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Harper Adams University

The effect of low ground pressure and controlled traffic farming systems on soil properties and crop development for three tillage systems

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Declaration

I declare that this thesis was written by myself, that the work contained is my own unless explicitly stated otherwise and that this work has not previously been submitted for a degree or any other qualification at Harper Adams University or any other institution.

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“Expect anything worthwhile to take a really long time.” - Debbie Millman

Publications

Millington, W.A., Misiewicz, P.A., Dickin, E.T, White, D.R, and Godwin, R.J. 2016. An investigation into the effect of soil compaction and tillage on plant growth and yield of winter barley (Hordeum vulgare L.). *ASABE Annual International Meeting, Orlando, Florida, USA, 17-20 July, 2016*, p. 162461725.

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List of abbreviations

%CV	coefficient of variation
ANOVA	analysis of variance
CTF	controlled traffic farming
CTF ut	controlled traffic farming untrafficked
CTF w	controlled traffic farming wheeled
g	gram(s)
GS	growth stage
ha	hectare(s)
IF	improved flex
K	Kelvin
LGP	random traffic farming low tyre inflation pressure
LSD	least significant difference
LTP1p	random traffic farming low tyre inflation pressure wheeled 1 pass
LTP2p	random traffic farming low tyre inflation pressure wheeled 2 passes
LTP3p	random traffic farming low tyre inflation pressure wheeled 3 passes
LTPut	random traffic farming low tyre inflation pressure untrafficked
LTPw	random traffic farming low tyre inflation pressure wheeled
m	metre(s)
mc	moisture content
Mg	megagram (syn. metric tonne)
mm	millimetre(s)
MPa	megapascal
N m	newton metre(s)
NDVI	normalized difference vegetation index
NLWR	non-limiting water range
OSR	oil seed rape
PAR	photosynthetically active radiation
PVC	polyvinyl chloride
R^2	coefficient of determination
REML	residual maximum likelihood
RTK	real time kinematic
SEM	standard error of the mean
SOM	soil organic matter
STP	random traffic farming standard tyre inflation pressure
STP 1p	random traffic farming standard tyre inflation pressure wheeled 1 pass
STP 2p	random traffic farming standard tyre inflation pressure wheeled 2 passes
STP 3p	random traffic farming standard tyre inflation pressure wheeled 3 passes
STP ut	random traffic farming standard tyre inflation pressure untrafficked
STP w	random traffic farming standard tyre inflation pressure wheeled
t	metric tonne(s)
TGW	thousand grain weight
ut	untrafficked
w	wheeled
wt	weight
X-ray CT	X-ray Computed Tomography

Abstract

Soil management is an integral part of agricultural systems, yet soil degradation from processes such as erosion, loss of organic matter and compaction, as a result of agriculture, is a worldwide environmental problem that threatens future crop yields. Modern crop production systems require increasingly more powerful and heavier machinery and consequential soil compaction is now a major problem, responsible for soil degradation of an area of 33 million ha in Europe.

This research examined the effect of differing soil management strategies (three traffic systems: Random Traffic Farming with standard tyre inflation pressure, Random Traffic Farming with low tyre inflation pressure and Controlled Traffic Farming on a sandy loam soil cultivated with three tillage systems: deep (250 mm), shallow (100 mm) and no-till), on crop growth and yield and the corresponding effect on soil physical properties using the innovative technique of X-ray Computed Tomography.

There was no significant difference in crop yield between deep and shallow tillage but deep tillage significantly (P=0.030) reduced the soil shear strength, leaving soils prone to compaction by subsequent field traffic. Using shallow rather than deep tillage provides an opportunity to reduce fuel costs associated with the reduction in draft force required for the tillage operations. Zero tillage significantly (P<0.001) reduced crop yields compared to shallow tillage by up to 15%.

As part of this study a novel technique was developed, for determining the total porosity that allowed a comparison of soil porosities derived from bulk density measurements and X-ray CT measured porosities and found that a constant of 31% could be added to the X-ray CT porosities to give the total physical soil porosity.

Chapter 1 Introduction

Since World War II, the Green Revolution has increased world food production through advances in agricultural technology and crop breeding providing food security for developed countries and reducing food shortages in developing areas of the world (Piesse and Thirtle, 2010). During this time the world population doubled whilst world cereal production tripled (Pingali, 2012). The increased crop yields increased supply, which resulted in relatively low food prices (Godfray, 2014) but the high yields of the new cereal varieties required high external inputs which increased water use, degraded soil and led to runoff of chemicals causing environmental damage (Pingali, 2012). Excess food production and the diversion of research funding to public issues over food security and agricultural environmental damage led to reduced investment in agricultural production research (Godfray, 2014; Piesse and Thirtle, 2010). Correspondingly crop yield growth in the last 20 years has stagnated (Godfray, 2014) although Pingali (2012) attributes some of this decline in yield growth rate to soil degradation.

Input costs for agriculture are directly linked to the price of oil because of the fuel needed for mechanised field operations, to power crop irrigation pumps, crop drying, transport and most importantly for the production of chemicals and fertilisers (Piesse and Thirtle, 2009; Triplett and Dick, 2008). UK wheat farmers use an output/fertiliser price ratio to determine inputs. Due to high fertiliser prices this leads to decreased application rate and consequently to likely reduced yields (Piesse and Thirtle, 2009). Nitrogen applications have changed little since the 1980's despite the requirement for modern cultivars needing an extra 20 kg N ha^{-1} per tonne of yield improvement depressing their optimum yield by 0.12 t ha^{-1} (Knight *et al.*, 2012).

Piesse and Thirtle (2010) thought the sudden food commodity price rises in 2007/2008 to be a wakeup call after 20 years of neglect in agricultural research. The increase in price volatility can be attributed to increased demand for food, climate change, the price of oil and the rise in demand for bio-fuel (Chen *et al.,* 2010). Besides competition from rising demand for bio-fuel consumption, crop production is under pressure from an increasing world population and a rapidly changing dietary requirement from growing affluence in developing nations (Ray *et al.,* 2013) especially in Southeast Asia (Godfray, 2014). It is estimated that the current world population is set to increase from a current 7 billion to between 8 and 10 billion by 2050 with most of the increase being in developing countries especially those in Western Asia and Africa where human fertility rates are still high (Lutz and Samir, 2010).

To feed this larger and more affluent population it is expected that agricultural production needs to double by 2050 (2.4% increase per year) but global yields in the four main crops (rice, wheat, maize and soybean) are currently only increasing between 0.9 and 1.6% per year with wheat yields in most of Europe growing at lower than 1% per year (Ray *et al.*, 2013). Mean wheat yields in the UK increased from 2.7 t ha^{-1} in the mid-1940s to 7.6 t ha^{-1} in the mid-1990s (Figure 1.1) equivalent to 0.1 t ha^{-1} increase per year (Knight *et al.*, 2012). Since 1996 the mean UK wheat yields have remained at 7.8 t ha^{-1} (DEFRA, 2017). It is suggested that this yield plateau is because wheat has reached its biophysical yield limit in the Northwest of Europe (Grassini *et al.,* 2013) but Cassman *et al.* (2003) state that yield growth effectively stops at 80% of yield potential as it requires whole system micro-management (i.e. soil, water, nutrients, crop and pest management) to make advances which may not be economic. If this yield growth system was micro-managed globally (mainly by improvements in water and nutrient supply) to raise yields to within 95% of yield potential for 16 major crops (i.e. barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower and wheat), then global food and feed crop production could be increased by 58% (Foley *et al.,* 2011).

