotations with deep rooting plants, organic amendments and reduced tillage used together, however, offer promise for soils, farming and the environment.

Based on our results there is no strong reason for not advocating reduced (non-inversion) tillage in preference to ploughing. Yield data over multiple years found shallow non-inversion tillage to have minimal impact for clay-loam soil at STAR, a slight negative impact for silt-loam soil at NFS and a very negative impact for sandy-loam soil at Mid-Pilmore. When decreased costs of labour and fuel were factored in, gross margins were best for deep non-inversion tillage for NFS (11% better) and STAR (4% better), followed by shallow non-inversion. The Mid-Pilmore experiment was not designed to deliver economic analysis, rather to study the interaction of genotype with soil conditions. The implementation of no-till and even reduced tillage to fit with plots that are of only 6 m length is not ideal. The Mid-Pilmore gross margins were 9% poorer for shallow non-inversion than plough over multiple growing seasons, but manageable pH shifts and a proliferation of weeds were contributing factors. Because Mid-Pilmore was run as a replicated experiment the opportunities to control weeds differently in different treatments was limited.

This economic advocacy is somewhat supported by benefits to the soil system, but not always in line with common thinking. Soil nutrients varied minimally due to tillage, apart from surface soils having more phosphorus (NFS and Mid-Pilmore) and deeper soils more nitrate (Mid-Pilmore) at harvest. From our results, reduced tillage does not increase the potential of soil to store carbon throughout its profile, although we did find more carbon in the surface of NFS soils under non-inversion tillage. We also found that a failure to account for stone content in current inventories produces a large error. At the CSC Balruddery, 5 annual additions of 35 t/ha compost with shallow-non-inversion tillage, provided 6 kg of carbon more per m^3 over the whole profile depth than the conventional management. 0.5% increase in stored carbon compared to no compost and ploughing.

The differences in genotype (variety) performance with tillage are the first data of this type for spring sown crops. That there are varietal differences in response to cultivation system coupled with a move to non-inversion cultivation (or No-Till) suggests that consideration should be given to the soil conditions under which plant breeding is performed.

7. References

Abdollahi, L & Munkholm, L.J. (2014). Tillage system and cover crop effects on soil quality: I. Chemical, Mechanical, and Biological Properties. Soil Science Society of America Journal 78, 262-270.

Afzalinia, S. and Zabihi, J. (2014). Soil compaction variation during corn growing season under conservation tillage. Soil & Tillage Research 137, 1-6.

Alamouti, M.Y. & Navabzadeh, M. (2007). Investigation of plowing depth effect on some soil physical properties. Pakistan Journal of Biological Sciences 10, 4510-4514.

Augeard, B., Bresson, L. M., Assouline, S., Kao, C. & Vauclin, M. (2008). Dynamics of soil surface bulk density: Role of water table elevation and rainfall duration. Soil Science Society of America Journal 72, 412-423.

Ballcoelho, B. R., Roy, R. C., Swanton, C. J. (1998). Tillage alters corn root distribution in coarse-textured soil. Soil & Tillage Research 45, 237–249.

Bresson, L.M., Moran, C.J. (2003). Role of compaction versus aggregate disruption on slumping and shrinking of repacked hardsetting seedbeds. Soil Science 168, 585-594.

Cavalieri, K. M. V., da Silva, A. P., Tormena, C. A., Leão, T. P. Dexter, A. R. Håkansson, I. (2009). Long term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferrasol in Paraná, Brazil. Soil & Tillage Research 103, 158-164.

Chamen, W. C. T., Moxey, A. P., Towers, W., Balana, B. & Hallett, P. D. (2015). Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil & Tillage Research 146, 10-25.

Dam, R.F., Mehdi, B.B., Burgess, M.S.E., Madramootoo, C.A., Mehuys, G.R. & Callum, I.R. (2005). Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil & Tillage Research 84, 41-53.

De Gryze, Steven, et al. (2008). The relationship between landform and the distribution of soil C, N and P under conventional and minimum tillage. Geoderma 144, 180-188.

Follett, R. F. & Peterson, G. A. (1988). Surface soil nutrient distribution as affected by wheat-fallow tillage systems. Soil Science Society of America Journal 52, 141-147.

Franzluebbers, A. J. & Hons, F.M. (1996). Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. Soil & Tillage Research 39, 229-239.

Grant, C. A. & Bailey, L. D. (1994). The effect of tillage and KCl addition on pH, conductance, NO3-N, P, K and Cl distribution in the soil profile. Canadian Journal of Soil Science 74, 307-314.

Gregory, A.S., Watts, C.W., Griffiths, B.S., Hallett, P.D., Kuan, H.L., & Whitmore, A.P. (2009). The effect of long-term soil management on the physical and biological resilience of a range of arable and grassland soils in England. Geoderma 153, 172-185.

Gregory, A.S., Watts, C.W., Whalley, W.R., Kuan, H.L., Griffiths, B.S., Hallett, P.D. & Whitmore, A.P. (2007). Physical resilience of soil to field compaction and the interactions with plant growth and microbial community structure. European Journal of Soil Science 58, 1221-1232.

Gregory, P. J., Bengough, A. G., George, T. S. & Hallett, P. D. (2013). Rhizosphere Engineering by Plants: Quantifying Soil–Root Interactions. In *Enhancing Understanding and Quantification of Soil–Root Growth Interactions*, 1-30.

Hallett, P. D. & Bengough, A. G. (2013). Managing the soil physical environment for plants. In *Soil Conditions and Plant Growth*, 238-268: Blackwell Publishing Ltd.

Hawes, C. (2015). Centre for sustainable cropping. The James Hutton Institute Annual Report, 2014.

Hodge, C.A.H., Burton, R.G.O., Corbett, W.M., Evans, R. & Seale, R.S. (1984). Soils and their use in Eastern England. Bulletin 13, Soil Survey of England and Wales, Harpenden. pp. 472.

Holanda, F. S. R., Mengel, D.B., Paula, M.B., Carvaho, J.G., & Bertoni, J.C. (1998). Influence of crop rotations and tillage systems on phosphorus and potassium stratification and root distribution in the soil profile. Communications in Soil Science & Plant Analysis 29, 2383-2394.

Holman, I. P., et al. (2003). The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. Hydrology and Earth System Sciences 7, 754-765.

Horn, R., (2004). Time dependence of soil mechanical properties and pore functions for arable soils. Soil Science Society of America Journal 68, 1131-1137.

Irving, G.C.J. & McLaughlin, M.J. (1990). A rapid and simple field test for phosphorus in Olsen and Bray No. 1 extracts of soil 1. Communications in Soil Science & Plant Analysis 21, 2245-2255.

Jabro, J.D., Iversen, W.M. Stevens, W.B., Evans, R.G., Mikha, M.M. & Allen, B.L. (2016). Physical and Hydraulic properties of a sandy loam soil under zero, shallow and deep tillage practices. Soil & Tillage Research 159, 67-72.

Keller T., Lamandé M., Peth S., Berli M., Delenne J.-Y., Baumgarten W., Rabbel W., Radjaï F., Rajchenbach J., Selvadurai A.P.S. & Or D. (2013). An interdisciplinary approach towards improved understanding of soil deformation during compaction. Soil & Tillage Research 128, 61-80.

Kuan, H.L, Hallett, P.D., Griffiths, B.S. Gregory, A.S., Watts, C.W. & Whitmore, A.P. (2007). The biological and physical stability and resilience of a selection of Scottish soils to stresses. European Journal of Soil Science 58, 811-821.

McKenzie, B.M. & Dexter, A.R. (1996). Methods for studying the permeability of individual soil aggregates. Journal of agricultural Engineering Research 65, 23-28.

Martin-Rueda, I., et al. (2007). Tillage and crop rotation effects on barley yield and soil nutrients on a Calciortidic Haploxeralf. Soil & Tillage Research 92, 1-9.

Martínez, E., Fuentes, J-P., Silva, P., Valle,S. & Acevedo, E. (2008). Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. Soil & Tillage Research 99, 232-244.

Morris, N.L., Stobart, R.M. & Orson, J.H. (2014). An appraisal of research, best practice and communication approaches for the management of soil structure, Felix Cobbold Trust Review.

Newton, A.C. & Hackett, C.A. (1994). Subjective components of mildew assessment on spring barley. European Journal of Plant Pathology 100, 395-412.

Newton, A.C., Guy, D.C., Bengough, A.G., Gordon, D.C., McKenzie, B.M., Sun, B., Valentine, T. & Hallett, P.D. (2012). Soil tillage effects on the efficacy of cultivar and their mixtures in winter barley. Field Crops Research 128, 91-100.

Roger-Estrade, J., Richard, G., Caneill, J., Boizard, H., Coquet, Y., Defossez, P. & Manichon, H. (2004). Morphological characterisation of soil structure in tilled fields: from a diagnosis method to the modelling of structural changes over time. Soil & Tillage Research 79, 33-49.

Salinas-Garcıa, J.R., Velazquez-Garcia, J.D., Gallardo-Valdez, A., Diaz-Mederos, P., Caballero-Hernandez, F., Tapia-Vargas, L.M., & Rosales-Robles, E. (2002). Tillage effects on microbial biomass and nutrient distribution in soils under rain-fed corn production in central-western Mexico. Soil & Tillage Research 66, 143-152.

Selles, F., Kochhann, R.A., Denardin, J.E., Zentner, R.P., & Faganello, A.. (1997). Distribution of phosphorus fractions in a Brazilian Oxisol under different tillage systems. Soil & Tillage Research 44, 23-34.

