Final Report

Platforms to Test and Demonstrate Sustainable Soil Management: Integration of Major UK Field Experiments

Ref: 11140022

Reporting Period: 2013-2016

Report Authors: Blair M. McKenzie[1], Mark Stalham[2], Paul D Hallett[3]

Date report submitted: 30 November 2017

Report No. 2018/3

1 James Hutton Institute, Invergowrie, Dundee DD2 5DA

2 NIAB CUF 219B Huntingdon Rd, Cambridge CB3 0DL

3 University of Aberdeen, Aberdeen, AB24 3UU

AHDB Potatoes is a division of the Agriculture and Horticulture Development Board.

Additional copies of this report and a list of other publications can be obtained from:

Publications

AHDB Potatoes
Stoneleigh Park
Kenilworth
Warwickshire
CV8 2TL

Tel: 02476 692051
E-mail: Potatoes.Publications@ahdb.org.uk

Our reports, and lists of publications, are also available at potatoes.ahdb.org.uk

CONTENTS

1. SUMMARY

1.1. Aim

This project used multiple field experiments, where potatoes were grown under commercial production, to test a range of hypotheses relating to the impact of management practices on soil physical quality. Practices tested included cultivation or destoning depths, alternative cultivation systems, organic matter additions and the impact of potato production on long-term soil conditions. We used multiple indexes of soil physical quality and compared the relative merits of each in different circumstances.

1.2. Methodology

Soil was sampled from multiple field sites across the UK at which potatoes were being grown. Soil was sampled at multiple depths (0, 15, 20 and 30 cm) and at different stages of potato production (pre-potatoes, post-planting, pre-harvest and post-harvest). The soil was sampled either as core samples with defined volume or as bulk loose soil. Samples were collected from recorded GPS locations to allow repeated sampling. The core samples were characterised for a range of indexes of soil physical quality including bulk density, plant available water, easily available water, least limiting water range and the "S" index. The bulk samples were used to assess the stability of the existing structure and to test the resistance and resilience of the structure to perturbations. The indexes, and their changes over time, were statistically analysed to understand the impacts of different management strategies on soil conditions. The approach used mirrored a sister project funded by AHDB Cereals and Oilseeds.

1.3. Key findings

Repeated soil sampling at GPS located points provides a useful way of monitoring soil conditions and linking them to management practices. The selection of sampling sites can be guided by rapid *in-situ* field measurements such a vane shear strength or VESS (Visual Evaluation of Soil Structure).

There are multiple measures of soil physical quality and the best one or combination depends on the specific hypothesis to be tested.

Consistent with Stalham and Allison (2015) cultivation and destoning operations should be no deeper than necessary and timed so that the soil is drier than the plastic limit. Deep destoning did not result in better soil conditions than shallow destoning.

Alternative cultivation (i.e. to ploughing) systems tested as part of R444 (Silgram *et al.* 2015). We found that within the potato beds the indexes of soil quality were better for water availability and root proliferation under the plough treatment.

We identified that applications of municipal compost over multiple years prior to potato cropping produced less-dense, softer, more-stable soil (than no application), particularly at 15 and 20 cm depths into the potato beds. While there can be some detrimental effects to soil quality associated with potato harvest the compost addition ameliorated some of these effects.

Carefully managed potato crops, cultivated and harvested when the soil conditions were near to optimal did not leave a detrimental legacy within the ploughing depth for subsequent crops, although there was some evidence of subsoil compaction.

1.4. Practical recommendations

There is no single index of soil physical quality applicable in all situations. The use of each particular index should be linked to specific questions related to crop production. Sampling locations may be informed by rapid survey and the use of GPS location benefits assessments over time.

Delaying tillage and planting operations until the soil is drier than the plastic limit over the working depth will help avoid compaction and clod formation.

There are no benefits of destoning deeper than necessary.

Repeated additions of organic matter (municipal compost) improved soil conditions for root proliferation and tuber expansion. The benefits persist after the potato crop.

Soil conditions within the potato beds were better under traditional ploughing than in alternative cultivation systems, however there may be other reasons (e.g. cost savings with decreased fuel use or decreased time needed to prepare beds associated with fewer machine passes) to advocate alternatives.

2. INTRODUCTION

As readers of this report may not be soil scientists it is worth clarifying some terminology and approaches here. The Plastic Limit (PL) of a soil is the water content (usually expressed by weight) at which the behaviour of the soil changes from friable (drier than the PL) to plastic (wetter than the PL). Soil that is friable will crumble into smaller aggregates under an applied stress (e.g. a tillage implement) with an associated increase in porosity. Soil that is plastic will fail by smearing with an increase in density along the failure plane. To prepare soil for planting potatoes the cultivation should thus be done while the soil is friable i.e. drier than the plastic limit. However the soil should not be too dry as the soil strength increases with drying. Soil with high strength takes more energy to work and the resulting aggregates tend to be finer than is desirable for planting. So there is an optimum soil water content for conducting tillage that is usually taken as just drier than the PL – sometimes given as 0.9 times the PL. A more detailed explanation of this soil behaviour can be found in a recent review of workability and fragmentation of soil (Obour et al 2017). The PL is positively correlated with both clay content and organic matter concentration i.e. soils with more clay and / or more organic matter will change behaviour from friable to plastic at greater water contents (Keller & Dexter 2012). In the U.K. soil preparation for potato production is done in spring. Due to winter rainfall with very low evaporation the soil is wet at the end of winter and dries from the surface down the profile. So while surface soil may be drier than the PL deeper into the profile the soil may be wetter than the PL and thus likely to deform by smearing. Potato harvest in the U.K. can be into late autumn. With rainfall and low evaporation at that time the soil may become wetter than the PL. Harvesting operations that lift the soil (wetter than the PL) to separate tubers will also cause smearing and damage the soil structure by creating dense clods. Compaction by machinery is also more problematic for soil wetter than the PL.

The production of potatoes and root crops involves extensive soil manipulation to create an environment in which tubers can easily expand and not be deformed or damaged by stones within the soil profile. The root system of the crop should be able to proliferate through the soil to access water and nutrients, but the soil must also have sufficient drainage so as not to become waterlogged. Research funded by AHDB and others has shown soil compaction to be a major issue in arable agriculture including potatoes (Stalham *et al.* 2007). Potato crops have additional impacts (compared with cereal crops) on soil. At planting, potato production systems involve the formation of beds which typically includes sieving the soil to remove stones and clods. Similarly, at harvest the soil is lifted and separated from the tubers by sieving. These sieving operations will disrupt pore networks existing in the soil and break apart stable aggregates. Beds formed for potato production can initially produce very favourable physical conditions for plant growth, but they can rapidly degrade over time due to slumping and the coalescence of the aggregated structure.

Research on minimising the impacts of potato production on soil structure is limited. There are some exceptions from studies in North America, but not all of these are relevant to U.K. conditions. Before this project started, Carter and co-workers studied several practices, including conducting the primary tillage in spring rather than, as was usual in Prince Edward Island, Canada, in the autumn preceding the crop (Carter *et al.* 2010). He also investigated the long-term influence of compost application in a potato rotation and found benefits in terms of improved soil water retention (Carter 2007). Carter *et al*. (2009) studied the influence of rotation and conservation tillage approaches in cropping systems including potato. The main differences in the approaches tested were the incorporation of clover residue into the soil before the potato crop and decreasing the depth and number of passes for the tillage operations. Benefits to the soil biology were noted but assessments of other properties were not reported. It is also worth noting that the rotations included potato crop at least every 3 years.

Since this project started, Li *et al.* (2015) have reported on soil quality attributes in a twelve year rotation experiment in Alberta, Canada. The rotation experiment included both potatoes and sugar beet. Interventions used included applications of feed-lot manure, use of cover crops and decreased tillage depth with fewer passes. They have reported improvements in water stable aggregation, microbial biomass and changes in the nature of the soil organic matter under their conservation approaches. However this work was confined to surface soil and did not report on changes in soil compaction, strength or water availability.

In the last 20 years, a number of new ways to quantify soil physical quality have been developed. Many are based on the distribution of different pore classes in soil, as these provide indicators of oxygen exchange and water transport to prevent hypoxia, water storage to resist drought and the presence of macropores to provide preferential channels for root growth (Czyz 2004; Hallett & Bengough 2013). A simple indicator, the S index, has been developed that uses the shape of the water retention curve (Dexter 2004a) to provide a numeric value that has been correlated to fragmentation of soil by tillage, seedbed degradation (Dexter 2004b) and the optimal water content for timing of tillage operations (Dexter *et al.* 2005). This approach is being adopted in other regions (Li *et al.* 2011), with over 370 citations to Dexter (2004a) from other field studies, but its theoretical basis has raised questions and verification against crop performance is needed. A more commonly used indicator to identify soil constraints to crop productivity is the least limiting water range, LLWR (daSilva & Kay 1996). It uses cut-off values of soil water content based on hypoxia, drought and mechanical impedance, to define the range of water contents where soil properties will not severely impede crop productivity. LLWR is based on several generalisations about soil behaviour that may not be observed in field conditions, where the structural heterogeneity of soil properties can have a large impact on crop productivity. For instance, LLWR defines 2 MPa as the cut-off mechanical impedance where root growth is completely restricted. Field penetrometer resistance that limits oat root growth, however, was found to be 4.6 to 5.1 MPa in untilled soil layers, as compared with 3.6 MPa for tilled topsoils (Ehlers *et al.* 1983) due to roots exploiting a network of continuous biopores in the untilled soil. Lack of access to subsoil resources limits crop productivity (McKenzie *et al.* 2009). There is clearly scope to better link indexes of soil quality to a wider range of crop production including for potatoes.

A limitation of many studies on the physical properties of seedbeds used for crop production is the collection of measurements at only one time in the growing season (Panini *et al.* 1997). For root crops in raised beds, soil structure may change continuously over time, with a potential that soils measured as good quality post-cultivation may be poor by harvest, or conversely. Moreover, potato crops have been associated with poor soil conditions over the following winter months (Palmer & Smith 2013), possibly having a knock-on impact to crops grown in the same field the following year.

At the time that this project was commissioned, AHDB were supporting other projects on soil management. The AHDB Cereals and Oilseeds had commissioned a sister project, Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments (RD-2012-3768). This has now reported as PR574 (McKenzie *et. al.* 2017). AHDB potatoes had commissioned project R459 Improving Cultivation Practices in Potatoes. R459 examined different depths of cultivation and worked closely with manufacturers (Stalham and Allison 2015). AHDB potatoes had also commissioned project R444, Managing cultivations and cover crops for improved profitability and environmental benefits in potatoes (Silgram *et al.* 2015). The current project described here aligned and sought synergy with these other projects in the methodologies used to characterise soil structure and stability and where possible collected samples from the same experiments.

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 and from soil amendments. 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 are known to have a large impact on crop yield potential. We related the soil physical measurements to indexes of suitability for root growth and, where appropriate, to crop yield to obtain a more holistic understanding of how soil tillage may influence productivity. 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 agronomists to implement. By measuring a range of properties and processing these into key indicators we aim to limit the range of indicators to those most appropriate. Soil physical characterisation was done on samples collected at multiple times during a growing season and from subsequent crops in the rotation, as described in section 3.1. 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 = 100 cm^3 volume) of soil from each platform (field experiment) detailed later for water retention and related measurements, and in some cases 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 – usually a combination of pre-planting, post-planting, pre-harvest and post-harvest. Samples collected on different dates were collected as near spatially as was feasible to earlier samples, using hand-held GPS units if available. However at one site GPS coverage was not sufficiently strong for repeated samples to be taken. Samples were taken at or near the surface (described as 0 cm) and below the normal depth of tillage (usually around

30 cm depth) being where any traffic or plough pan may occur. Samples were also collected from within the topsoil Ap horizon, usually at 15 cm depth. For sampling pre- and post-potatoes this is within the main rooting zone of a cereal crop. For potato crops where the soil is formed into beds this is within the main part of the soil bed where tuber expansion will occur. In selected cases, samples were also taken at 20 cm depth from the top of the bed in attempts to identify if particular tillage systems were smearing the soil at the depth of working. 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 (or suctions as they are negative potentials) used were saturation = -0.01 kPa and -1, -5, -20, -50, -300, and -1500 kPa. The only exception to this range of suctions was for the first samples taken at the Slade farm site. In these first samples -0.01 kPa and -1, -5, -20, -50, -100, -500 and -1500 kPa were used. However the results from the 100 and 500 kPa measurements were very similar (i.e. only limited water was stored between these suctions) and to increase sample throughput, we standardised on a single measurement at 300 kPa. To complete a water retention curve on an individual soil core can take 2 months depending on the clay content of the sample. 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 eight values in the range between 4.5 mm and 9.75 mm depth were averaged to provide a mean resistance.

The data from this characterisation were 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 it was proposed by Dexter (2004a).

For sites managed in association with NIAB-CUF, *in situ* soil resistance readings were taken using an Eijkelkamp Penetrograph penetrometer (1 cm^2 60° cone tip) in the centre of the ridge to a depth of 50 cm immediately following planting. Three replicate readings of resistance were taken in each plot of all experiments. Similarly soil aggregate size distribution within the ridges of potato crops was measured by grading a large-volume (2.0 l) soil sample taken at planting and again at final harvest. After removing 1 cm of soil from the apex of the ridge, a lidded 20 x 10 x 10 cm deep steel box was pushed into the centre of the ridge mid-way between two plants and extracted by sliding a flat plate underneath and excavating with a spade. The soil was transferred to a plastic bag, weighed and sealed. At a subsequent date, the sample was carefully tipped into aluminium trays and dried at 105 °C for 24 h, then reweighed and sieved into ten grades (< 2, 2-6, 6-10, 10-15, 15-20, 20-25, 25-30, 30 35, 35-40 and 40-45 mm) using a combination of potato riddle grids and Endacott soil sieves. The soil in each grade was weighed and the weight fractions in each grade calculated.

The stability of loose soil collected at the same time as the cores was used to determine aggregate stability in water. Two approaches to measure stability were used. Both deployed the commercially available Eijkelkamp Wet Sieving Apparatus. Soil is place on sieves that are vertically oscillated in cans 80% filled with water at a frequency of 34 cycles/min for three minutes and the weight of soil remaining on the sieves determined (and corrected for initial water content). These sieves were then moved up and down by the machine into cans 80 %

filled with water. The principle being that unstable aggregates break apart and pass through the sieve to be collected in the water-filled can underneath the sieve. Water stable aggregation (WSA), i.e. the soil remaining on the sieves, is expressed as a percentage of the initial dry weight of soil.

In the first approach 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. This was done in triplicate for all sampling point and depth combinations. The second approach used duplicate sub-samples extracted from the oven-dried soil from the ridge bulk density cores (described above). Four grams (+/- 0.1 g) of soil aggregates from the ridge was placed onto the sieves (either 0.25 or 2 mm aperture). The samples were pre-moistened using a plant sprayer 5 min before submerging them. In both approaches, all soil remaining on the sieve was washed into small aluminium trays and dried at 105 °C for 24 h. The dried weight of soil represented the stable aggregate fraction. The water stable aggregate (WSA) data are presented on a proportional scale with 1 = all soil remaining on sieve.

General statistical analysis was taken under advice or by Dr Katharine Preedy of BioSS. Analysis was performed in Genstat v 17 or v 18 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.

3.2. Soil Resilience

Soil preparation for potato production involves deep and repeated tillage to produce a fine seedbed. Bed forming applies a light stress to improve how well the seed potato is in contact with the soil and the overall stability of the soil. Over time, stresses from weather or field operations can change the physical structure of the soil, producing less favourable conditions for potato production. Section 3.1 describes how we obtained a range of physical measurements that were repeated at multiple times during and beyond the growing season. The measurements of bulk density, water retention characteristics or soil strength were applied to a given sampling date, with multiple samples required throughout the year to assess changes. In Figure 3.2.1 it can be observed that during the growing season, an initially open pore structure may coalesce over time, and compaction from field operations may restrict root growth to depth. One measurement that has been widely used to assess the susceptibility of soils to physical changes over time is the water stable aggregation (WSA) (Bartoli *et al.* 2016) described in 3.1 above. This simple index measures the susceptibility of soil aggregates to breakdown when they wet rapidly e.g. from rainfall, with the data used to understand the risks of erosion and surface sealing. 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 in conservation tillage systems, greater aggregate stability and less erosion risk occurs. Deep cultivation for potato production dilutes carbon from the soil surface by mixing it with the soil.

Deeper in the rooting zone of soil other processes cause soil structure to change over the growing season (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 (Hakansson *et al*., 2012). The potential impacts are dramatic. Bresson & Moran (2003) 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), with root crops like potatoes associated more frequently with fields where structural conditions are very poor (Hallett *et al*., 2016; Palmer and Smith, 2013). 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 can persist for long periods of time, particularly in the subsoil.

Just from a visual examination of the surface of potato field, it is evident that soil physical conditions change over the growing season. The physical measures described in Section 3.1 provide robust data on soil physical conditions for potato production, but the measurements are expensive to conduct and were selected to pick out key physical indicators of soil structure that could be deployed in cost-effective monitoring programmes. Even with more focussed and inexpensive measurements of key physical parameters, field measurements over time are affected by local weather conditions and are cumbersome to implement as fields require return visits.

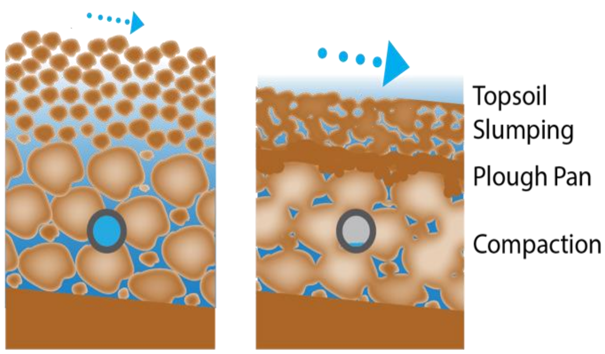

Figure 3.2.1: ***The physical structure of soil can degrade through inter-linked processes of compaction and slumping during a growing season.***

This has been overcome by the development of 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). To date, however, these measurements have not been compared to time-dependent measurements of soil physical conditions for crop growth, so their practical value is unknown.

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 as part of the HGCA funded platforms project, we replaced 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.

3.2.1. Soil Preparation

Resilience assays were only conducted once during the growing season, on soil collected at post-planting. Field replication and treatments were identical to the intact soil cores described in section 3.1. Bulk soil samples were taken at the top of the ridge 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 from the top of the ridge 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 rewetted 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

These 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. At the end of the load cell a round platen was 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 compression of soil when a potato ridge is formed 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. Following compression, the core was saturated and then equilibrated to -5 kPa. This provided a measurement of the relaxation of the soil pore structure following compaction.

3.3. Yield

For the sites in England a final harvest of 3 m from a single row was taken in August-September when the crop was ready for commercial harvesting. The tubers were graded, counted and weighed in 10 mm increments. A representative sample of tubers weighing *c*. 500 g was dried at 90 °C for 48 h to measure tuber dry matter concentration ([DM]). Fifty tubers were assessed for incidence and severity (% surface area (SA) infected) of common scab in the categories of 0, 0-1, 2-5, 5-10 % SA and then in 10 % increments. Tubers were also assessed for type, incidence and severity of tuber cracking, greening and other growth defects at final harvest. For the Slade farm site in Scotland harvest and yield were done and reported as part of project R444. For the CSC Balruddery site harvest data were taken from the CSC annual reports. The two contrasting managements in the CSC include the compost additions and less overall nitrogen fertiliser to the sustainable management. For this reason direct comparison of yields cannot be attributed to differences in soil management alone and in the context of this report are of limited value.

3.4. Sites

This project was designed to add value to existing experiments that included potatoes in the rotation. The sites in England were described in the Final Report of Potato Council Project R459 Improving cultivation practices in potatoes to increase window of workability and soil structural stability (Stalham and Allison 2015) and R444 Managing cultivations and cover crops for improved profitability and environmental benefits in potatoes (Silgram *et al.* 2015).). All experiments were irrigated according to the NIAB CUF Potato Irrigation Scheduling model. Briefer details of the experimental treatments selected for Project 11140022 (formerly R467) are given below. The experiments at sites in Scotland were at Slade farm, described in R444 Managing cultivations and cover crops for improved profitability, and environmental benefits in potatoes (Silgram *et al.* 2015) at the Centre for Sustainable Cropping at James Hutton Institutes Balruddery farm.

3.4.1. GVAP Hales Hospital (2013)

The GVAP Hales Hospital site (52.5197 °N, 1.5193 °E) was managed by Stuart Liddell of GVAP and comprised of a randomised block design with four replicates of six destoning depth treatments. The site was a sandy clay loam (60 % sand, 18 % silt, 22 % clay, 2.2 % OM) and planted with Maris Piper on 11/04/13. It was destoned using a Grimme CS170 with 28 mm web towed by a New Holland T6080 tractor. The shallowest (24 cm) and deepest (36 cm) treatments were selected for Project 11140022.

Soil sampling was on the following dates with crop stages indicated:

11/04/13 Winter wheat stubble pre-potatoes
08/07/13 Pre-harvest potatoes
08/10/13 Post-harvest potatoes (uncultivated)
19/05/14 Winter wheat standing crop
19/08/14 Winter wheat stubble
26/03/15 Sugar beet planted

From the soil samples collected, we performed water retention and micropenetrometer analysis to determine the soil quality indicators described above (Methods Section 3.1). These were (soil dry) bulk density, macroporosity, plant available water (PAW), Easily Available Water (EAW), Least Limiting Water Range (LLWR) and “S” from the slope at the point of inflection indicated from the van Genuchten fit of the water retention curve. Soil samples were from the surface (0 cm), 15 cm (in the bed or in the cultivated Ap horizon and at 30 cm (below normal ploughing depth). The same methodology was applied for all sites described below and so this text applies to each site but will not be repeated every time.

3.4.2. GVAP The Cliff (2014)

This experiment was conducted in The Cliff field, Hales, Norfolk (52.5246 °N, 1.5446 °E) farmed by Greenvale AP Ltd and was located on a sandy clay loam soil (55 % sand, 19 % silt, 26 % clay, 1.8 % OM). It was bedformed and destoned on 01/04/14 and planted on the same day with Jelly seed. It was destoned using a Grimme CS170 with 28 mm web towed by a Case 145 tractor. There were three destoning depth treatments and four replicates laid out in a randomised block design. The shallowest (25 cm) and deepest (45 cm) treatments were selected for 11140022.

Soil sampling was on the following dates with crop stages indicated:
01/04/14 Cereal stubble pre potatoes
19/05/14 Post-planting potatoes
30/09/14 Post-harvest potatoes
26/03/15 Winter wheat standing crop

3.4.3. Stevenson Langlands

This experiment was conducted in Langlands, Aythorpe Roding, Essex (51.8085 °N, 0.2900 °E) managed by Tom Stevenson of Stevenson Bros. It was located on a clay loam soil (26 % sand, 46 % silt, 29 % clay, 2.3 % OM). The experimental area was re-bedformed from over-wintered beds on 01/04/14 and destoned and planted on 04/04/14 using Picasso seed. It was destoned using a Pearson Megastar Gen-2 towed by a John Deere 6930 tractor. There were six destoning depth treatments and four replicates laid out in a randomised block design. The shallowest (22 cm) and deepest (33 cm) treatments were selected for 11140022.
Soil sampling was on the following dates with crop stages indicated:
13/08/13 Cereal stubble pre-potatoes
19/05/14 Post-planting potatoes
03/09/14 Post-harvest potatoes (uncultivated)
09/07/15 Winter wheat standing crop
14/07/16 Winter beans standing crop

3.4.4. GVAP Workhouse (2015)

This experiment was conducted in Workhouse field, Hales, Norfolk (52.5228 °N, 1.5196 °E) farmed by Greenvale AP Ltd and was located on a loamy sand soil (81 % sand, 12 % silt, 7 % clay, 1.6 % OM). It was bedformed and destoned on 01/04/15 and planted on the same day with Jelly. It was destoned using a Grimme CS170 with 28 mm web towed by a New Holland T6080 tractor. There were three destoning depth treatments and four replicates laid out in a randomised block design. The shallowest (25 cm) and deepest (45 cm) treatments were selected for 11140022.
Soil sampling was on the following dates with crop stages indicated:
26/03/15 Winter wheat stubble pre-potatoes
02/07/15 Pre-harvest potatoes
16/03/16 Ploughed

3.4.5. Stevenson Waterloo (2015)

This experiment was conducted in Waterloo field, Aythorpe Roding, Essex (51.7896 °N, 0.2596 °E) farmed by Stevenson Bros. It was located on a clay soil (22 % sand, 38 % silt, 40 % clay, 4.4 % OM). The experimental area was re-bedformed from over-wintered beds on 12/04/15 and destoned and planted on 13/04/15 using Picasso seed. It was destoned using a Pearson Megastar Gen-2 towed by a John Deere 6930 tractor. There were three destoning depth treatments and four replicates laid out in a randomised block design. The shallowest (22 cm) and deepest (33 cm) treatments were selected for 11140022.

Soil sampling was on the following dates with crop stages indicated:

12/08/14 Winter wheat stubble pre-potatoes

09/0715 Pre-harvest potatoes

06/05/16 Winter wheat standing crop

3.4.6. Tern Farm (2013)

At the Tern Farm site near Telford (52.7561 °N, 2.5646 °W), a comparison was made between a conventional soil preparation of Plough (+ bedformer + destoner) and a Tillerstar unit (which includes tiller/clod separater, destoner and bedformer in a single pass machine). The experiment was managed by Martyn Silgram and Di Williams of ADAS, and comprised a randomised block design with four replicates. The plough treatment was cultivated to 22 cm depth using a 5-furrow reversible plough and a John Deere 6930 on 17/04/13. The secondary cultivations (including Tillerstar) were conducted on 26 April. The destoned plots were worked to 35 cm. The Tillerstar (two-bed version, 2013 model) was operated at 30 cm depth and towed with a Massey Ferguson 8670 tractor. The site was a sandy loam (65 % sand, 17 % silt, 18 % clay, 1.6 % OM) and planted with Maris Piper on 26 April.

Soil from the potato beds (or the locations where beds were to go or had been) were sampled as in the protocols described above on the dates below and with the indicated crop status:

17/04/13 Winter wheat stubble pre-cultivation (ploughed on 17/04/13 post sampling)

12/08/13 Pre-harvest potatoes

22/01/14 Post-harvest potatoes

23/05/14 Spring barley standing crop

12/02/15 Spring barley stubble

17/07/15 Spring barley standing crop

3.4.7. Slade Farm (2015)

This experiment was conducted at Slade Farm between Forfar and Arbroath in eastern Scotland. Details of the site can be found in Final Report of Potato Council Project R444. The soil at the site is loamy sand texture with relatively low stone content. A comparison was made between a conventional soil preparation of Plough to 33 cm (+ bedformer + destoner), a Simba Great Plans DTX unit with a tine to 40 cm depth and a disc at 13-14 cm depth (+ bedformer + shallow destoner), and a Tillerstar unit (which includes tiller/clod separater, destoner and bedformer in a single pass machine). The site was managed by Stuart Wale of SRUC, and comprised a randomised block design with four replicates. The plough treatment was with a 7-furrow reversible plough. The shallow destoning was destoned to 22 cm. The George Moate Tillerstar (two-bed version, 2013 model) was operated at 30 cm depth.

3.4.8. Centre for Sustainable Cropping Balruddery

Unlike the other sites, the Centre for Sustainable Cropping (CSC) has potatoes in a six year rotation. Each of the 6 fields is split into two different management systems. Half of the field is grown with conventional management, the other half is grown with management deemed "sustainable". The main differences between the management systems for potato production were that 35 t/ha of compost (PAS 100) was applied to the sustainable treatment.
Over the four years of this project potatoes were grown in four fields in rotation. In 2013 field M (Den South), in 2014 field P (Estate), in 2015 field O (Kennels) and in 2016 field N (Pylon). Soil in this experiment was sampled as shown in Table 3.4.8.1. The soil across the farm are from 2 soil series: Garvock and Mountboy. Garvock is a brown earth with free natural drainage (Haplic Cambisol) developed on locally derived often stony drift. Mountboy series is a brown earth with imperfect natural drainage (Epistagnic Cambisol) developed on finer textured till.

Table 3.4.8.1 Soil sampling by depth and field in the CSC Balruddery (NS = not sampled).

Season (Field)	Depths pre-planting	Depths post-planting	Depths pre-harvest	Depths post-harvest
2013 (M)	NS	0,15,20,30	0,15,20,30	0,30
2014 (P)	0,15,30	0,15,20,30	0,15,20,30	0,30
2015/16 (0)	0,30	0,15,20,30	0,15,20,30	0,15,30
2016 (N)	0,15,30	0,15,20,30	0,15,20,30	NS

4. RESULTS

4.1. Destoning depths

4.1.1. GVAP Hales Hospital

GVAP Hales Hospital considered the deepest and shallowest destoning with soil sampling across six dates and examined the changes in soil quality indicators over time. With sampling over subsequent crops (see 3.4.1) long-term impact of the production systems on soil conditions could also be assessed. Soil sampling as cores were taken at 0, 15 and 30 cm depths to evaluate conditions at the soil surface (0 cm), within the bed at a depth important for crop roots and tuber expansion (15 cm) and below the normal depth of cultivation (30 cm). Cores were 5 cm in length and sampling procedure has been described in 3.1 Methods (above).

With measurements taken immediately after planting the potato crop, the soil penetration resistance was lower with deep destoning. Below 40 cm the soil strength is greater than 2 MPa indicating some compaction but there was no indication of differences between destoning depths (Figure 4.1.1.1).