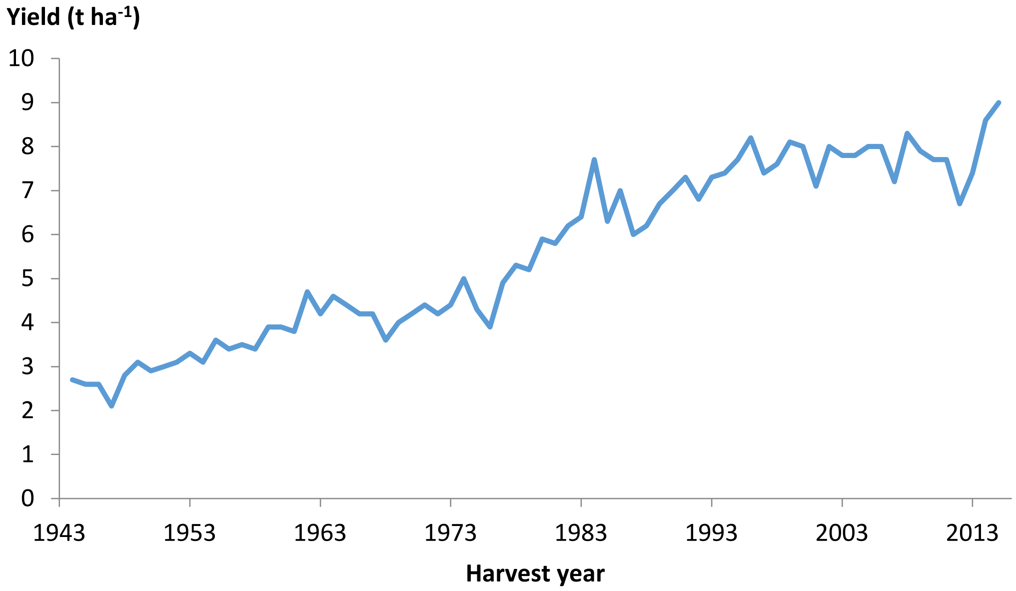

Figure 1.1 - UK mean wheat yields from 1945 to 2015

(Source adapted from: DEFRA, 2017)

The development of agricultural systems to feed a growing population have impacted on the environment by expansion into natural habitats, clearing large areas of grassland, savanna, temperate forests and biodiversity rich tropical forests. Over the last 50 years agricultural intensification has increased the use of artificial fertilisers by 500% and 70% of current global freshwater consumption is used for irrigation (Foley *et al.*, 2011; WWAP, 2018). This intensification has increased the amount of mechanisation for tillage, planting and harvesting and relies on the extensive use of fossil fuel (Haygarth and Ritz, 2009). Agriculture is responsible for 30-35% of greenhouse gas emissions as well as causing widespread pollution and degradation of water (Foley *et al.,* 2011).

Further expansion of agricultural systems to meet future demand for food would come at a high environmental cost from increasing carbon emissions and further reducing biodiversity. There are opportunities to increase yields through more efficient use of cultivated land and the dissemination of best practice (Ray *et al.,* 2013). Any intensification of production needs to be sustainable, conserving the environment by protecting natural capital and ecosystem services whilst becoming more efficient with the use of technology and agricultural inputs (Lampkin *et al.*, 2015).

Soils are the natural capital of agriculture providing crop yields as well as functions that combat pests, control greenhouse gases and retain nutrients. The European arable farming practice of short rotations, high fertiliser and herbicide use and reduced input of manure and straw inclusions has led to soil degradation through compaction, salinisation, erosion and reduction in soil organic matter (SOM) (Hedlund, 2012). Anthropogenic soil degradation is not a modern problem. Since the invention of the 'ard', a wooden plough derived from a digging stick, allowed conversion of natural ecosystems over to agricultural use 10,000 to 12,000 years ago (Lal, 2007a) humans have been depleting the productivity of their soils through poor soil management leading to erosion and reduced soil fertility. These losses were often slow enough not to be noticed over one lifetime but added up over the centuries and the resultant ever declining yields contributed to the downfall of ancient civilisations including Greece and Rome (Montgomery, 2012).

To make modern crop production systems highly productive and to lower costs, agricultural machinery has become more powerful and has correspondingly become heavier (Tullberg *et al.*, 2007). Consequential soil compaction from heavy machinery is now a major problem in agriculture and responsible for soil degradation of an area of 33 million ha in Europe (Kroulik *et al.*, 2009). Increased loads applied to soil increases subsoil compaction, which is difficult to remove (Kroulik *et al.*, 2009). Tillage to remove traffic induced soil compaction is seen by many to be more of a problem than soil compaction as it results in soil structure degradation and erosion. Reduced tillage (non-inversion tillage), an alternative to conventional mouldboard ploughing (Warner *et al.,* 2016) (made possible as the use of broad-spectrum herbicides has removed the need to bury weeds (Triplett and Dick, 2008)), is considered to be a solution for tillage induced soil degradation (Tullberg *et al.*, 2007). Chamen *et al.* (2015) identified the use of low ground pressure tyres and the adoption of controlled traffic farming as methods to avoid soil compaction. Lower stresses in the soil under low ground pressure systems limit bulk density increases due to a more even distribution of vehicle loads over a larger tyre/soil footprint (Vermeulen and Perdock, 1994). In controlled traffic systems agricultural vehicles are confined to permanent traffic lanes on the field by matching of vehicle wheel spacings leaving cropping areas free of any vehicular compaction (Raper, 2005; Gasso *et al.*, 2013). Low ground pressure and controlled traffic systems have evolved to maintain soil structure and thereby reduce agricultural energy inputs whilst promoting high crop yields.

In an effort to reduce soil erosion and improve soil water retention, conservation tillage combined with retaining year round crop cover (known as conservation agriculture) has developed (Boone, 1988) with the aim of minimising soil disturbance by reduced tillage using non-inversion tines opposed to ploughing but preferably by direct drill (no-till). Retaining surface crop residues promote biological processes in the soil which protect the soil and retain moisture leading to sustainable yields (Jones *et al.*, 2006). In the UK reduced tillage is used for more than 40% of arable land but only 5% of arable land is no-till (Godwin, 2014) compared to over 20% of agricultural land in the USA (Hallett and Bengough, 2013). Despite the benefits of non-inversion tillage many farmers are reluctant to drop a plough based system due to fears of reduced yields, reluctance to adopt new technology or peer pressure that reduced tillage fields appear to be badly managed due to retention of surface crop residues (Jones *et al.*, 2006; Townsend *et al.*, 2016). Plough based systems are still needed in the production of root crops and the adoption of direct drilling is dependent on suitable soils and effective drills (Tivy, 1990).

Varying amounts of traffic and tillage can produce a range of soil conditions that affect the growth of a crop and ultimately its yield. Figure 1.2 shows the effects of traffic and tillage on crop growth. If soil composition (i.e. the spatial distribution of mineral, organic and chemical components within the soil) remains largely unchanged, weeds are controlled and field operations carried out correctly, then soil structure is the major factor that affects yield (Boone, 1988).