Singh, P., Heikkinen, J., Ketoya, E., Nuutinen, V., Palojärvi, A., Sheehi, J., Esala, M., Mitra, S., Alakukku, L. & Regina, K. (2015). Tillage and crop residue management methods had minor effects on the stabilization of top soil carbon in a 30-year field experiment. Science of the total environment 518-519, 337-344.

Six, J., Bossuyt, H., Degryze, S. & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil & Tillage Research 79, 7-31.

Stobart, R., Hallett, P.D., George, T.S., Morris, N.L., Newton, A.C., Valentine, T.A. & McKenzie, B.M. (2014). Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments. Aspects of Applied Biology, 127 (Precision Decisions for Profitable Cropping), pp233-240.

Stobart, R. & Bingham, I.J. (2013). Impact of previous cropping on winter oilseed rape, HGCA Project Report 519, pp. 80.

Stobart, R., Hallett, P.D., George, T.S., Morris, N.L., Newton, A.C., Valentine, T.A. & McKenzie B.M. (2016). Soil tillage and crop output in long running UK field experiments, 14th ESA Congress (Edinburgh).

Stobart, R. & Morris, N.L. (2015). The impact of repeated brassica cover crops use on system performance and oilseed rape yield. Aspects of Applied Biology, 129 (Getting the most out of cover crops), 51-56.

Stobart. R., Morris, N.L., Hinton, N., Fielding, H. & Stoate, C. (2016). Evaluation of sustainable soil management and cover crop practices. 14th European Society of Agronomy Congress (Growing landscapes – Cultivating innovative agricultural systems). 5-9 September 2016, Edinburgh.

Sun, B., Hallett, P., Caul, S., Daniell, T.J. & Hopkins, D.W. (2011). Distribution of soil carbon and microbial biomass in arable soils under different tillage regimes. Plant Soil 338, 17-25.

Thomas, G. A., Dalal, R.C. & Standley, J. (2007). No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil & Tillage Research 94, 295-304.

Tobias, S., Hennes, M., Meier, E. & Schulin, R. (2001). Estimating soil resilience to compaction by measuring changes in surface and subsurface levels. Soil Use and Management 17, 229-234.

Unger, P. W. (1991). Organic matter, nutrient, and pH distribution in no-and conventional-tillage semiarid soils. Agronomy Journal 83, 186-189.

Valentine, T. A., Hallett, P. D., Binnie, K., Young, M. W., Squire, G. R., Hawes, C. & Bengough, A. G. (2012). Soil strength and macropore volume limit root elongation rates in many UK agricultural soils. Annals of Botany 110, 259-270.

van Genuchten, M.Th., (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892-898.

West, T.O & Post, W, M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66, 1930-1946

Wheater, H. & Evans, E. (2009). Land use, water management and future flood risk. Land Use Policy 26, S251-S264.

White, R.E. (1987) Introduction to the Principles and Practice of Soil Science. Second Edition Blackwell London.

Zhang, B., Horn, R. & Hallett, P. (2005). Mechanical resilience of degraded soil amended with organic matter. Soil Science Society of America Journal 69, 864-871.

Zornoza, R., Acosta, J.A., Bastida, F., Domínguez, S.G., Toledo, D.M. & Faz, A. (2015) Identification of sensitive indicators to assess the interrelationship between soil quality, management practices and human health. Soil 1, 173-185.

8. Acknowledgements

This project used existing long-term experiments which have been supported by a range of organizations. The experiments in Scotland have financial support from the Rural & Environment Science & Analytical Services Division of the Scottish Government. The experiments in England have financial support from the Felix Thornley Cobbold Trust, The Chadacre Agricultural Trust, The Morley Agricultural Foundation and the JC Mann Trust. The authors thank the many farm and trials staff at the James Hutton Institute, NIAB TAG and private farmers who have worked diligently to support the various platforms.

9. Appendices

9.1. Appendix 1 Plant populations and ear counts from STAR and NFS trials

Appendix Table 1. Winter wheat plant population (18/12/12) and ear count (05/07/13) summary information from STAR year 8 (2012/2013).

	Plants/m^2					Ears/m^2				
Tillage	Winter	Spring	Cont	Alt Fallow	Mean	Winter	Spring	Cont	Alt Fallow	Mean
Plough	114	123	110	116	116	341	402	302	305	338
Managed	124	126	103	106	115	356	465	233	295	337
Shallow	81	114	67	126	97	323	373	135	283	279
Deep	122	130	72	143	117	281	397	197	394	317
Average	110	123	88	123		325	409	217	319	
P value	P<0.001					P=0.0001				
LSD (/m^2)	30.4					48.6				
CV %	16.4					8.7				

Appendix Table 2. Plant population (08/01/14, winter crops and 02/05/14 spring crops) and ear count (27/06/14) summary information from STAR year 9 (2013/2014).

	Plants/m^2					Ears/m^2			
Tillage	Winter (OSR)	Spring (S oats)	Cont (WW)	Alt Fallow		Winter	Spring	Cont	Alt Fallow
Plough	95	156	137	-		-	-	398	-
Managed	21	158	171	-		-	-	404	-
Shallow	77	130	198	-		-	-	415	-
Deep	72	125	166	-		-	-	428	-
Average	*66*	*142*	*168*	-		-	-	*411*	-
P value	NS	NS	P<0.05			NS			
LSD (/m^2)	99.6	42.8	8.0			38.4			
CV %	53.9	15.1	9.6			4.7			

Note: OSR plant counts were subject to a high degree of variability due to volunteers, notably in the plough treatments.

Appendix Table 3. Winter wheat plant population (18/12/12) and ear count (05/07/13) summary information from STAR year 10 (2014/2015).

	Plants/m^2					Ears/m^2				
Tillage	Winter	Spring	Cont	Alt Fallow	Mean	Winter	Spring	Cont	Alt Fallow	Mean
Plough	115	137	132	130	129	370	379	347	354	363
Managed	119	135	123	102	120	352	369	346	371	360
Shallow	120	128	115	117	120	393	375	318	382	367
Deep	114	120	135	115	121	369	374	333	370	362
Average	117	130	126	116		371	374	336	369	
P value	NS					P=0.01				
LSD (/m^2)	31.1					32.5				
CV %	15.3					5.4				

Appendix Table 4. Plant population (03/12/15, winter crops and 22/03/16 spring crops) and ear count (14/06/16) summary information from STAR year 9 (2015/2016).

	Plants/m^2					Ears/m^2			
Tillage	Winter (W bean)	Spring (S bean)	Cont (WW)	Alt Fallow		Winter	Spring	Cont	Alt Fallow
Plough	26	20	149	-		-	-	295	-
Managed	20	31	154	-		-	-	246	-
Shallow	25	-	172	-		-	-	278	-
Deep	-	22	154	-		-	-	275	-
Average	*24*	*24*	*157*	-		-	-	*274*	-
P value	NS	NS (P=0.19)	NS			NS (P=0.10)			
LSD (/m^2)	11.2	12.1	33.0			39.2			
CV %	21.0	24.4	10.5			7.2			

Note: the deep tillage winter beans and shallow tillage spring beans were both crop failures.

Appendix Table 5. Spring barley plant population (31/05/13) and ear count (12/07/13) summary information NFS year 6 (2012/2013).

	Plants/m^2				Ears/m^2		
	No cover crop	Cover crop	Mean		No cover crop	Cover crop	Mean
Plough	96	94	*95*		294	290	292
Managed	93	96	*95*		290	289	290
Shallow	101	86	*94*		287	280	284
Deep	79	96	*88*		284	283	285
Average	*92*	*93*	-		*289*	*286*	
P value	NS (P=0.15)				NS		
LSD (/m^2)	15.0				37.3		
CV %	11.0				8.8		

Appendix Table 6. Winter oilseed rape plant population (06/12/13) NFS year 7 (2013/2014).

	Plants/m^2		
	No cover crop	Cover crop	Mean
Plough	47	44	47
Managed	34	36	35
Shallow	31	36	34
Deep	40	41	41
Average	38	39	-
P value	P=0.0001		
LSD (/m^2)	5.8		
CV %	10.1		

Appendix Table 7. Winter wheat plant population (17/11/14) and ear count (21/07/15) summary information NFS year 8 (2014/2015).

	Plants/m^2				Ears/m^2		
	No cover crop	Cover crop	Mean		No cover crop	Cover crop	Mean
Plough	110	107	109		322	330	326
Managed	111	110	111		303	312	308
Shallow	118	113	156		285	294	290
Deep	119	113	116		314	320	317
Average	115	111			306	314	
P value	NS				NS (P=0.11)		
LSD (/m^2)	12.9				32.1		
CV %	7.8				7.0		

Appendix Table 8. Spring oat plant population (05/11/15) NFS year 9 (2015/2016).