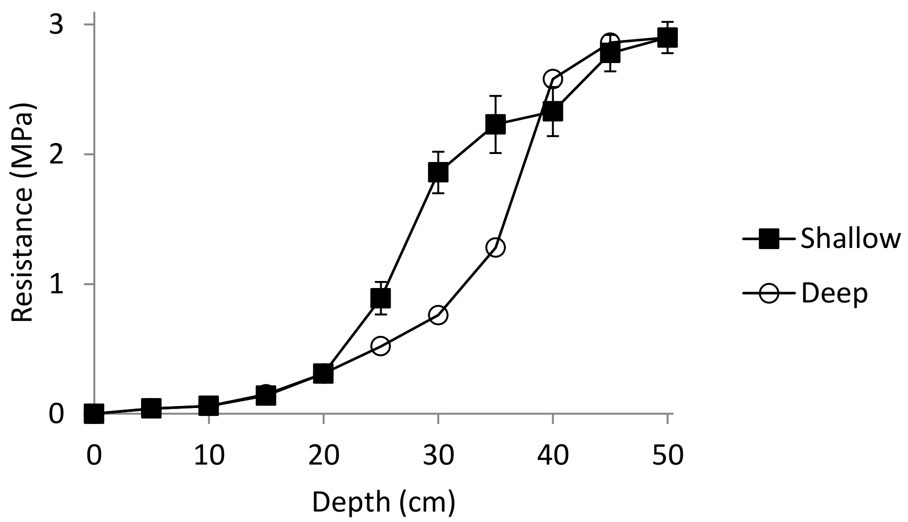

Figure 4.1.1.1. Effect of destoning depth on soil penetration resistance at planting in GVAP Hales Hospital

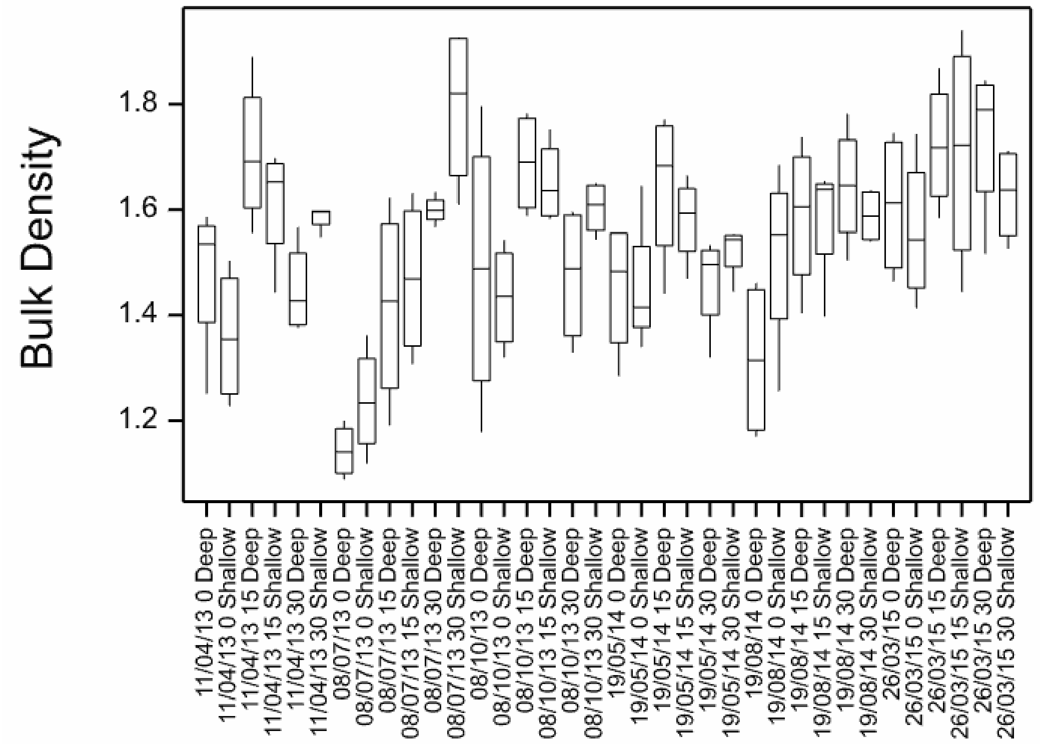

Figure 4.1.1.2 Soil Bulk Density (gcm^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

Figure 4.1.1.2 is a box and whisker plot of bulk density by treatment over time. The values are within the normal ranges for agricultural soils. On 08/07/13 the bulk densities at the surface and at 15 cm depth appear lower than at other times. Apart from a small increase between August 2014 and Spring 2015 no significant trends are apparent.

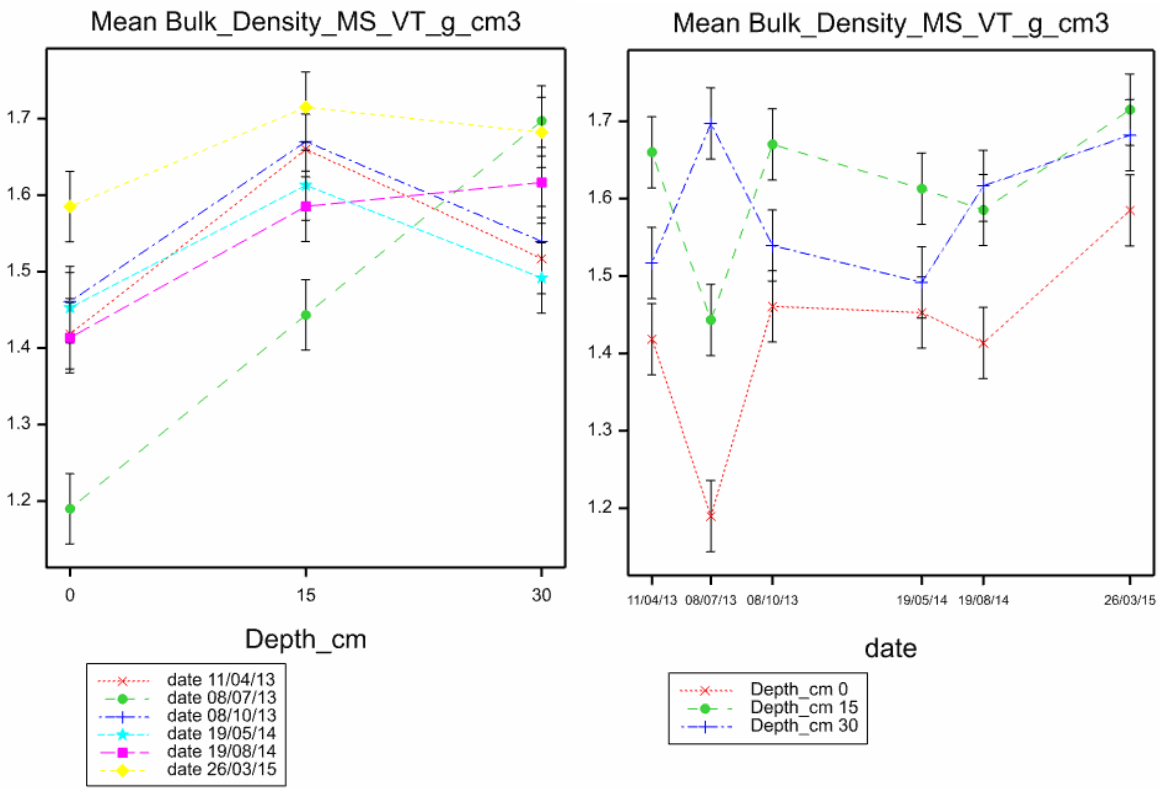

Figure 4.1.1.3 a,b show the effects of sampling depth and sampling date on bulk density as means with standard errors.

Here and throughout in all interaction and mean plots, the error bars represent the standard error of the estimate of the mean. Destoning depth was not a significant factor for bulk density, but date, depth and depth x date were all significant (Figure 4.1.1.3). The soil bulk density was lowest at 0 and 15 cm depth but greatest at 30 cm during potato production. By the wheat crop following potatoes, the bulk density for all three depths was similar to the condition prior to the potato crop. The data suggest that bulk density was greatest at the final sampling date after sugar beet had been planted. At 15 cm depth the bulk density was smallest for that depth during potato production, presumably due to the samples being taken in the hilled-up soil. At other sampling dates the soil at 15 cm depth was often marginally greater than at 30 cm depth.

Low soil macroporosity has been suggested as a factor linked to restrictions for root proliferation (Valentine *et al*. 2012). Macroporosity for the GVAP Hales Hospital site is presented as a box and whisker plot below.

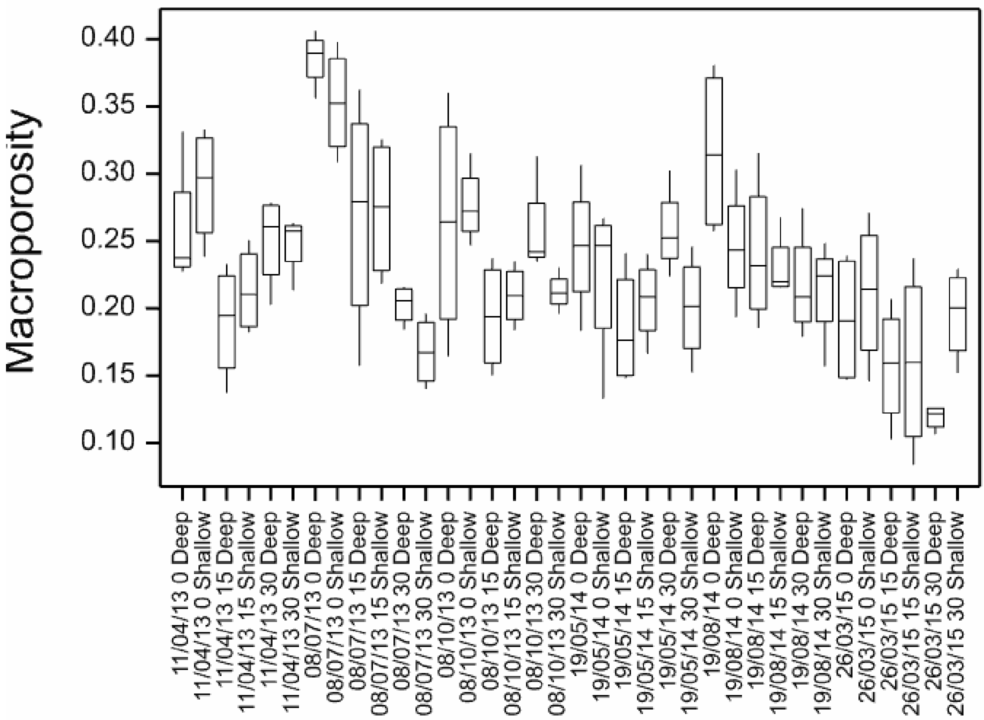

Figure 4.1.1.4 Macroporosity (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

Destoning depth was marginally not significant for macroporosity ($p = 0.053$) but date, depth and depth x date were all significant at ($p < 0.001$) (Figure 4.1.1.4).

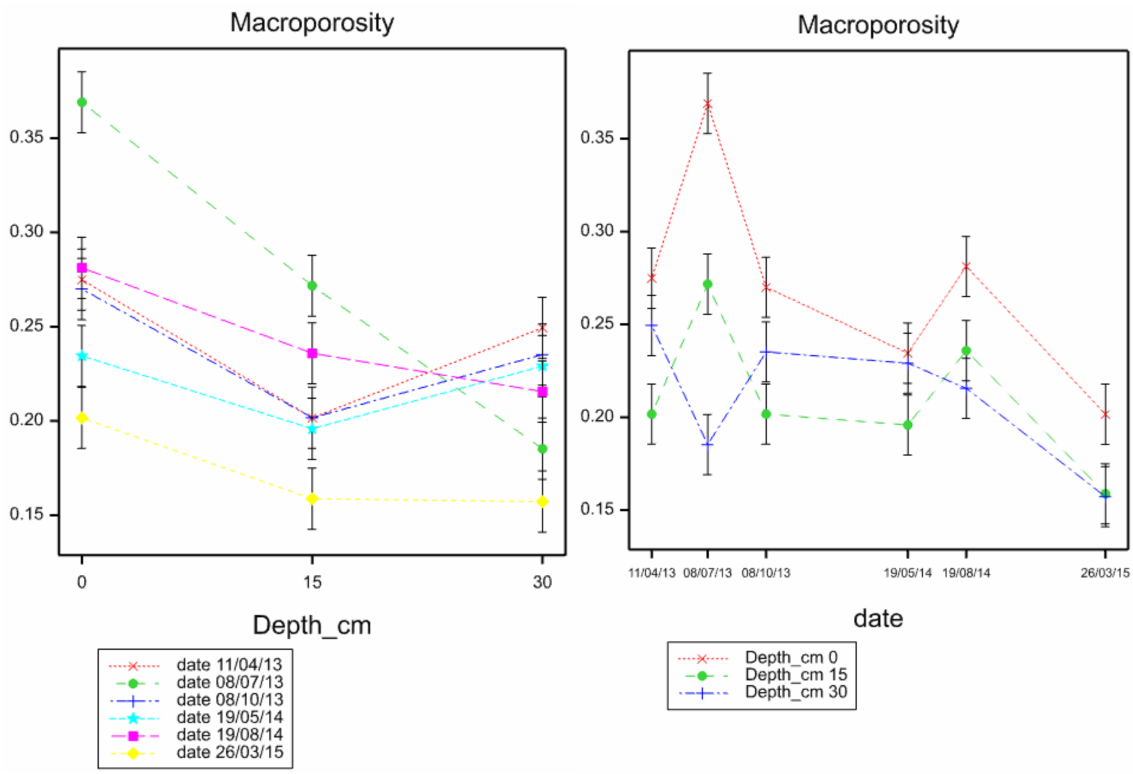

Figure 4.1.1.5 a,b shows the effects of sampling depth and sampling date on soil macroporosity as means with standard errors.

Macroporosity is a subset of total porosity and is part of the total porosity most likely to be altered by management such as tillage or bed-forming. Consequently macroporosity shows inverse behaviour to bulk density. Figures 4.1.1.5 a & b show patterns that could be expected from the inverse of bulk density with greatest values in the surface soil, particularly in the potato beds. From the samples taken after potato, the macroporosity has largely returned to the state prior to potatoes. The lowest values of macroporosity are at the final sampling date. None of the values reported here are less than the 0.10 m^3m^{-3} that is proposed (Da Silva *et al*. 1994) as a minimum value needed for aeration not to limit root proliferation.

As described in section 3 Materials and Methods, Plant Available Water (PAW) is the amount of water available for plant uptake that the soil can store. It is usually taken as the difference between field capacity (5 kPa matric suction) and permanent wilting point (1500 kPa matric suction). PAW (m^3m^{-3}) for the GVAP Hales Hospital site is presented as a box and whisker plot below.

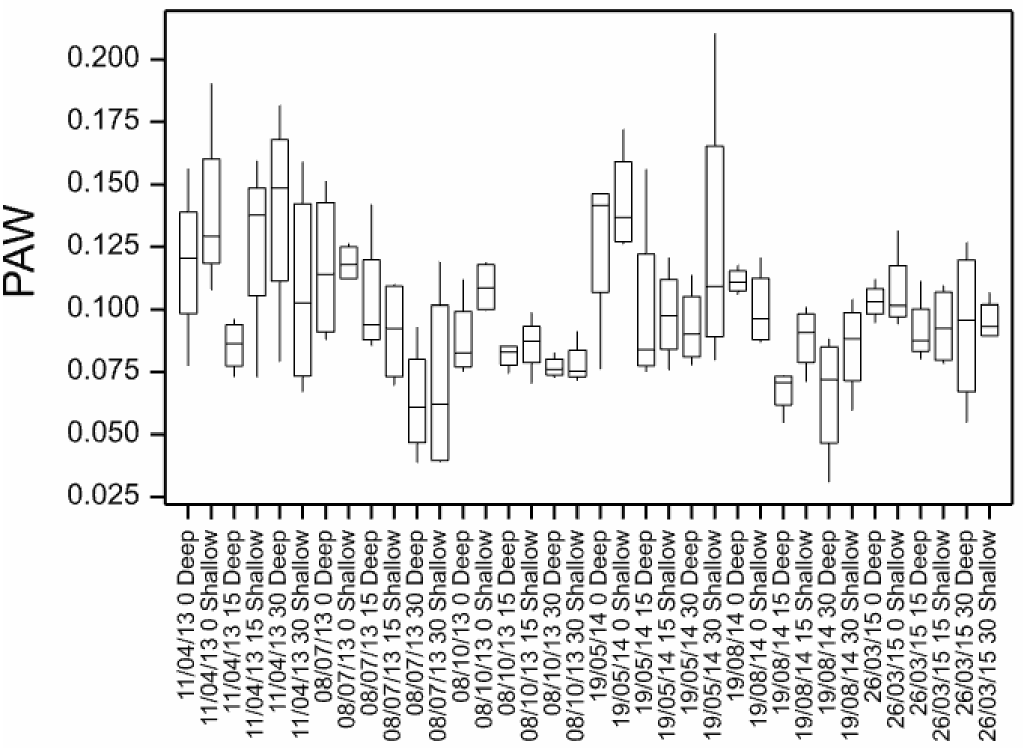

Figure 4.1.1.6 Plant Available Water (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

Destoning depth was of marginal significance ($p = 0.049$) with a mean value for all depth and dates of 0.0959 m^3m^{-3} for deep destoning and 0.1036 m^3m^{-3} for shallow destoning. However this result should be treated with some caution, as prior to the potato crop it is implicit that no difference between treatments should be expected and it is unlikely that any effect would persist well after potato harvest. On 08/07/13 i.e. in the soil pre-potato harvest there was no difference in PAW between the treatments (Figure 4.1.1.6).

Date and depth were both strongly significant ($p<0.001$) but no interaction terms were significant.

Easily Available Water (EAW) is a subset of PAW, being the water held between field capacity and -300 kPa water potential. In the analysis of EAW it became apparent from the diagnostic plots (data not shown) that two samples were significant outliers. Statistical analysis was performed including these outliers by ANOVA. Analysis excluding these two samples made the design unbalanced and so analysis on this basis was performed by REML. For both analysis forms, the main effects of destoning depth, date and depth were all significant as are the interactions depth x date and destoning depth x depth x date. For the REML analysis (but not for the ANOVA) the additional interaction destoning depth x depth was also significant. The figures shown for EAW are from the REML analysis.

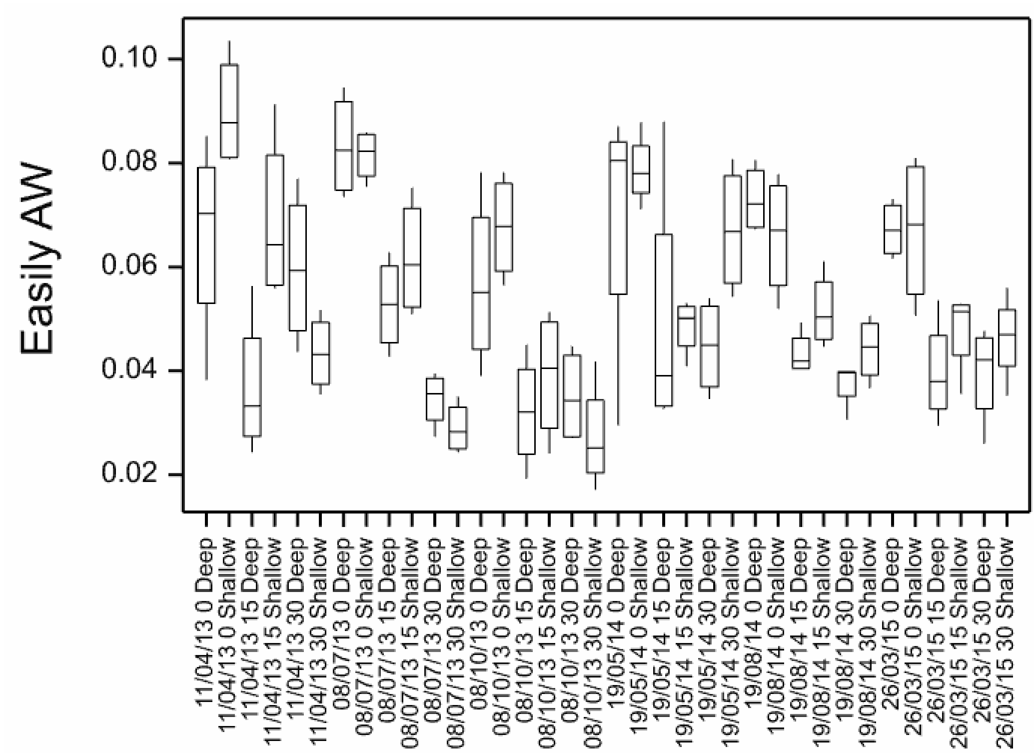

Figure 4.1.1.7 Easily Available Water (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

The pattern of data for EAW shown in Figure 4.1.1.7 has some similarities with Figure 4.1.1.6 but more clearly highlights some effects. For example the decrease in EAW with depth during potato production (date 08/07/13) is apparent with 0 cm around 0.08, 15 cm around 0.06 and 30 cm less than 0.04 m^3m^{-3}.

Changes in EAW with time for the two destoning treatments can be seen in Figure 4.1.1.8

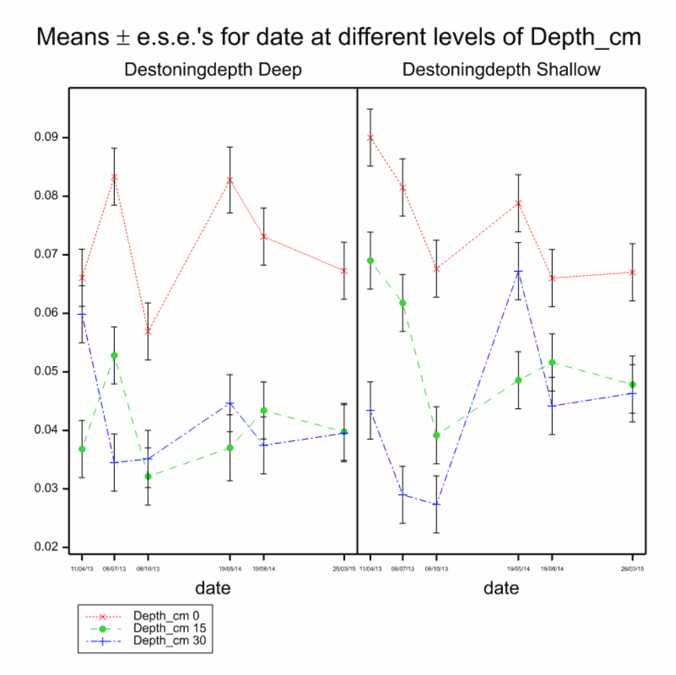

Figure 4.1.1.8 Easily Available Water (m^3m^{-3}) for each depth of destoning by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

While there is some variability at all three depths over the two years covered, there is no clear trend for increased or decreased EAW.

The Least Limiting Water Range (LLWR) quantifies the opportunity for easy root proliferation by including aeration and soil strength with water status as limiting factors. For the soils studied here lack of aeration was not identified as a limiting factor, but soil strength was identified as a limiting factor even when soil water was available for plant uptake. For the statistical analysis of LLWR, the transformation of $\log_{10}$ (LLWR+0.1) was used to achieve normally distributed data.

Destoning depth had no significant effect on LLWR for the Hales Hospital site. Date, depth and the depth x date interaction were all significant.

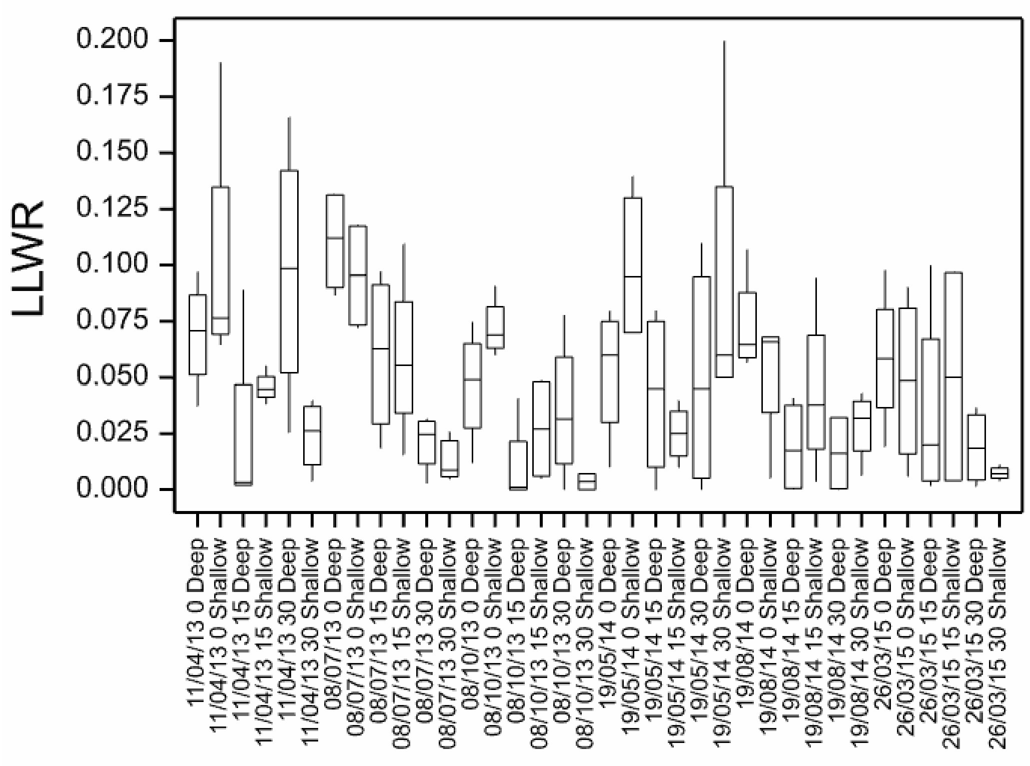

Figure 4.1.1.9 Least Limiting Water Range (LLWR) (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

LLWR cannot exceed PAW. The amount to which LLWR is less than the PAW is driven by the limitation due to soil strength. Figure 4.1.1.9 shows the LLWR values for the Hales Hospital site. Comparison with Figure 4.1.1.6 shows the extent to which LLWR values are less than PAW and hence the overall limitation to root proliferation from soil strength.

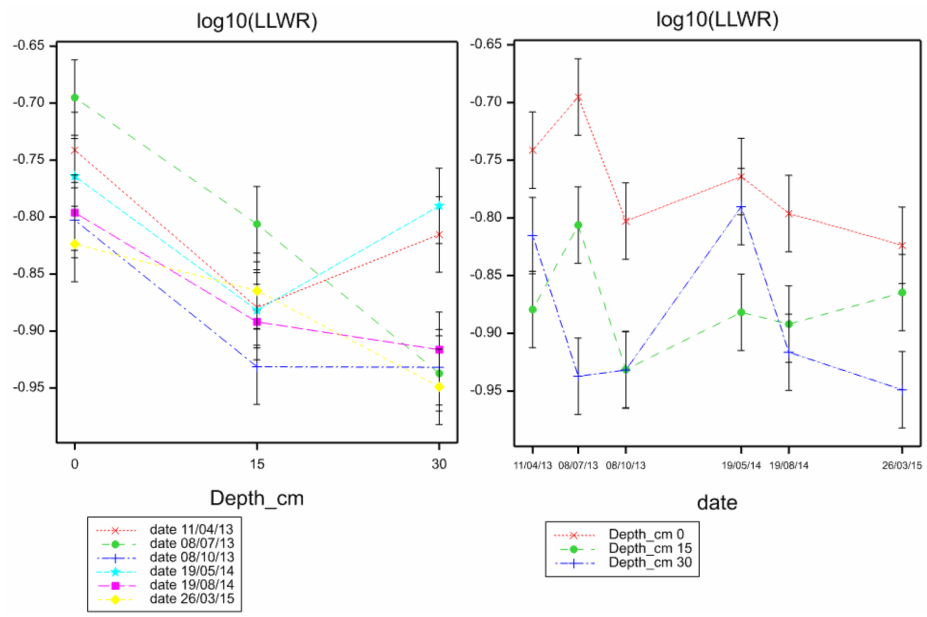

Figure 4.1.1.10 a,b Log transformed LLWR for depth and date at GVAP Hales Hospital site.

As with most of the other soil quality indicators above, Figure 4.1.1.10 a,b shows that for the sampling on 08/07/13, the soil physical conditions in the surface and at 15 cm depth (into the potato bed) were as good or better than at other times. The conditions at 30 cm depth at that time were amongst the poorest observed. However any differences did not persist and conditions post potato production were not poorer than prior to the potato crop. As destoning depth was not significant the data on Figure 4.2.1.9 are not separated by destoning depth.

The final soil quality indicator determined on the samples was the S value; being the slope of the water retention curve at the point of inflection. As described above (section 3.1) a large slope represents a greater diversity of pore sizes from which increased heterogeneity of the soil environment can be inferred. For statistical analysis the S value was log transformed. For S, destoning depth, date, depth and depth x date were all significant.