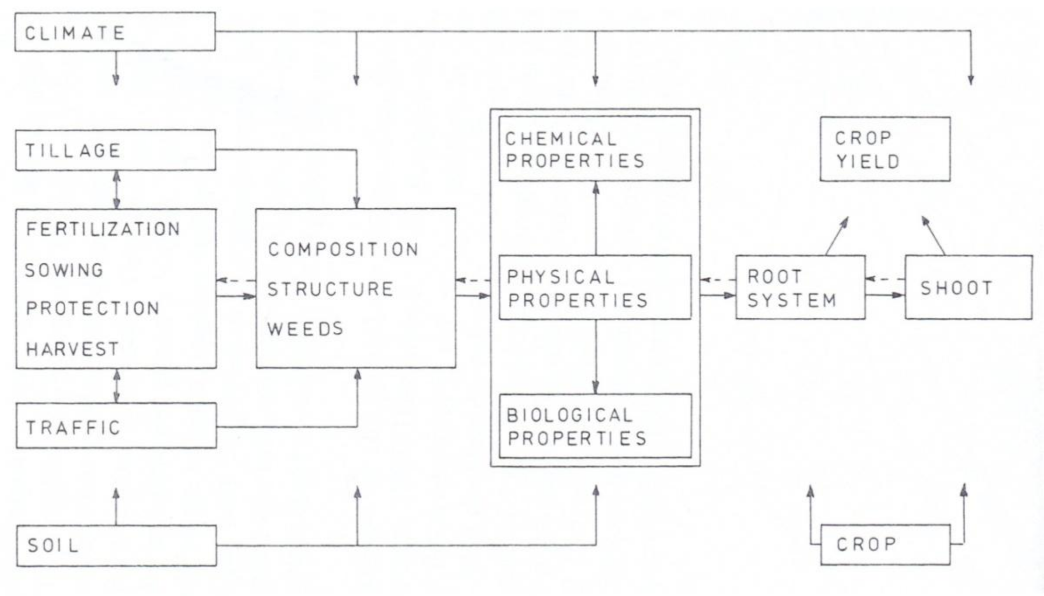

Figure 1.2 - Factors influencing traffic and tillage induced crop responses

(Source adapted from: Boone, 1988)

Tillage is an integral part of a cropping system which also includes the crop (and crop rotation), sowing and harvest as well as fertiliser and crop protection inputs. It is also necessary to counteract the effect from vehicular traffic associated with the necessary field operations (Boone, 1988).Tillage is required to produce a good soil structure that best promotes plant establishment and root development. Soil structure is dependent on the size, shape and arrangement of aggregated particles (peds) and is influenced by soil texture, SOM and soil physical processes. Agricultural soil management aims to produce a 'crumb' which has small porous and water stable peds but it is the resultant size and continuity of the soil pore air space between them that is the best measure of soil structure (Tivy, 1990).

The heterogeneous nature of soil makes assessment of structure difficult (Munkholm *et al.*, 2013). Porosity in the soil consists of a variety of pore shapes and sizes which have different effects on the movement and storage of water, aeration and resistance to root growth (Kay and VandenBygaart, 2002). Determination of dry bulk density is a widely accepted means of identifying changes in soil compaction and total soil porosity in response to vehicular traffic and mechanical breaking from tillage operations (Campbell, 1994) but it does not allow the quantification of pore sizes and distribution within the soil. X-ray Computed Tomography (CT) is a non destructive 3D imaging technique that can effectively be used to measure soil pore size and distribution (Rab *et al.*, 2014). It uses mathematical reconstructions from attenuation of radiation to produce stacked 2D images to produce 3D models of the soil sample (Vaz *et al.*, 2011) allowing visualisation of changes in pore system structure through the soil profile. Although Garbout *et al.* (2013)

and Beraldo *et al.* (2014) have used X-ray CT to quantify the effect that different soil tillage techniques have on soil structural quality, the use of X-ray CT has not previously been used to measure the properties of soil from a long-term traffic and tillage trial.

1.1 This research

The research presented in this thesis is part of a longer term (10 year) programme and follows on from previous research based on the long term trial on the Large Marsh field at Harper Adams University, UK (52° 46' 56.316'' N, 2° 25' 45.1704'' W). The trial was set up to investigate the effect of three traffic systems (Random Traffic Farming - standard tyre inflation pressure (STP), Random Traffic Farming - low tyre inflation pressure (LTP) and Controlled Traffic Farming (CTF)) and three tillage systems (deep (250mm), shallow (100mm) and no till) on soil properties, crop yield and energy requirements (Smith *et al.*, 2014).

Earlier work indicated benefits to plot crop yields from Controlled Traffic Farming with increased yields (no significant difference) in winter wheat (Trticum aestivum) and winter barley (Hordeum vulgare) of 1.5 t ha^{-1} and 1 t ha^{-1} respectively compared to Random Traffic (standard tyre inflation pressure) Farming. Random Traffic Farming - low tyre inflation pressure plots gave 4% more winter wheat yield (no significant difference) than from standard tyre inflation pressure plots. These increased flexion tyres produced 52% lower soil pressure at 300 mm depth but the stresses where 38% higher at 150 mm depth than standard tyres. Other benefits were reduced soil compaction and improved infiltration (Smith, E., 2016). The reduction in tillage intensity reduced required draft power and fuel consumption (Arslan *et al.*, 2014).

This research advances the work done by Smith, E. (2016) by extending the cereal crop rotation by a further three years (five years total) by the using spring crops. It investigates whether the repeated application of the traffic and tillage treatments has a differing effect from those previously identified over two cropping seasons. Smith, E. (2016) used indirect methods to determine soil properties such as bulk density and water infiltration. This research uses the novel X-ray CT technique to directly assess the effect of the traffic and tillage treatments on soil porosity, pore size distribution and pore connectivity which are important parameters of soil structure that affect soil water movement, plant nutrient availability and soil aeration important for crop growth and yield.

Field traffic and tillage can change the physical, chemical and biological properties of soil (Figure 1.2) with the potential to limit crop growth. However, soil structure is considered the main factor affecting yield due to its influence on soil heat, water, aeration properties as well as its mechanical resistance (Boone, 1988). The time constraints for this research limited the measurement of soil properties to the physical properties that relate to soil structure.

1.1.1 Research central hypothesis

The hypothesis for this research was that field traffic and tillage change the structure of soil which can be measured by changes in soil bulk density and penetration resistance, soil porosity and soil pore connectivity and that changes to soil structure affects crop growth and yield measureable by crop establishment, crop growth and harvestable yield. By reducing soil traffic and tillage intensity by using Controlled Traffic Farming (CTF), low inflation pressure (LTP) and reduced tillage systems soil bulk density and penetration resistance are decreased and soil porosity, soil pore connectivity and crop yields are increased.

1.1.2 Research aim

Ingram (2008) found that whilst many farmers had an intimate knowledge of their soils they lacked knowledge of good soil management especially regarding cultivation and needed to learn the consequences of poor management decisions and how to examine and interpret soil condition. In order for farmers to make considered decisions about strategic tillage to overcome problems with their soils they need to have the required knowledge (Giller *et al*, 2015) and this research was intended to contribute to that knowledge.

The aim of this research was to determine the effect of differing soil management strategies on a sandy loam soil (three traffic systems: Random Traffic Farming with standard tyre inflation pressure, Random Traffic Farming with low tyre inflation pressure and Controlled Traffic Farming for soils cultivated with three tillage systems: deep (250 mm), shallow (100 mm) and zero (no-till)) on crop growth and yield and the corresponding effect on soil physical properties using the innovative technique of X-ray Computed Tomography.

1.1.3 Research main objectives

1. To determine the benefits of low tyre inflation pressure (LTP) and controlled traffic farming (CTF) systems upon soil structure and crop yields for an arable rotation for three tillage systems (deep, shallow and no-till).

2. To determine the benefits of reduced tillage upon soil structure and crop yields for an arable rotation for three traffic systems (Random Traffic Farming with standard tyre inflation pressure, Random Traffic Farming with low tyre inflation pressure and Controlled Traffic Farming).

3. To determine the effects of the contrasting traffic and tillage management systems upon soil structure using X-ray Computed Tomography correlating this to measured soil and crop parameters.

1.2 Thesis outline

The timeline for the Harper Adams University Traffic and Tillage trial is shown in Table 1.1. The research presented in this thesis relates to the three years work carried out during the period January 2015 to December 2017 but reference is made to results from years 2012 to 2014 and is cited accordingly.