	Plants/m^2		
	No cover crop	Cover crop	Mean
Plough	160	166	163
Managed	158	168	163
Shallow	172	168	170
Deep	163	158	161
Average	163	165	
P value	NS		
LSD (/m^2)	20.5		
CV %	8.5		

9.2. Appendix 2 Managed approach cultivation summary for STAR and NFS trials

Appendix Table 9. Managed approach cultivation summary for STAR (Years 2006-2016)

	Winter cropping	**Spring cropping**	**Alternate fallow**	**Continuous Wheat**
2006 **WW+break**	Sub-cast (20cm) Rolls *As deep*	Plough Spring tine Cultivator drill *As plough*	None	Plough Cultipress (x1) Cultivator drill Rolls *As plough*
2007 **WW**	Sumo (10cm) Cultivator drill Rolls *As shallow*	Sumo (20cm) Cultivator drill Rolls *As deep*	Sumo (20cm) Cultivator drill Rolls *As deep*	Plough Combi-drill Rolls *As plough*
2008 **WW+break**	Seed broadcast Plough Cultipress (x1) -	Plough Combi-drill *As plough*	None	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*
2009 **WW**	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*	Plough Cultipress (x2) Cultivator drill *As plough*	Plough Cultipress (x2) Cultivator drill *As plough*	Plough Cultipress (x2) Cultivator drill *As plough*
2010 **WW+break**	Sub-cast (20cm) Rolls *As deep*	Plough Claydon drill *As plough*	Combi-drill All approaches	Plough (20cm) Cultipress (x2) Cultivator drill Roll *As plough*
2011 **WW**	Sumo (10cm) Cultivator drill Rolls *As shallow*	Sumo (10cm) Cultivator drill Rolls *As shallow*	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*
2012 **WW+break**	Plough Claydon drill As plough	Sumo (20cm) As deep	Combi-drill All approaches	Sumo (20cm) Cultipress (x1) Cultivator drill As deep
2013 **WW**	Sumo (20cm) Cultipress (x1) Combi drill *As deep*	Sumo (20cm) Cultipress (x1) Combi drill *As deep*	Sumo (10cm) Cultipress (x1) Combi drill *As shallow*	Sumo (20cm) Cultipress (x1) Combi drill *As deep*
2014 **WW+break**	*Sub-cast (low disturbance)* -	*Sumo (20cm)* *Power harrow* *Drill* *As deep*	*Combi-drill* All approaches	Sumo (20cm) Cultipress (x1) Tine drill As deep
2015 **WW**	Sumo (10cm) Power Harrow (x1) Weaving tine drill *Roll* *As shallow*	Plough Power Harrow (x2) Weaving tine drill Roll *As plough*	Sumo (20cm) Power Harrow (x1) Weaving tine drill *Roll* *As deep*	Sumo (20cm) Power Harrow (x1) Weaving tine drill *Roll* *As deep*
2016 **WW +** **break**	Plough Power Harrow Weaving Drill As plough	Plough Power Harrow Weaving Drill As plough	*Power Harrow* *Seed broadcast* *Rolled* *All approaches*	Sumo (20cm) Power Harrow (x1) Weaving tine drill *As deep*

Appendix Table 10. Managed approach cultivation summary for NFS (Years 2008-2016)

	No cover crop	**With cover crop**
2008 **WW**	Sumo (10cm) Cultivator drill *As shallow*	Sumo (10cm) Cultivator drill *As shallow*
2009 **Break**	Sumo (20cm) Cultivator drill Roll x2 *As deep*	Sumo (10cm) Cultivator drill Roll x2 *As shallow*
2010 **WW**	Sumo (20cm) Cultivator drill *As deep*	Sumo (20cm) Cultivator drill *As deep*
2011 **Break**	Plough Shakerator drill *As plough*	Plough Shakerator drill *As plough*
2012 **WW**	Sumo (20cm) Shallow disc Cultivator drill *As deep*	Sumo (20cm) Shallow disc Cultivator drill *As deep*
2013 **Break**	Sumo (20cm) Shallow disc Cultivator drill Roll *As deep*	Sumo (20cm) Shallow disc Cultivator drill Roll *As deep*
2014 **WOSR**	Sumo (20cm) Cultivator drill Roll *As deep*	Sumo (20cm) Cultivator drill Roll *As deep*
2015 **WW**	Sumo (10cm) Cultivator drill Roll *As shallow*	Sumo (10cm) Cultivator drill Roll *As shallow*
2016 **Break**	Sumo (10cm) Cultivator drill Roll *As shallow*	Sumo (10cm) Cultivator drill Roll *As shallow*

9.3. Appendix 3 Cost and margin breakdown for STAR trial

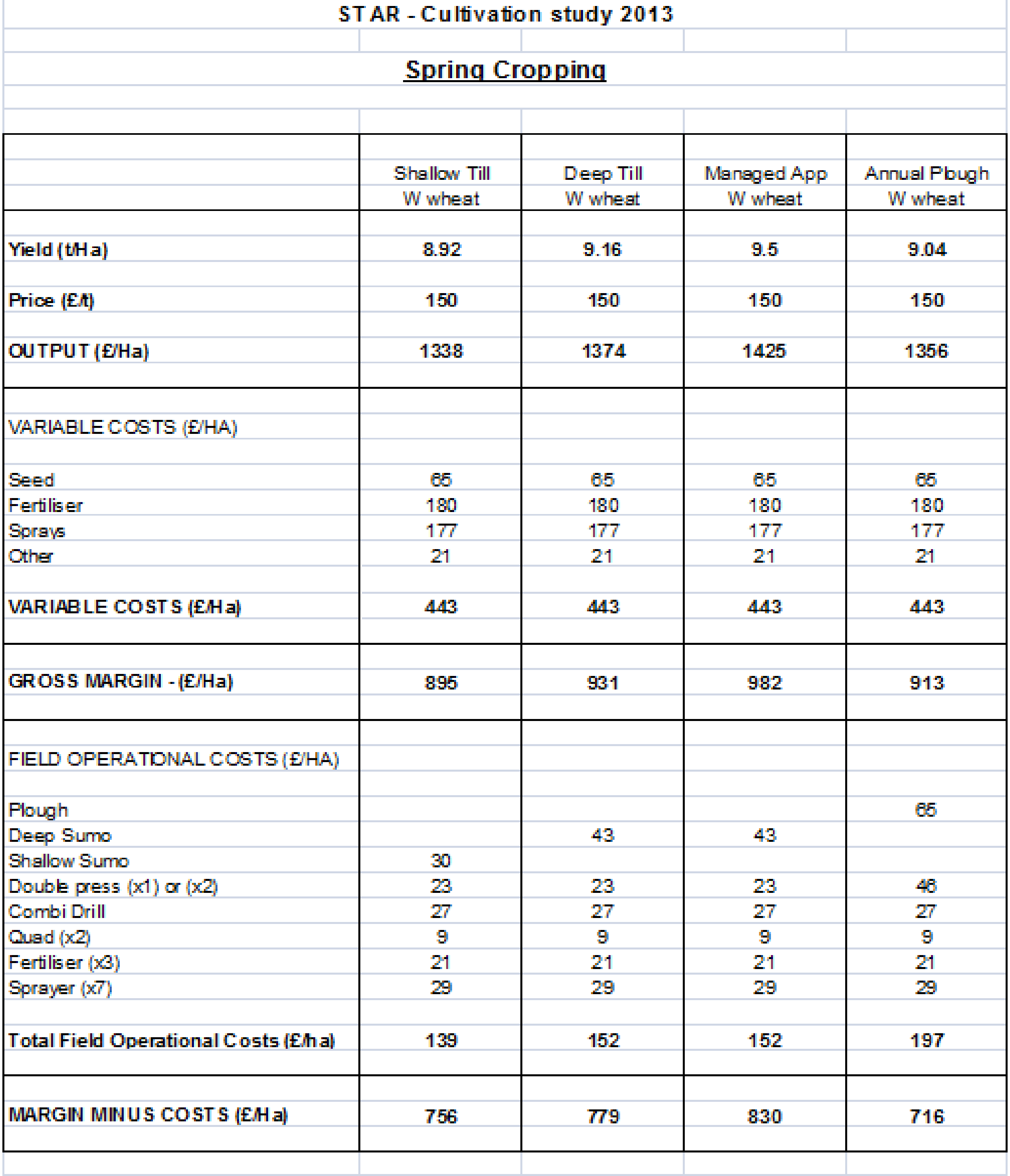
Appendix Table 11a. STAR cost and margin breakdown 2012/13 (Winter Cropping)

STAR - Cultivation study 2013

Winter Cropping

	Shallow Till W wheat	Deep Till W wheat	Managed App W wheat	Annual Plough W wheat
Yield (t/Ha)	**8.62**	**8.66**	**8.92**	**9.39**
Price (£/t)	**150**	**150**	**150**	**150**
OUTPUT (£/Ha)	**1293**	**1299**	**1338**	**1409**
VARIABLE COSTS (£/HA)				
Seed	65	65	65	65
Fertiliser	180	180	180	180
Sprays	177	177	177	177
Other	21	21	21	21
VARIABLE COSTS (£/Ha)	**443**	**443**	**443**	**443**
GROSS MARGIN - (£/Ha)	**850**	**856**	**895**	**966**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				65
Deep Sumo		43	43	
Shallow Sumo	30			
Double press (x1) or (x2)	23	23	23	46
Combi Drill	27	27	27	27
Quad (x2)	9	9	9	9
Fertiliser (x3)	21	21	21	21
Sprayer (x7)	29	29	29	29
Total Field Operational Costs (£/ha)	**139**	**152**	**152**	**197**
MARGIN MINUS COSTS (£/Ha)	**711**	**704**	**743**	**768**

Appendix Table 11b. STAR cost and margin breakdown 2012/13 (Spring Cropping)