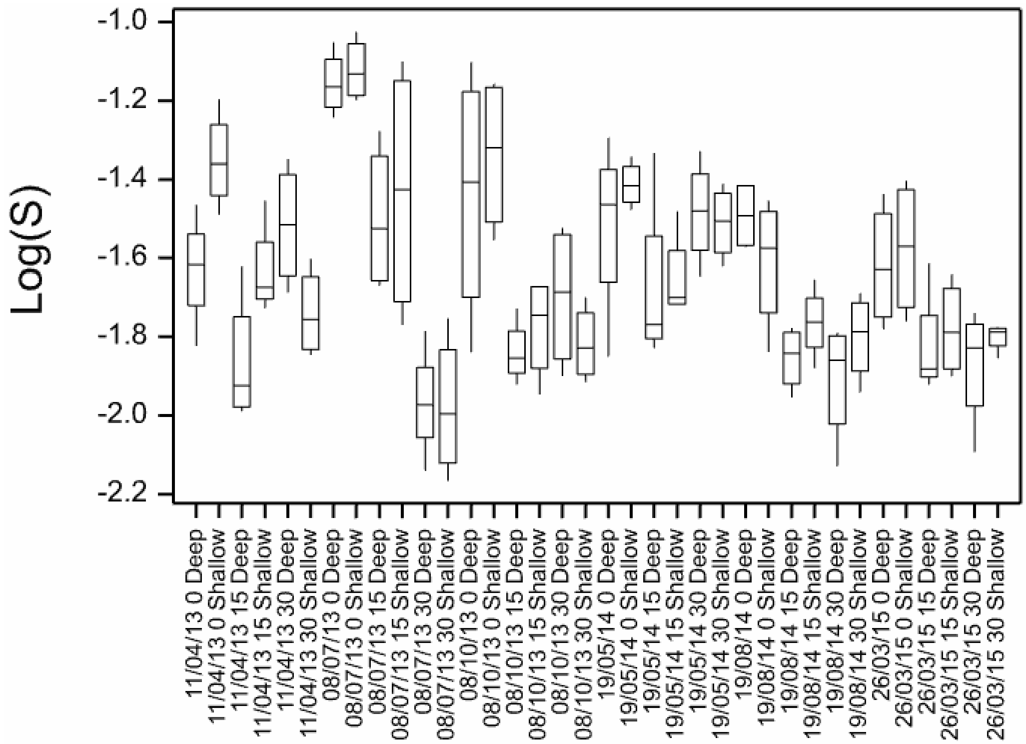

Figure 4.1.1.11 Log_{10}"S" depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP Hales Hospital site.

Deep destoning was associated with lower values of S ($log_{10}S$ = -1.659 s.e. 0.007 i.e. S = 0.0219) than shallow destoning ($log_{10}S$ = -1.616 s.e. 0.007 i.e. S = 0.242). As can be seen on Figure 4.1.1.11, some of this overall difference appears before the potato crop was planted. Dexter (2004a) suggests that values of S < 0.020 are associated with very poor soil physical conditions and that a value around 0.035 (i.e. $log_{10}S$ = -1.456) could be seen as a boundary between poor and good soil physical condition. On that basis, only surface soils at this site would be considered as being in good physical condition.

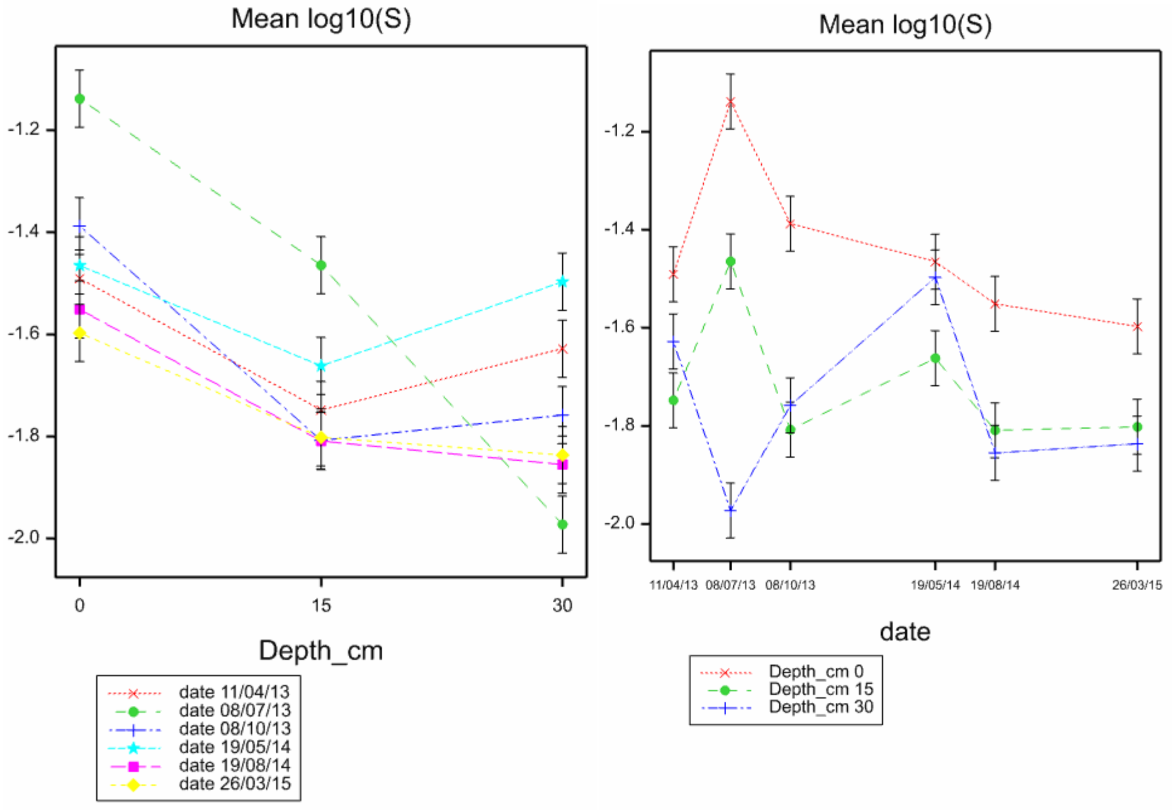

Figure. 4.1.1.12 a,b Log$_{10}$S for depth and date at GVAP Hales Hospital site.

Trends with depth and time for S shown in Figure 4.2.1.12 are similar to the other soil quality measures. These trends show greater S values in surface soil than at other depths, soil within the potato beds (i.e. at 15 cm) at good condition, and lowest S values at 30 cm depth during the potato crop but subsequently increasing. The entire experimental site was deep-ripped to 40 cm and ploughed to 35 cm depth in October 2013 before drilling the succeeding winter wheat crop.

4.1.2. GVAP The Cliff

Similar to the approach taken at the GVAP Hales Hospital site, The Cliff site compared soil physical conditions under deep and shallow destoning and included sampling soil from the subsequent cereal crop six months after potato harvest. As with Hales Hospital soil sampling was as cores at 0, 15 and 30 cm. There were four sampling dates allowing assessment to be made of the different phases in a cropping rotation. Mark Stalham, who collected the soil samples, noted on 30/09/14 at post-harvest potatoes that the soil was sampled after extensive traffic at harvest and the surface condition appeared poor.

Measurements of soil penetration resistance were taken immediately after planting the potato crop in GVAP The Cliff. The soil was not loosened to such a great extent by deep destoning as in a sandier soil on the opposite side of the field, most probably as working soil beyond the PL depth resulted in large quantities of soil being deposited in the wheeling with no increase in bed depth. There was no indication that compaction in the deep destoning treatment was different from the shallow treatment (Figure 4.1.2.1).

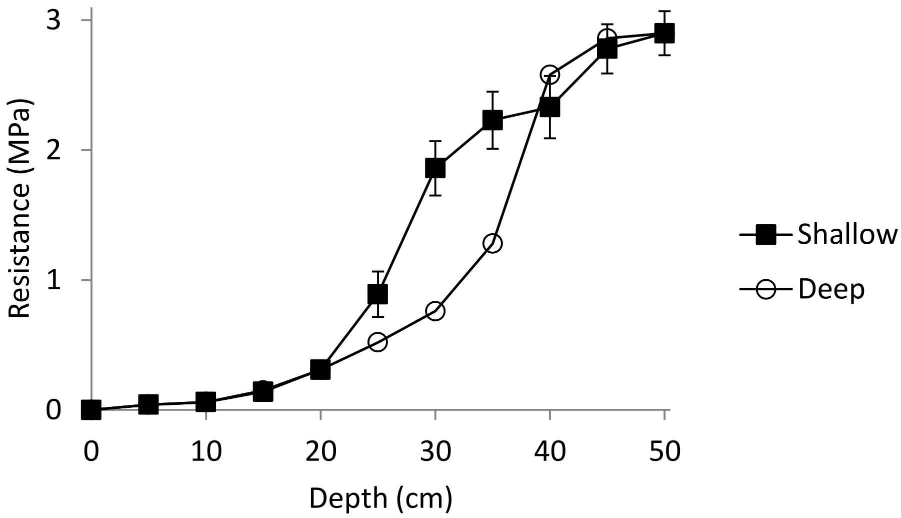

Figure 4.1.2.1. Effect of destoning depth on soil penetration resistance at planting in GVAP The Cliff

The soil bulk density was not significantly affected by destoning practice, although there was a non-significant trend (p = 0.062) for bulk density across all dates and depths to be greater under deep destoning (Figure 4.1.2.2). Date, depth and the interaction depth x date were significant.

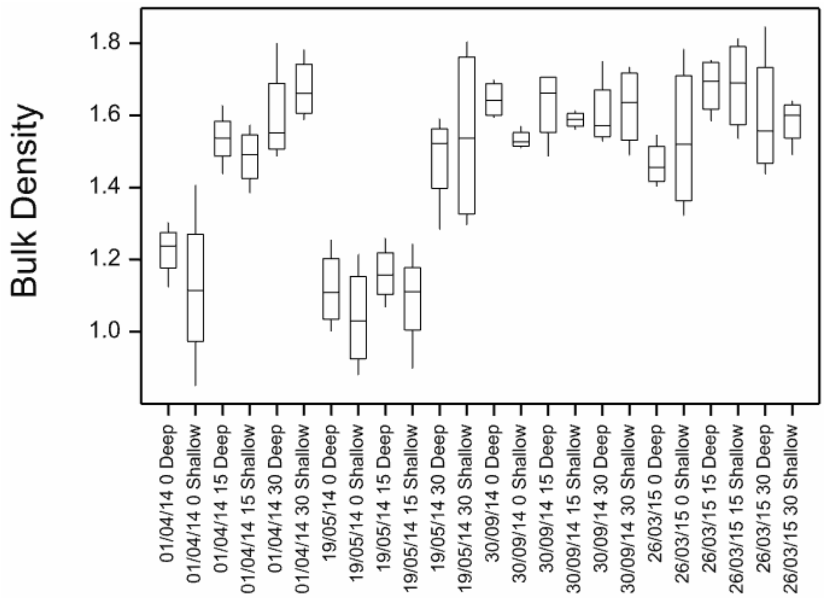

Figure 4.1.2.2 Soil Bulk Density (gcm^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP The Cliff site.

Soil bulk density remained largely unchanged at 30 cm depth over the sampling dates (Figure 4.1.2.2). The changes with depth and date can be seen in Figure 4.2.2.3 a,b.

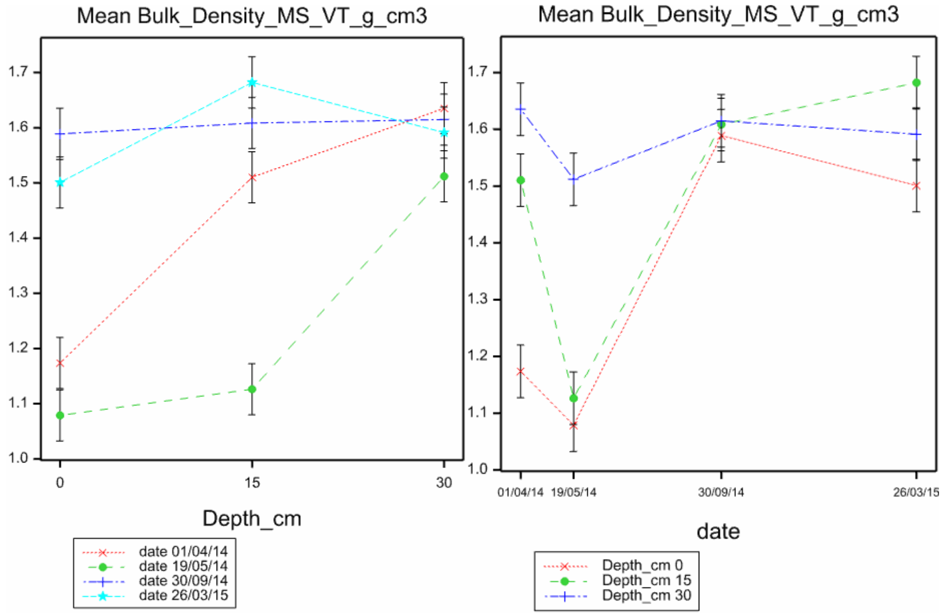

Figure 4.1.2.3 a,b shows the effects of sampling depth and sampling date on bulk density as means with standard errors for GVAP The Cliff site.

The soil bulk density at the surface was lower on the first two sampling dates than on the latter two sampling dates (Figure 4.1.2.3 a,b). At 15 cm depth the soil was least dense on 19/05/14 which corresponds to the sampling from within the potato bed. Interestingly, the density of surface soil increased after potato harvest and remained around 1.5 gcm^{-3} into the winter wheat crop. Date, depth and the interaction depth x date were significant for macroporosity (all $p < 0.001$) but there was no effect of destoning depth on macroporosity.

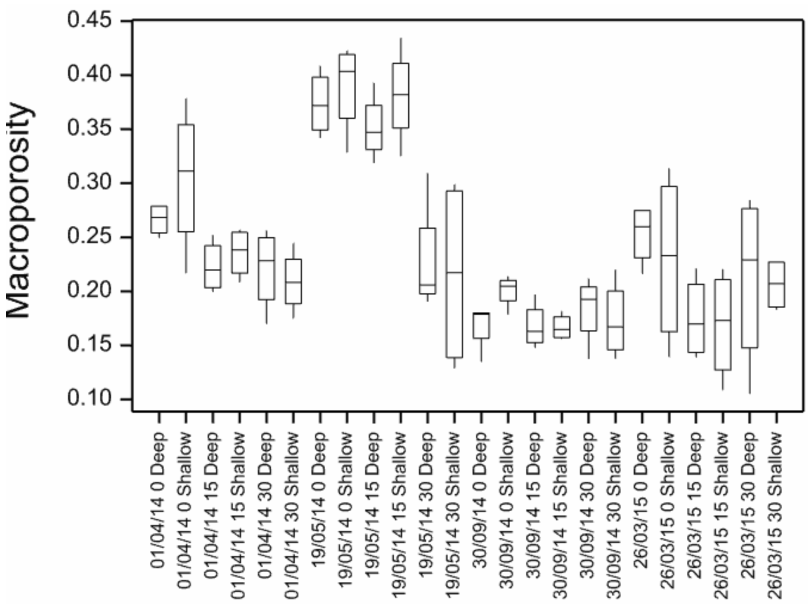

Figure 4.1.2.4 Macroporosity (m^{3}m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP The Cliff site.

Macroporosity was greatest at 0 and 15 cm depths during the potato crop (Figure 4.1.2.4), but this had decreased immediately after potato harvest. None of the macroporosity values were sufficiently low to suggest that lack of aeration would become limiting, but as previously noted, Valentine *et al*. (2012) have identified low macroporosity soils with limitations to root growth. The changes in macroporosity with time and depth are apparent from Figure 4.1.2.5 a,b.

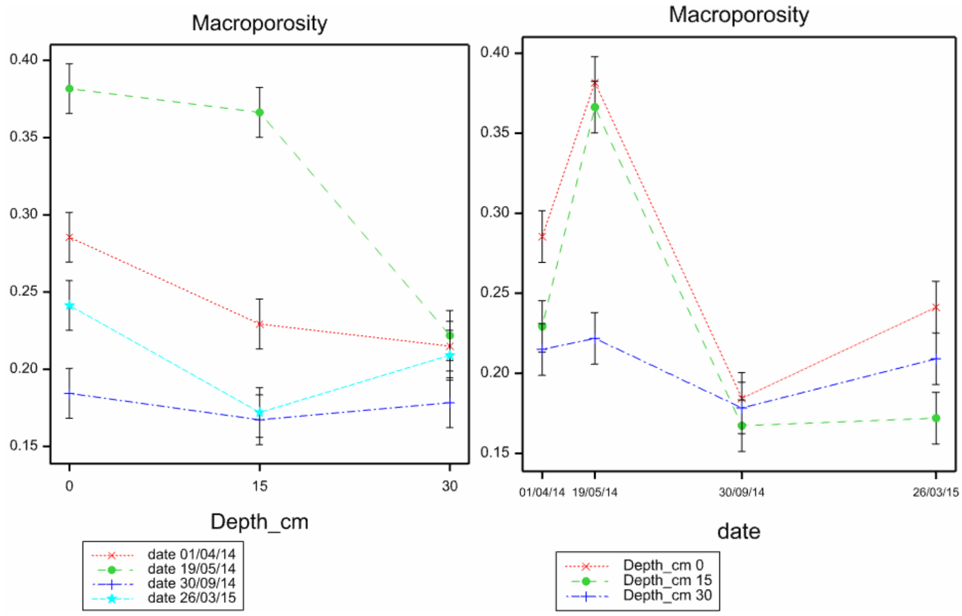

Figure 4.1.2.5 a,b Macroporosity (m³m⁻³) for depth and date of sampling (0, 15 and 30 cm) for GVAP The Cliff site.

PAW is variable in the surface after planting potatoes as shown by the data spread on 19 May 2014 (Figure 4.1.2.6).

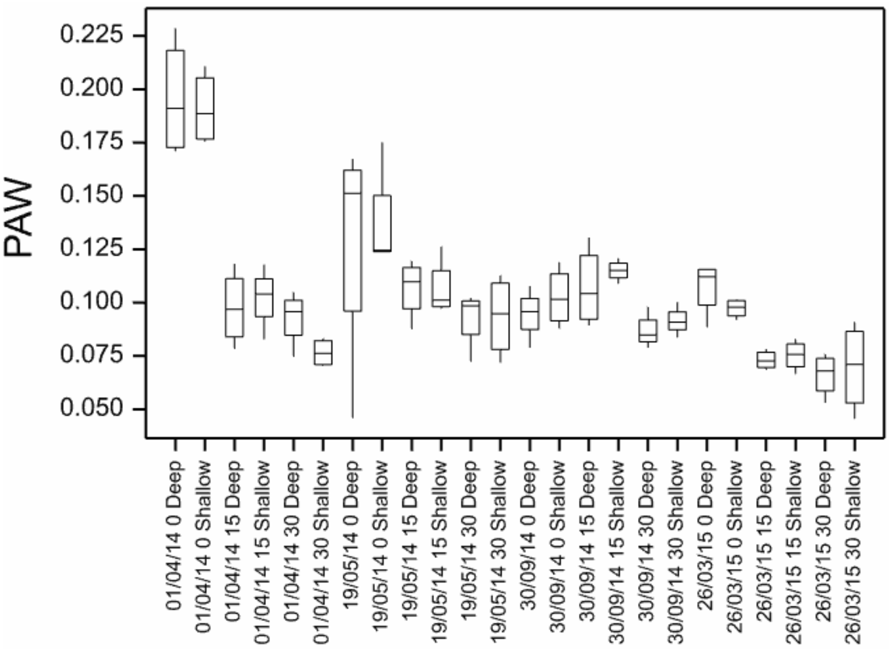

Figure 4.1.2.6 Plant Available Water (m³m⁻³) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP The Cliff site.

There is an effect of depth and an interaction depth x date that are both significant at $p < 0.001$. However, destoning depth did not significantly affect PAW (Figure 4.1.2.7).

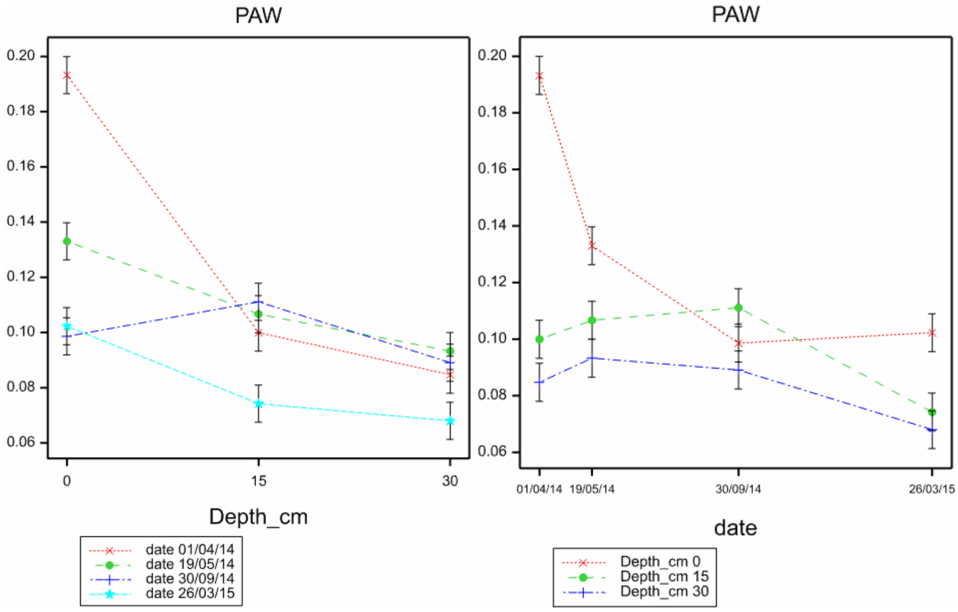

Figure 4.1.2.7 a,b Plant Available Water PAW (m^3m^{-3}) for depth and date of sampling (0, 15 and 30 cm) for GVAP The Cliff site.

The PAW values are greater at this site than at the Hales Hospital site which is likely due to the greater clay content in the soil. As for PAW, destoning depth did not significantly affect EAW but there were significant effects of date, depth and the interaction depth x date – all significant at $p < 0.001$.

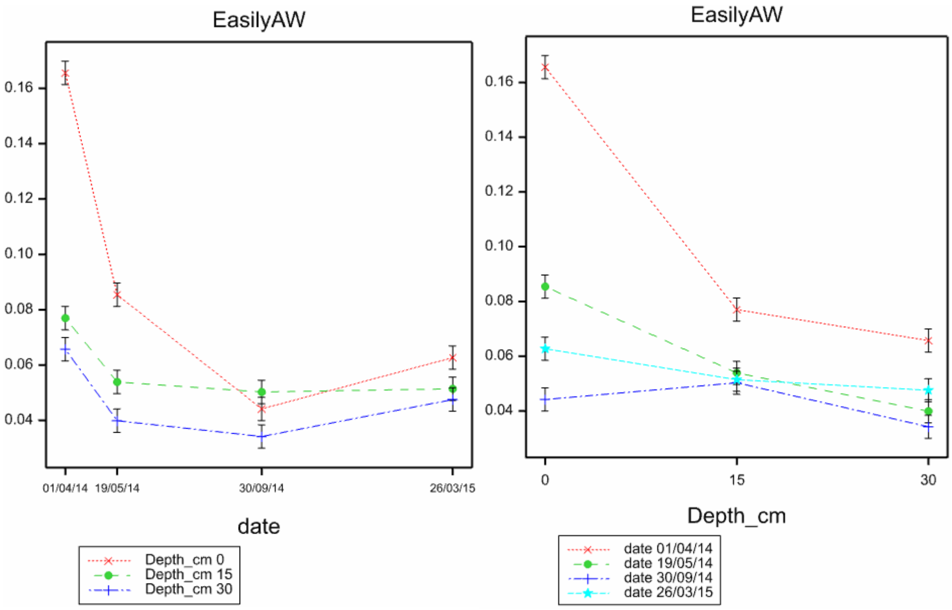

Figure 4.1.2.8 a,b Easily Available Water EAW (m^3m^{-3}) for date and depth of sampling (0, 15 and 30 cm) for GVAP The Cliff site.

Like the PAW, the EAW values were particularly large at the time of the first sampling in April 2014 (Figure 4.1.2.8 a,b) when the soil was under a cereal stubble. It may be that these large values are associated with root material from the cereal crop being included in the core samples.

For statistical analysis, Least Limiting Water Range (LLWR) data were log transformed to normalise the residuals. The destoning depth treatments had no significant effect on LLWR. Date and depth of sampling and the interaction between them were significant effects on LLWR ($p < 0.001$). As with PAW and EAW, the initial values from samples taken at the surface in the cereal stubble are very high (Figure 4.1.2.9).

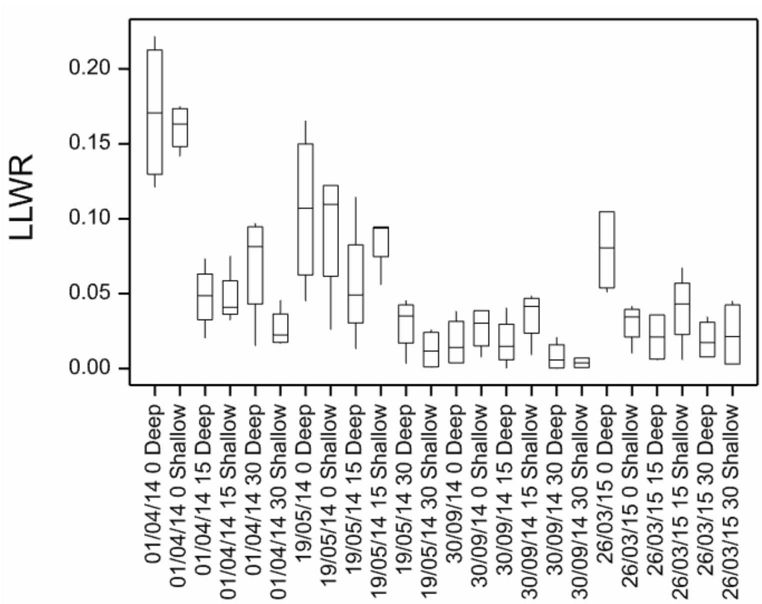

Figure 4.1.2.9 Least Limiting Water Range LLWR (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for GVAP The Cliff site.

Figure 4.1.2.10 shows that the LLWR values are lowest in September 2014 just after potato harvest but there is an indication of some recovery in the subsequent cereal crop. This is particularly the case for the surface soil.

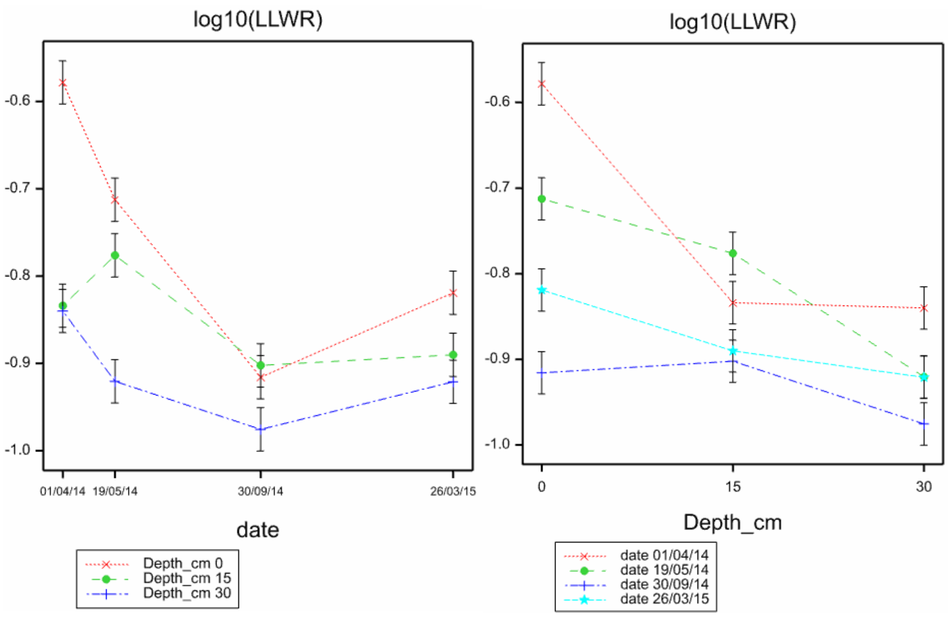

Figure 4.1.2.10 a,b Least Limiting Water Range LLWR (m^3m^{-3}) for date and depth of sampling (0, 15 and 30 cm) for GVAP The Cliff site.

As with the LLWR data, the S data were log transformed for statistical analysis and as for LLWR date, depth and the interaction between them depth x date significantly influenced ($p < 0.001$) the S value. Destoning depth is also significant ($p = 0.037$), with shallow destoning (grand mean across all dates and depths = 0.021) leading to slightly lower values of S than deep destoning (grand mean across all dates and depths = 0.022). Such a small difference may be statistically significant but is likely to be immaterial for soil management or crop production.