Table 1.1 - Timeline for the Traffic and Tillage trial, Harper Adams University, UK

	Previous research			**This research**		
Season	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17
Trial Year	Establishment	1	2	3	4	5
Crop	Winter wheat	Winter wheat	Winter barley	Winter barley	Winter cover crop/ Spring oats	Spring wheat

The thesis is divided into nine chapters as shown in the schematic diagram at Figure 1.3. A structured literature review (Chapter 2) follows on from this introductory chapter. The general methodology section (Chapter 3) details the methodology for the Large Marsh field trial at Harper Adams University, UK over the three years of research. The results and specific methodologies for the research undertaken during the three year research period are split as follows: Chapter 4 - Soil physical properties: In-field measurements, Chapter 5 - Soil physical properties: X- ray Computed Tomography and Chapter 6 - Crop growth and yield experiments. The Discussion (Chapter 7) and Conclusion (Chapter 8) relate to the main findings from the research and the thesis is concluded with Recommendations for future work in Chapter 9.

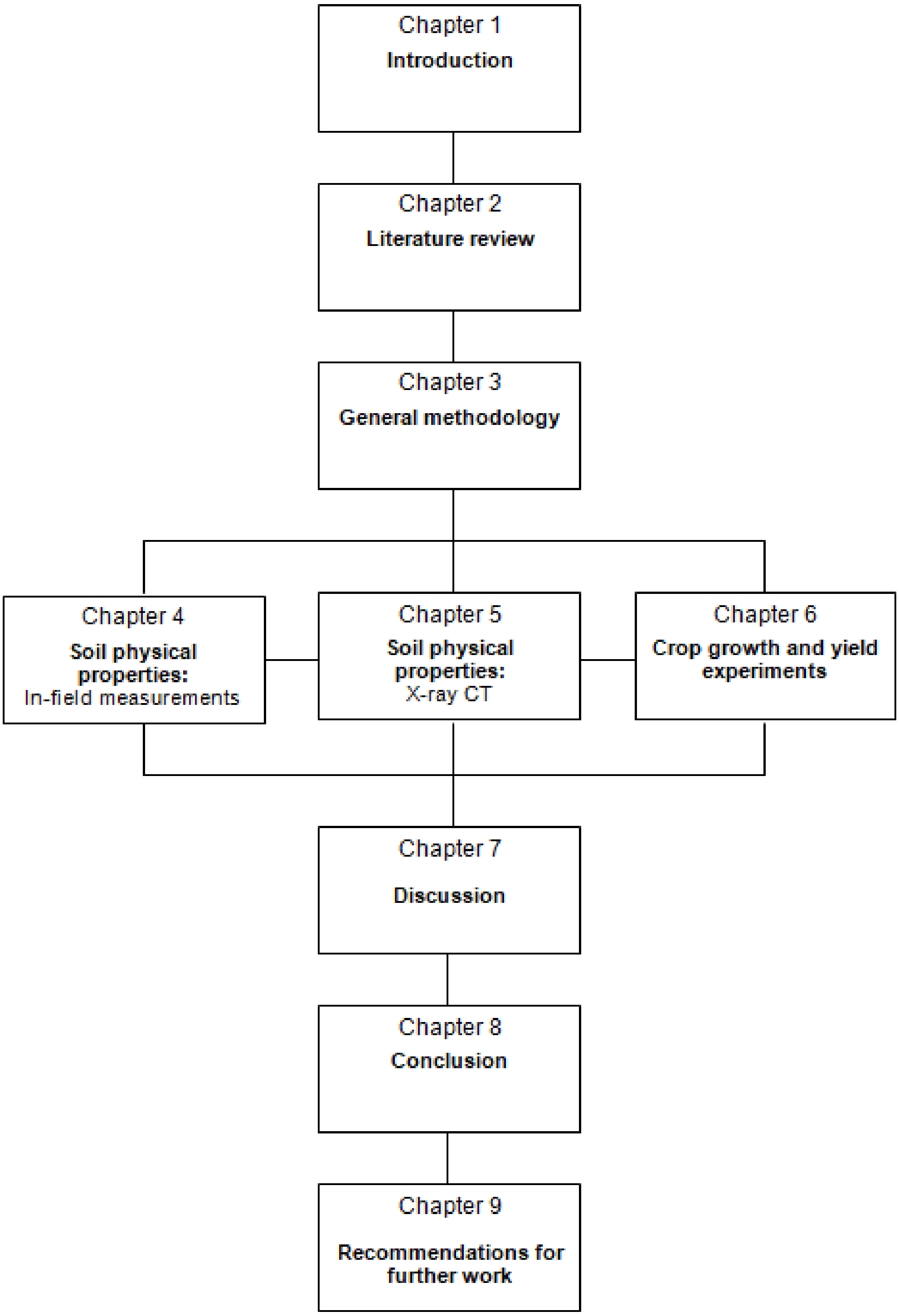

Figure 1.3 - Schematic diagram of the structure of the thesis

Chapter 2 Literature review

2.1 Soil quality and soil structure

Soil management is an integral part of agricultural systems yet soil degradation from processes such as erosion, loss of organic matter and compaction as a result of agriculture is a worldwide environmental problem that threatens current and future crop yields (Pagliai *et al.*, 2004; Kibblewhite *et al.*, 2008). According to Arshad and Coen (1992) exploitation of natural resources causes soil degradation but a focus on the environment is likely to increase soil quality. Although soils have a fundamental quality due to their physical, biological and chemical properties it is how the soil is managed that ultimately affects soil quality (Doran, 2002). Changes in soil quality over time can be used as an indicator of sustainable soil management (Doran, 2002) and determine the capacity of the soil to sustain productivity whilst maintaining air and water quality and support animal and plant health (Herrick, 2000). These soil functions are intrinsically linked to the structure of the soil and therefore soil degradation (in the form of erosion, compaction and desertification) is due to decline of the soil structure (Pagliai *et al.*, 2004; Lal, 1997).

Soil structure is the *'mutual arrangement, orientation and organisation*' of soil particles but can be described by pore size distribution, the permeability of the soil to air and water or mechanical soil properties (Hillel, 1971). From an agricultural perspective the best soil structure is the structure that has optimal soil porosity, aggregation and water and air permeability to give crop roots the most favourable conditions to produce the highest crop yield (Kohnke, 1979). Unlike soil texture, which is stable over time, soil structure can change quickly in response to natural conditions, soil management and biological activity (Hillel, 1971). Soil pore arrangement, size and distribution affects the storage and movement of gases and water within the soil that are important in the development and growth of plants (Pagliai and Vignozzi, 2002). As most changes in soil structure involve changes in soil porosity it is probably the best indicator of soil structure quality. Changes to pore size, shape, orientation and connectivity can be used to describe the effect on soil porosity by different management practices (Pagliai and Vignozzi, 2002). Analysis of soil pore size distribution is useful for determining water infiltration rates, soil water storage capacity and available water and aeration for plant use (Cary and Hayden, 1973).

The system of pores within the soil is essential for the transport of air and water (Eden *et al.*, 2011) and nutrients necessary for the growing plant. Porosity in the soil consists of a variety of pore shapes and sizes which have different effects on the movement and storage of water, aeration and resistance to root growth. Macro pores (>30 µm diameter) allow water infiltration and drainage and have the most influence on soil aeration (Kay and VandenBygaart, 2002). Macro pores are relatively resistant to vertical compression making their structure an effective measure of soil quality (Lipiec *et al.*, 2006 and Kay and VandenBygaart, 2002). Pores between 30 µm and 0.2 µm diameter (meso pores) are important for storage of water that is available to the plant. Pores below 0.2 µm diameter store water that is not available to the plant and they do not support microbiological activity (Kay and VandenBygaart, 2002). For good plant growth soil needs sufficient large pores to allow drainage of rain (or irrigation) water and support initial root growth and also enough pores of a size small enough to prevent gravitational emptying whilst still large enough to release water to the plant root system (Cary and Hayden, 1973).