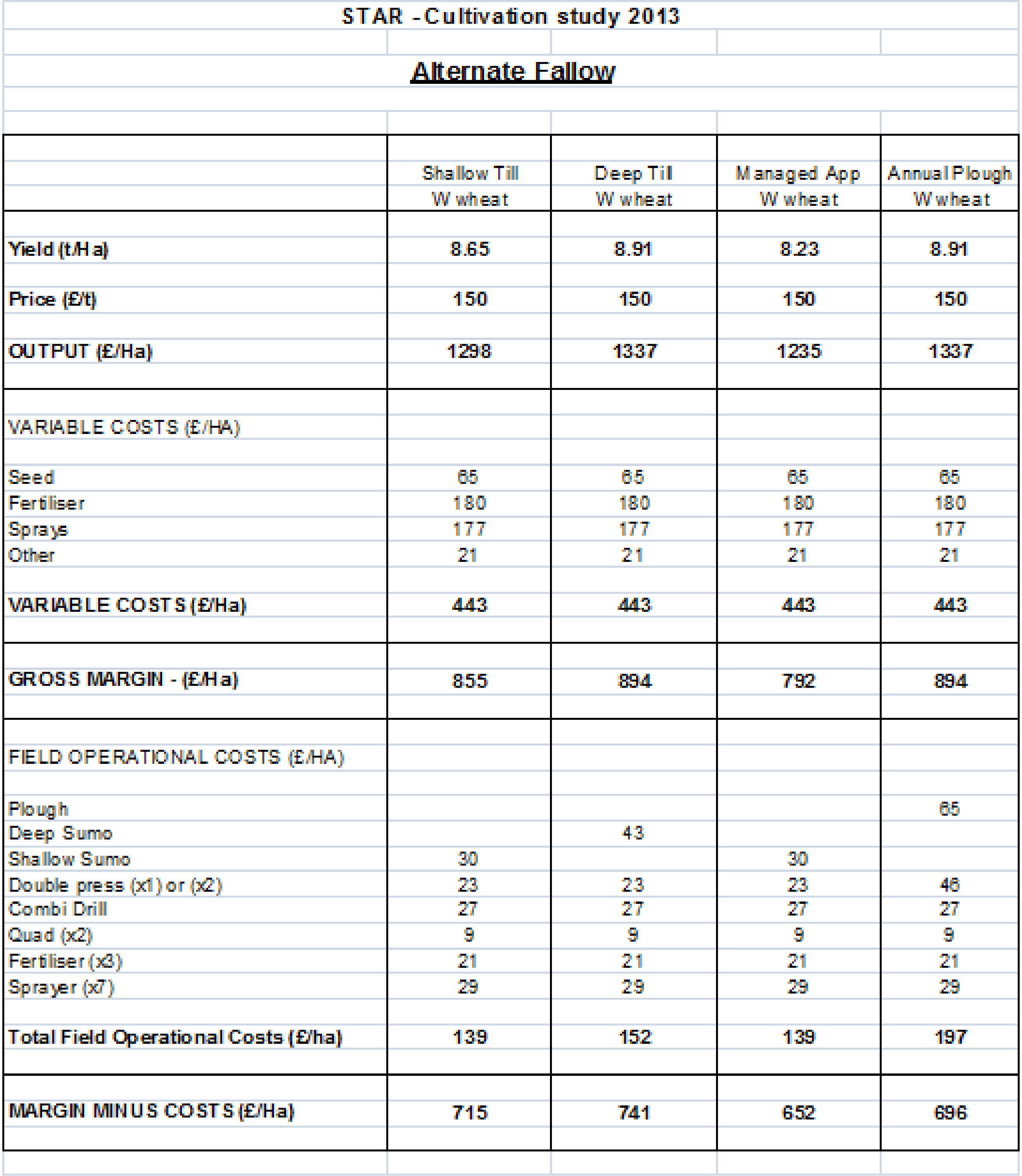


STAR - Cultivation study 2013

Spring Cropping

	Shallow Till W wheat	Deep Till W wheat	Managed App W wheat	Annual Plough W wheat
Yield (t/Ha)	**8.92**	**9.16**	**9.5**	**9.04**
Price (£/t)	**150**	**150**	**150**	**150**
OUTPUT (£/Ha)	**1338**	**1374**	**1425**	**1356**
VARIABLE COSTS (£/HA)				
Seed	65	65	65	65
Fertiliser	180	180	180	180
Sprays	177	177	177	177
Other	21	21	21	21
VARIABLE COSTS (£/Ha)	**443**	**443**	**443**	**443**
GROSS MARGIN - (£/Ha)	**895**	**931**	**982**	**913**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				65
Deep Sumo		43	43	
Shallow Sumo	30			
Double press (x1) or (x2)	23	23	23	46
Combi Drill	27	27	27	27
Quad (x2)	9	9	9	9
Fertiliser (x3)	21	21	21	21
Sprayer (x7)	29	29	29	29
Total Field Operational Costs (£/ha)	**139**	**152**	**152**	**197**
MARGIN MINUS COSTS (£/Ha)	**756**	**779**	**830**	**716**

Appendix Table 11c. STAR cost and margin breakdown 2012/13 (Alternate Fallow)



STAR - Cultivation study 2013

Alternate Fallow

	Shallow Till W wheat	Deep Till W wheat	Managed App W wheat	Annual Plough W wheat
Yield (t/Ha)	**8.65**	**8.91**	**8.23**	**8.91**
Price (£/t)	**150**	**150**	**150**	**150**
OUTPUT (£/Ha)	**1298**	**1337**	**1235**	**1337**
VARIABLE COSTS (£/HA)				
Seed	65	65	65	65
Fertiliser	180	180	180	180
Sprays	177	177	177	177
Other	21	21	21	21
VARIABLE COSTS (£/Ha)	**443**	**443**	**443**	**443**
GROSS MARGIN - (£/Ha)	**855**	**894**	**792**	**894**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				65
Deep Sumo		43		
Shallow Sumo	30		30	
Double press (x1) or (x2)	23	23	23	46
Combi Drill	27	27	27	27
Quad (x2)	9	9	9	9
Fertiliser (x3)	21	21	21	21
Sprayer (x7)	29	29	29	29
Total Field Operational Costs (£/ha)	**139**	**152**	**139**	**197**
MARGIN MINUS COSTS (£/Ha)	**715**	**741**	**652**	**696**

Appendix Table 11d. STAR cost and margin breakdown 2012/13 (Continuous Wheat)

STAR - Cultivation study 2013

Continuous WW

	Shallow Till W wheat	Deep Till W wheat	Managed App W wheat	Annual Plough W wheat
Yield (t/Ha)	**5.85**	**6.48**	**7.84**	**7.08**
Price (£/t)	**150**	**150**	**150**	**150**
OUTPUT (£/Ha)	**878**	**972**	**1176**	**1062**
VARIABLE COSTS (£/HA)				
Seed	65	65	65	65
Fertiliser	180	180	180	180
Sprays	177	177	177	177
Other	21	21	21	21
VARIABLE COSTS (£/Ha)	**443**	**443**	**443**	**443**
GROSS MARGIN - (£/Ha)	**435**	**529**	**733**	**619**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				65
Deep Sumo		43	43	
Shallow Sumo	30			
Double press (x1) or (x2)	23	23	23	46
Combi Drill	27	27	27	27
Quad (x2)	9	9	9	9
Fertiliser (x3)	21	21	21	21
Sprayer (x7)	29	29	29	29
Total Field Operational Costs (£/ha)	**139**	**152**	**152**	**197**
MARGIN MINUS COSTS (£/Ha)	**295**	**377**	**581**	**422**

Appendix Table 12a. STAR cost and margin breakdown 2013/14 (Winter Cropping)

STAR - Cultivation study 2014

Winter Cropping

	Shallow Till WOSR	Deep Till WOSR	Managed App WOSR	Annual Plough WOSR
Yield (t/Ha)	**3.78**	**4.67**	**4.12**	**4.68**
Price (£/t)	**280**	**280**	**280**	**280**
OUTPUT (£/Ha)	**1058**	**1308**	**1154**	**1310**
VARIABLE COSTS (£/HA)				
Seed	65	65	65	65
Fertiliser	156	156	156	156
Sprays	126	126	126	126
Other	9	9	9	9
VARIABLE COSTS (£/Ha)	**356**	**356**	**356**	**356**
GROSS MARGIN - (£/Ha)	**702**	**951**	**797**	**954**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				63
Deep Sumo		42		
Shallow Sumo	30		30	30
Power Harrow				39
Rolls	13	13	13	13
Quad (x1)	5	5	5	5
Fertiliser (x2)	14	14	14	14
Sprayer (x4)	17	17	17	17
Total Field Operational Costs (£/ha)	**78**	**90**	**78**	**180**
MARGIN MINUS COSTS (£/Ha)	**624**	**861**	**719**	**774**

Appendix Table 12b. STAR cost and margin breakdown 2013/14 (Spring Cropping)

STAR - Cultivation study 2014

Spring Cropping

	Shallow Till S Oats	Deep Till S Oats	Managed App S Oats	Annual Plough S Oats
Yield (t/Ha)	**6.27**	**5.22**	**6.21**	**6.47**
Price (£/t)	**100**	**100**	**100**	**100**
OUTPUT (£/Ha)	**627**	**522**	**621**	**647**
VARIABLE COSTS (£/HA)				
Seed	72	72	72	72
Fertiliser	81	81	81	81
Sprays	70	70	70	70
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**223**	**223**	**223**	**223**
GROSS MARGIN - (£/Ha)	**404**	**299**	**398**	**424**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				63
Deep Sumo		42	42	
Shallow Sumo	30			
Power Harrow				39
Cult Drill	28	28	28	28
Claydon Drill				
Rolls (x1)	13	13	13	13
Quad				
Fertiliser (x2)	14	14	14	14
Sprayer (x4)	17	17	17	17
Total Field Operational Costs (£/ha)	**102**	**114**	**114**	**174**
MARGIN MINUS COSTS (£/Ha)	**302**	**185**	**284**	**250**