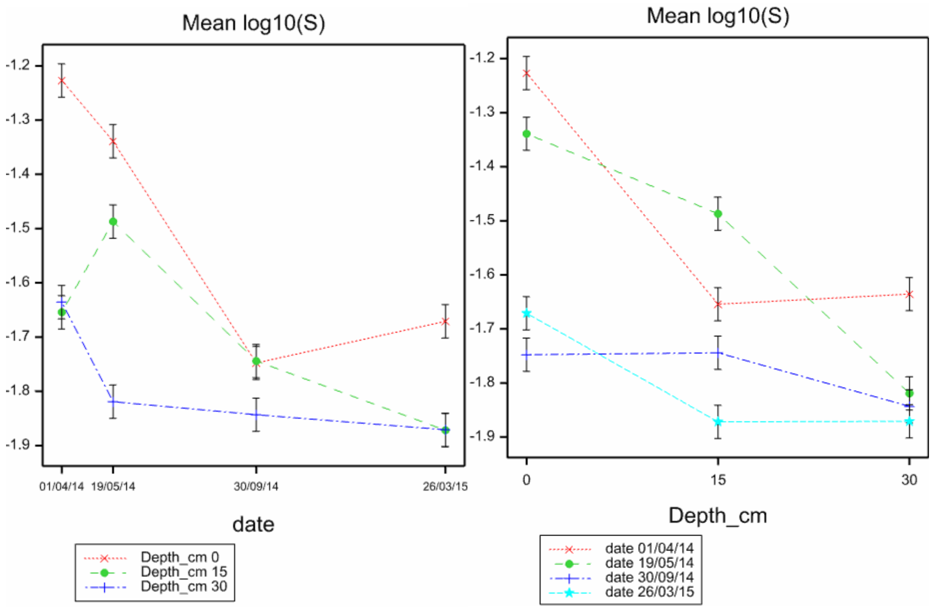

Figure 4.1.2.11 a,b Log10 S for date and depth of sampling (0, 15 and 30 cm) for GVAP The Cliff site.

The suggestion of rebound in the soil quality indicator that was noted for the LLWR data does not appear for the log 10 S values (Figure 4.1.2.11 a, b).

4.1.3. Stevenson Langlands

There was one experimental treatment with two levels – deep and shallow destoning. Four replicate blocks were used and one core was taken from each of the two treatment levels in each block on each of four dates (August 2013 cereal stubble pre-planting; May 2014 post-planting potatoes; September 2014 post-harvest potatoes (uncultivated and July 2015 winter wheat standing crop)

In Langlands, destoning depth had little effect on soil resistance measured at planting. Also, there was no indication that destoning at the deepest depth resulted in higher soil resistance at 35 cm than when destoning shallower (Figure 4.1.3.1).

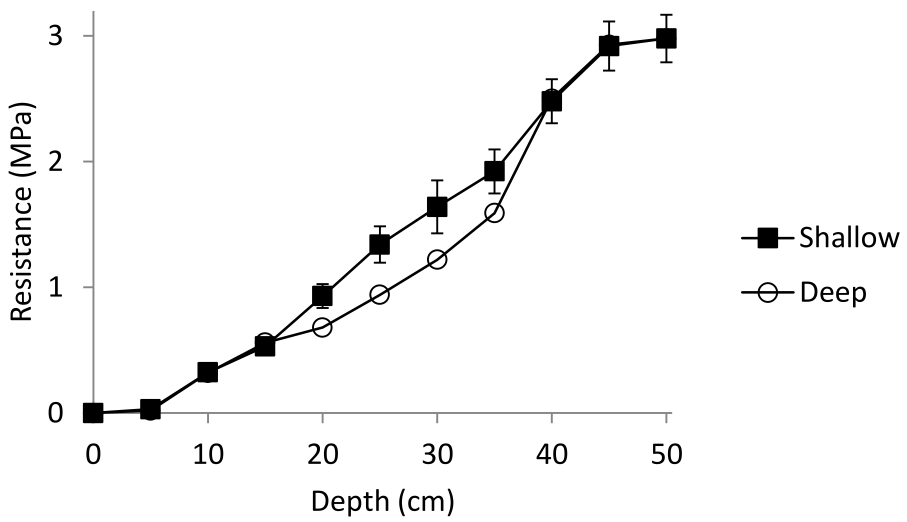

Figure 4.1.3.1. Effect of destoning depth on soil penetration resistance at planting in Stevenson Langlands

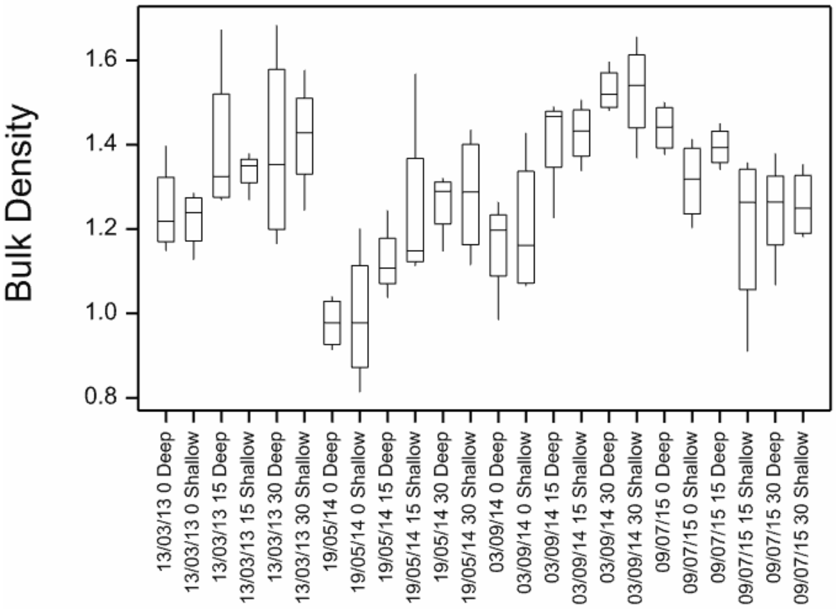

Figure 4.1.3.2 Soil Bulk Density (gcm^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Deep or Shallow destoning) over time for the Stevenson Langlands site.

From Figure 4.1.3.2 there is no clear or obvious trend in bulk density over time, although surface bulk densities are lowest in May 2014 after potatoes had been planted. As with other data (e.g. Figures 4.1.1.2 and 4.1.2.2. above) destoning practice had no significant effect on the soil bulk density. Date, depth and the interaction depth x date all had significant ($p < 0.001$) effects on soil bulk density.

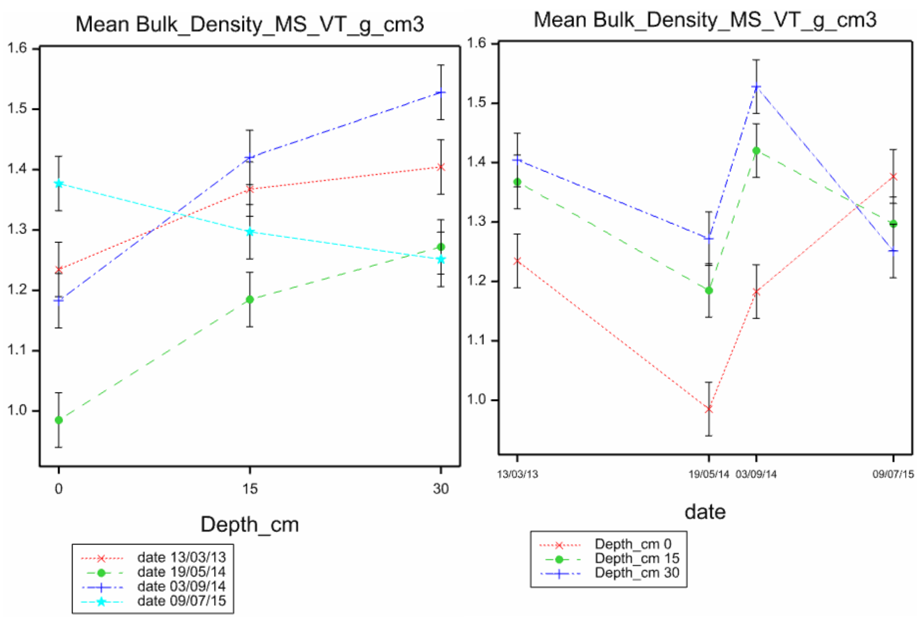

Figure 4.1.3.3 a,b Soil Bulk Density (gcm^{-3}) by sampling depth and sampling date for the Stevenson Langlands site.

There is no significant difference between bulk density at 15 and 30 cm, but with the exception of July 2015 when the soil was under a winter wheat crop, the bulk density was lowest in the surface soil. For macroporosity date ($p < 0.001$), depth ($p < 0.001$) and the interaction date x depth ($p = 0.009$) were significant but destoning treatment had no significant effect.

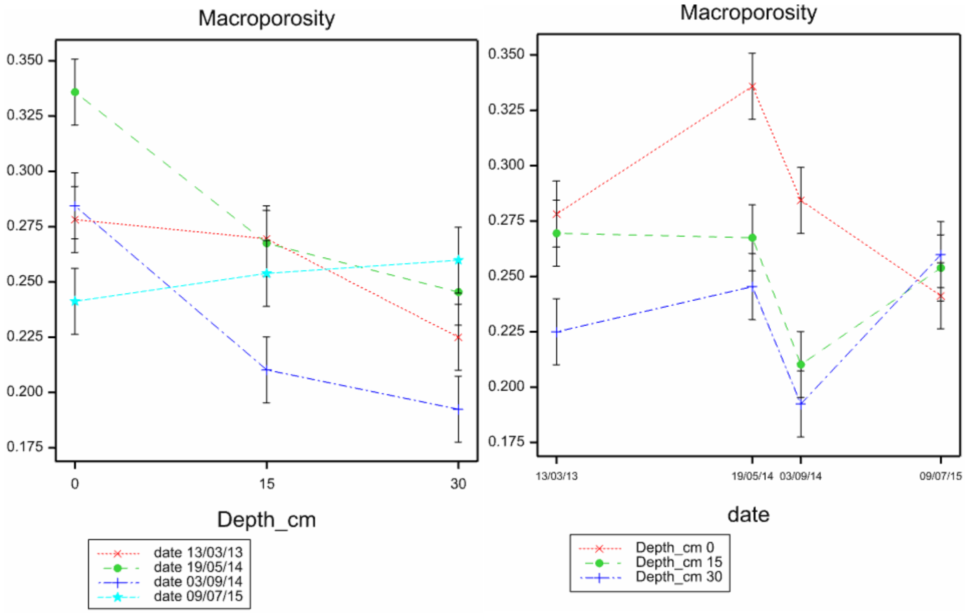

Figure 4.1.3.4. a,b Macroporosity (m^3m^{-3}) by sampling depth and sampling date for the Stevenson Langlands site.

In 2013, before planting potatoes, there was less macroporosity at 30 cm that nearer the soil surface (Figure 4.1.3.4 a,b). In 2014 macroporosity was greatest in the surface, both post-planting and post-harvest. The increase in macroporosity at 15 and 30 cm in 2015 may be associated with tillage post-potatoes being deeper than usual.

Plant available water has a similar response to macroporosity. Date ($p < 0.017$), depth ($p < 0.001$) and the interaction between them ($p < 0.001$) were significant, but destoning depth had no effect.

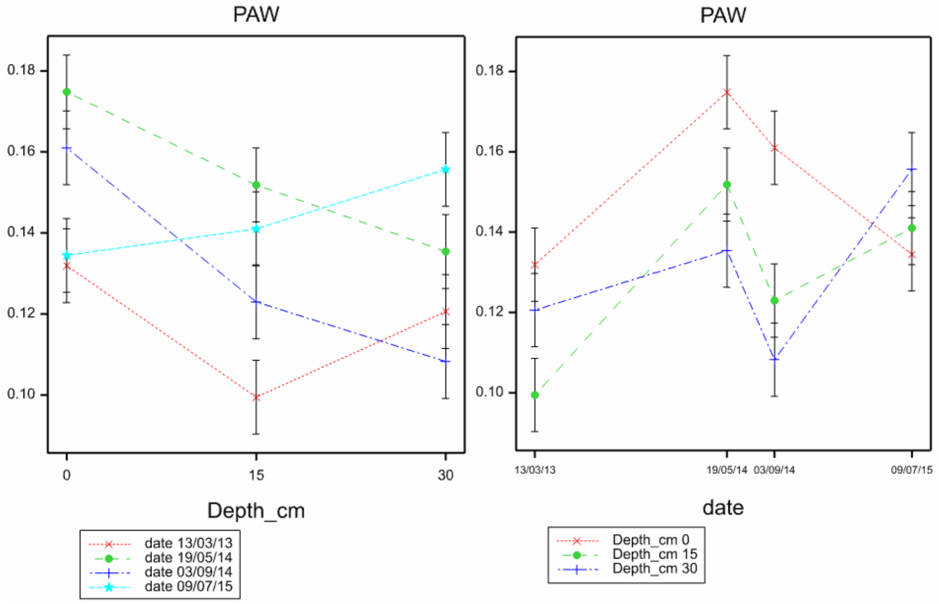

Figure 4.1.3.5 a,b Plant Available Water (PAW) (m^3m^{-3}) by sampling depth and sampling date for the Stevenson Langlands site.

As for macroporosity, PAW increased at all depths (Figure 4.1.3.5 a,b) with the start of potato production and decreased immediately after potato harvest. However, after potato harvest only at 30 cm depth were the values less than the initial state. The increase in PAW by July 2015 is most likely associated with some form of deep tillage prior to drilling the cereal crop. Easily available water (EAW) and Least limiting water range (LLWR) were analysed in log transformed form, and date, depth and the interaction between them were all significant ($p < 0.001$) but destoning treatment had no significant effect. The pattern of data with increases associated with the formation of the potato beds, a decrease particularly at depth after potato harvest and a subsequent increase is consistent with data for macroporosity and PAW (data not shown).

The S index was log transformed for statistical analysis and as with other properties at this site date, depth and the interaction between them were significant ($p < 0.001$), but the destoning treatment had no significant effect on S.

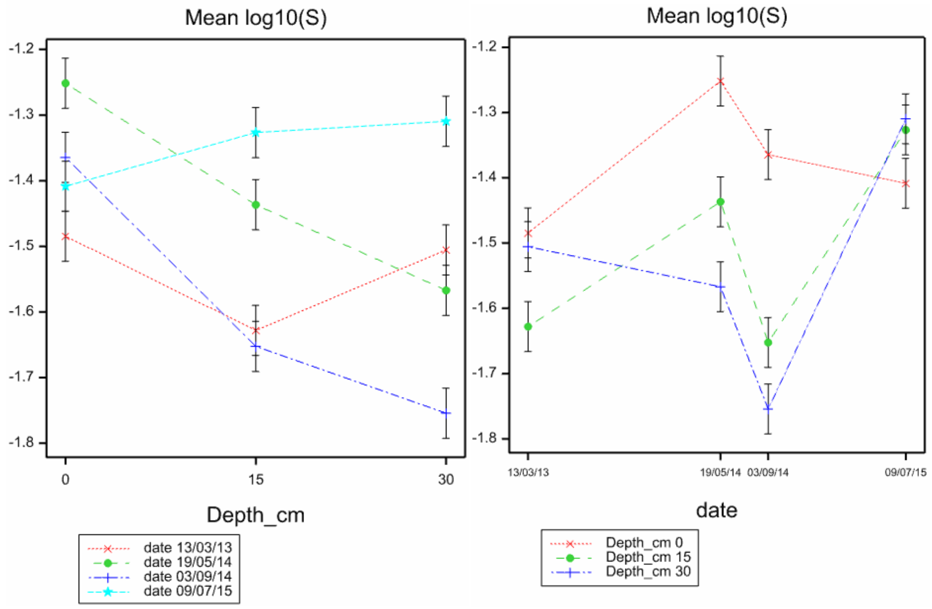

Figure 4.1.3.6 log10 S by sampling depth and sampling date for the Stevenson Langlands site.

The pattern of S values with depth and time is similar to the other indexes. The largest values of S were found in the soil from the recently formed beds soon after potato planting and the lowest values at 30 cm depth soon after potato harvest. The increase in S values post potato harvest appears greater at this site that at the other sites. While this may be associated with deeper cultivation, there is also likely to be a contribution from a restructuring of the clay particles in response to wetting and drying. The clay percentage is slightly greater at this site than at the Hales Hospital or the Cliff sites.

4.2. Alternative Cultivations

4.2.1. ADAS Tern farm site

The site was a comparison of conventional soil preparation (tillage) for potatoes (denoted as ploughing) and the use of a novel tillage system called (and marketed as) Tillerstar. For more details see Potato Council Report R444.

Soil sampling was as cores at 0, 15 and 30 cm. There were six sampling dates allowing assessment to be made of the different phases in a cropping rotation. Four potato beds were sampled from each treatment. In all but the box plots graphs bars represent the standard error of the difference.

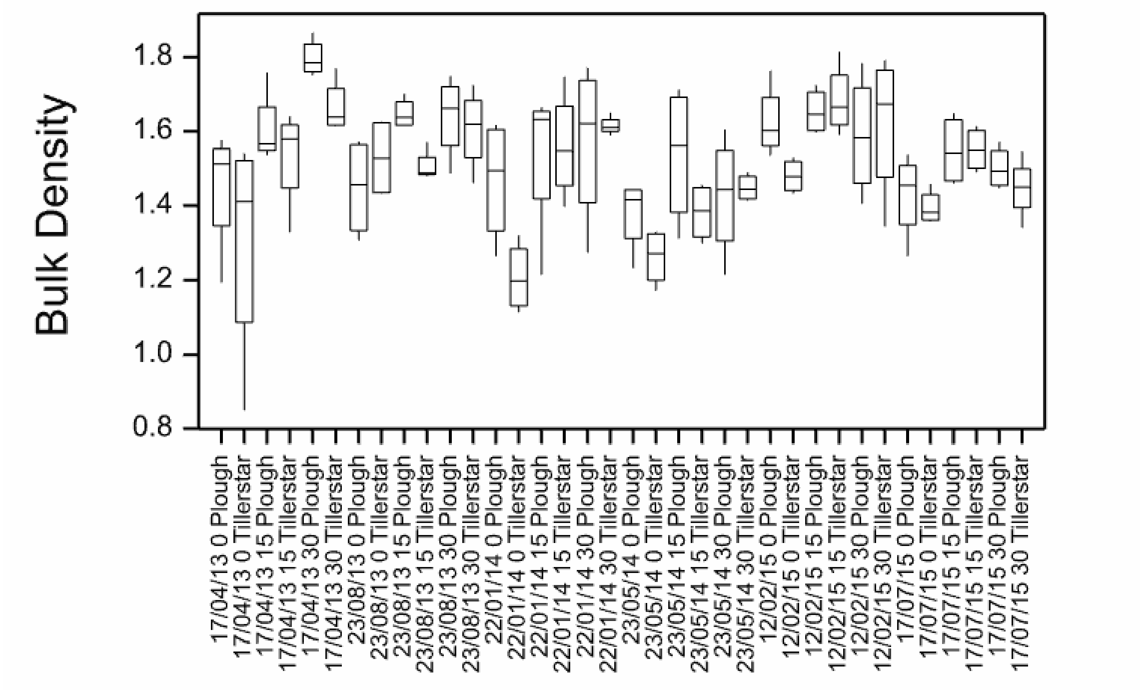

Figure 4.2.1.1 Soil Bulk Density (gcm^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Plough or Tillerstar) over time for the ADAS managed site at Tern Farm.

Figure 4.2.1.1 is a boxplot representation of the soil bulk density over time. At first sight it may appear that the bulk density is less in the Tillerstar treatment, but any effect was small and there was no significant difference between tillage systems. Analysis shows that date, depth and the interaction between them were significantly different. As expected, bulk density was consistently lower at the surface (0 cm) than at other depths. There was no consistent relationship between time of year of sampling and bulk density.

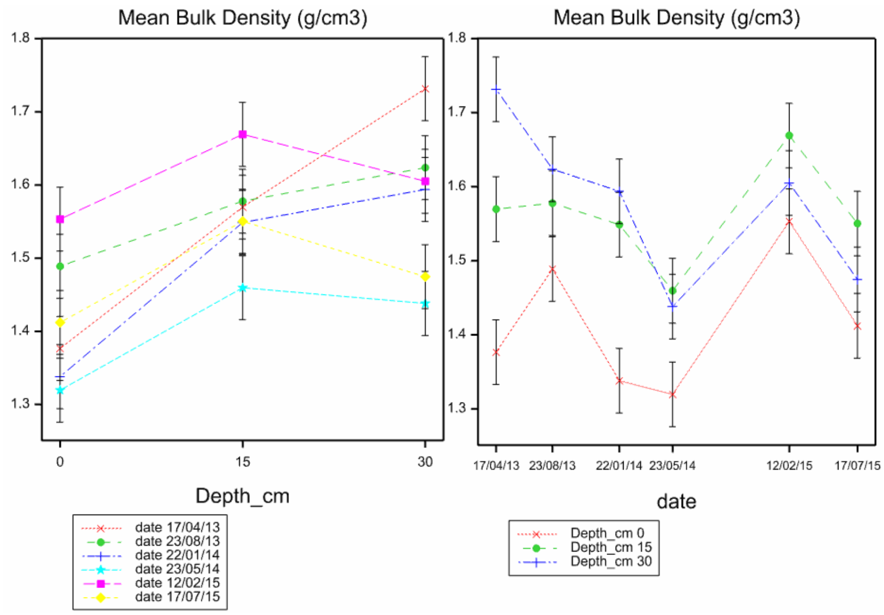

Figure 4.2.1.2 a,b show the effects of sampling depth and sampling date on bulk density as means with standard errors for the ADAS-managed site at Tern Farm.

As there was no effect of tillage treatment, Figures 4.2.1.2 a,b show the bulk density for depth and date of sampling with tillage treatments combined. Bulk density was lowest in the surface soil, but interaction between date and depth was evident as on several dates the maximum bulk density was at 15 cm depth (Figure 4.2.1.2a). This was also identifiable with bulk density being greatest at 30 cm prior to May 2014, but greatest at 15 cm after that date. The experimental site was ploughed in March 2014 at 30cm prior to drilling spring barley. The change in bulk density occurred during the barley crop and there is no evidence that it could be attributed to the potato crop.

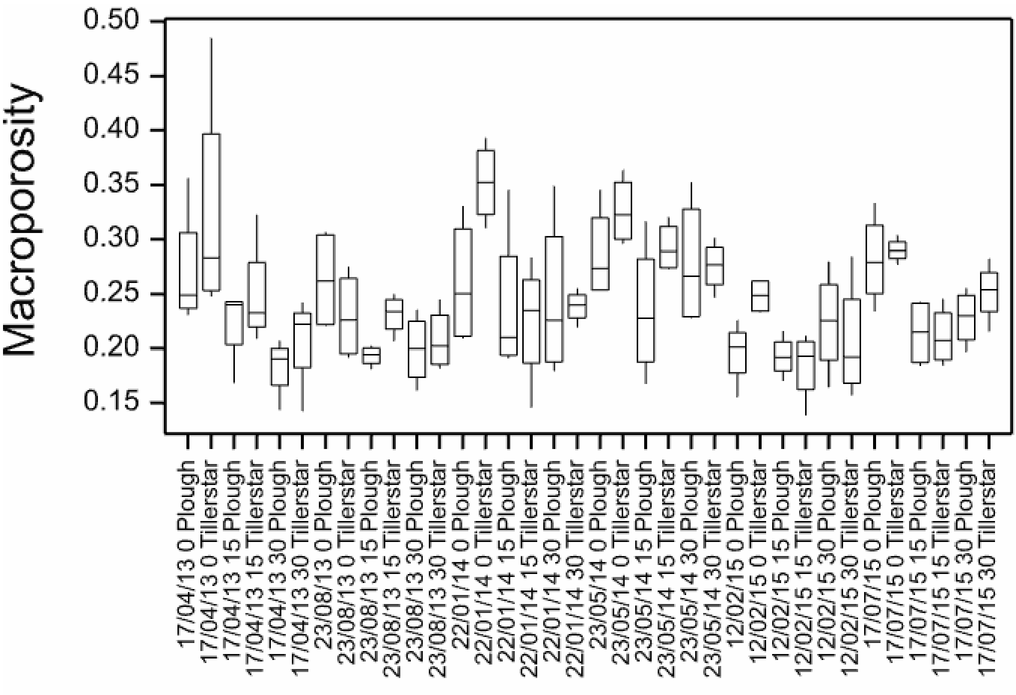

Figure 4.2.1.3 Macroporosity (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Plough or Tillerstar) over time for the ADAS managed site at Tern Farm.

From Figure 4.2.1.3 there is no clear trend in macroporosity. For statistical analysis the data were $\log_{10}$ transformed so that they are approximately normally distributed with treatment combinations.

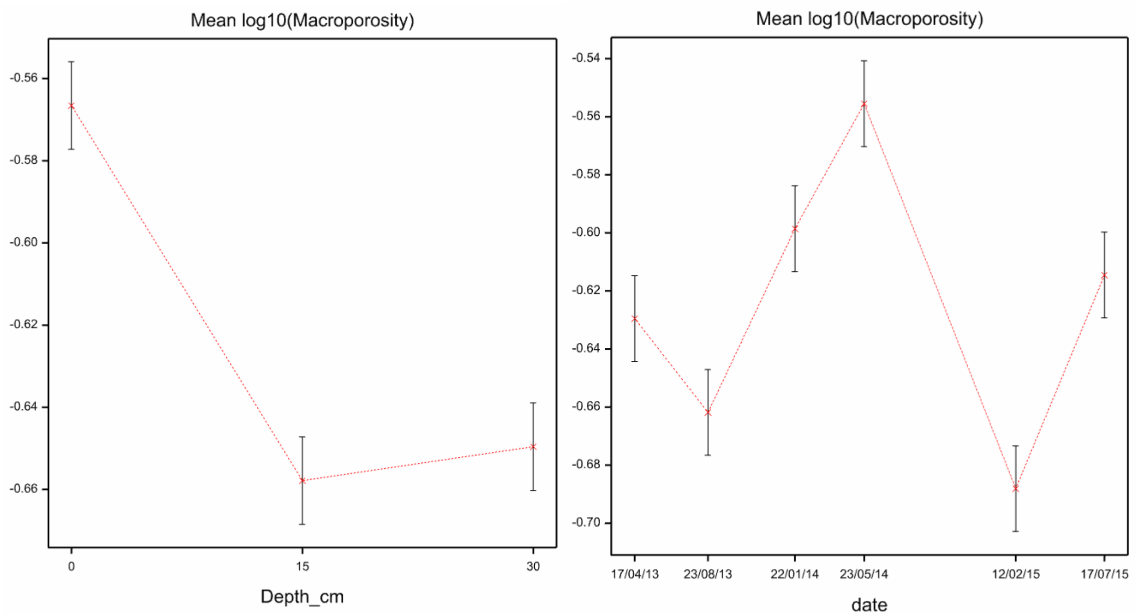

Figure 4.2.1.4 a,b Macroporosity (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) and over time for the ADAS managed site at Tern Farm. Values are estimate means across all dates and treatments.

Date and depth were both significant effects but there were no interactions. Macroporosity was greatest in the surface soil and not different between 15 and 30 cm depths. There was no trend for macroporosity to increase or decrease over time.

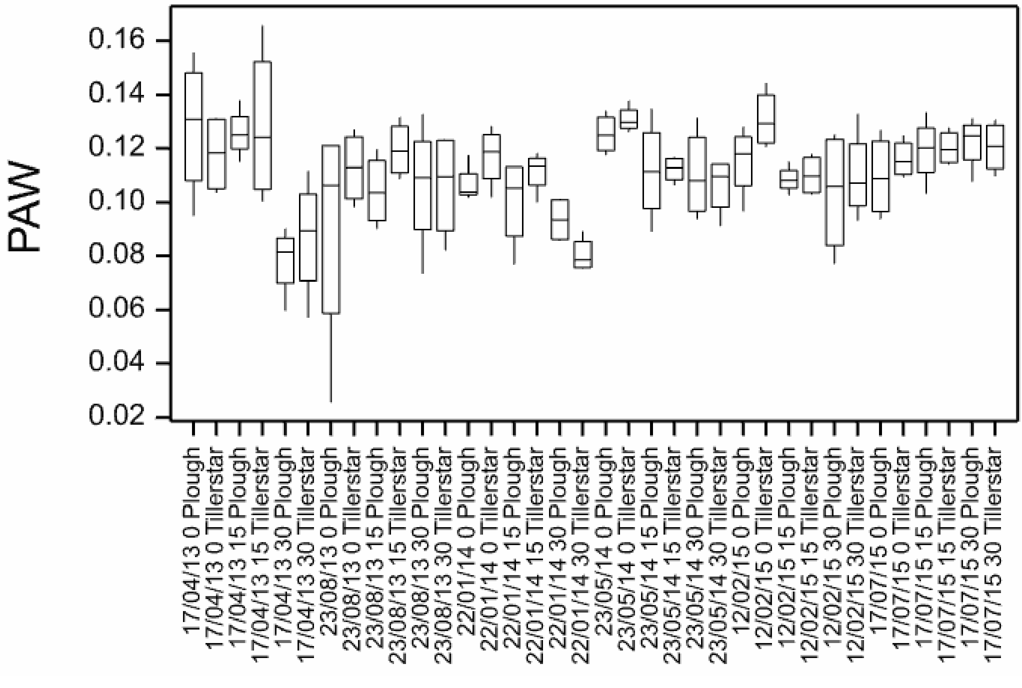

Figure 4.2.1.5 Plant Available Water (PAW) (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Plough or Tillerstar) over time for the ADAS managed site at Tern Farm.

As with bulk density, date, depth and the interaction between them are significant for PAW (Figure 4.2.1.5). Tillage treatment had no significant effect.