2.2 Soil compaction

When a stress is applied to soil in excess of the soil strength soil compaction occurs (Lipiec *et al.*, 2003a). Soil compaction mainly affects larger soil pores reducing soil porosity for a given mass (Berisso *et al.*, 2012), increasing bulk density and reducing the proportion of large to small pores (Kim *et al.*, 2010) and can have an effect throughout the whole soil profile (Troldborg *et al.*, 2013). Figure 2.4 shows the effects of soil stress on soil properties and processes. The reduction in macro porosity from soil compaction can be sufficient to restrict root survival (Rab *et al.*, 2014) leading to the reduction in crop yield (Czyz, 2004).

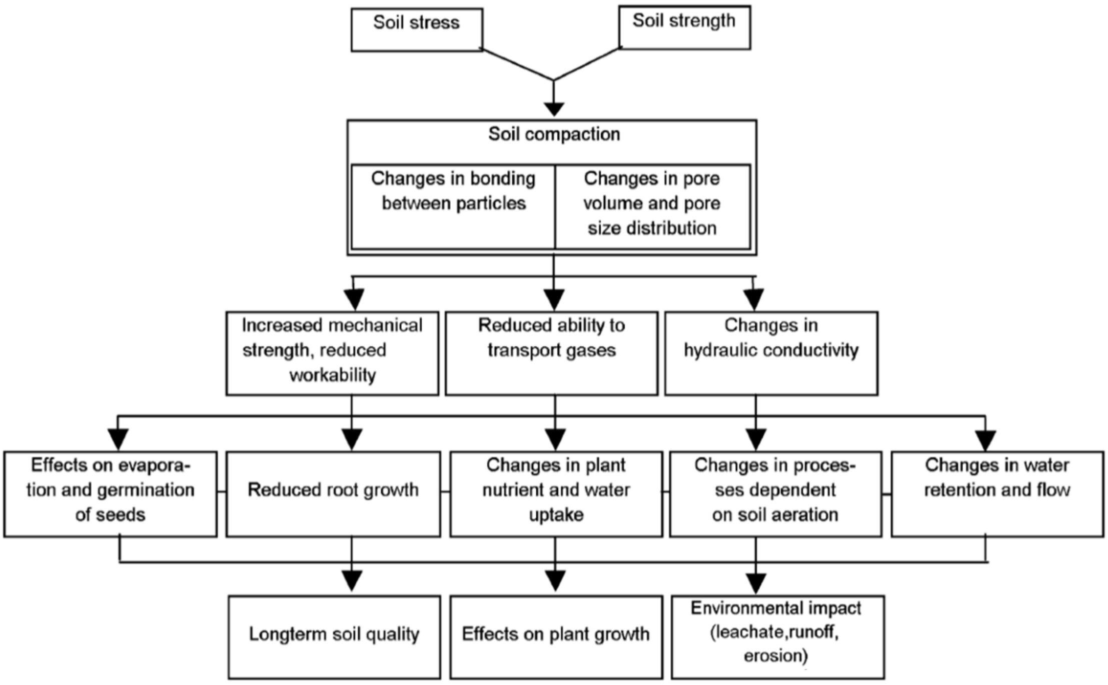

Figure 2.1 - The effect of soil stress on soil properties and processes

(Source adapted from: Lipiec *et al.*, 2003a)

From a crop production perspective soil compaction only becomes a problem when it makes changes in soil properties that affect profitability. These changes can be split into those that directly affect root growth or indirectly affect crop growth and activity by changing the balances between soil aeration, moisture and temperature (Saini, 1980). Soil compaction from vehicular traffic reduces the ability of rainfall to infiltrate soil (Tullberg *et al.*, 2007). Kaspar *et al.* (2001) found that vehicular traffic reduced soil infiltration rates by between 38-54% compared to untrafficked soil in a three year study on a sloping field in Iowa, USA. Reduced soil infiltration can increase waterlogging and produce greater surface runoff, leading to soil loss (Tullberg *et al.*, 2007) and pollution of waterways by lost nutrients and pesticides (Keller *et al.*, 2013).

Compaction by agricultural machinery changes soil pore structure, affecting thermal conductivity (Lipiec *et al.*, 2003b) and increases soil bulk density and strength, alters soil pore size distribution and reduces soil aeration. These decrease root and shoot growth leading to reduced nutrient use efficiency (Fageria, 1992) that affects crop root growth and function and reduces yields (Lipiec *et al.*, 2003b). Soil compaction can result in reduced root penetration in the soil, reducing the number and length of roots, a decrease in leaf thickness and an increase in the dry mass shoot:root ratio and a reduction in crop yield (Grzesiak *et al.*, 2013). Soil compaction can have a positive or negative effect upon crop yields depending upon precipitation. In dry years, yields in moderately compacted areas can be greater than in non-compacted areas but reduced in wetter years (Raper, 2005).

Plant available water can be defined as the difference in soil water between field capacity and permanent wilting point (Kirkham, 2005) or the water retained in the soil between the suctions of 0.05 and 15 bar (Hall *et al.*, 1977). For many crops, yields are reduced before the soil water content reaches permanent wilting point due to the energy required to extract water at high suctions indicating that soil water is not equally available between field capacity and permanent wilting point (Kirkham, 2005). Figure 2.2 shows that as soil bulk density increases, soil available water decreases. This would reduce the ability of the soil to provide sufficient water for plant growth during prolonged dry spells.

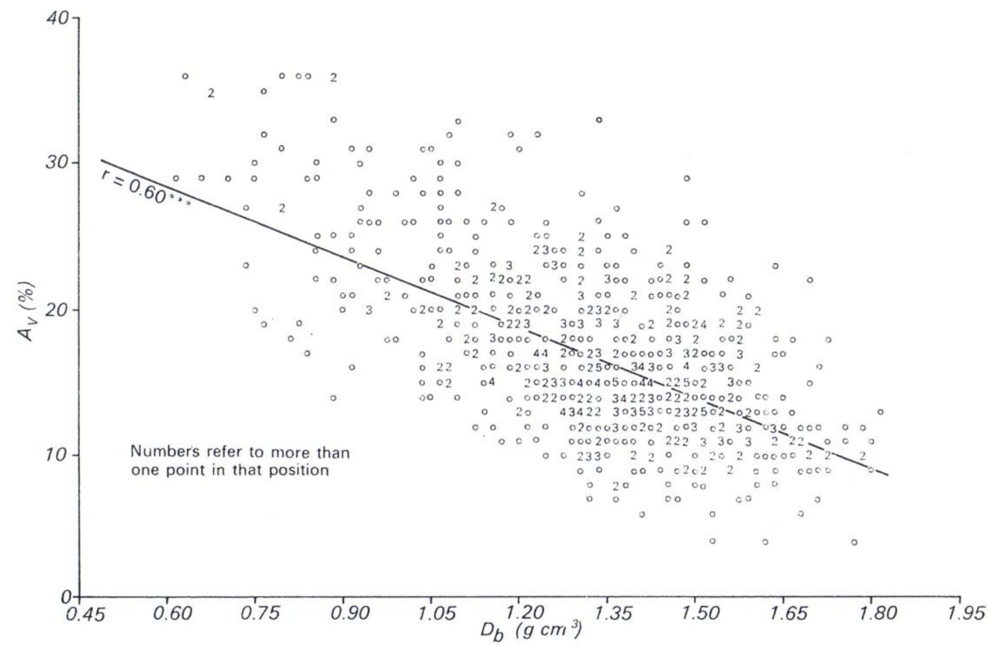

Figure 2.2 - Relationship between soil bulk density and available water

(Source adapted from: Hall *et al.*, 1977)

Compaction reduces soil moisture at low suction due to the reduction in inter-aggregate pore space (Figure 2.3). However this reduction corresponds to an increase in the volume of intermediate sized pores associated with plant available water. The amount of micro pore space is largely unaffected by compaction (Hillel, 2004).