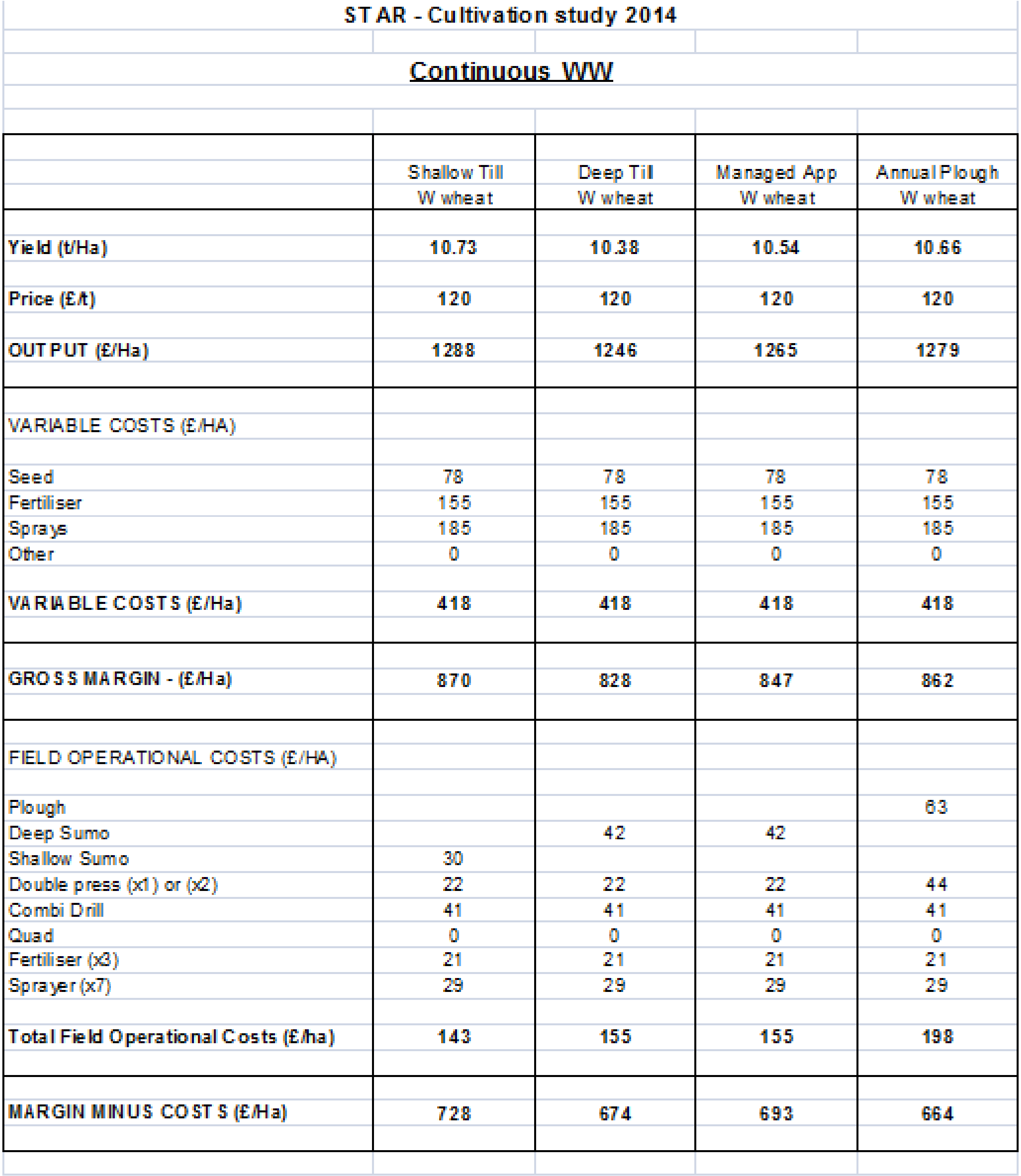
Appendix Table 12c. STAR cost and margin breakdown 2013/14 (Alternate Fallow)

STAR - Cultivation study 2014

Alternate Fallow

	Shallow Till Fallow	Deep Till Fallow	Managed App Fallow	Annual Plough Fallow
Yield (t/Ha)	**0.00**	**0.00**	**0.00**	**0.00**
Price (£/t)	**0**	**0**	**0**	**0**
OUTPUT (£/Ha)	**0**	**0**	**0**	**0**
VARIABLE COSTS (£/HA)				
Seed	44	44	44	44
Fertiliser	0	0	0	0
Sprays	10	10	10	10
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**54**	**54**	**54**	**54**
GROSS MARGIN - (£/Ha)	**-54**	**-54**	**-54**	**-54**
FIELD OPERATIONAL COSTS (£/HA)				
Combi Drill	41	41	41	41
Rolls (x1)	13	13	13	13
Sprayer (x3)	12	12	12	12
Total Field Operational Costs (£/ha)	**66**	**66**	**66**	**66**
MARGIN MINUS COSTS (£/Ha)	**-120**	**-120**	**-120**	**-120**

Appendix Table 12d. STAR cost and margin breakdown 2013/14 (Continuous Wheat)



STAR - Cultivation study 2014

Continuous WW

	Shallow Till W wheat	Deep Till W wheat	Managed App W wheat	Annual Plough W wheat
Yield (t/Ha)	**10.73**	**10.38**	**10.54**	**10.66**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1288**	**1246**	**1265**	**1279**
VARIABLE COSTS (£/HA)				
Seed	78	78	78	78
Fertiliser	155	155	155	155
Sprays	185	185	185	185
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**418**	**418**	**418**	**418**
GROSS MARGIN - (£/Ha)	**870**	**828**	**847**	**862**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				63
Deep Sumo		42	42	
Shallow Sumo	30			
Double press (x1) or (x2)	22	22	22	44
Combi Drill	41	41	41	41
Quad	0	0	0	0
Fertiliser (x3)	21	21	21	21
Sprayer (x7)	29	29	29	29
Total Field Operational Costs (£/ha)	**143**	**155**	**155**	**198**
MARGIN MINUS COSTS (£/Ha)	**728**	**674**	**693**	**664**

Appendix Table 13a. STAR cost and margin breakdown 2014/15 (Winter Cropping)

STAR - Cultivation study 2015

Winter Cropping

	Shallow Till WW	Deep Till WW	Managed App WW	Annual Plough WW
Yield (t/Ha)	**11.74**	**11.89**	**11.56**	**12.14**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1409**	**1427**	**1387**	**1457**
VARIABLE COSTS (£/HA)				
Seed	67	67	67	67
Fertiliser	164	164	164	164
Sprays	129	129	129	129
Other	7	7	7	7
VARIABLE COSTS (£/Ha)	**366**	**366**	**366**	**366**
GROSS MARGIN - (£/Ha)	**1043**	**1061**	**1021**	**1091**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				61
Deep Sumo		41		
Shallow Sumo	29		29	
Power Harrow	38	38	38	76
Combi Drill	41	41	41	41
Rolls	13	13	13	13
Quad (x1)	5	5	5	5
Fertiliser (x3)	21	21	21	21
Sprayer (x6)	24	24	24	24
Total Field Operational Costs (£/ha)	**170**	**182**	**170**	**240**
MARGIN MINUS COSTS (£/Ha)	**872**	**878**	**851**	**850**

Appendix Table 13b. STAR cost and margin breakdown 2014/15 (Spring Cropping)

STAR - Cultivation study 2015

Spring Cropping

	Shallow Till WW	Deep Till WW	Managed App WW	Annual Plough WW
Yield (t/Ha)	**11.61**	**11.68**	**11.77**	**11.67**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1393**	**1402**	**1412**	**1400**
VARIABLE COSTS (£/HA)				
Seed	67	67	67	67
Fertiliser	164	164	164	164
Sprays	147	147	147	147
Other	7	7	7	7
VARIABLE COSTS (£/Ha)	**384**	**384**	**384**	**384**
GROSS MARGIN - (£/Ha)	**1009**	**1017**	**1028**	**1016**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			61	61
Deep Sumo		41		
Shallow Sumo	29			
Power Harrow	38	38	38	76
Combi Drill	41	41	41	41
Rolls (x1)	13	13	13	13
Quad (1)	5	5	5	5
Fertiliser (x3)	21	21	21	21
Sprayer (x7)	29	29	29	29
Total Field Operational Costs (£/ha)	**175**	**187**	**207**	**245**
MARGIN MINUS COSTS (£/Ha)	**834**	**830**	**821**	**771**

Appendix Table 13c. STAR cost and margin breakdown 2014/15 (Alternate Fallow)

STAR - Cultivation study 2015

Alternate Fallow

	Shallow Till WW	Deep Till WW	Managed App WW	Annual Plough WW
Yield (t/Ha)	**12.11**	**12.23**	**12.24**	**11.93**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1453**	**1468**	**1469**	**1432**
VARIABLE COSTS (£/HA)				
Seed	67	67	67	67
Fertiliser	164	164	164	164
Sprays	129	129	129	129
Other	7	7	7	7
VARIABLE COSTS (£/Ha)	**366**	**366**	**366**	**366**
GROSS MARGIN - (£/Ha)	**1087**	**1101**	**1103**	**1065**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				61
Deep Sumo		41	41	
Shallow Sumo	29			
Power Harrow	38	38	38	76
Combi Drill	41	41	41	41
Rolls (x1)	13	13	13	13
Quad (x1)	5	5	5	5
Fertiliser (x3)	21	21	21	21
Sprayer (x6)	24	24	24	24
Total Field Operational Costs (£/ha)	**170**	**182**	**182**	**240**
MARGIN MINUS COSTS (£/Ha)	**917**	**919**	**920**	**825**

Appendix Table 13d. STAR cost and margin breakdown 2014/15 (Continuous Wheat)