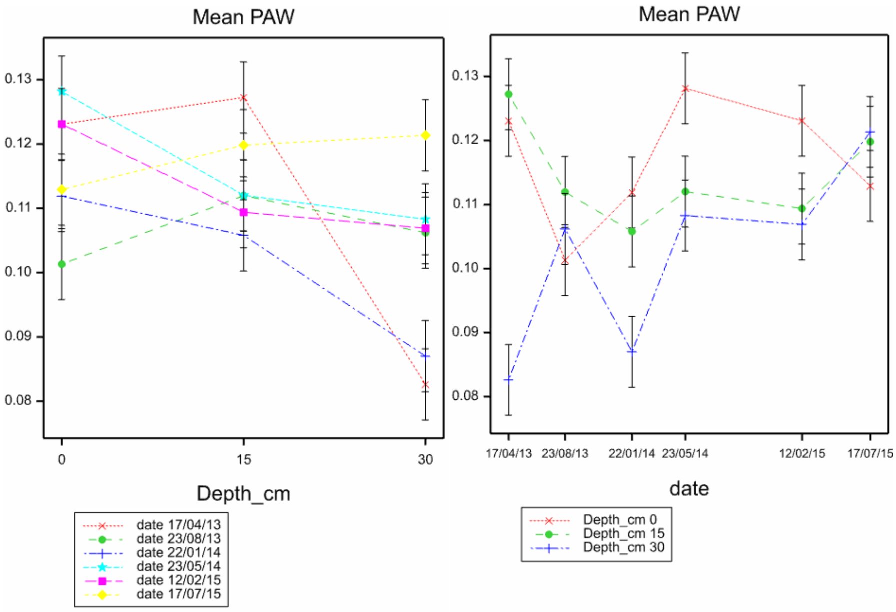

Figure 4.2.1.6 a,b show the effects of sampling depth and sampling date on Plant Available Water (m^3m^{-3}) as means with standard errors over time for the ADAS managed site at Tern Farm.

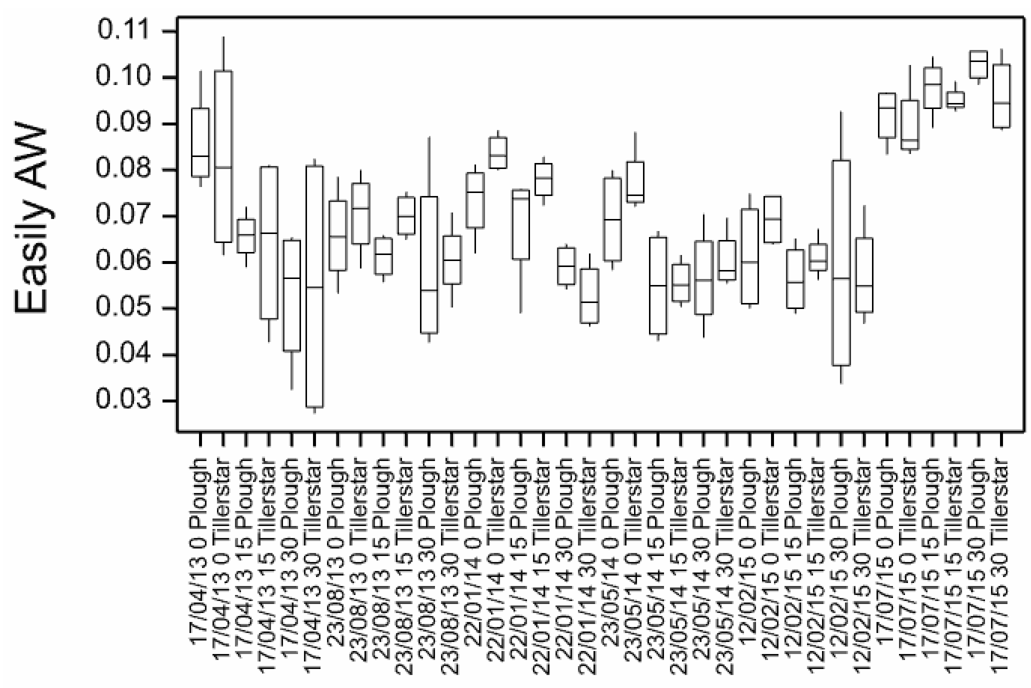

Figure 4.2.1.7 Easily Available Water (EAW) (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Plough or Tillerstar) over time for the ADAS managed site at Tern Farm.

The box and whisker plot shows that EAW was variable but interestingly at the final sampling was at the greatest amounts across all depths and all sampling dates. For easily available water (EAW), tillage treatment had no significant effect (Figure 4.2.1.8 a,b) but date, depth and the interaction between them were all significant.

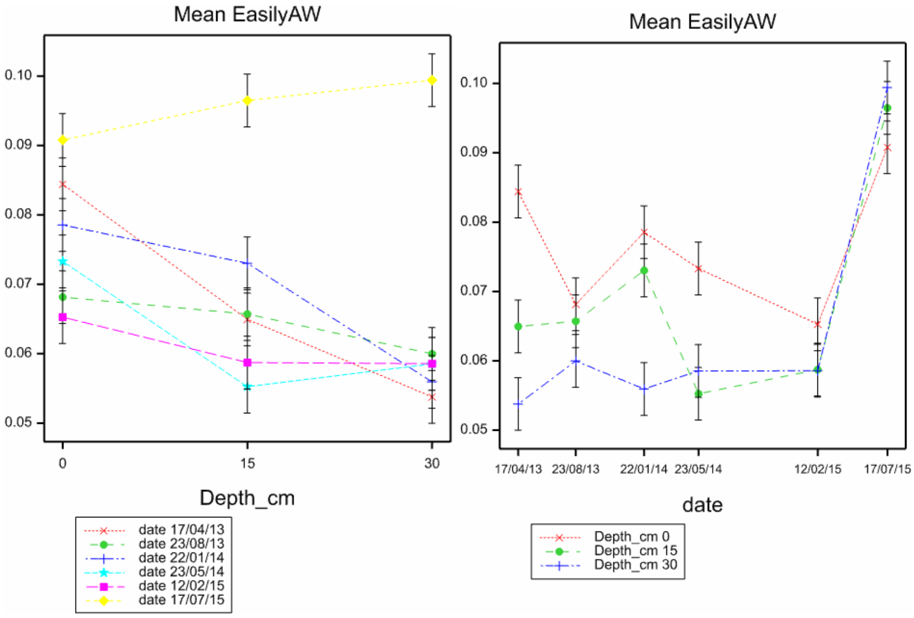

Figure 4.2.1.8 a,b show the effects of sampling depth and sampling date on Plant Available Water (m^3m^{-3}) as means with standard errors over time for the ADAS managed site at Tern Farm.

Due to the high soil strength values (determined by micropenetrometer), even when the soil was near to field capacity, there were several zero (or near zero) values of LLWR. So values of LLWR were generally low, although they were greatest on the last sampling date.

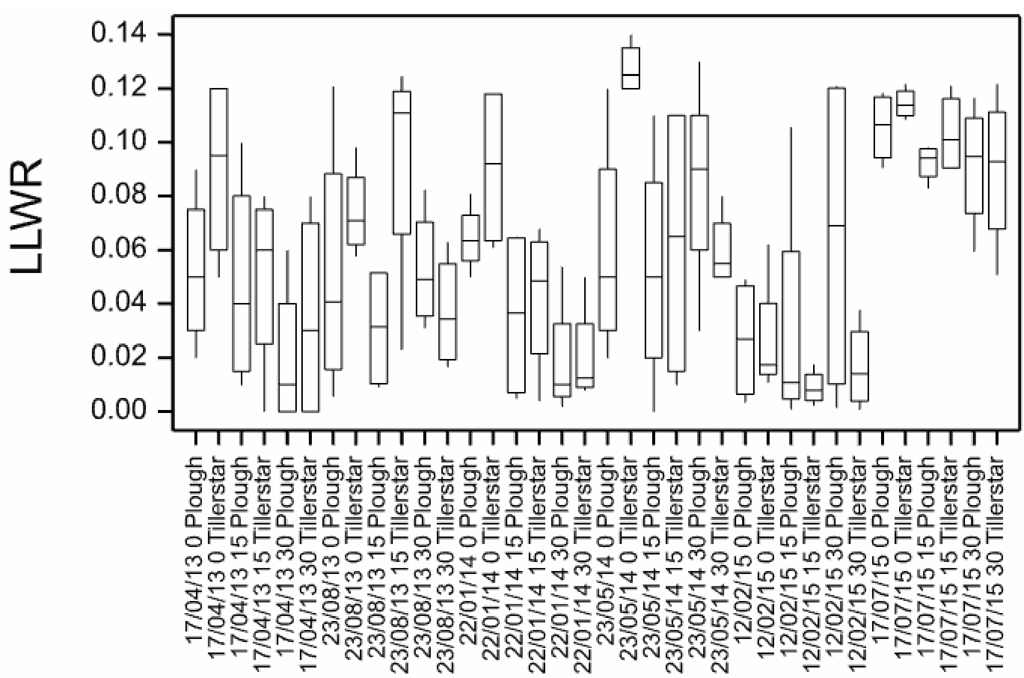

Figure 4.2.1.9 Least Limiting Water Range (LLWR) (m^3m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Plough or Tillerstar) over time for the ADAS managed site at Tern Farm.

Due to the number of zero values a $\log_{10}$ (LLWR+0.1) transformation was used for statistical analysis. Similar to the other soil quality indexes above, date, depth and the interaction between date and depth were all significant, but unlike the other indices, the interaction between tillage x depth was also significant.

4.2.2. SRUC Slade Farm Site

As noted above, the Slade farm site posed a particular challenge in that due to its location and the equipment available it was not possible to obtain accurate GPS locations. Hence it was not possible to return with certainty to the locations of the individual potato beds after harvest. Analysis was thus confined to post-planting (May) and pre-harvest (August) data. Soil cores were taken from 0, 15, 20 and 30 cm. The 20 cm depth was an additional sample to focus on the depth of cultivation for the non-ploughing treatments. We used analysis of variance with a block structure with fixed effects of soil-cultivation x date x depth.

Date ($p = 0.003$), depth ($p < 0.001$) and depth x soil cultivation ($p = 0.16$) were significant factors. The boxplot Figure 4.2.2.1 shows the increase in bulk density with depth for the two sampling dates.

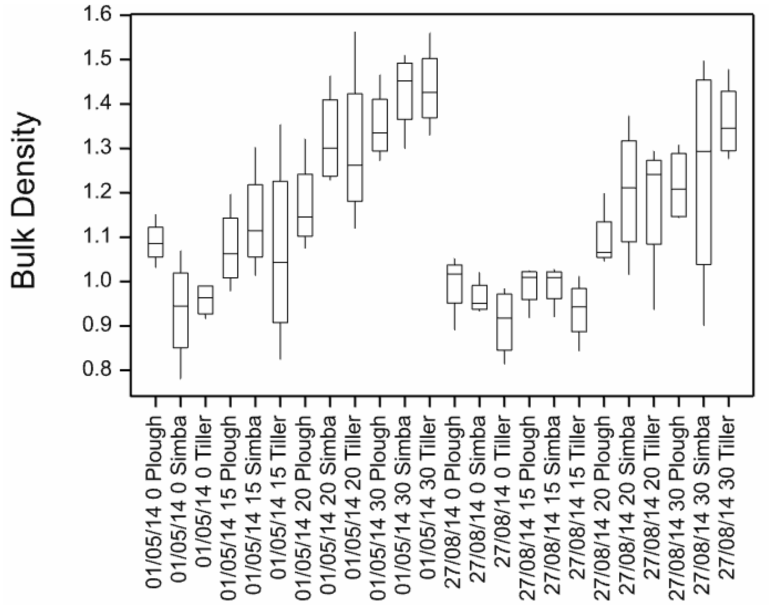

Figure 4.2.2.1 Soil bulk density (g cm^{-3}) for depth of sampling (0, 15, 20 and 30 cm) by treatment (Plough, Simba or Tillerstar) over time for the SRUC managed site at Slade Farm.

In general, there is little difference in bulk density between 0 and 15 cm depth. Below 15 cm there is an increase in bulk density with depth. The soil bulk density in the two non-ploughing treatments is very similar (across both dates) as shown in Figure 4.2.2.1. The bulk density in the plough treatment is marginally greater at the surface than the non-ploughing treatments (1.04 vs 0.94 g cm^{-3}) but less at 20 cm (1.13. vs 1.20 g cm^{-3}) and at 30 cm (1.29 vs 1.37 g cm^{-3}).

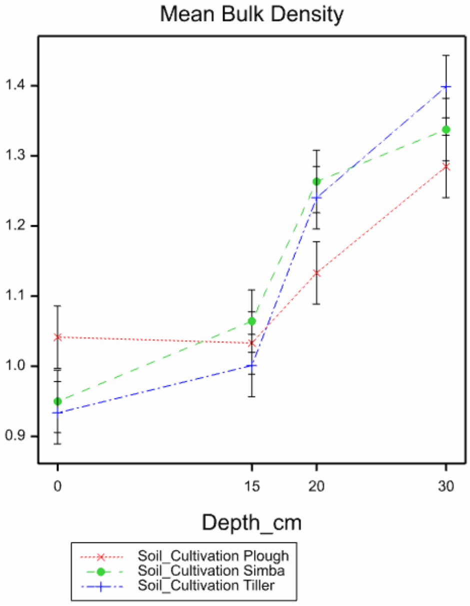

Figure 4.2.2.2 Soil Bulk Density (g cm^{-3}) for depth of sampling (0, 15, 20 and 30 cm) by treatment (Plough, Simba or Tillerstar) for both dates combined for the SRUC managed site at Slade Farm.

Date, depth and soil cultivation were all significant effects ($p < 0.001$) for Plant Available Water (PAW). The box plot (Figure 4.2.2.3) shows PAW is greater post-planting than pre-harvest in all cultivation systems.

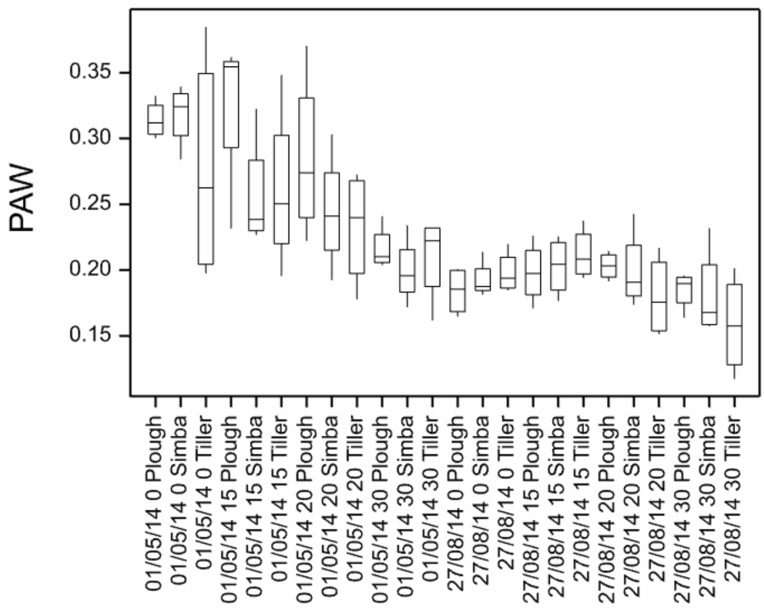

Figure 4.2.2.3 Plant Available Water (PAW) (m^3 m^{-3}) for depth of sampling (0, 15 and 30 cm) by treatment (Plough, Simba or Tillerstar) over time for the SRUC managed site at Slade Farm.

There is little difference between the treatments for PAW with the exception that at 15 and 20 cm depth the PAW was greater in the plough than in the other 2 treatments (Figure 4.2.2.4).

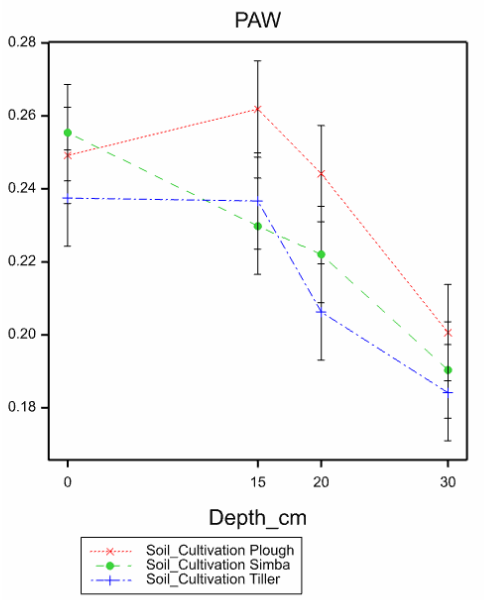

Figure 4.2.2.4 Plant Available Water (PAW) (m^3 m^{-3}) for depth of sampling (0, 15, 20 and 30 cm) by treatment (Plough, Simba or Tillerstar) for both dates combined for the SRUC managed site at Slade Farm.

As was noted in the Materials and Methods (section 3.1 Soil structure and stability), the first samples processed for water retention in this project were from Slade farm. For these samples 2 matric suctions (100 and 500 kPa) were used rather than 300 kPa (which became the project standard). Easily Available Water (EAW) is used here as the water held between 5 and 300 kPa. For these first few samples we estimated the 300 kPa suction value from the other 2 points. We note therefore that the EAW data for Slade farm include a few points where the drier limit is estimated.

Including the estimated data, date ($p = 0.003$), depth of sampling ($p < 0.001$) and the interaction soil cultivation x depth ($p = 0.016$) are all significant factors for Easily Available Water. As with bulk density and PAW, the EAW values change little between 0 and 15 cm depth but decrease markedly below 15 cm. At both 20 cm and 30 cm EAW values are greater in the plough than the non-plough treatments. Because some values are estimated (all be it from closely related values) the EAW results should be used with caution.

For Least Limiting Water Range (LLWR) not only are date ($p = 0.023$) and depth of sampling ($p < 0.001$) significant, but there is also a significant 2-way interaction between depth x date and a significant, but not strong, 3-way interaction of soil cultivation x depth x date ($p = 0.046$).

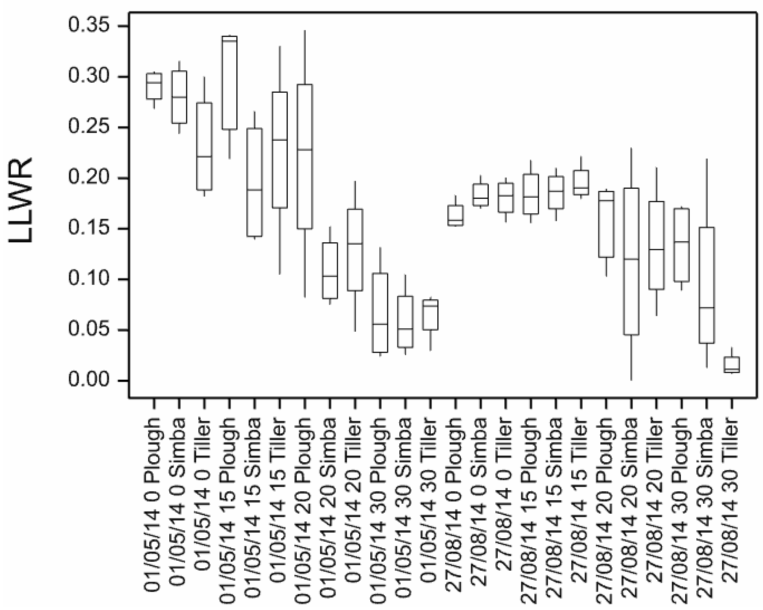

Figure 4.2.2.5 Least Limiting Water Range (m^3 m^{-3}) for depth of sampling (0, 15, 20 and 30 cm) by treatment (Plough, Simba or Tillerstar) over time for the SRUC managed site at Slade Farm.

The boxplot (Figure 4.2.2.5) shows that the variability of LLWR at 0 and 15 cm depths decreases from post-planting to pre-harvest indicating some settling of the beds.

The 3-way interaction (seen in Figure 4.2.2.6 a) shows that the plough treatment has a greater LLWR at both 15 and 20 cm depth post-planting. Figure 4.2.2.6 b shows that both the plough and the Simba treatments had greater LLWR values than the Tillerstar at 30 cm depth pre-harvest.

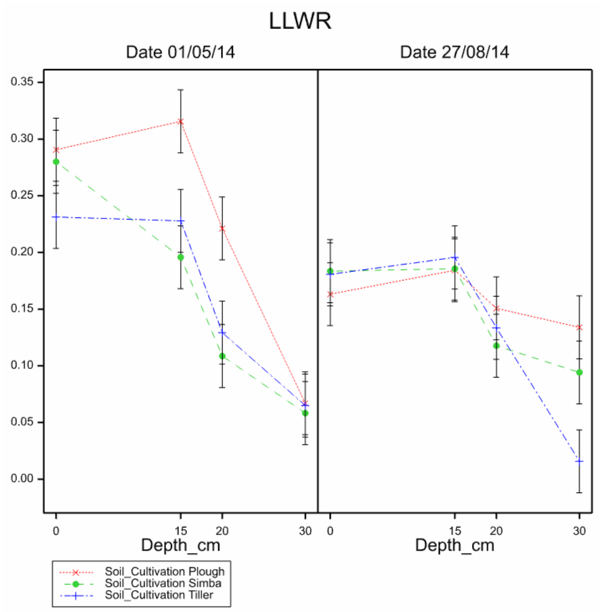

Figure 4.2.2.6 a,b shows the LLWR for post-planting (a) and for pre-harvest (b) for the depth of sampling (0, 15, 20 and 30 cm) by treatment (Plough, Simba or Tillerstar) at the SRUC managed site at Slade Farm.

The only single factor that significantly influenced the S values was depth ($p < 0.001$), but the interactions soil cultivation x depth ($p = 0.006$) and depth x date ($p = 0.004$) are also significant. As in all cases, the statistical analysis of S required data to be log transformed. In general, S decreased with depth, but there was no difference between 0 and 15 cm depth in the pre-harvest data. The most notable difference between the treatments (Figure 4.2.2.7), is that at 20 cm depth the value for the plough treatment (log value of -1.2 is S = 0.063) is greater than for both the non-plough treatments (log value of -1.38 is S = 0.041).

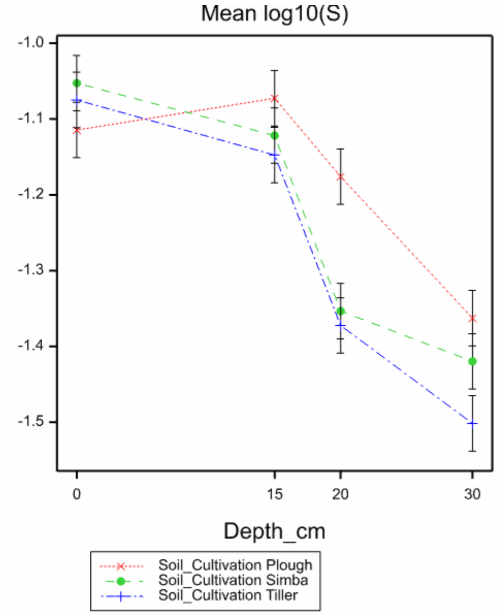

Figure 4.2.2.7 log10 S for depth of sampling (0, 15, 20 and 30 cm) by treatment (Plough, Simba or Tillerstar) for both dates combined for the SRUC managed site at Slade Farm.

4.2.3. Soil stability WSA at Slade Farm

Samples of bulk soil were taken at the pre-harvest stage from 0 cm surface, 15 cm mid-bed, 20 cm base of the bed and 30 cm sub-soil from the plough and the Simba tillage systems. Water Stable Aggregates were measured for 0.25 and 2 mm. Somewhat surprisingly, there was no effect of either tillage or depth on the percentage stable at 2 mm. For the 0.25 mm WSA there was a significant effect of depth ($p < 0.001$) but no effect of tillage system (Figure 4.2.3.1). Stability increased with depth.

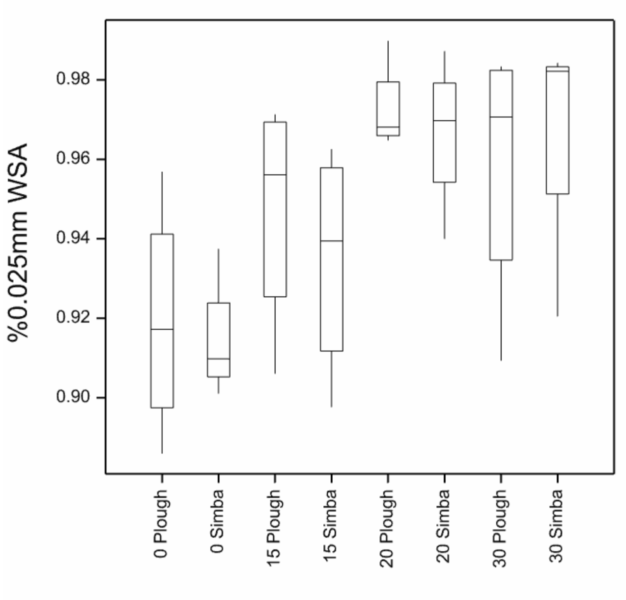

Figure 4.2.3.1 Shows the WSA 0.25 mm for soil collected pre-harvest from Slade farm under soil preparation of ploughing or by the Simba system.

4.3. Centre for Sustainable Cropping, (CSC) Balruddery

4.3.1. CSC soil quality indicators for post-planting and pre-harvest

All observations were taken pre-harvest at depth 0 cm surface, 15 cm mid-bed, 20 cm base of the bed and 30 cm sub-soil. Samples were collected in all four years – 2013, 14, 15 and 16.
The first part of the statistical analysis of the CSC data was to compare the effects of soil management within the potato beds post-planting and pre-harvest. The analysis used a straightforward factorial ANOVA with data from all depths and all years to investigate soil management, depth and time of sampling. As described in 3.4.8 The main differences between the management systems for potato production were that 35 t/ha of compost (PAS 100) was applied to the sustainable treatment. While soil organic matter concentrations were not measured as part of this project they were determined as part of the AHDB Cereals and Oilseeds Platforms project (https://cereals.ahdb.org.uk/media/1280245/pr574-final-project-report.pdf). That project determined that the soil carbon content was greater under the sustainable treatment than under the conventional treatment. The increase was approximately 6 kg of carbon more per m^3 on average.

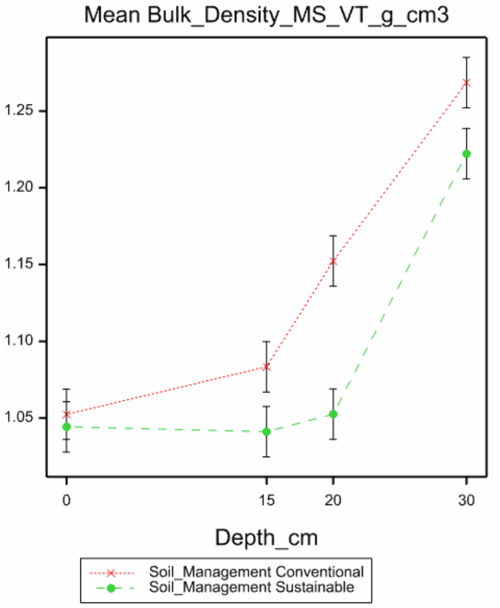

Figure 4.3.1.1 soil bulk density (gcm^{-3}) for depth of sampling (0, 15, 20 and 30 cm) and soil management across four years in the CSC at Balruddery.

Soil management ($p < 0.001$) and depth ($p < 0.001$) and the interaction between the two ($p < 0.001$) were significant, the time of sampling was not (Figure 4.3.1.1). For the conventional management, soil bulk density increased with depth while in the sustainable management the soil bulk density remained small (approx. 1.05 g cm^{-3}) throughout the potato bed and only increased at 30 cm depth.

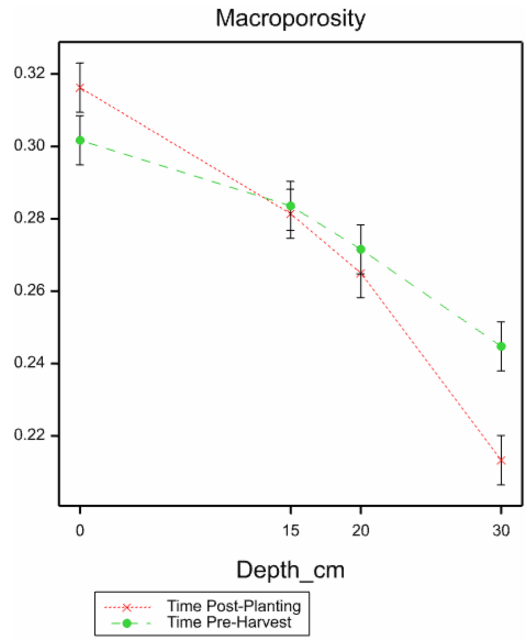

Figure 4.3.1.2 Macroporosity (m^{3}m^{-3}) for depth of sampling (0, 15, 20 and 30 cm) and soil management across four years in the CSC at Balruddery across both treatments.

Depth ($p < 0.001$) and depth x time ($p < 0.001$) were significant effects on macroporosity (Figure 4.3.1.2) but soil management was not. As expected, macroporosity decreased with depth, but was always greater than 0.2 m^3m^{-3} and thus was sufficiently large for aeration to be sufficient (i.e. not limiting) for plant growth.