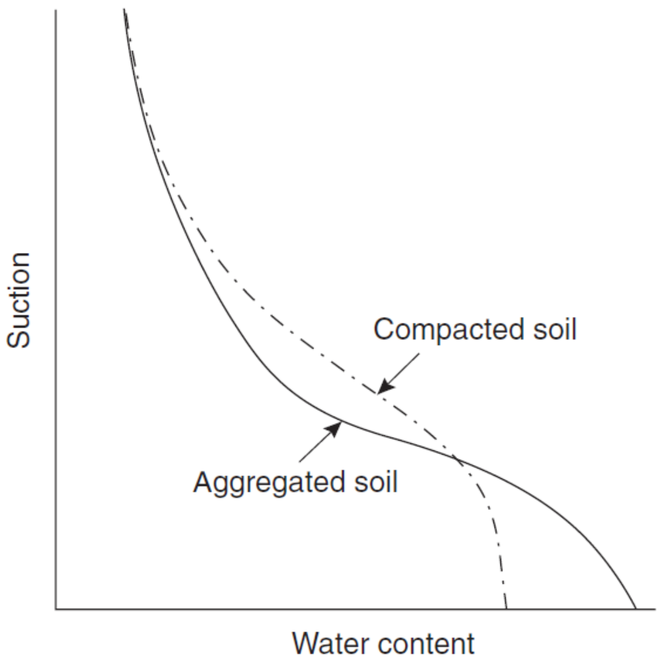

Figure 2.3 - The effect of soil compaction on soil water retention

(Source adapted from: Hillel, 2004)

The non-limiting water range (NLWR) is the soil water content between the limits where soil aeration (upper) and mechanical resistance (lower) restrict plant growth (Figure 2.4). Increasing water content reduces mechanical resistance but also decreases soil aeration. The increase in soil bulk density and associated change in soil pore size distribution due to soil compaction reduces the NLWR because mechanical resistance and restricted oxygen availability restrict root growth (Kirkham, 2005).

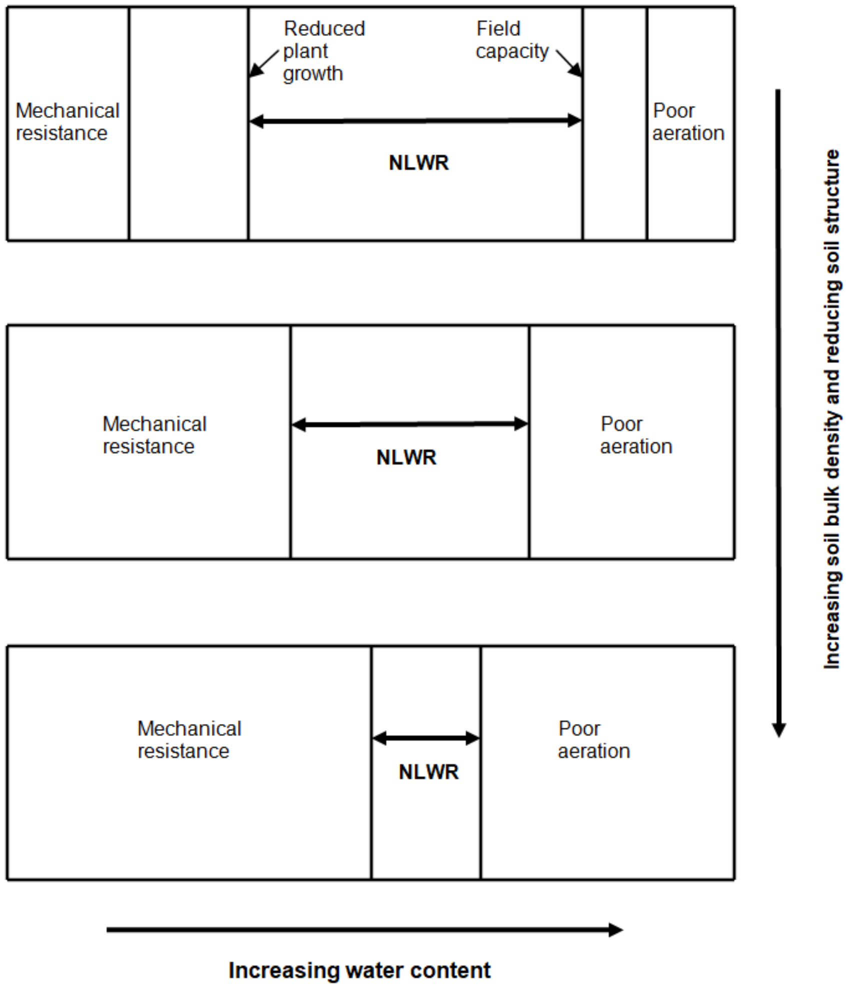

Figure 2.4 - The effect of increasing water content and soil bulk density on the non-limiting water range (NLWR)

(Source adapted from: Kirkham, 2005)

Compaction of the soil at 100-150 mm depth below the seedbed reduces crop growth in wet conditions due to waterlogging (Ball and Ritchie, 1999). Simojoki *et al.* (1991) observed decreased diffusion due to reduced air filled porosity in wet compacted soils leading to low yield from low nitrogen uptake. Wet soils limiting soil aeration leads to reduced root growth and crop yield (Czyz, 2004). Sienkiewicz (1984) cited by Lipiec and Simota (1994) found that sugar beet emergence decreased in wet soils as the seeding depth increased from 20 to 40 mm depth. During dry periods higher yields in compacted soils are due to improved germination and more efficient use of water (Voorhees, 1987) likely due to increased unsaturated hydraulic conductivity and increased soil to root contact (Arvidsson, 1999).

Root systems are often reduced in length due to increased soil bulk density. Cracks and biopores, associated with earthworms, provide opportunities for root elongation leading to '*heterogeneous root distribution*' that are not always a precursor for lower crop yields (Glab and Kopec, 2008). Poor root development due to compacted soil may not reduce yield (Sadras *et al.*, 2005) if the roots are able to access sufficient water and nutrients needed by the plant shoots (Taylor and Brar, 1991). The presence of macro pores in the soil can provide the means by which roots can bypass areas of compaction to access nutrients and water (Lipiec *et al.*, 2006).

Ball *et al.* (1997) cited by Wilson *et al.* (2013) studied the relationship between soil bulk density and spring barley growth under zero tillage. They found that soil porosity was more critical to limiting yields than soil strength. Soil compaction is the reduction in porosity for a given mass but this reduction is mainly from large pores (Berisso *et al.*, 2012). The resultant higher volumes of small macropores are more susceptible to waterlogging and consequential anaerobic conditions that lead to denitrification and reduced root growth (Czyz, 2004). As soil compaction increases, the proportion of water to air in the pores increases (Badalikova, 2010). Repeated wheelings can compact soil to an extent where root air availability limits root development and reduces plant growth and yield (Czyz, 2004). The reduction in oxygen in the soil due to a higher percentage of water filled pores has been seen to restrict the roots ability to overcome soil mechanical impedance (Russell, 1977). A microplot experiment on heavy loamy sand soil in Poland by Czyz *et al.* (2001) found aeration became a limiting factor for barley emergence when the soil was compacted to 1.67 Mg m^{-3}. Optimum soil density for root growth and yield was when soil was slightly compacted to 1.43 Mg m^{-3}. Root growth was found to be limited by both compacted and loose soil and yield was positively correlated to total root mass. Crop responses to traffic and tillage can be divided into pre or post establishment. Root and shoot growth is directly affected pre-establishment and the growth and activity of the root system is mainly the post-establishment response (Boone, 1988). Reduced crop establishment may occur in response to increased weed population and crop residues left on the soil surface as a result of reduced tillage (Vakali *et al.*, 2011; Freer, 2006). Other factors that may affect crop response include changes to soil structure that affect the distribution of chemicals and organic matter within the soil, seed placement and reduced efficiency of applied herbicides (Boone, 1988).