STAR - Cultivation study 2015

Continuous WW

	Shallow Till WW	Deep Till WW	Managed App WW	Annual Plough WW
Yield (t/Ha)	**11.04**	**10.98**	**11.44**	**10.84**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1325**	**1318**	**1373**	**1301**
VARIABLE COSTS (£/HA)				
Seed	67	67	67	67
Fertiliser	164	164	164	164
Sprays	129	129	129	129
Other	7	7	7	7
VARIABLE COSTS (£/Ha)	**366**	**366**	**366**	**366**
GROSS MARGIN - (£/Ha)	**959**	**951**	**1007**	**935**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				61
Deep Sumo		41	41	
Shallow Sumo	29			
Power Harrow	38	38	38	76
Combi Drill	41	41	41	41
Rolls	13	13	13	13
Quad (x1)	5	5	5	5
Fertiliser (x3)	21	21	21	21
Sprayer (x6)	24	24	24	24
Total Field Operational Costs (£/ha)	**170**	**182**	**182**	**240**
MARGIN MINUS COSTS (£/Ha)	**788**	**769**	**824**	**694**

Appendix Table 14a. STAR cost and margin breakdown 2015/16 (Winter Cropping)

STAR - Cultivation study 2016

Winter Cropping

	Shallow Till Wbeans	Deep Till Wbeans	Managed App Wbeans	Annual Plough Wbeans
Yield (t/Ha)	**3.22**	**0.00**	**2.96**	**2.89**
Price (£/t)	**140**	**140**	**140**	**140**
OUTPUT (£/Ha)	**451**	**0**	**414**	**405**
VARIABLE COSTS (£/HA)				
Seed	124		124	124
Fertiliser	0		0	0
Sprays	126		126	126
Other	0		0	0
VARIABLE COSTS (£/Ha)	**250**	**0**	**250**	**250**
GROSS MARGIN - (£/Ha)	**201**	**0**	**164**	**155**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			54	54
Shallow Sumo	28			
Power Harrow			33	33
Cult Drill	26		26	
Quad (x1)	5		5	5
Sprayer (x4)	15		15	15
Total Field Operational Costs (£/ha)	**74**	**0**	**133**	**107**
MARGIN MINUS COSTS (£/Ha)	**127**	**0**	**32**	**48**

Appendix Table 14b. STAR cost and margin breakdown 2015/16 (Spring Cropping)

STAR - Cultivation study 2016

Spring Cropping

	Shallow Till Sbeans	Deep Till Sbeans	Managed App Sbeans	Annual Plough Sbeans
Yield (t/Ha)	**0.00**	**1.26**	**2.83**	**1.46**
Price (£/t)	**140**	**140**	**140**	**140**
OUTPUT (£/Ha)	**0**	**176**	**396**	**204**
VARIABLE COSTS (£/HA)				
Seed		176	176	176
Fertiliser		0	0	0
Sprays		152	152	152
Other		0	0	0
VARIABLE COSTS (£/Ha)	**0**	**328**	**328**	**328**
GROSS MARGIN - (£/Ha)	**0**	**-152**	**68**	**-124**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			54	54
Deep Sumo		38		
Power Harrow		33	33	33
Cult Drill		26	26	
Quad (x1)		5	5	5
Sprayer (x6)		23	23	23
Total Field Operational Costs (£/ha)	**0**	**124**	**140**	**114**
MARGIN MINUS COSTS (£/Ha)	**0**	**-276**	**-72**	**-238**

Appendix Table 14c. STAR cost and margin breakdown 2015/16 (Alternate Fallow)

STAR - Cultivation study 2016

Alternate Fallow

	Shallow Till Cover Crop	Deep Till Cover Crop	Managed App Cover Crop	Annual Plough Cover Crop
Yield (t/Ha)	**0.00**	**0.00**	**0.00**	**0.00**
Price (£/t)	**0**	**0**	**0**	**0**
OUTPUT (£/Ha)	**0**	**0**	**0**	**0**
VARIABLE COSTS (£/HA)				
Seed	44	44	44	44
Fertiliser	0	0	0	0
Sprays	18	18	18	18
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**62**	**62**	**62**	**62**
GROSS MARGIN - (£/Ha)	**-62**	**-62**	**-62**	**-62**
FIELD OPERATIONAL COSTS (£/HA)				
Power Harrow	33	33	33	33
Broadcast	23	23	23	23
Rolls (x1)	12	12	12	12
Quad (x1)	5	5	5	5
Sprayer (x2)	8	8	8	8
Total Field Operational Costs (£/ha)	**80**	**80**	**80**	**80**
MARGIN MINUS COSTS (£/Ha)	**-142**	**-142**	**-142**	**-142**

Appendix Table 14d. STAR cost and margin breakdown 2015/16 (Continuous Wheat)

STAR - Cultivation study 2016

Continuous WW

	Shallow Till WW	Deep Till WW	Managed App WW	Annual Plough WW
Yield (t/Ha)	**7.08**	**7.05**	**7.88**	**7.05**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**850**	**846**	**946**	**846**
VARIABLE COSTS (£/HA)				
Seed	59	59	59	59
Fertiliser	156	156	156	156
Sprays	208	208	208	208
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**424**	**424**	**424**	**424**
GROSS MARGIN - (£/Ha)	**426**	**422**	**522**	**422**
FIELD OPERATIONAL COSTS (£/HA)				
Plough				54
Deep Sumo		38	38	
Shallow Sumo	28			
Power Harrow	33	33	33	66
Cult Drill	26	26	26	26
Quad (x1)	5	5	5	5
Fertiliser (x3)	18	18	18	18
Sprayer (x7)	27	27	27	27
Total Field Operational Costs (£/ha)	**136**	**146**	**146**	**195**
MARGIN MINUS COSTS (£/Ha)	**290**	**276**	**376**	**227**

9.4. Appendix 4 Cost and margin breakdown for NFS trial

Appendix Table 15a. NFS cost and margin breakdown 2012/13 (No cover crop)

NEW FARMING SYSTEMS - Cultivation study 2013

Spring barley

	SB - cover crop Shallow Till	SB - cover crop Deep-till	SB - cover crop Plough	SB - cover crop Managed approach (Deep)
Yield (t/Ha)	**4.70**	**5.17**	**5.28**	**5.09**
Price (£/t)	**155**	**155**	**155**	**155**
OUTPUT (£/Ha)	**729**	**801**	**818**	**789**
VARIABLE COSTS (£/HA)				
Seed (SB)	68	68	68	68
Fertiliser	96	96	96	96
Sprays	103	103	103	103
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**267**	**267**	**267**	**267**
GROSS MARGIN - (£/Ha)	462	535	552	522
FIELD OPERATIONAL COSTS (£/HA)				
Plough			65	
Shallow disc (x1)	32	32	32	32
Deep Sumo		43		43
Shallow Sumo	30			
Cult Drill	27	27	27	27
Fertiliser x2	12	12	12	12
Sprayer x6	25	25	25	25
Total Field Operational Costs (£/ha)	**126**	**139**	**161**	**139**
MARGIN MINUS COSTS (£/Ha)	**336**	**396**	**391**	**384**

Appendix Table 15b. NFS cost and margin breakdown 2012/13 (With cover crop)

NEW FARMING SYSTEMS - Cultivation study 2013

Spring barley

	SB + cover crop Shallow Till	SB + cover crop Deep Till	SB + cover crop Plough	SB + cover crop Managed approach (Deep)
Yield (t/Ha)	**4.85**	**5.13**	**5.27**	**5.31**
Price (£/t)	**155**	**155**	**155**	**155**
OUTPUT (£/Ha)	**752**	**795**	**817**	**823**
VARIABLE COSTS (£/HA)				
Seed (SB)	68	68	68	68
Seed (Fodder Radish)	30	30	30	30
Fertiliser	96	96	96	96
Sprays	127	127	127	127
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**194**	**194**	**194**	**194**
GROSS MARGIN - (£/HA)	**558**	**601**	**623**	**629**
FIELD OPERATIONAL COSTS (£/HA)				
Broadcast (Fodder Radish)	12	12	12	12
Plough			65	
Shallow disc (x1)	32	32	32	32
Deep Sumo		43		43
Shallow Sumo	30			
Cult Drill	27	27	27	27
Rolls	14	14	14	14
Fertiliser x2	12	12	12	12
Sprayer x6	25	25	25	25
TOTAL FIELD OPERATIONAL COSTS (£/ha)	**152**	**165**	**187**	**165**
MARGIN MINUS COSTS (£/Ha)	**406**	**436**	**436**	**464**

Appendix Table 16a. NFS cost and margin breakdown 2013/14 (No cover crop)

NEW FARMING SYSTEMS - Cultivation study 2014

Winter Oilseed rape

	WOR - cover crop Shallow Till	WOR - cover crop Deep-till	WOR - cover crop Plough	WOR - cover crop Managed approach (15 cm)
Yield (t/Ha)	**4.19**	**3.96**	**3.63**	**4.42**
Price (£/t)	**280**	**280**	**280**	**280**
OUTPUT (£/Ha)	**1173**	**1109**	**1016**	**1238**
VARIABLE COSTS (£/HA)				
Seed (WOR)	45	45	45	45
Fertiliser	154	154	154	154
Sprays	112	112	112	112
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**311**	**311**	**311**	**311**
GROSS MARGIN - (£/HA)	**863**	**798**	**706**	**927**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			65	
Deep Sumo		43		43
Shallow Sumo	30			
Cult Drill	27	27	27	27
Rolls	14	14	14	14
Fertiliser x2	12	12	12	12
Sprayer x6	25	25	25	25
TOTAL FIELD OPERATIONAL COSTS (£/ha)	**108**	**121**	**143**	**121**
MARGIN MINUS COSTS £/Ha)	**755**	**677**	**563**	**806**