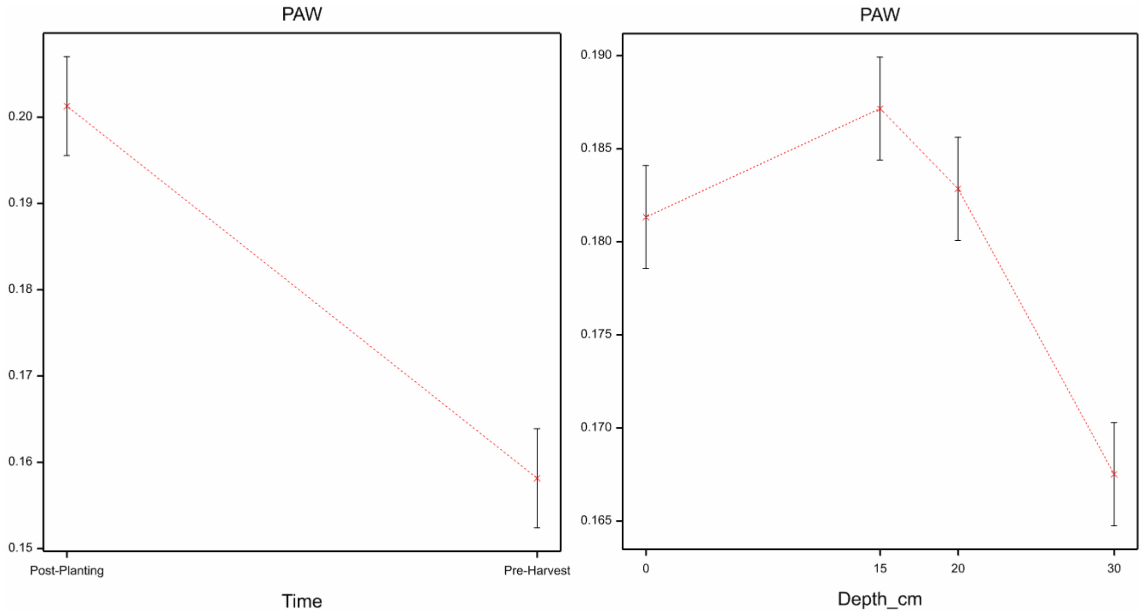

Figure 4.3.1.3 a,b show the effects of sampling time and depth on Plant Available Water (m^3m^{-3}) in the CSC at Balruddery over the experimental period and for both treatments.

There was a significant ($p < 0.001$) decrease in PAW during the season (Figure 4.3.1.3 a) independent of soil management. There was also a significant ($p < 0.001$) depth effect on PAW with the most water stored in the middle of the potato bed and least stored in the subsoil (Figure 4.4.1.3 b). This result is similar to the response of Easily Available Water with no significant impact of soil management (data not shown).

For statistical rigour, the LLWR data were log transformed for analysis.

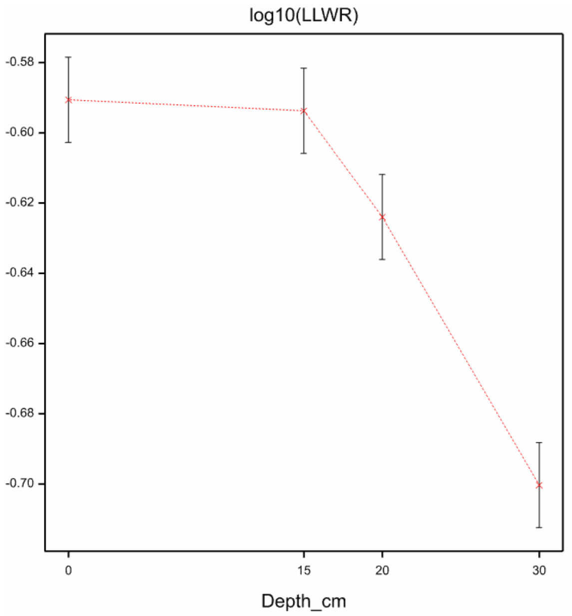

Figure 4.3.1.4 Least Limiting Water Range (LLWR) (m^3m^{-3}) for depth of sampling (0, 15, 20 and 30 cm) in the CSC at Balruddery.

There was no effect of time of sampling or of soil management on LLWR. The depth effect (Figure 4.3.1.4) can be seen as no change from the soil surface to mid-bed and then a decrease with depth.

There was a significant effect of soil management, depth and the interaction between them (all at $p < 0.001$) on the "S" index.

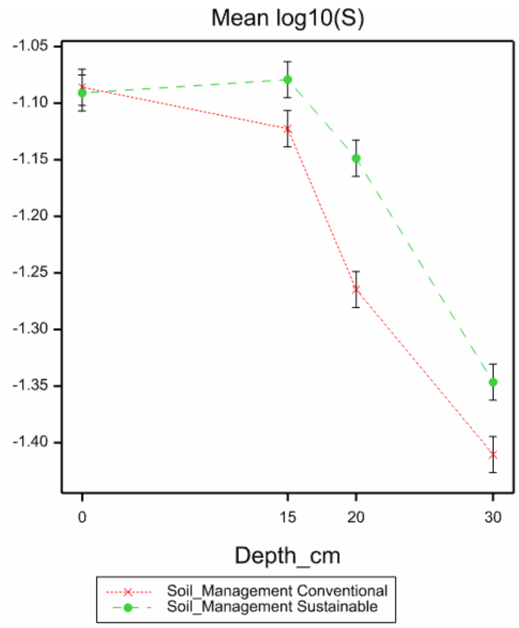

Figure 4.3.1.5 Log10 S for depth of sampling (0, 15, 20 and 30 cm) and soil management across four years in the CSC at Balruddery.

Figure 4.3.1.5 shows that while there is a decrease in S value with depth in the conventional management, the sustainable management is more homogeneous throughout the entire bed.

4.3.2. CSC soil quality indicators for post-planting, pre-harvest and post-harvest

To test the effects of potato harvesting on soil conditions we analysed soil cores from 0 and 30 cm depths taken post-planting, pre-harvest and within one month post-harvest.
For bulk density, sampling depth, time and the interaction between them were significant ($p < 0.001$). There was also a significant interaction between soil management and depth ($p = 0.040$).

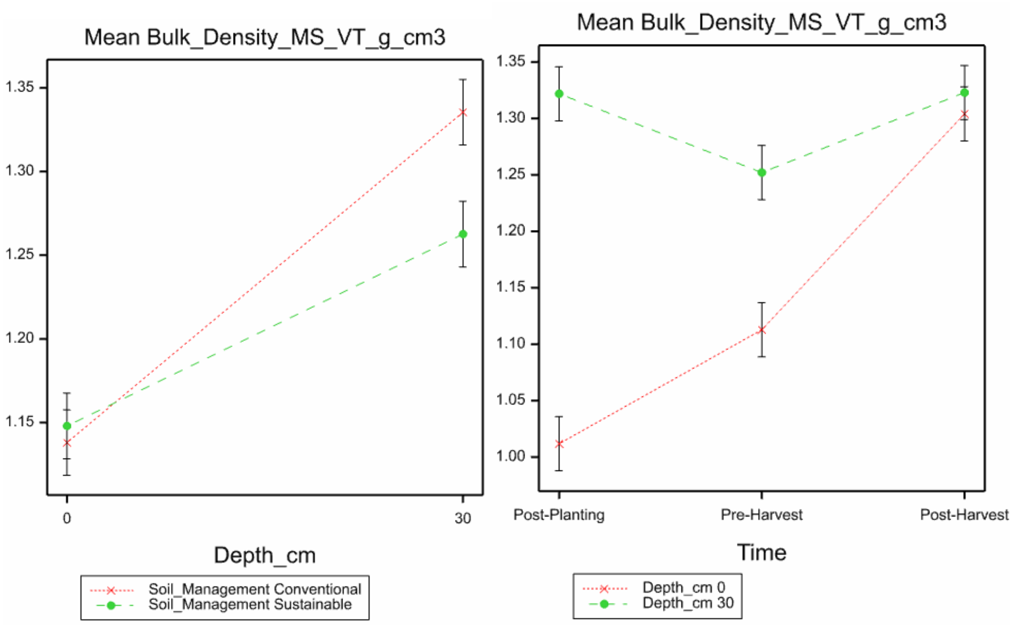

Figure 4.3.2.1 a,b soil bulk density (gcm^{-3}) for depth (0 and 30 cm) and time of sampling (post-planting, pre-harvest and post-harvest) across all sampling points and for both treatments.

That the bulk density is greatest under the conventional management at 30 cm (Figure 4.3.2.1a) is consistent with the data shown in Figure 4.3.1.1. The bulk density at 30 cm depth was not different after harvest from what it was post-planting (Figure 4.4.2.1b). However there was a large increase in bulk density in the surface soil associated with harvesting.
The increase in bulk density is clearly associated with a loss of macroporosity (Figure 4.3.2.2) in the surface soil. The change during the potato growing season is not large (0.335 at post-planting to 0.3 m^{3}m^{-3} at pre-harvest for the surface soil), but the change to post-harvest is from 0.3 to approx. 0.19 m^{3}m^{-3}.

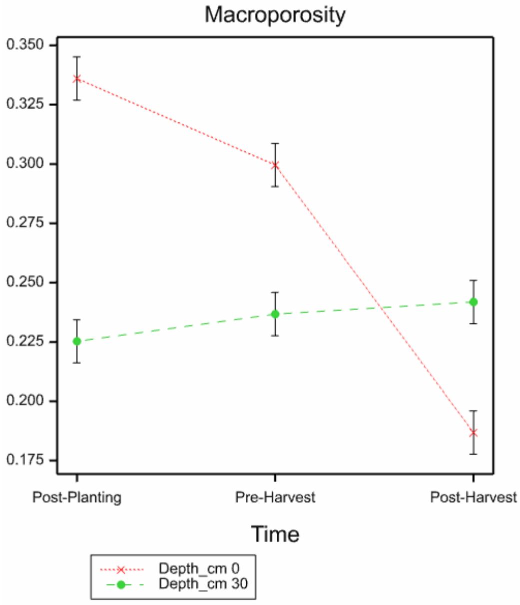

Figure 4.3.2.2 macroporosity (m³m⁻³) for depth (0 and 30 cm) and time of sampling (post-planting, pre-harvest and post-harvest) across both treatments.

Soil management did not directly influence macroporosity, but clearly sampling time and depth and the interaction between them are significant ($p < 0.001$).
That the increase in bulk density is mainly due to the loss of macroporosity rather that to changes in other pore sizes can be seen in the box and whisker plot of Plant Available Water (PAW) (Figure 4.3.2.3).

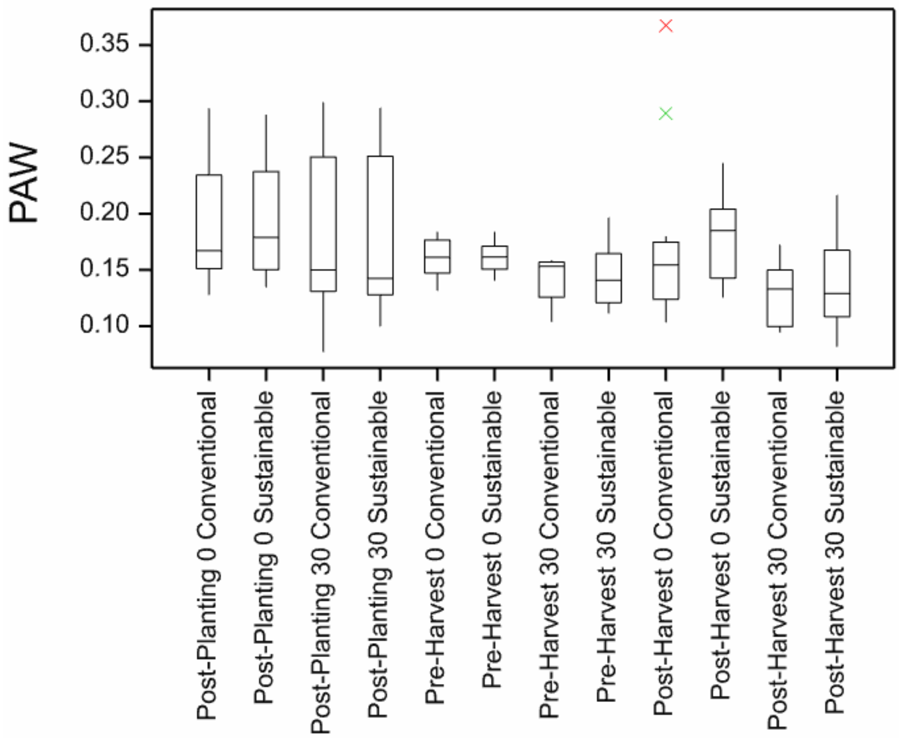

Figure 4.3.2.3 PAW (m^3m^{-3}) for time, depth and soil management.

While Figure 4.3.2.3 shows that there is greater variability at post-planting than at other times there is no change between pre-harvest and post-harvest.

For LLWR, time and depth were significant ($p < 0.001$), but soil management was not. LLWR was less at 30 cm than at 0 cm and decreased from (log-0.66 = 0.219 m^3m^{-3} to log-0.79 = 0.162 m^3m^{-3}) post-harvest (Figure 4.3.2.4a,b).

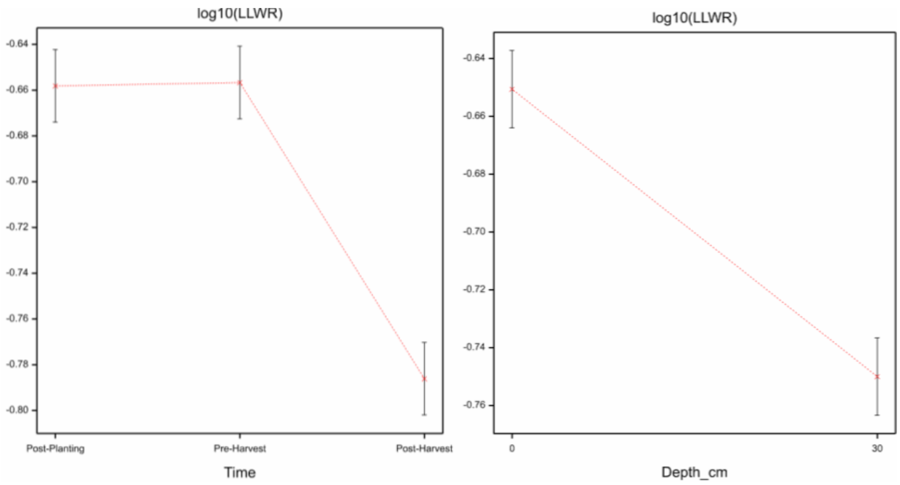

Figure 4.3.2.4 a,b LLWR (m^3m^{-3}) for time of sampling (post-planting, pre-harvest and post-harvest) and depth (0 and 30 cm).

For the S index, the effect of time and depth and the interaction between them was significant. Soil management ($p = 0.044$) was also significant and there was an interaction between soil management and depth ($p = 0.039$).

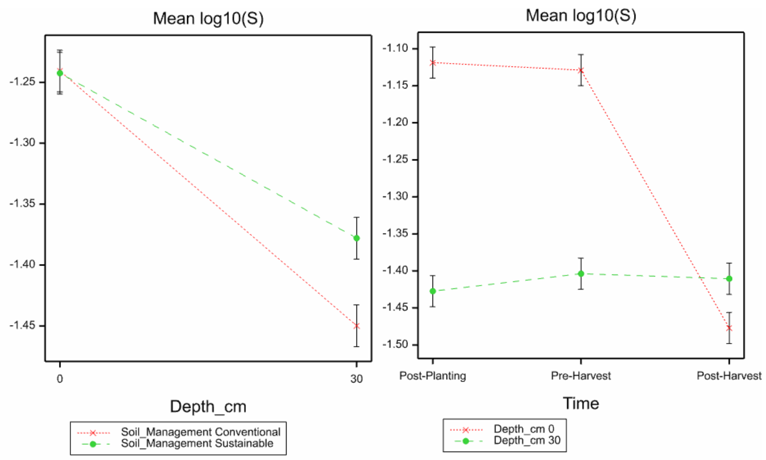

Figure 4.3.2.5 a,b Log 10 S for depth and time of sampling (post-planting, pre-harvest and post-harvest).

S decreased with depth from surface values (from log-1.25 = 0.056 to log-1.37 = 0.042 for the sustainable management and to log-1.45 = 0.035 for conventional management) (Figure

4.3.2.5 a,b). So the effect of soil management manifests at 30 cm depth but not at the surface. That is the value of S is consistently greater under sustainable management at 30 cm depth. S did not change over time at 30 cm depth. The S value of the surface soil decreased significantly after harvest (from log-1.12 = 0.076 to around log-1.45 = 0.035). Dexter (2004a) suggested that the boundary between soils with good and poor structural quality occurs at a value around S = 0.035.

4.3.3. CSC soil quality indicators to assess the changes from pre-planting through planting to pre-harvest

To investigate changes in soil parameters from pre-planting through to post-planting and pre-harvest the data were analysed using ANOVA with the same blocking structure.

For bulk density, depth, time of sampling and the interaction between them were all significant ($p < 0.001$). Soil management had a marginal effect ($p < 0.052$) and there was a three way interaction of soil management x depth x time ($p < 0.020$).

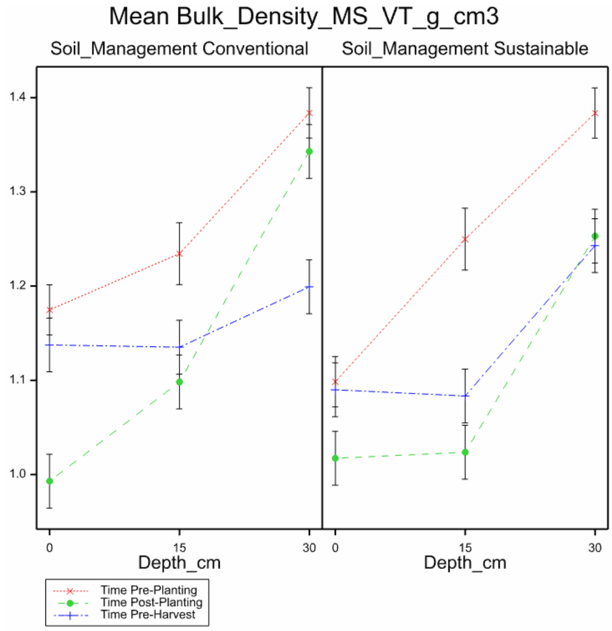

Figure 4.3.3.1 a,b soil bulk density (gcm^{-3}) for depth (0, 15 and 30 cm) and soil management.

Figure 4.3.3.1 a,b shows that in general bulk density decreases with depth. The bulk density pre-planting was not different between soil management treatments. Post-planting the soil was less dense at 15 and at 30 cm depth in the sustainable management although this did not persist until pre-harvest.

Soil macroporosity was affected by depth, time of sampling and the interaction between them ($p < 0.001$) (Figure 4.3.3.2).

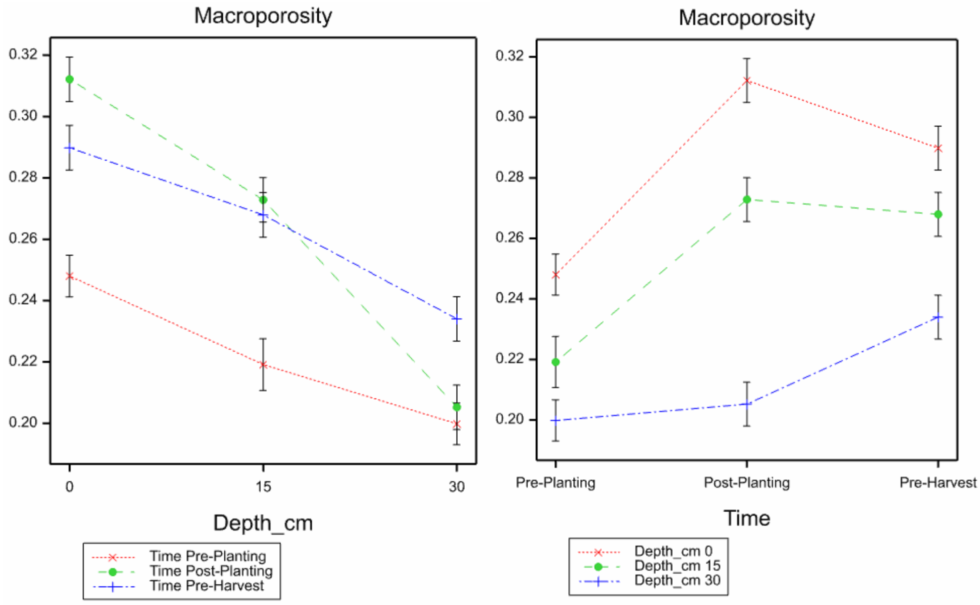

Figure 4.3.3.2 a,b macroporosity (m^3m^{-3}) for depth (0, 15 and 30 cm) and for time of sampling.

Soil management was not a significant factor in the value of macroporosity which decreased with depth. For the surface soil (0 cm) and at 15 cm depth the extensive soil manipulation associated with planting increased macroporosity and this increase persisted throughout the growing season. The explanation for the small increase in macroporosity at 30 cm between planting and pre-harvest is not obvious but may be associated with biological activity.

Similar to macroporosity, the plant available water (PAW) was not affected by soil management but changed with depth ($p < 0.01$) and time of sampling ($p < 0.001$) (Figure 4.3.3.3). There was no interaction of depth and time of sampling and hence these are not separated in the figure.

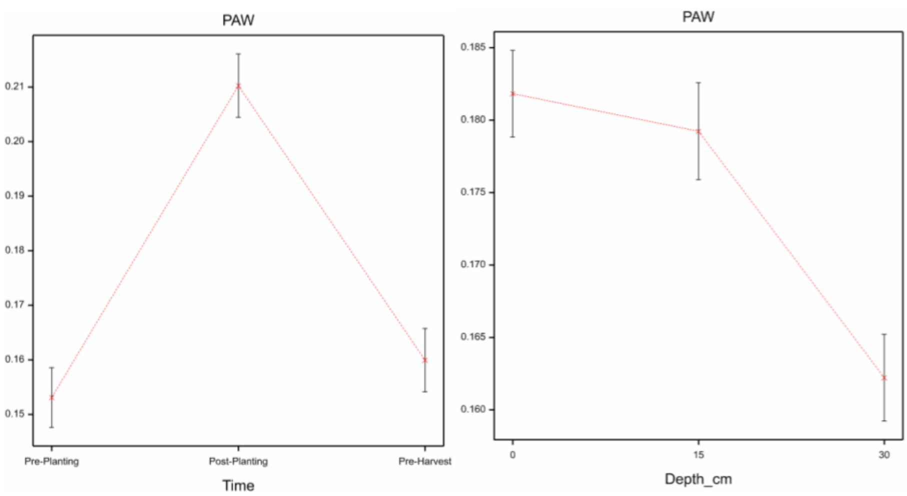

Figure 4.3.3.3 a,b plant available water (PAW) (m^3m^{-3}) for time of sampling and for depth (0, 15 and 30 cm).

Similar to the response of macroporosity to tillage there was an increase in PAW associated with tillage for planting but unlike the increase in macroporosity which persists through the season (certainly at 0 and 15 cm) the PAW decreased between planting to pre-harvest. So while the soil pore spaces larger than 30 µm in diameter remain, there was a loss of water holding pores.

To better understand the difference in pore responses from planting to pre-harvest, Figure 4.3.3.4 a,b shows the Easily Available Water (EAW). PAW corresponds to water held between matric suctions between 5 and 1500 kPa while EAW is a subset of this corresponding to matric suctions between 5 and 300 kPa.

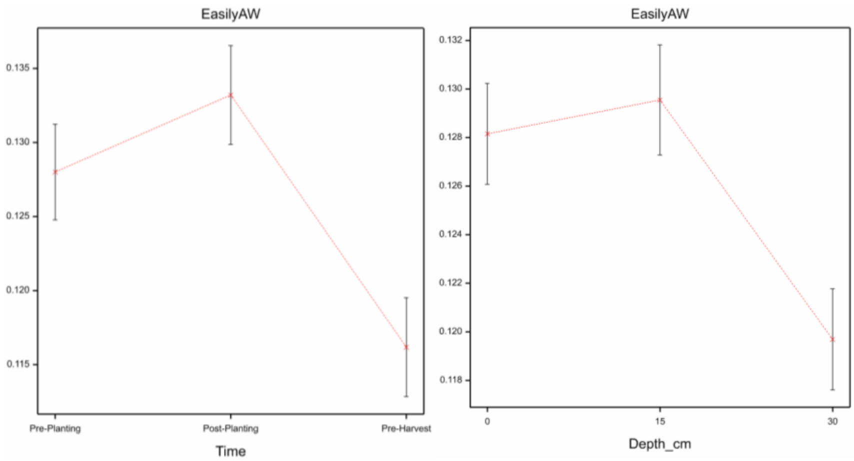

Figure 4.3.3.4 a,b easily available water (EAW) (m^3m^{-3}) for time of sampling and for depth (0, 15 and 30 cm).

Depth and time of sampling had significant effects on EAW but soil management did not. The changes in EAW while significant are small. For example, the difference between post-planting and pre-harvest was approximately 0.017 m^3m^{-3}, while the change in PAW over the same time was 0.051 m^3m^{-3}. Hence most of the loss of porosity (0.034 m^3m^{-3}) was in pore sizes where the plant cannot easily extract water and is unlikely to be of agronomic importance.

The least limiting water range (analysed as log transformed data to ensure the residuals are normally distributed) was affected by depth ($p < 0.001$) and by time of sampling ($p < 0.001$) and there was an interaction between soil management x depth ($p = 0.034$). At 30 cm depth there was little change throughout the year (i.e. from pre-planting to post-planting and pre-harvest) suggesting that the planting process did not have a significant effect on the soil at this depth (Figure 4.3.3.5 a). The influence of management on the LLWR was significant within the potato bed (i.e. at 15 cm depth) but not at the surface or at 30 cm (Figure 4.3.3.5. b).

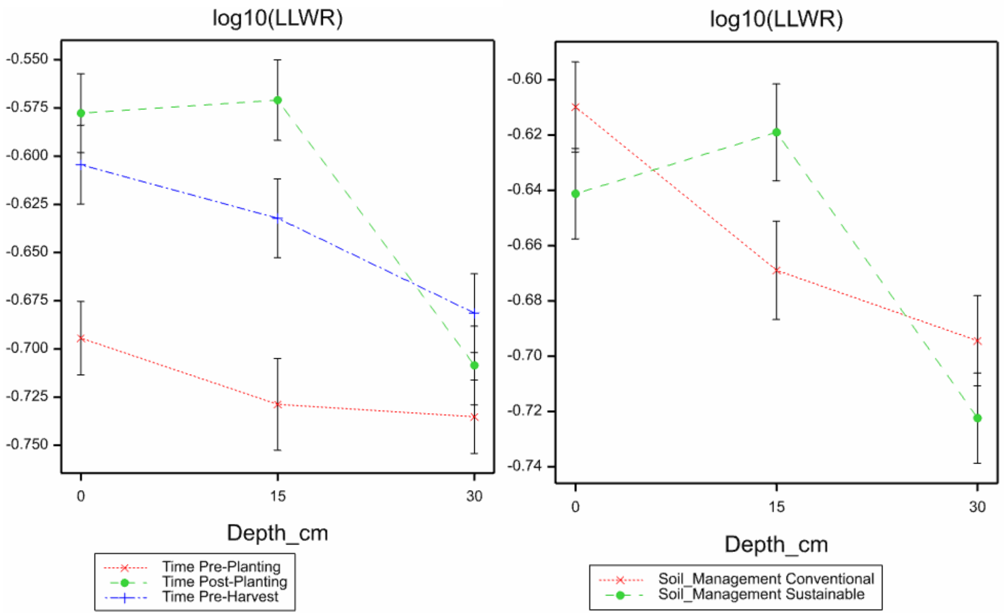

Figure 4.3.3.5 Log transformed LLWR for (a) time of sampling and depth (0, 15 and 30 cm) with the management treatments combined and (b) for soil management and depth for all times of sampling.

For the S data (analysed as log transformed) there was a significant effect of depth ($p < 0.001$), time of sampling ($p < 0.001$) and the interaction between them ($p < 0.001$) but not of soil management. S is always lowest at the greatest depth (i.e. 30 cm) but the change at 30 cm depth is a slight increase over the season (Figure 4.3.3.6). This may be a response to the temporary removal of overburden associated with lifting the soil for planting. The tillage associated with planting results in an increase of S values at both 0 and 15 cm depths.

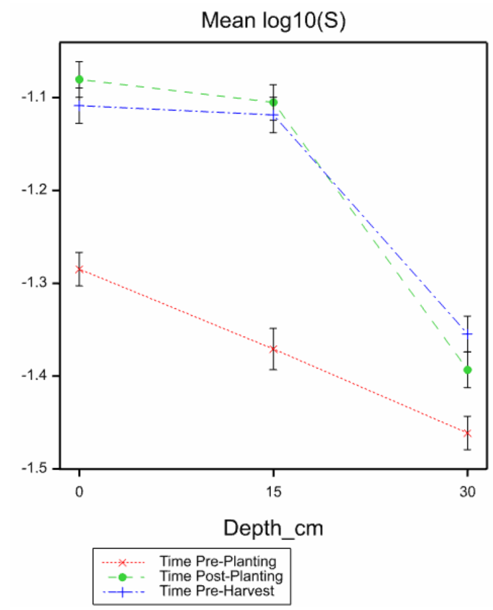

Figure 4.3.3.6 Log transformed S for (a) time of sampling and depth (0, 15 and 30 cm) with the management treatments combined.

4.3.4. Soil stability WSA in CSC

All observations were taken pre-harvest at depth 0 cm surface, 15 cm mid-bed, 20 cm base of the bed and 30 cm sub-soil. Samples were collected in all four years – 2013, 14, 15 and 16. In all cases Water Stable Aggregates were measured for 0.25 mm and 2 mm. Despite there being large variation from year to year and between fields the effects of soil management (p = 0.009) and depth (p < 0.001) were both significant for WSA 0.25 mm.