Arvidsson (1999), in a field experiment on silty clay soil in Sweden, found reduced uptake of nutrients in barley in both compacted and loose soils compared to moderately compacted soil, which gave 20% higher yields. This may have been because of reduced root to soil contact in the loose soil and oxygen deficiency immediately following compaction treatments in compacted soil. Soil aeration is particularly reduced by surface soil compaction whilst deeper compaction can cause problems from poor drainage increasing instances of waterlogging (Stepniewski *et al.*, 1994). A soil structure study by Bullock *et al.* (1985) found that the volume of air filled pores in wheeled soil varied throughout the season with greater volumes in the summer, which reduced over winter. They also found that over time the soil porosity at 0-50mm depth is restored but deeper in the profile (especially at 50-100mm) there was still a shortage of air filled pore space. The loosening of a soil by tillage can produce a warmer top layer than in compacted soil leading to better root development early in the growing season (Lipiec *et al.*, 2003b).

2.3 Agricultural traffic and compaction

It has long been known that soil compaction can lead to yield losses and as far back as 1898 Ewald Wollny identified that the relationships between soil structure and plant growth should be investigated to improve soil properties and increase yields. At that time research was focused on increasing crop yields and paid little attention to soil problems (Horn *et al.*, 1995). It is now evident that modern crop production systems are adversely affected by widespread soil compaction (Soane and Van Ouwerkerk, 1995). It was estimated in 1991 that 68 million ha of worldwide agricultural land was damaged by soil compaction of which 33 million ha (~ 50%) was in Europe (Gasso *et al.*, 2014; Kroulik *et al.*, 2009). In Australia around 30% (4 million ha) of the 'wheat belt' is degraded by compaction (Hamza and Anderson, 2005) and soil damage in the Murray-Darling basin was estimated (in 1991) to cost agriculture A$144 million (Tullberg *et al.*, 2007). Farmers are governed by world market prices and ever reducing subsidies which requires them to make increasing efficiencies by growing in size or using more efficient machinery to stay in business (Ansorge and Godwin, 2007). This has led to the increase in size and weight of agricultural machinery used in the field with a consequential increased risk of traffic induced soil compaction (Raper, 2005; Gasso *et al.*, 2014; Spoor, *et al.*, 2003).

The degree of compaction of a soil due to the stresses applied by a vehicle tyre is governed by the soils strength which is related to mechanical strength (determined by soil texture and soil organic matter content), tillage layer and moisture content (Hamza and Anderson, 2005). Wet soils are less able to resist vehicular compaction (Chamen *et al.,* 2015) as found by Voorhees *et al.* (1986) or as expressed by Harris (1971), for a given load an increase in soil moisture leads to greater soil compaction. As a soil gets wetter the inter-particle friction decreases which leads to greater soil deformation under loading (Peth *et al.,* 2010). Stresses in the soil under a load become more concentrated downwards as the soil becomes wetter and therefore they penetrate deeper into the soil profile (Håkansson and Petelkau, 1994). Wet soils deform plastically and the load stresses become concentrated towards the axis of the load (Söhne,1958). This can be seen in Figure 2.5. The pressure curves under the tyre in a dry soil are more circular. For the wet soil, as the stresses are more concentrated about the load axis, the pressure curve becomes elongated and the stresses propagate deeper into the soil profile.

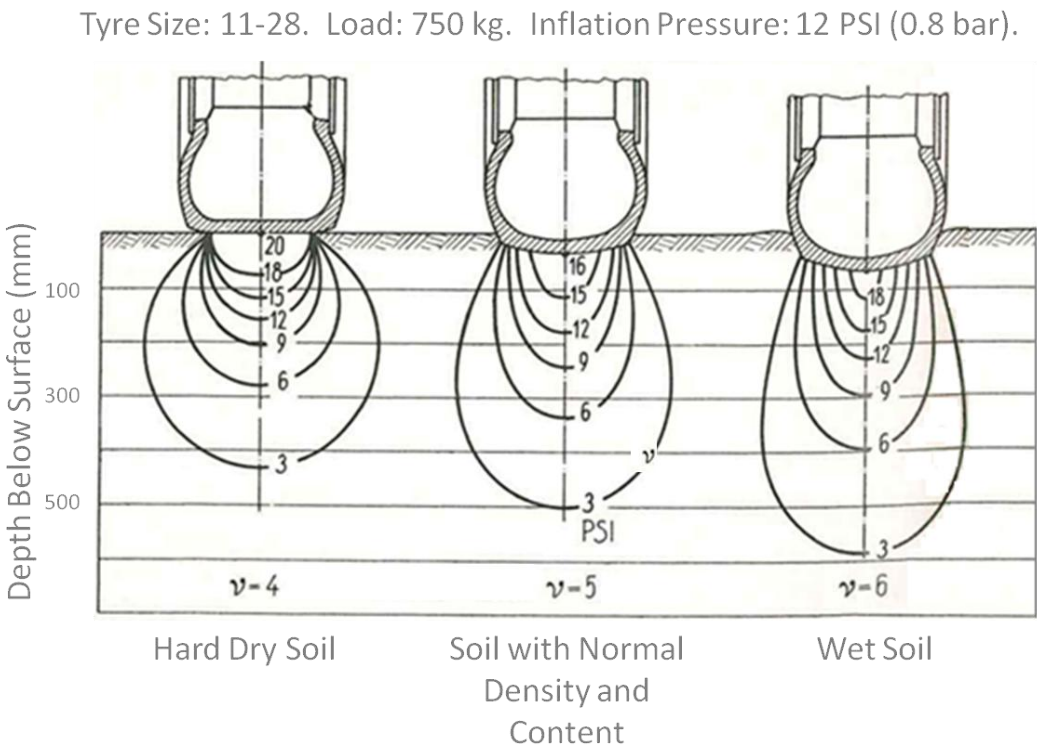

Figure 2.5 - Pressure curves under a tractor tyre for different soil moisture content where v = Froehlich concentration factor

(Source adapted from: Söhne,1958)

Larson and Gupta (1980) showed in laboratory tests that soil aggregates do not shear under increasing load until the minimum pore water pressure is reached. This critical stress was found to decrease with increasing soil moisture. Gelder *et al.* (2007) observed that compaction treatments (300 kPa applied stress) in a field experiment in Iowa, when applied to soils drier than 25% gravimetric water content, did not reach the critical stress for the soil, resulting in no significant compaction or subsequent difference in crop growth.

The soil water potential is dependent upon previous soil moisture history (Taylor and Ashcroft, 1972). A drying soil (desorption) will be wetter than the wetting soil (sorption) at the same suction and this is known as hysteresis (Hillel, 1971). This is because soil pores need more suction for water to empty (due to surface tension) than is needed to fill and is known as the 'ink bottle' effect (Ward and Robinson, 2000). When a pore is emptying, the suction required relates to the size of the narrowest part (neck) of the pore but when filling, the suction required is reduced to a value that corresponds to the widest part of the pore. Therefore at a given suction a drying soil contains more water than a wetting soil (Marshall, 1959; Wild, 1988). This difference in soil moisture can be up to 15% dependent upon soil type as calculated by Witkowska-Walczak (2006). The hysteresis in the moisture characteristic curves is shown at Figure 2.6.