Appendix Table 16b. NFS cost and margin breakdown 2013/14 (With cover crop)

NEW FARMING SYSTEMS - Cultivation study 2014

Winter Oilseed rape

	WOR + cover crop Shallow Till	WOR + cover crop Deep Till	WOR + cover crop Plough	WOR + cover crop Managed approach (15 cm)
Yield (t/Ha)	**4.00**	**3.72**	**3.30**	**4.12**
Price (£/t)	**280**	**280**	**280**	**280**
OUTPUT (£/Ha)	**1120**	**1042**	**924**	**1154**
VARIABLE COSTS (£/HA)				
Seed (OSR)	45	45	45	45
Fertiliser	154	154	154	154
Sprays	112	112	112	112
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**311**	**311**	**311**	**311**
GROSS MARGIN - (£/HA)	**809**	**731**	**613**	**843**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			65	
Deep Sumo		43		43
Shallow Sumo	30			
Cult Drill	27	27	27	27
Rolls	14	14	14	14
Fertiliser x2	12	12	12	12
Sprayer x6	25	25	25	25
FIELD OPERATIONAL COSTS (£/ha)	**108**	**121**	**143**	**121**
MARGIN MINUS COSTS (£/Ha)	**701**	**610**	**470**	**722**

Appendix Table 17a. NFS cost and margin breakdown 2014/15 (No cover crop)

NEW FARMING SYSTEMS - Cultivation study 2015

Winter wheat

	WW - cover crop Shallow Till	WW - cover crop Deep-till	WW - cover crop Plough	WW - cover crop Managed approach (15 cm)
Yield (t/Ha)	**10.26**	**11.33**	**10.61**	**10.72**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1231**	**1360**	**1273**	**1286**
VARIABLE COSTS (£/HA)				
Seed (WW)	56	56	56	56
Fertiliser	141	141	141	141
Sprays	152	152	152	152
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**349**	**349**	**349**	**349**
GROSS MARGIN - (£/Ha)	882	1011	924	937
FIELD OPERATIONAL COSTS (£/HA)				
Plough			63	
Power Harrow				
Shallow disc	32	32	32	32
Deep Sumo		42		
Shallow Sumo	30			30
Double press				
Cult Drill	28	28	28	28
Rolls	14	14	14	14
Quad				
Fertiliser x3	17	17	17	17
Sprayer x7	29	29	29	29
Total Field Operational Costs (£/ha)	**150**	**162**	**183**	**150**
MARGIN MINUS COSTS (£/Ha)	**732**	**848**	**741**	**787**

Appendix Table 17b. NFS cost and margin breakdown 2014/15 (With cover crop)

NEW FARMING SYSTEMS - Cultivation study 2015

Winter Wheat

	WW + cover crop Shallow Till	WW + cover crop Deep Till	WW + cover crop Plough	WW + cover crop Managed approach (15 cm)
Yield (t/Ha)	**10.65**	**11.21**	**10.78**	**10.50**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**1278**	**1345**	**1294**	**1260**
VARIABLE COSTS (£/HA)				
Seed (WW)	56	56	56	56
Fertiliser	141	141	141	141
Sprays	152	152	152	152
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**349**	**349**	**349**	**349**
GROSS MARGIN - (£/Ha)	**929**	**996**	**945**	**911**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			63	
Shallow disc	32	32	32	32
Deep Sumo		42		
Shallow Sumo	30			30
Cult Drill	28	28	28	28
Rolls	14	14	14	14
Fertiliser x3	17	17	17	17
Sprayer x7	29	29	29	29
Total Field Operational Costs (£/ha)	**150**	**162**	**183**	**150**
MARGIN MINUS COSTS (£/Ha)	**779**	**834**	**761**	**761**

Appendix Table 18a. NFS cost and margin breakdown 2015/16 (No cover crop)

NEW FARMING SYSTEMS - Cultivation study 2016

Spring Oat

	SOat - cover crop Shallow Till	SOat - cover crop Deep-till	SOat - cover crop Plough	SOat - cover crop Managed approach (10 cm)
Yield (t/Ha)	**8.12**	**8.22**	**8.11**	**8.06**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**974**	**986**	**973**	**967**
VARIABLE COSTS (£/HA)				
Seed (WW)	64	64	64	64
Fertiliser	60	60	60	60
Sprays	76	76	76	76
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**200**	**200**	**200**	**200**
GROSS MARGIN - (£/Ha)	**774**	**786**	**773**	**767**
FIELD OPERATIONAL COSTS (£/HA)				
Plough			61	
Shallow disc (x1)	35	35	35	35
Deep Sumo		38		
Shallow Sumo	28			28
Cult Drill	26	26	26	26
Rolls	13	13	13	13
Quad x2	9	9	9	9
Fertiliser x2	10	10	10	10
Sprayer x5	19	19	19	19
Total Field Operational Costs (£/ha)	**140**	**150**	**173**	**140**
MARGIN MINUS COSTS (£/Ha)	**634**	**636**	**600**	**627**

Appendix Table 18b. NFS cost and margin breakdown 2015/16 (With cover crop)

NEW FARMING SYSTEMS - Cultivation study 2016

Spring Oat

	SOat + cover crop Shallow Till	SOat + cover crop Deep Till	SOat + cover crop Plough	SOat + cover crop Managed approach (10 cm)
Yield (t/Ha)	**8.17**	**8.15**	**8.03**	**8.11**
Price (£/t)	**120**	**120**	**120**	**120**
OUTPUT (£/Ha)	**980**	**978**	**964**	**973**
VARIABLE COSTS (£/HA)				
Seed (SOat)	64	64	64	64
Seed (Fodder Radish)	30	30	30	30
Fertiliser	60	60	60	60
Sprays	76	76	76	76
Other	0	0	0	0
VARIABLE COSTS (£/Ha)	**230**	**230**	**230**	**230**
GROSS MARGIN - (£/HA)	750	748	733	743
FIELD OPERATIONAL COSTS (£/HA)				
Broadcast (Fodder Radish)	22	22	22	22
Plough			61	
Shallow disc	35	35	35	35
Deep Sumo		38		
Shallow Sumo	28			28
Cult Drill	26	26	26	26
Rolls	13	13	13	13
Quad x2	9	9	9	9
Fertiliser x2	10	10	10	10
Sprayer x5	19	19	19	19
Total Field Operational Costs (£/ha)	**162**	**172**	**195**	**162**
MARGIN MINUS COSTS (£/Ha)	**588**	**576**	**538**	**581**

9.5. Appendix 5 Cost and margin breakdown for Mid Pilmore trial

Appendix Table 19. Mid Pilmore cost and margin breakdown 2012/13

Mid Pilmore - Cultivation study 2013

Spring barley

	SB - All Shallow non-inversion	SB - All Deep Inversion	SB - All Inversion
Yield (t/Ha)	**5.37**	**5.60**	**5.55**
Price (£/t)	**155**	**155**	**155**
OUTPUT (£/Ha)	**832**	**868**	**860**
VARIABLE COSTS (£/HA)			
Seed (SB)	79	79	79
Fertiliser	88	88	88
Sprays	57	41	41
Other	0	0	0
VARIABLE COSTS (£/Ha)	**225**	**208**	**208**
GROSS MARGIN - (£/Ha)	608	660	652
FIELD OPERATIONAL COSTS (£/HA)			
Plough		83	65
Power Harrow	28	28	28
Shallow Sumo	30		
Cult Drill	27	27	27
Fertiliser x2	14	14	14
Sprayer x2 or x3	13	8	8
Total Field Operational Costs (£/ha)	**112**	**160**	**142**
MARGIN MINUS COSTS (£/Ha)	**496**	**500**	**510**

Appendix Table 20. Mid Pilmore cost and margin breakdown 2013/14

Mid Pilmore - Cultivation study 2014

Spring barley

	SB - All Shallow non-inversion	SB - All Deep Inversion	SB - All Inversion
Yield (t/Ha)	**4.00**	**4.58**	**4.58**
Price (£/t)	**140**	**140**	**140**
OUTPUT (£/Ha)	**560**	**641**	**641**
VARIABLE COSTS (£/HA)			
Seed (SB)	70	70	70
Fertiliser	79	79	79
Sprays	52	52	52
Other	0	0	0
VARIABLE COSTS (£/Ha)	**201**	**201**	**201**
GROSS MARGIN - (£/Ha)	**359**	**440**	**440**
FIELD OPERATIONAL COSTS (£/HA)			
Plough		83	63
Power Harrow	28	28	28
Shallow Sumo	30		
Cult Drill	29	29	29
Fertiliser x2	14	14	14
Sprayer x2	8	8	8
Total Field Operational Costs (£/ha)	**109**	**162**	**142**
MARGIN MINUS COSTS (£/Ha)	**250**	**278**	**298**

Appendix Table 21. Mid Pilmore cost and margin breakdown 2014/15

Mid Pilmore - Cultivation study 2015

Spring barley

	SB - All Shallow non-inversion	SB - All Deep Inversion	SB - All Inversion
Yield (t/Ha)	**4.80**	**5.65**	**5.76**
Price (£/t)	**135**	**135**	**135**
OUTPUT (£/Ha)	**648**	**763**	**778**
VARIABLE COSTS (£/HA)			
Seed (SB)	72	72	72
Fertiliser	77	77	77
Sprays	46	46	46
Other	0	0	0
VARIABLE COSTS (£/Ha)	**195**	**195**	**195**
GROSS MARGIN - (£/Ha)	453	568	583
FIELD OPERATIONAL COSTS (£/HA)			
Plough		85	63
Power Harrow	27	27	27
Shallow Sumo	30		
Cult Drill	28	28	28
Fertiliser x2	14	14	14
Sprayer x2	8	8	8
Total Field Operational Costs (£/ha)	**107**	**162**	**140**
MARGIN MINUS COSTS (£/Ha)	**346**	**406**	**442**