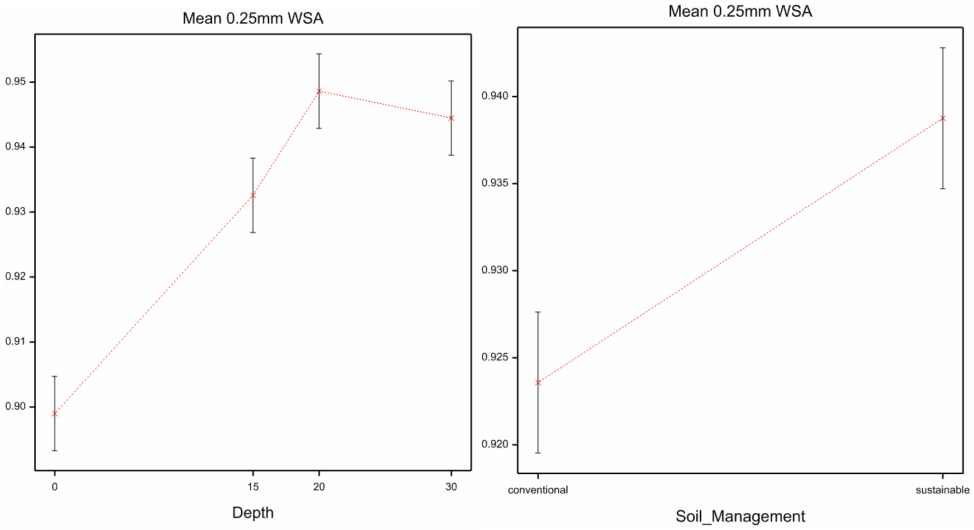

Figure 4.3.4.1 a,b shows the WSA 0.25 mm for soil collected pre-harvest from the CSC Balruddery. The analysis is for sampling from four consecutive years.

Figure 4.3.4.1a shows the soil was least stable (WSA 0.25 mm) at the surface where the soil has been disturbed by cultivation and exposed to weathering. Figure 4.3.4.1b shows that the soil is more stable under the sustainable soil management. Greater stability is likely to be associated with a decreased propensity for the soil to slump and erode. However while the difference may be statistically signficant the magnitude of the difference (0.924 vs 0.938) is unlikely to have impact in practice.

For 2 mm WSA depth there was a statistically significant effect (p < 0.001), but not for soil management.

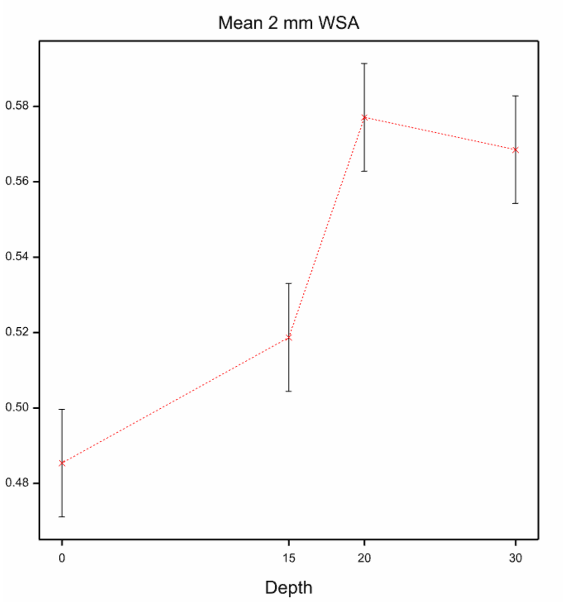

Figure 4.3.4.2 shows the WSA 2 mm for soil collected pre-harvest from the CSC Balruddery. The analysis is for sampling from four consecutive years.

The soil was less stable at 2 mm than at 0.25 mm (Figure 4.3.4.2), but the pattern of stability with depth was consistent for the two measurement sizes. That management was not a significant factor for 2 mm is interesting. In soil with greater proportions of clay texture (than in the CSC), increased concentrations of organic matter are typically associated with aggregation at the larger scale (i.e. 2 mm). It may be that in the sandy textured soil of the CSC the compost additions are not yet sufficient to create compound particles of multiple inorganic grains.

4.3.5. Rates of work of destoning machinery

Table 4.3.5.1 shows the spot rates of work for the destoner in the depth treatments at all sites. There was an overall reduction in work rate of 56 % by destoning to the full working depth of each machine compared with the shallowest setting.

Table 4.3.5.1 Rate of destoning in six experiments with destoner depth as a treatment

	Rate of destoning (ha/h)		
Site	Shallow	Deep	S.E.
2013 ADAS Tern	-	-	-
2013 Hales Hospital	0.23	0.11	0.011
2014 The Cliff	0.24	0.18	0.009
2014 Langlands	0.73	0.26	0.032
2015 Workhouse	0.37	0.14	0.018
2015 Waterloo	0.69	0.33	0.068
Mean	0.45	0.20	

4.3.6. Soil aggregate size distribution in ridge

Measurements of mean aggregate size and the proportion of aggregates >6 mm diameter were made from samples of soil extracted from potato ridges at planting and harvest and the results are shown in Table 4.3.6.1 and Table 4.3.6.2.

At the ADAS Tern site, shallow destoning had a larger overall aggregate size than deep destoning and mean aggregate size decreased slightly between planting and harvest.
At GVAP Hales Hospital, the shallower destoning depth had a lower proportion of aggregates >6 mm at both planting and harvest than the deepest, but mean aggregate size increased from planting to harvest.

At GVAP The Cliff, there was no effect of destoning depth on mean aggregate size or proportion of aggregates >6 mm at either planting or harvest, but there was a small increase in mean aggregate size from planting to harvest even though there was no change in the proportion of aggregates >6 mm.

At Stevenson Langlands, mean aggregate size in the ridge was large owing to the high clay content of the soil but there was no significant effect of destoning depth on mean ped size or proportion of large aggregates. Overall, there was a reduction in aggregate size between planting and harvest.

At GVAP Workhouse, mean aggregate size was not affected by destoning depth but aggregate size tended to decrease between planting and harvest.
At Stevenson Waterloo, mean aggregate size was increased at planting by deep destoning largely as a consequence of fewer peds < 2 mm in deep versus shallow destoning. Aggregate size decreased considerably between planting and emergence.

Table 4.3.6.1 Effect of destoning depth and time of sampling on mean aggregate size (mm) in six experiments with destoner depth as a treatment.

	Planting			Harvest		
Site	Shallow	Deep	S.E.	Shallow	Deep	S.E.
2013 ADAS Tern	7.6	6.9	0.31	7.2	6.4	0.42
2013 Hales Hospital	7.9	9.7	0.57	10.9	11.7	1.30
2014 The Cliff	11.4	9.8	0.72	12.0	11.2	1.26
2014 Langlands	12.8	14.4	1.59	10.5	10.9	0.90
2015 Workhouse	6.6	6.9	1.48	3.4	4.6	1.08
2015 Waterloo	12.3	15.0	0.56	7.6	8.2	0.28
Mean						

Table 4.3.6.2 Effect of destoning depth and time of sampling on the proportion of aggregates >6 mm (%) in six experiments with destoner depth as a treatment. Samples marked † were taken in July not at harvest as soil was saturated at harvest.

	Planting			Harvest		
Site	Shallow	Deep	S.E.	Shallow	Deep	S.E.
2013 ADAS Tern	38.3	36.8	1.60	36.3	33.8	1.40
2013 Hales Hospital	43.1	56.2	2.04	48.1	57.2	2.09
2014 The Cliff	63.9	56.2	2.89	62.8	57.2	3.36
2014 Langlands	59.3	63.7	4.80	48.4	51.8	2.62
2015 Workhouse	27.1	31.9	5.78	20.4†	23.0†	3.78
2015 Waterloo	59.7	70.1	2.66	38.9	42.7	1.07
Mean	51.2	56.6		42.5	44.3	

4.3.7. Water stable aggregation

At GVAP Workhouse, there was no significant effect of destoning depth on WSA (> 2 and > 0.25 mm) at planting or harvest (Figure 4.3.7.1). From planting and emergence to harvest, the overall trend was for WSA > 2 mm to remain constant but for WSA > 0.25 mm to decrease.

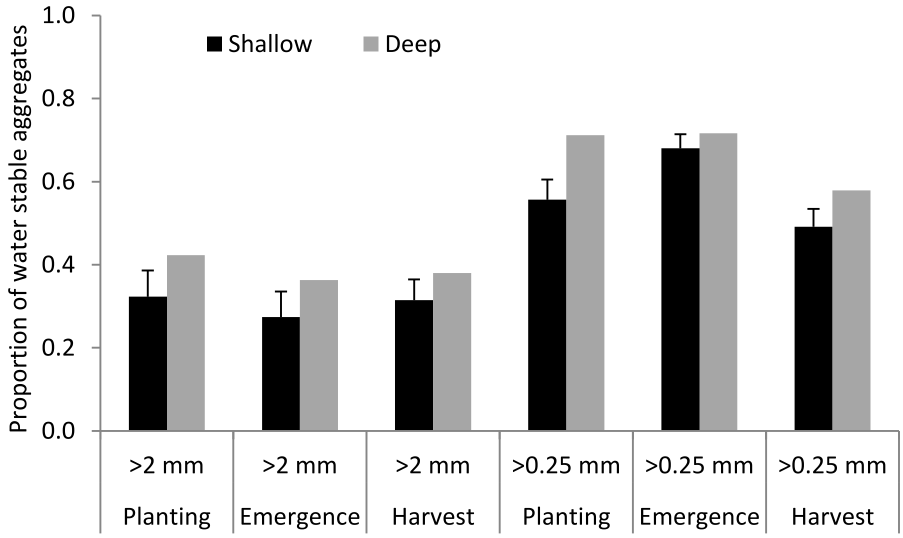

Figure 4.3.7.1 GVAP Workhouse: effect of destoning depth on proportion of water stable aggregates by weight at planting and harvest. Error bars based on 6 D.F.

At Stevenson Waterloo at planting, shallow destoning had a smaller proportion of WSA > 2 mm than deep but there was no effect of destoning depth on WSA > 0.25 mm at this time (Figure 4.3.7.2). At harvest, there was no effect of destoning depth on either fine or coarse WSA. The change in WSA > 2 mm between planting and harvest was greater for deep than shallow destoning depths and the overall trend was for WSA to decrease. There was no effect of destoning depth on the change in WSA > 0.25 mm between planting and harvest.

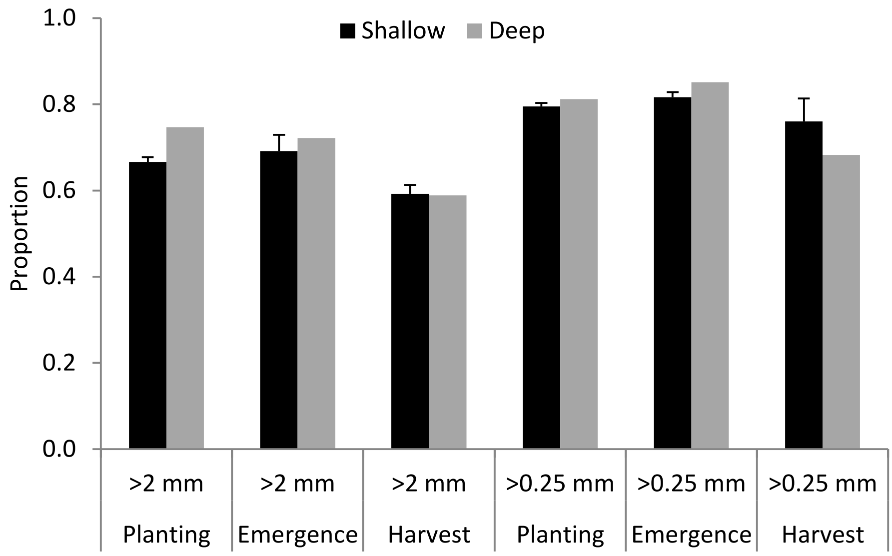

Figure 4.3.7.2 Stevenson Waterloo: effect of destoning depth on proportion of water stable aggregates by weight at planting, emergence and harvest. Error bars based on 6 D.F.

4.3.8. Yield and tuber quality

Table 4.3.8.1 shows the tuber yields and quality for the destoner depth treatments at all sites. Overall, there was a 4.9 t/ha yield reduction by cultivation soil at the maximum depth possible using the destoner compared with the shallowest, probably as a consequence of soil damage and compaction. The proportion of packable tubers was unaffected by destoner depth, demonstrating that common scab and greening are not increased by destoning potato beds shallower than the typical commercial depths used by the industry.

Table 4.3.8.1 Tuber yields and proportion of packable tubers in six experiments with destoner depth as a treatment.

	Yield (t/ha)			Proportion of packable tubers (%)		
Site	Shallow	Deep	S.E.	Shallow	Deep	S.E.
2013 ADAS Tern	60.9	58.6	1.69	93.8	94.2	1.80
2013 Hales Hospital	48.7	43.1	2.60	97.0	99.5	2.01
2014 The Cliff	68.8	62.0	3.20	94.4	95.2	2.60
2014 Langlands	52.5	48.6	2.23	93.7	94.7	1.83
2015 Workhouse	64.4	57.2	2.03	96.9	97.8	1.78
2015 Waterloo	67.2	64.0	1.90	100.0	100.0	0.00
Mean	60.5	55.6	-8 %	96.0	96.9	+1 %

4.4. Resistance & Resilience

The rapid and inexpensive resilience assays were applied to soils under different farming practices at the Slade farm managed by SRUC and Balruddery CSC field experiments. At Slade, a range of potato tillage practices was compared, whereas at the CSC the potato phase of a crop rotation under either ‘conventional’ or ‘sustainable’ practice was compared.

4.4.1. Soil Compaction Resistance & Resilience

Figures 4.4.1.1 to 4.4.1.3 illustrate the change in total soil porosity of a repacked soil core in the laboratory in response to stresses equivalent to the rolling of the soil ridge (50 kPa) and under a tractor wheel (200 kPa). The initial porosity of the loosely packed soil at the start of the test varied depending on soil management practice for Balruddery ($P<0.001$) and Slade ($P<0.01$), and varied between sampling times. Subsequent compression to a stress, similar to rolling potato ridges, caused a marked decrease in soil porosity, resulting in a mechanically more stable soil. However, this stress and a subsequently greater stress equivalent to a tractor wheel, resulted in similar compaction between different soil management practices for Balruddery, and although statistical differences between tillage practices were found for Slade ($P<0.01$), the difference in porosity was only about 2%. After either the 50 kPa or 200 kPa stress was removed, a slight recovery in porosity occurred due to the inherent elasticity of the soil. The greater this recovery, the greater the resilience of the soil, but it was similar between different management practices for both field experiments. Over time, the migration of water into a compacted zone and the removal of the compaction stress, can allow the soil to recover more. At Balruddery, the Sustainable soils recovered more than the Conventional soils ($P<0.01$) on some sampling occasions, but no differences between tillage practices were found for Slade. The amount of recovery was very large, sometimes to porosities that were greater than the 50 kPa compression stress, but caution is needed in interpreting these results. Whereas the compression phase of the test measured soil volume directly from a mechanical test rig, the final relaxation phase measured volume directly with callipers. This is a potential source of experimental error.

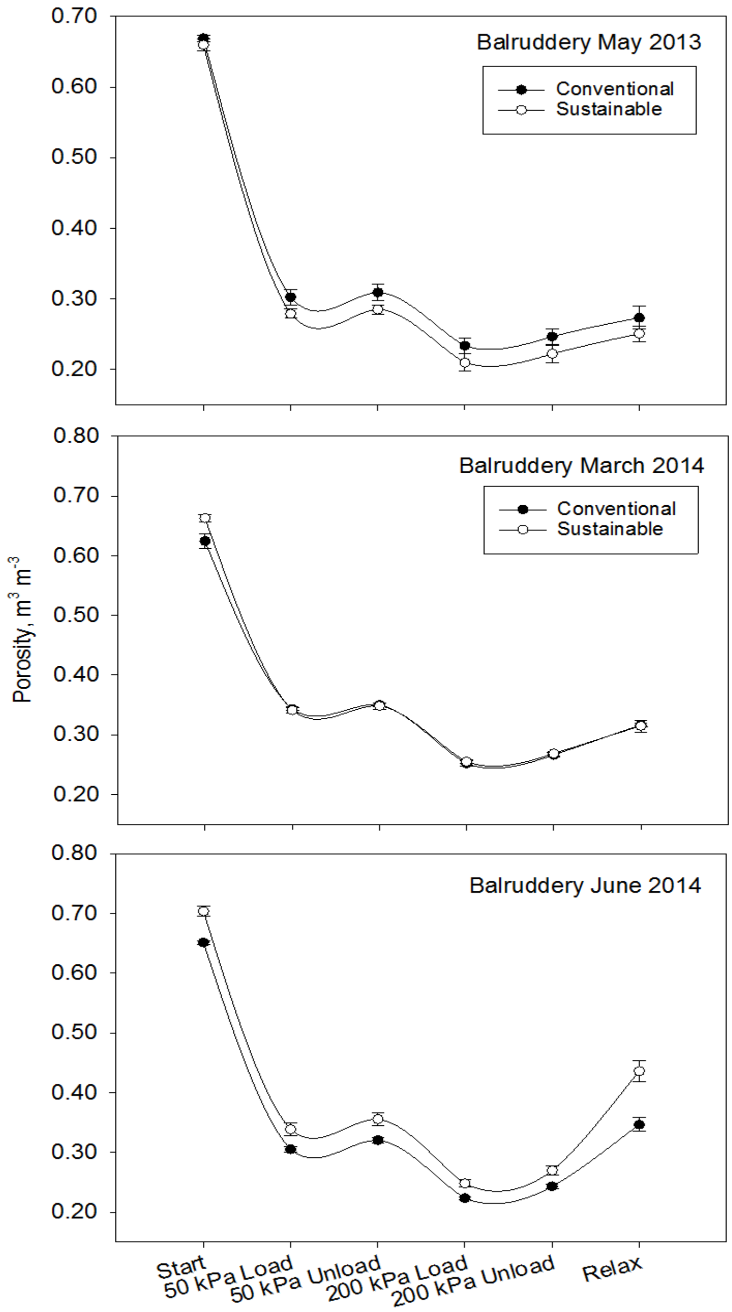

Figure 4.4.1.1 - Compression and rebound of surface soil for the Balruddery CSC field experiment in 2013 and 2014. Sustainable is a combination of shallow non-inversion tillage for crops other than potato in the rotation and compost addition, whereas Conventional is ploughing to 20 cm with no compost added.

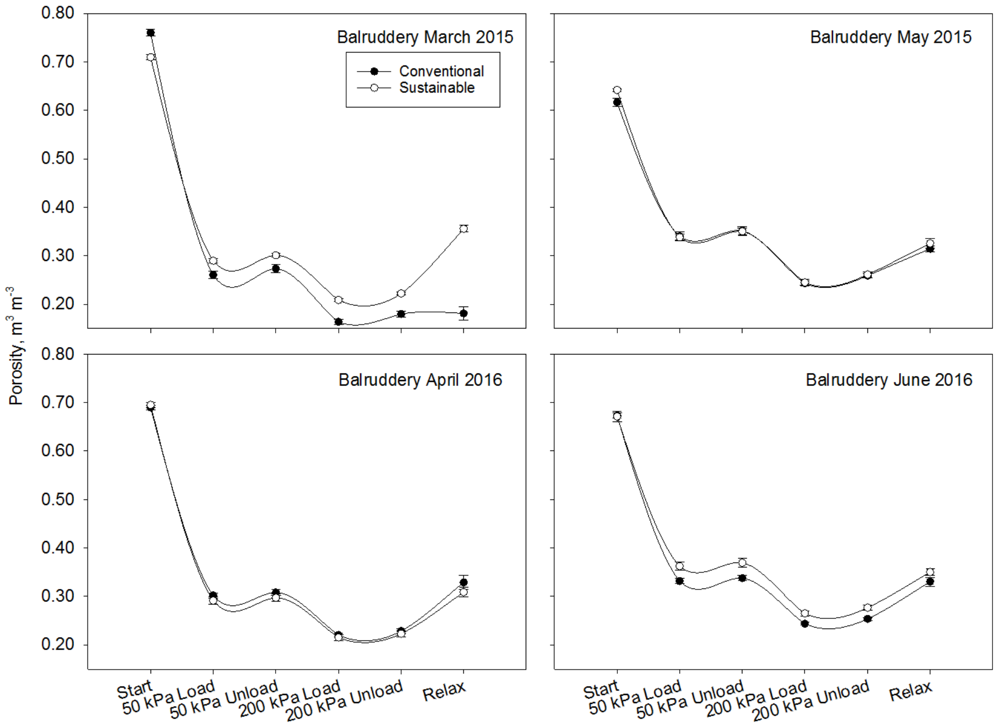

Figure 4.4.1.2 - Compression and rebound of surface soil for the Balruddery CSC field experiment in 2015 and 2016. Sustainable is a combination of shallow non-inversion tillage for crops other than potato in the rotation and compost addition, whereas Conventional is ploughing to 20 cm with no compost added.

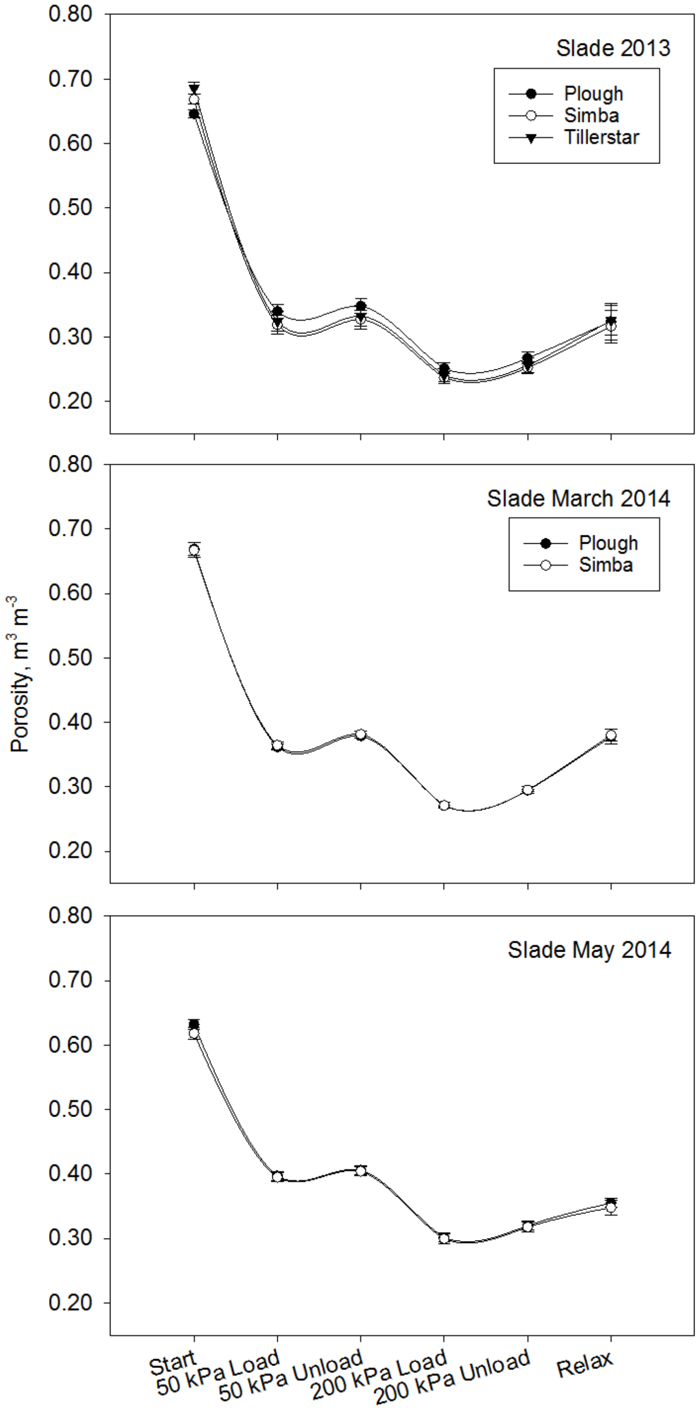

Figure 4.4.1.3 - Compression and rebound of surface soil for the Slade Field Experiment.

4.4.1. Soil Slumping Resistance & Resilience

The slumping of the soil due to prolonged wetting, follow by subsequent recovery when the soils are drained, is illustrated in Figures. 4.4.2.1 – 4.4.2.3. Data are expressed as air-filled porosity (AFP) so that they tie in more closely with the soil physical measurements on intact field cores. The line at 0.10 m^3 m^{-3} AFP indicates roughly where hypoxia risk would occur, and is the aeration cut-off of the LLWR. The initial wetting stress at AF1 resulted in significant differences between management treatment for Balruddery (P<0.01), but not between tillage treatments in Slade. In 2013 and 2014 for Balruddery, the measurements were erratic between sampling events (P<0.001), with March 2013 having very low AFP values.

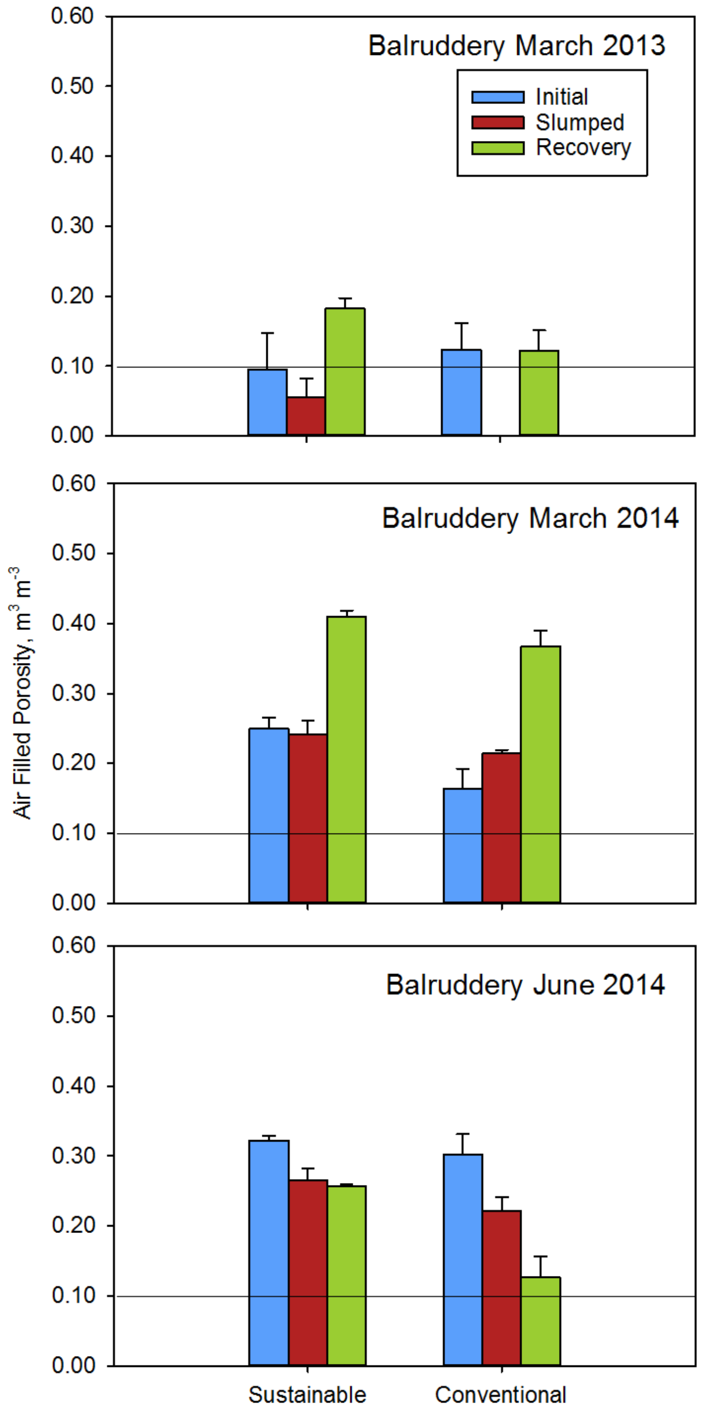

Figure 4.4.2.21 Slumping and rebound of surface soil for the Balruddery CSC field experiment in 2013 and 2014.