Appendix Table 22. Mid Pilmore cost and margin breakdown 2015/16

Mid Pilmore - Cultivation study 2016

Spring barley

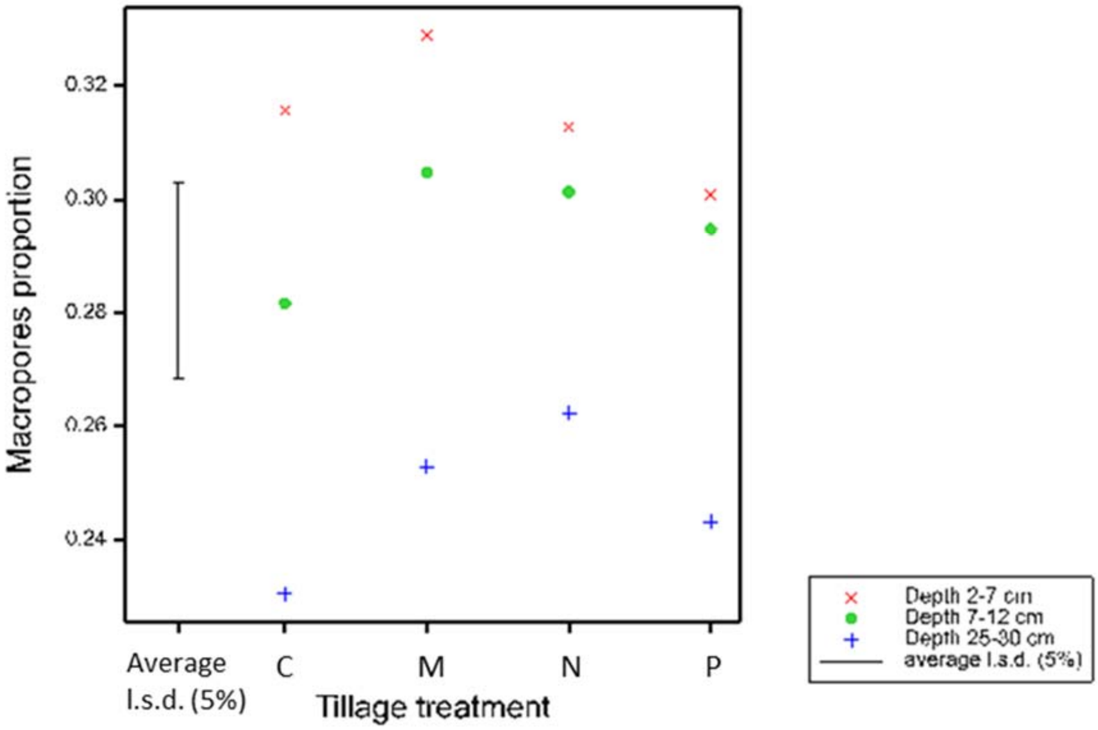
	SB - All Shallow non-inversion	SB - All Deep Inversion	SB - All Inversion
Yield (t/Ha)	**3.59**	**4.88**	**4.75**
Price (£/t)	**130**	**130**	**130**
OUTPUT (£/Ha)	**467**	**634**	**618**
VARIABLE COSTS (£/HA)			
Seed (SB)	70	70	70
Fertiliser	64	64	64
Sprays	73	73	73
Other	0	0	0
VARIABLE COSTS (£/Ha)	**207**	**207**	**207**
GROOS MARGIN - (£/Ha)	**260**	**428**	**411**
FIELD OPERATIONAL COSTS (£/HA)			
Plough		85	61
Power Harrow	24	24	24
Shallow Sumo	28		
Cult Drill	26	26	26
Fertiliser x2	12	12	12
Sprayer x2	8	8	8
Total Field Operational Costs (£/ha)	**98**	**155**	**131**
MARGIN MINUS COSTS (£/Ha)	**162**	**273**	**280**

9.6. Student project summary

In the parent project, RD-2012-3786, state-of-the-art approaches were used to produce and assess indicators of soil physical functioning and structure over relatively long-term field experiments. These included water retention characterisation, penetration resistance, a seedling growth assay, aggregate stability and soil resilience to slumping and compression. These methods are costly and time consuming and therefore inaccessible to many land managers.

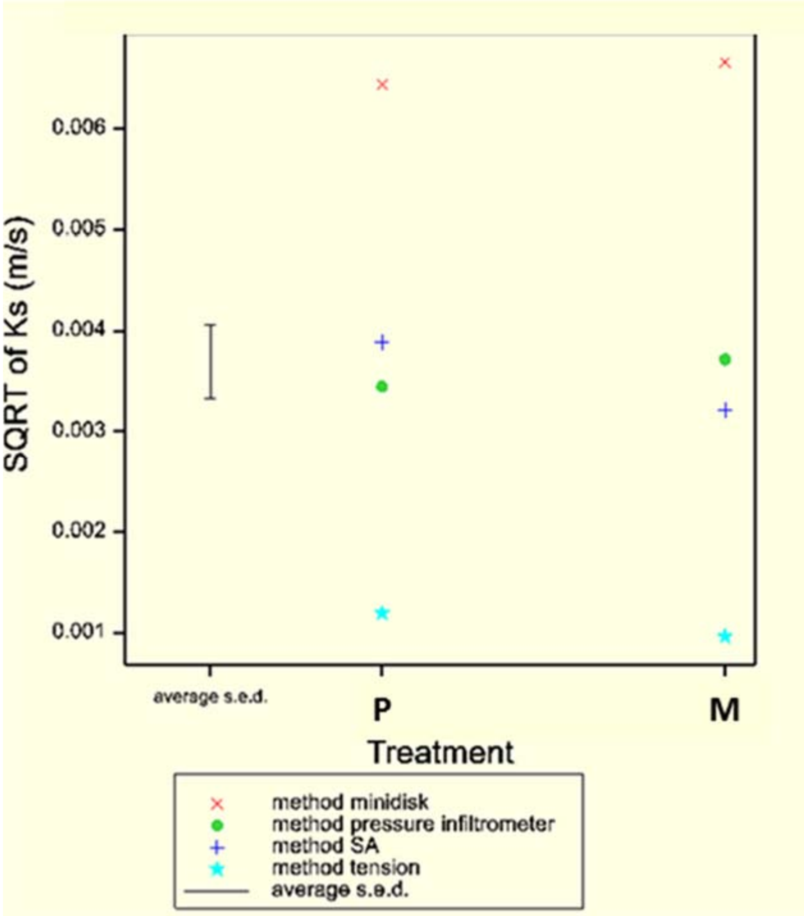
A summer project funded by the AHDB's student bursary aimed at evaluating the use of hydraulic conductivity as an indicator of soil physical functioning in comparison with lab-obtained indicators. Hydraulic conductivity is a property associated with the porosity and structure of the soil which can be evaluated with field methods. There are many commercially available instruments for the determination of hydraulic conductivity, many of them costly. Therefore, a second objective of the student project was to assess whether growers could make similar measurements with inexpensive methods.

In the first objective, hydraulic conductivity was compared to macroporosity calculated from water release curves in the parent project. Saturated hydraulic conductivity is associated to macroporosity because macropores are the main pathways for the rapid infiltration of water. In the parent project there were no statistically significant differences in macroporosity between tillage treatments in Mid-Pilmore (Appendix Figure 1). But because the water retention data provides a complete pore size distribution, other indicators such as Easily Available Water (EAW) were derived.



Appendix Figure 1 Macroporosity by tillage treatment and depth in Mid-Pilmore calculated from water release curve data for August 2013 in spring barley plots. C= compaction, M= shallow non-inversion tillage, N= no-till, P= conventional plough.

The student project, in accordance with the macroporosity assessment, found no statistically significant differences in hydraulic conductivity between plough and shallow non-inversion tillage in Mid-Pilmore using a range of commercially available devices and a self-assembled method (Appendix Figure 2). The self-assembled method consisted of a drain pipe hammered into the ground to prevent lateral flow from the sampling area and a plastic bottle used to keep a constant-head well over the soil. An air inlet tube maintained the constant-head and controls the head height, following the principles of the Mariotte's bottle. The self-assembled method proved to produce results comparable to most of the commercial devises, in particular the Guelph pressure infiltrometer.



Appendix Figure 2 Mean plot of square root of saturated hydraulic conductivity by each method in conventional plough (P) and shallow non-inversiton tillage (M) plots in Mid-Pilmore, August 2015. SA= self-assembled instrument.

Although macroporosity and hydraulic conductivity did not seem to be affected by tillage treatment in Mid-Pilmore, the effect of tillage treatment on macroporosity can be more marked in soils with heavier texture. Adequate levels of macroporosity are important for root elongation, providing oxygen and pathways for roots in soils with high mechanical impedance (Valentine et al., 2012).

The measurement of hydraulic conductivity with the self-assessed method has the potential to be used by land managers as an indicator of macroporosity. However, the assessment of soil quality has long been a challenging issue because soils present high variability in properties and functions. This is why it is important to adopt a combination of indicators, being lab or field measured, that encompass physical, chemical and biological characteristics (Zornoza et al., 2015).