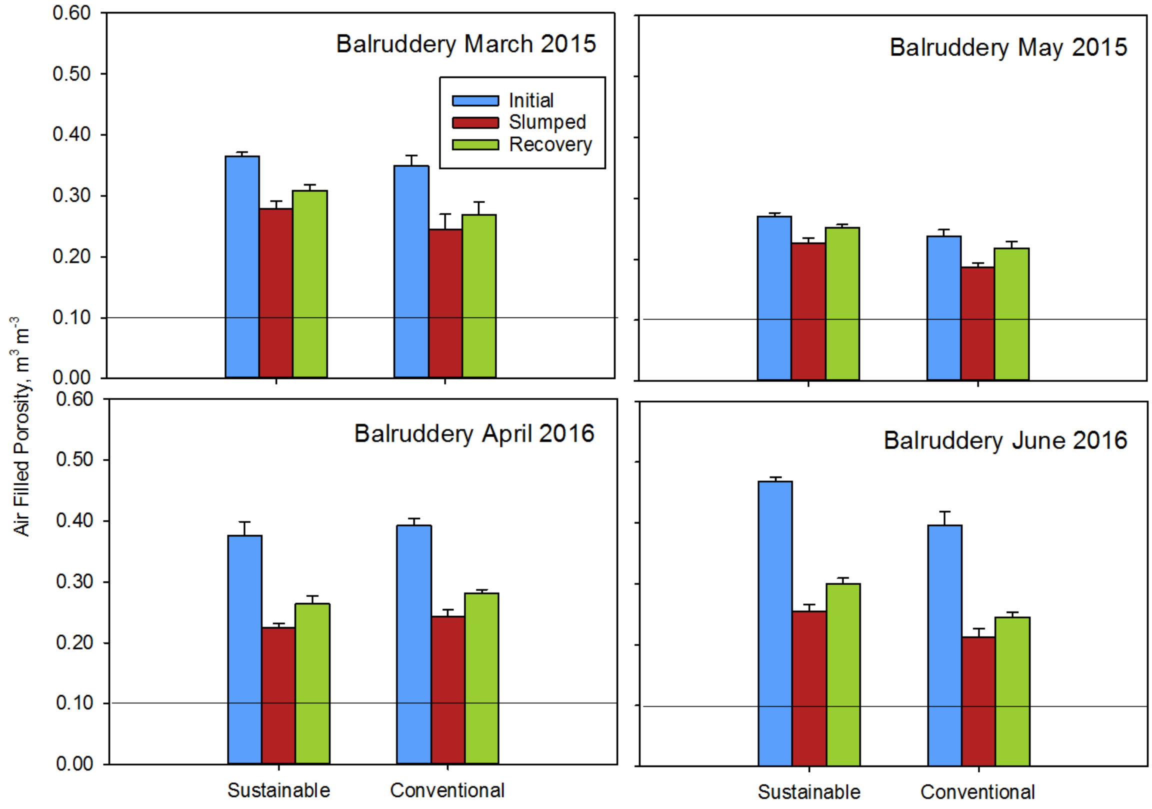

Figure 4.4.2.2 Slumping and rebound of surface soil for the Balruddery CSC field experiment in 2015 and 2016.

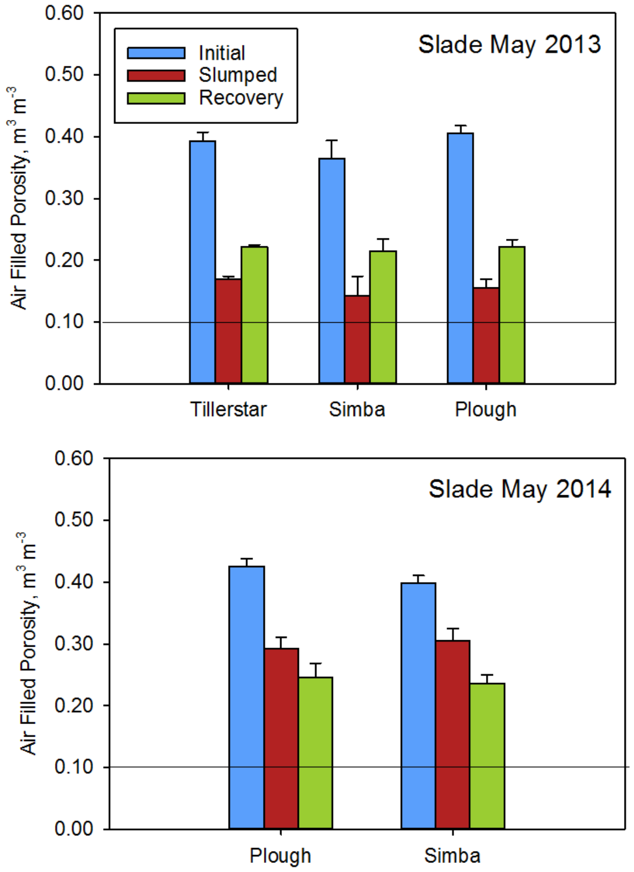

Figure 4.4.2.3 Slumping and rebound of surface soil for the Slade Field Experiment.

5. Discussion

The cultivation window in spring depends on the soil type and wetness of the soil. In order to produce sufficient soil for a potato seedbed, at least 20 cm of soil is required and on heavier soils, at this depth soil can be wetter than the Plastic Limit (PL) for cultivation. During April, when most potatoes in the UK are planted, the weather can be extremely variable. Optimum workability and fragmentation from tillage requires the soil to be drier than the Plastic Limit (Obour *et. al.* 2017). Although, April is often dry, the temperature and rainfall can change markedly. Growers often experience the situation of soil being too wet at depth yet drying rapidly on the surface as the day warms up. Cultivation such as ploughing or bedforming brings large clods of wet, unweathered soil onto the surface. These clods can dry hard within a few hours, necessitating intensive bedtilling operations in an effort to reduce the clod size sufficiently for the destoner to work at an acceptable rate. Without cultivating soil, drying to the depths needed to produce adequate soil for destoning is very slow and growers are left in a quandary: progress with cultivation in the knowledge that soil damage will occur or wait until the soil is fit to cultivate. Therefore, the cultivation window is often narrower than expected. With better knowledge of the critical depths of cultivation on heavier soils, growers would be able to judge a more effective cultivation strategy. The overall trend of cultivation depth on the soil variables measured was that they had little overall effect on density and aggregate size distribution of soil within the ridge. Shallow, less intensive destoning (including widening the gaps in star separators or increasing the web pitch) often produces a visually cloddy surface to the bed prior to planting and this convinces growers that they may have a potential problem with respect to damage levels or clod at harvest. However, measurements showed that internally within the bed, the size distribution of aggregates was similar at harvest irrespective of cultivation intensity and the amount of diesel consumed during cultivation. Differences in aggregate size distribution are often created at planting by varying the intensity of rotary and destoning cultivation, but these largely disappeared by emergence and tuber initiation, the critical phase for having finer soil in the ridge to control common scab. This does not negate the fact that there are large differences between soil types and sites, but altering the operation of the cultivation tools at planting seems to be a relatively ineffective means of producing a ridge of the optimum range of aggregate size.

The clay content of the soil was the over-riding factor in mean aggregate size and the proportion of aggregates > 6 mm, with higher clay content leading to larger aggregates. In Projects R459 and 11140022, soil OM was only loosely related to clay content, with high clay content soils generally having greater OM content than sandy soils, but there was a range of OM content in the soils tested owing to previous cropping and practice of manuring.

Analysis of the data collected both Project R459 and 11140022 does not allow the optimal ped size distribution for seedbeds to be determined but the data indicate ridges should be composed of larger aggregates in sandy soils and of similar aggregate sizes to that achieved commercially on clay soils currently. There were very few examples of excessively cloddy seedbeds produced on heavy soils as most clods under such circumstances were removed to the furrow by destoners. There were examples of overly-fine seedbeds produced on sandy soils, largely as a consequence of low OM, excessively deep destoning and finer-pitch webs (often deemed a necessity on stony soils). Water stable aggregates tended to decrease between planting or emergence and harvest, but most of the changes were small (-0.02 to -0.07). In line with effects on aggregate size distributions, cultivation machinery had surprisingly little effect on WSA.

Producing the optimum aggregate size distribution with existing equipment may prove difficult on certain soils and the main problem lies in not producing excessively-fine aggregates in the pursuit of breaking down larger clods. Destoning / declodding is largely carried out by machines that operate on two principles: traditional web-only based machinery and star machines. Web-only machines were developed in the 1970's at the Scottish Institute for Agricultural Engineering to remove stones from ridges and reduce damage to tubers at harvest and are still the most effective design currently available to separate stones from soil, albeit with a slow rate of work. During the 1980's, a pressure to work soils faster and under wetter conditions lead to development of star machines, which have a series of rollers with 'star' fingers at the front of the machine combined with web(s) at the rear to achieve the final separation of over-sized clods. Star machines are more suitable for breaking up clods than web machines, but there is a tendency for operators to close up the gaps between star rollers to avoid stones being pulled through into the seedbed but this leads to excessive grinding of soil at the front of the machine, particularly when a new set of stars is used.

Soil should not be cultivated deeper than is necessary to produce destoned beds of *c*. 27-28 cm (sandy soils) and 24-26 cm (clay soils) in depth prior to planting. Although it is recognized that processing crops require less finely-structured soil owing to the reduced importance of common scab, soil is routinely cultivated deeper and more aggressively than is required for growing high yields of packing quality potatoes. Destoning deeper than 35 cm on sandy soils and deeper than 28 cm on heavy soils will result in reduced yields. However, destoning to 27-28 cm on sandy soils when it is common practice destone to 35-38 cm can increase yield by c. 1.8 t/ha (Stalham & Allison 2015). On heavier soils, the penalty for cultivating below the critical depth can be greater (i.e. 3-5 t/ha), so destoned beds as shallow as 22-24 cm can result in improved yields and yet still provide sufficient soil to plant and harvest tubers with minimal damage.

Figures 4.1.1.1, 4.1.2.1 and 4.1.3.1 show that at planting the soil to the depth of cultivation (around 30 cm) has penetration resistances seldom in excess of 2 MPa – a value often taken as critical for preventing root proliferation. However, in all these cases. below the depth of cultivation the soils have penetration resistances up to and in excess of 3 MPa. At planting these subsoils will be wet after winter and strength values will increase with soil drying as the growing season progresses. Hard, dense subsoils have also been reported from cropping systems that do not have potatoes in the rotation (McKenzie *et al*. 2017).

In section 4.2 we reported on the soil physical conditions in the two sites managed by ADAS and SRUC as part of R444. These made comparison of potato production under conventional ploughing (with shallow destoning) with cultivation using the Simba DTX system and cultivation using the George Moate Tillerstar system. In the surface soil the differences in soil bulk density between systems were small and not strongly significant. Deeper into the beds (i.e. at 15 or 20 cm) the ploughed treatment held more Plant Available Water (PAW) than the non-plough systems. This improvement in soil conditions is magnified at these depths when soil strength is taken into account with the Least Limiting Water Range (LLWR). The LLWR is greater at 15 and 20 cm depth at post-planting under the plough treatment but this advantage improvement did not persist until pre-harvest nearly four months later.

The improvements in soil physical conditions that were suggested in R444 (Silgram *et. al.* 2015) have been quantified here, using multiple indexes of soil quality. These superior conditions at the middle and base of the potato beds under the plough treatment would have provided the crops with greater access to water both by the soil holding more water (PAW) and by providing easier access through root proliferation in the softer soil (LLWR). However as was suggested by Silgram *et al.* (2015) if sufficient water is provided through irrigation there may be no benefit from the improved soil conditions.

The main difference in the two production systems at the Centre for Sustainable Cropping at Balruddery was that the sustainable half of the experiment received repeated applications of PAS 100 compost each and every year prior to cultivation (while the conventional half did not). Because the soils on the site are shallow and stony there were no differences in destoning depth between the halves. As the sustainable half receives lower nutrient inputs it was deemed inappropriate to report yield data as the causes of any differences may be due to a range of factors. We were able to compare the soil conditions created by the different managements (as in section 4.3). The first analysis (4.3.1) compared soil conditions in the potato beds from post-planting to pre-harvest. While at the surface of the beds conditions were similar, the sustainable management created a better soil environment (lower bulk

density and greater S values) below the surface. These differences were particularly pronounced at 15 and 20 cm depths – where tuber expansion occurs.
Changes in soil conditions in the CSC from post-planting through pre-harvest to post-harvest were analysed in 4.3.2 and all assessment of the impact of potato harvest operations for soil from 0 and 30 cm depths. Harvesting operations were associated with decreases in soil quality indexes for the surface soil (e.g. macroporosity and S value) for both management systems. At 30 cm (below the harvester working depth) changes in indexes of soil physical quality were less pronounced (and not significant for several indexes). The exception was the S value that showed some amelioration of harvesting effects in the sustainable management (Figure 4.3.2.5).

The impact of planting operations was considered in section 4.3.3. Clearly the tillage and bed-forming operations loosened the soil (decreased bulk density) and increased macroporosity at 0 and 15 cm depths. The changes also occurred for other indexes but the persistence of the improvements varied. PAW and EAW increased post-planting but then decreased by pre-harvest. LLWR and S value did not show similar peaks. For WSA, there is a significant management effect with the soil being more stable in the sustainable management. However this improvement is unlikely to have major practical benefits.
The slumping resilience test measured a range of macroporosity values that were in line with the upper and lower values found for the intact field cores sampled at different times during the growing season. The initial conditions closely matched freshly produced potato seedbeds and the worst conditions in the field were similar to the values after recovery from slumping. As a rapid test, it offers promise. Earlier measurements for the Balruderry CSC were erratic, which could be due to the operator and early implementation of the technique, but the final two years of measurements were consistent. By determining air-filled porosity (i.e. macroporosity) with this approach, hypoxia risk can be estimated against a cut-off of 0.10 m^3 m^{-3}. As the soils are sieved at the beginning of the measurement, they represent a freshly tilled seedbed (Kuan *et al.*, 2007). Therefore the test could likely be deployed at different times in the growing season, as supported by the similar results found for April and June 2016 for the CSC experiment.

The compaction resilience assay resulted in total porosities that were smaller than measurements in the field. This was likely due to the compaction stress being applied when the soils were at field capacity (-5 kPa), which will be wetter than the PL when field operations would be likely to occur. In many of our tests we observed water being expelled from the sample. Air-filled porosity (data not shown) sometimes dropped to 0 m^3 m^{-3}, since compression removed all of the air-filled pores. The assay picked up good recovery of both Balruddery CSC and Slade soils to compaction, with the sustainable management at the CSC being more resistant and more resilient to compaction than the Conventional practice. This would be expected due to the greater organic matter in the Sustainable practice (Kuan *et al*., 2007) from compost amendments. The compaction resilience assay provides a worst case scenario of traffic on fields just after free drainage following rainfall (Gregory *et al*., 2009). It appears to be sensitive to management and has been deployed in a number of studies. Despite the test using sieved soils, in both 2014 and 2016 for Balruddery, compression resilience changed slightly between spring and summer sampling with the same trend observed in both years. This could be due to changes to the structure of the 4 mm sieved aggregates caused by crop growth or cultivation.

Mechanistic understanding from the resistance and resilience assays was complemented by analysis of samples taken over multiple years to consider any long-term impacts of potato production. Data from four sites described in section 3.4 (GVAP Hales Hospital, GVAP The Cliff, Stevenson Langlands and Tern Farm) were used. These analyses used soil collected from 0, 15 and 30 cm depths. Across the four sites there are no clear trends that can be associated with the potato phase of the rotation. For example S values shown in Figures 4.1.1.12, 4.1.2.11, 4.1.3.6 and box and whisker plots of LLWR shown in Figures 4.1.1.9, 4.1.2.9, 4.2.1.9 are variable over time. Similarly while specific operations such as bed forming can be identified at the post-planting stage the values in subsequent crops are not consistently higher or consistently lower than the initial conditions. Any effects on soil physical conditions below 30 cm depth are unknown. Repeated sampling to below 30 cm requires machine-driven coring-equipment and becomes prohibitively expensive to do on a repeated basis. Computer modelling approaches may be better suited to understanding the soil response at depth to particular operations, particularly as soil wetness will have a major impact.

This project used multiple measures of soil quality that characterised the soil structure and its stability. These intensely studied measures were based on samples collected *in situ* and transported to the laboratory for analysis. Many of the measures used information derived from all or part of a water retention curve. Data generated from these measurements could then be used to calculate parameters relevant to crop productivity such as water available between field capacity (free drainage) and permanent wilting (drought), PAW and more easily available water, EAW. PAW was further refined by incorporating strength data to determine the LLWR. LLWR consistent had smaller values than PAW for all sites examined, showing the importance of soil strength to limiting crop productivity in the UK. An easy to interpret parameter S incorporated the entire water retention curve to provide a measurement of the distribution of pore sizes as a soil physical quality indicator. So there are a range of indexes that cover different aspects of soil physical quality. The selection of which one to use depends on the specific question to be asked.

Bulk density is easy to measure and provides an indirect assessment of the total pore space available in soils. Bulk density be can relatively easily implemented at limited cost and without needed specialist equipment or extensive training. However bulk density data are affected considerably by soil texture and organic matter concentrations, so a value of say 1.5 g cm^{-3} may be very limiting for crop productivity in one soil type, but fair for another soil type. Moreover, the units g $cm^{-3}$are hard to conceptualise. On many of the sites examined, bulk density showed changes over time associated with destoning or cultivation activities. It also identified differences between cultivation systems. However, the responses observed did not always reflect conditions of relevance to the crop such as Plant- or Easily- Available Water.

Soil physical indicators derived from the water retention curve require more sophistication and time to conduct and interpret. As a result, they had not been tested thoroughly to date, with the results generated in this report and its sister AHDB report PR574 (McKenzie *et al*. 2017) providing a unique data-set to evaluate soil physical quality indicators that can be deployed in practice.

Using the CSC as an example, bulk density picked up less of a difference between 15 cm and 30 cm soil than macroporosity. A weakness of bulk density is that it is related to total porosity, but in the field the drainage of pores, dictated by the size of pores and how they are connected, also affects crop growth (Reynolds *et al*. 2002). For these reasons the use of bulk density to quantify soil conditions is of limited value unless it is supplemented with other data.

Macroporosity can be measured on inexpensive, self-built sand tables, so it is feasible to establish as a standard technique. It has particular use for potato and root crops (e.g. carrots) where beds are formed to allow easy expansion of tubers or elongation of vegetable roots. Macroporosity also performed well in quantifying changes in the beds over a growing season. When the soil use changed as part of a rotation from, e.g. potato beds to cereal crops, macroporosity was of less use as the magnitude of the changes associated with the rotation masked more subtle differences associated with particular management practices.

EAW and PAW are more sophisticated measures than bulk density or macroporosity. However the information derived from these indexes relates directly to the capacity of the soil to provide water to the crop. EAW has the benefit that it can be measured more quickly and with less expensive pressure plate apparatus that can operate from a standard compressor (300 kPa). Moreover it picked up similar trends to PAW and is affected more by larger pores that are more likely to be influenced by soil management practices. From a full water retention curve it is also possible to calculate S from the slope of the drainage characteristics across a range of water potentials. S provides a number that can be interpreted against cut-off values of good and poor soil physical quality, with much of the soil beneath the surface layer at the sites we examined showing poor quality.

There are limitations to the use of the S index. Reynolds *et al.* (2009) found that builder's sand, despite being a poor growth medium for crops, could produce good values for S. They argued that if S is used, it needs to also consider other soil physical quality measurements like EAW, PAW and macroporosity. Li *et al.* (2011) found the S index useful for assessing soil quality under different tillage, stubble and field traffic treatments. Certainly the determination and interpretation of the S index requires a high level understanding of soil physics. While the S index performed well in this project it is probably best used in conjunction with more accessible indexes.

LLWR clearly has benefits to measurements based just on water retention as it also considers mechanical impedance to root growth. At all sites the LLWR was less than PAW, suggesting that soil strength is a limiting soil physical parameter that needs to be measured. However in soils with significant proportion of coarse sand the micropenetrometer data needed to properly determine LLWR becomes highly variable. The replication needed to produce increases as a result making LLWR extremely time consuming to determine. This coupled with the need for a specialist loading frame to power the micropenetrometer mean that determination of LLWR is expensive. For this reason the determination and use of the LLWR is likely to be confined to answer specific hypotheses related to root proliferation – which was the original purpose of the index.

WSA quantified some differences in soil stability associated with changes in management e.g. addition of organic matter. However while significant differences were found here the magnitude of these differences were small and unlikely to guide soil management decisions. There are several likely reasons for the small scale of the differences found. First the soils in the UK are relatively young and generally have calcium as the dominant cation on the exchange complex. Hence the soils are generally inherently stable. Similar responses have been found in the national soil inventory for Scotland. Added to this is that potatoes are generally grown on high value agricultural land – usually land class 1 or 2. By definition these soils tend to be very stable. WSA is thus not a suitable tool for general soil quality monitoring in most potato growing regions of the UK.

Field measurements of penetration resistance found values >2MPa beneath the plough layer, which will severely limit root proliferation. Measures such as field penetrometers, shear vanes or possibly visual soil assessment to identify areas or depths of soil that have been affected by management have the advantage of being rapid. These rapid measures coupled with GPS technology that allows easy, repeatable return to locations of interest can greatly enhance approaches to understanding the impact of agricultural practices on soil quality. Rapid identification of zones of interest within the soil and the ability to resample can guide sampling and focus the use of more accurate soil quality indexes to address specific hypotheses, inform mechanistic understanding and inform practical management decisions.

6. CONCLUSIONS

This project used multiple field experiments, where potatoes were grown under commercial production, to test a range of hypotheses relating to the impact of practices on soil physical quality. Soil physical quality was determined in each case and the relative merits of different indexes considered. What became apparent was the advantage of using hand held GPS to allow repeated sampling from nearly the same location. We were then able to use statistically robust methods to analyse long-term (including within and over multiple year) changes in soil conditions.

In spring the soil dries from the surface, so at depth the soil may be wetter than the plastic limit. Cultivating soil wetter than the Plastic Limit risks smearing the soil, causing compaction and can bring large unweathered clods to the surface. Consistent with Stalham and Allison (2015) cultivation and destoning operations should be no deeper than necessary and timed so that the soil is drier than the plastic limit. Evidence was found that subsoils, below 30 cm depth, were likely to limit root proliferation as, even when at optimum water status, penetration resistances were well in excess of 2 MPa. Numerous other studies across the UK (e.g. Valentine *et al.* 2012) have identified problems associated with subsoil compaction. We found no evidence that shallow destoning created conditions that were any less favourable for potato production than deeper destoning. Given the fuel and time savings of shallower destoning identified by Stalham and Allison (2015) we support the practice of not cultivating soils deeper than necessary.

Alternative cultivation systems were tested as part of project R444 (Silgram *et al.* 2015). At the soil surface we found only minor differences in soil conditions under the different cultivation systems. We did identified that within the potato beds (at 15 and 20 cm depths) the indexes of soil quality were under the plough treatment were better for water availability and root proliferation than under the alternative systems. These benefits to soil conditions did not result in differences in crop yields as the crop water needs were met by irrigation (Silgram *et al.* 2015).

At the Centre for Sustainable Cropping (CSC) Balruddery, we identified improvements in soil conditions associated with multiple applications of municipal compost. These benefits manifested as less-dense, softer, more stable soil particularly at 15 and 20 cm depths. While there were some detrimental effects on soil quality associated with harvesting in some cases the compost addition ameliorated some of these effects.

The ability to repeat sampling over time allowed impact of potato production to be put into the context of a crop rotation. Across four sites where we sampled soil pre-planting, during the potato crop, soon after harvest and well into subsequent crops. While there were was considerable variability and changes caused by particular management practices, there were no long-term trends (positive or negative) in soil conditions, within the topsoil that could be linked specifically to potato production.

We characterised soil physical conditions using a range of indexes and note the need to select any index in the context of the scientific hypothesis being tested. We have identified some indexes that have particular use in understanding responses to soil management, some that are of limited use under UK conditions and some that can with care be used as more general measures of soil quality. There is an opportunity to better deploy the more sophisticated and time consuming indexes by linking them to field measurements, especially when this can be done with repeated sampling at known locations.

7. REFERENCES

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.

Bartoli, F., Hallett, P. & Cerdan, O. (2016). Le Bissonnais, Y. 1996. Aggregate stability and assessment of crustability and erodibility: 1. theory and methodology. European Journal of Soil Science, 47, 425-437. European Journal of Soil Science 67, 5-10.

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.

Carter, M.R. (2007). Long-term influence of compost on available water capacity of a find sandy load in a potato rotation. Canadian Journal of Soil Science 87, 535-539.

Carter, M.R., Noronha, R.D., Peters, R.D., & Kimpinski, J. (2009). Influence of conservation tillage and crop rotation on the resilience of an intensive long-term potato cropping system: Restoration of soil biological properties after the potato phase. Agriculture, Ecosystem and Environment 133, 32-39.

Carter, M.R., Peters, R.D., & Sanderson, J.B. (2010). Conservation tillage in potato rotations in eastern Canada. 5th International Conference on Land Degradation, Bari Italy. Land degradation and desertification: assessment, mitigation and remediation pages 627-637.

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.

Czyz, E.A. (2004). Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil & Tillage Research 79, 153-166.

Da Silva, A.P. & Kay, B.D. (1996). The sensitivity of shoot growth of corn to the least limiting water range of soils. Plant & Soil 184, 323-329.

Dexter, A.R. (2004a). Soil physical quality – Part 1. Theory, effects of soil texture, density and organic matter and effects on root growth. Geoderma 120, 201-214.

Dexter, A.R. (2004b). Soil physical quality – Part 2. Friability, tillage, tilth and hard-setting. Geoderma 120, 215-225.

Dexter, A.R., Czyz, E.A., & Gate, O.P. (2005). Soil structure and the saturated hydraulic conductivity of subsoils. Soil & Tillage Research 79, 185-189.

Ehlers, W., Kopke, U., & Hesse, F. (1983). Penetration resistance and root-growth of oats in tilled and untilled loess soil. Soil & Tillage Research 3, 261-275.

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.

Hakansson, I., Keller, T., Arvidsson, J. & Rydberg, T. (2012). Effects of seedbed properties on crop emergence. 5. Effects of aggregate size, sowing depth and simulated rainfall after sowing on harmful surface-layer hardening. Acta Agriculturae Scandinavica Section B-Soil and Plant Science 62, 362-373.

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.

Hallett, P.D., Hall, R., Lilly, A., Baggaley, N., Crooks, B., Ball, B.C., Raffan, A., Braun, H., Russell, T., Aitkenhead, M., Riach, D., Rowan, J.S., & Long, A. (2016). Effect of soil structure and field drainage on water quality and flood risk. CREW2014_03.

Holman, I.P., Hollis, J.M., Bramley, M.E., & Thompson, T.R.E. (2003). The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. Hydrology and Earth Systems Sciences 7, 754-765.

Keller, T., & Dexter, A.R. (2012). Plastic limits of agricultural soils as functions of soil texture and organic matter content. Soil Research 50, 7- 17.

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.

Li, L., Chan, K.Y., Niu, Y., Guangdi, L., Oates, A., Dexter, A.R., & Huang, G. (2011). Soil physical qualities in an Oxic Paleustalf under different tillage and stubble management practices and application of S theory. Soil & Tillage Research 113, 82-88.

Li, L., Larney, F.J., Angers, D.A., Pearson, D.C., & Blackshaw, R.E. (2015). Surface soil quality attributes following 12 years of conventional and conservation management on irrigated rotations in southern Alberta. Soil Science Society of America Journal 79, 930-942.

McKenzie, B.M., Bengough, A.G., Hallett, P.D., Thomas, W.T.B., Foster, B., & McNicol, J.W. (2009). Deep rooting and drought screening of cereal crops: A novel field based method and its application. Field Crops Research 112, 165-171.

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

McKenzie, B.M., Tisdall, J.M., & Vance, W.H. (2011). Soil Physical Quality in Encyclopedia of Agrophysics. Springer The Netherlands pp 770-777.

McKenzie, B.M., Stobart, R., Brown, J.L., George, T.S., Morris, N., Newton, A.C., Valentine, T.A. & Hallett, P.D. (2017). Final Report Project PR574: Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments. Stoneleigh: Agricultural and Horticultural Development Board.

Obour, P.B., Lamande, M., Edwards, G., Sorensen, C.G., & Munkholm, L.J. (2017). Predicting soil workability and fragmentation in tillage: a review. Soil Use and Management 33, 288-298.

Palmer, R.C. & Smith, R.P. (2013). Soil structural degradation in SW England and its impact on surface-water runoff generation. Soil Use and Management 29, 567-575.

Panini, T., Torri, D., Pellegrini, S., Pagliai, M. & Sanchis, M.P.S. (1997). A theoretical approach to soil porosity and sealing development using simulated rainstorms. Catena 31, 199-218.

Silgram, M., Williams, D., Wale, S., & Griffin-Walker, R. (2015). Final Report Project R444: Managing cultivations and cover crops for improved profitability and environmental benefits in potatoes. Stoneleigh: Agricultural and Horticultural Development Board.

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.

Stalham, M. A., Allen, E.J., Rosenfeld, A.B. & Herry, F.X. (2007). Effects of soil compaction in potato (*Solanum tuberosum*) crops. Journal of Agricultural Science 145, 295-312.

Stalham, M. A. & Allison, M. F. (2015). Final Report Project R459: Improving cultivation practices in potatoes to increase window of workability and soil structural stability. Stoneleigh: Agricultural and Horticultural Development Board.

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.

8. ACKNOWLEDGEMENTS

The authors especially thank the technical team and senior colleagues at NIAB CUF including: Marc Allison, David Firman, Gerdientje Bouwhuis, Joanna Barton, Matthew Meddick, Simon Smart, Ben Brown, Jamie Oakley, Jennifer Preston, Dale Bailey and Algida Valentinaviciene. Also they thank the technical support, CSC team and farm staff at the James Hutton Institute including: Jennifer Brown, Euan Caldwell, Cathy Hawes, Magda Krol, and Anna Taylor. Much of the statistical analysis was performed by, or under the guidance of, Dr Katharine Preedy from BioMathematics and Statistics Scotland. We sincerely thank her for contributions.

The help and support of the following people should be acknowledged: David Whattoff and Simon Griffin and their soil sampling team at SOYL, Stuart Liddell and Sam Coates at Greenvale AP Ltd, Tom and Allen Stevenson at Stevenson Bros and Tony Reilly at M & RG Levin (Tern Farm). The patience of farm staff subjected to various demands on their skills by the authors is also appreciated. The feedback from commercial managers, growers,

agronomists and machinery operators on the relative practical merits and failures of the experimental treatments was highly valued and will be used to guide the recommendations from this project.