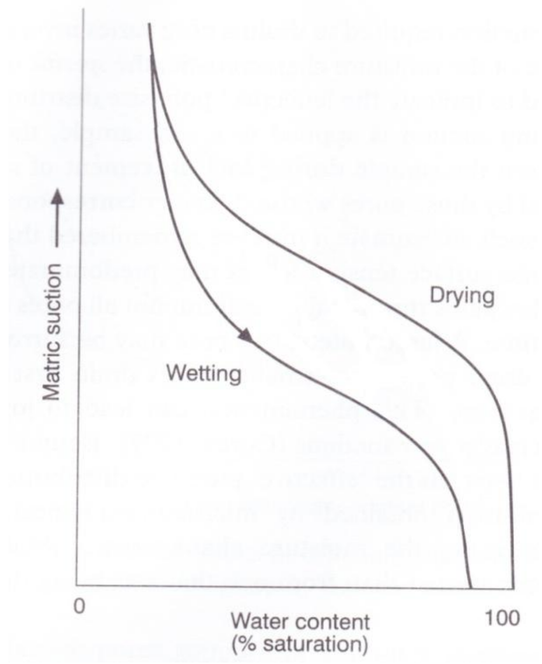

Figure 2.6 - Hysteresis in the moisture characteristic showing the wetting and drying curves

(Source adapted from: Ward and Robinson, 2000)

This hysteresis is associated with the capillary fringe above the water table as shown in Figure 2.7. The capillary fringe will be thicker in a drying soil than in a wetting soil (Taylor and Ashcroft, 1972). The intensity of hysteresis can be reduced (drying and wetting curves are closer together) by soil compaction as the increase in soil bulk density produces a more uniform distribution of small soil pores (Kaboosi, 2014). Although hysteresis is not that important when measuring effects on soils such as infiltration (wetting) or evaporation (drying) it can be important when measuring the effect of processes that occur when water is under redistribution (when soils are drying and wetting at the same time). It is possible to have soil layers that are at the same equilibrium but will have different moisture content due to having different moisture histories (Hillel, 1971). Rajaram and Erbach (1997) found that soil shear strength was higher in soil that was wetting compared to a drying soil and tillage of soils that were drying fractured into large and less stable aggregates. This suggests that when considering tillage operations as well as soil water content, soil wetting or drying needs to be taken into account. The height at which water rises in soil due to capillary action is usually between 0.6 and 1.8 metres and is dependent on the space between soil particles. The water rises towards the surface where it is lost by evaporation. Compaction of soil near the surface increases the rate at which soil water is lost. Tillage can be used to break the capillary system in compacted soils by forming a layer of coarse loose material at the soil surface (Sinnott, 1935).

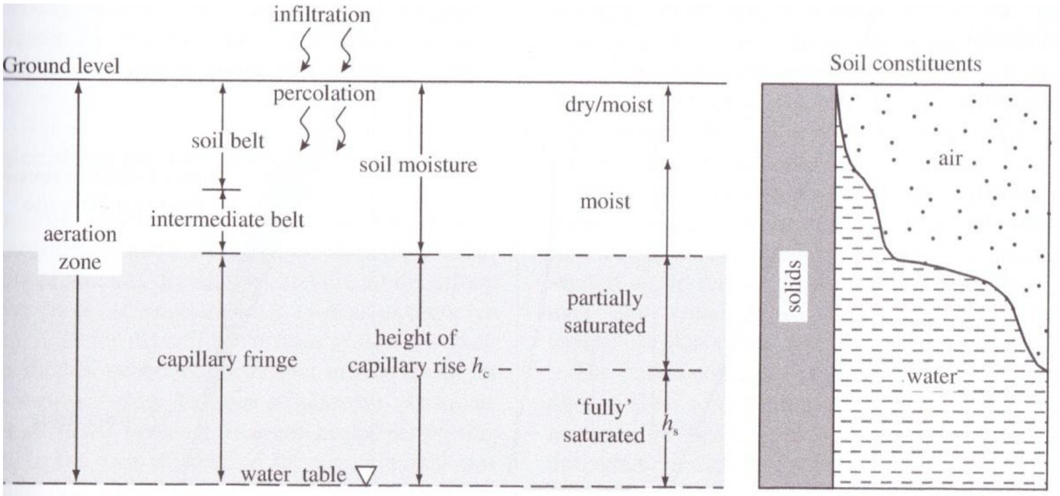

Figure 2.7 - Soil moisture profile in the aeration zone as the result of capillary rise

(Source adapted from: Barnes, 2010)

Recently tilled soils have no inherent strength to support vehicular traffic (Raper, 2005). Spoor *et al.*, (2003) identified that coarser texture soils especially with low clay content were more susceptible to compaction than fine textured soils and that soils that had low initial bulk densities (<1.40 Mg m^{-3}) were also more susceptible than higher bulk density soils to compaction. For a given soil texture, stresses due to vehicle traffic are transmitted deeper into the profile as a result of increases in load or soil moisture and by the reduction in soil aggregation or soil density (Horn *et al.,* 2003). Increased vehicular loads increase the compaction effect, as can smaller loads applied by repeated wheelings (Raper, 2005). Soil compaction in the upper soil profile is mainly due to the ground contact pressure from the tyre (or track) but compaction in the subsoil is determined by axle load. Repeated wheelings of vehicles with smaller loads can also produce compaction in the subsoil. Compacted soil loses elasticity and compacts the soil layer below it when subjected to another wheeling. Successive wheelings push the compaction deeper into the soil profile (Håkansson and Petelkau, 1994). Czyz (2004) found that by increasing tractor passes from 1 pass to 4 passes increased soil bulk density of a sandy loam soil by between 10.3 and 13.8%. Measurements in a soil bin in Auburn, USA by Horn *et al.* (2003) showed that bulk density of a clay soil at all depths (0-350 mm) increased with successive wheelings. After 10 wheelings the bulk density was 1.69 Mg m^{-3}. Up to 90% of compaction caused by multiple wheelings of a wet soil are as a result of the first pass of the vehicle (Badalíková, 2010). Chyba (2012) when investigating the properties of the soil used in this study, found that compared to untrafficked soil the first pass of a vehicle reduced the soil water infiltration rate by 82%.

Uncontrolled agricultural field traffic is a common feature of modern farming with some fields covered many times by implement wheelings during a cropping season (Benjamin and Mikha, 2010). In the Czech Republic Kroulík *et al.*(2009) mapped the passage of all machinery over agricultural fields for all operations carried out over a cropping season to evaluate wheeled tracking area. Each machine was equipped with a DGPS (Differential Global Positioning System) signal receiver. Position was logged every 2 seconds and stored electronically to be interpreted using ArcGis 9.2 software (as illustrated by Figure 2.8). They calculated that 88% of the field was run over at least once for a conventional tillage system (mouldboard plough based) and 91% of this area was repeatedly run over (Table 2.1).

Table 2.1 - Area run over by machinery used in a conventional tillage (plough based) system as calculated by Kroulík *et al.*, 2009

Operation	**Operating width (m)**	**Area run over (%)**
Stubble breaking	6.0	18.9
Liquid manure application	12.0	9.1
Ploughing	10.0	44.6
Pre-sowing preparation	6.0	32.4
Seeding	24.0	19.2
Spraying	7.5	2.5
Harvest	36.0	21.7
Grain disposal	9.0	3.9
Run-over total (%)		87.5
Repeatedly run-over (%)		90.9

(Source adapted from: Kroulík *et al.*, 2009)

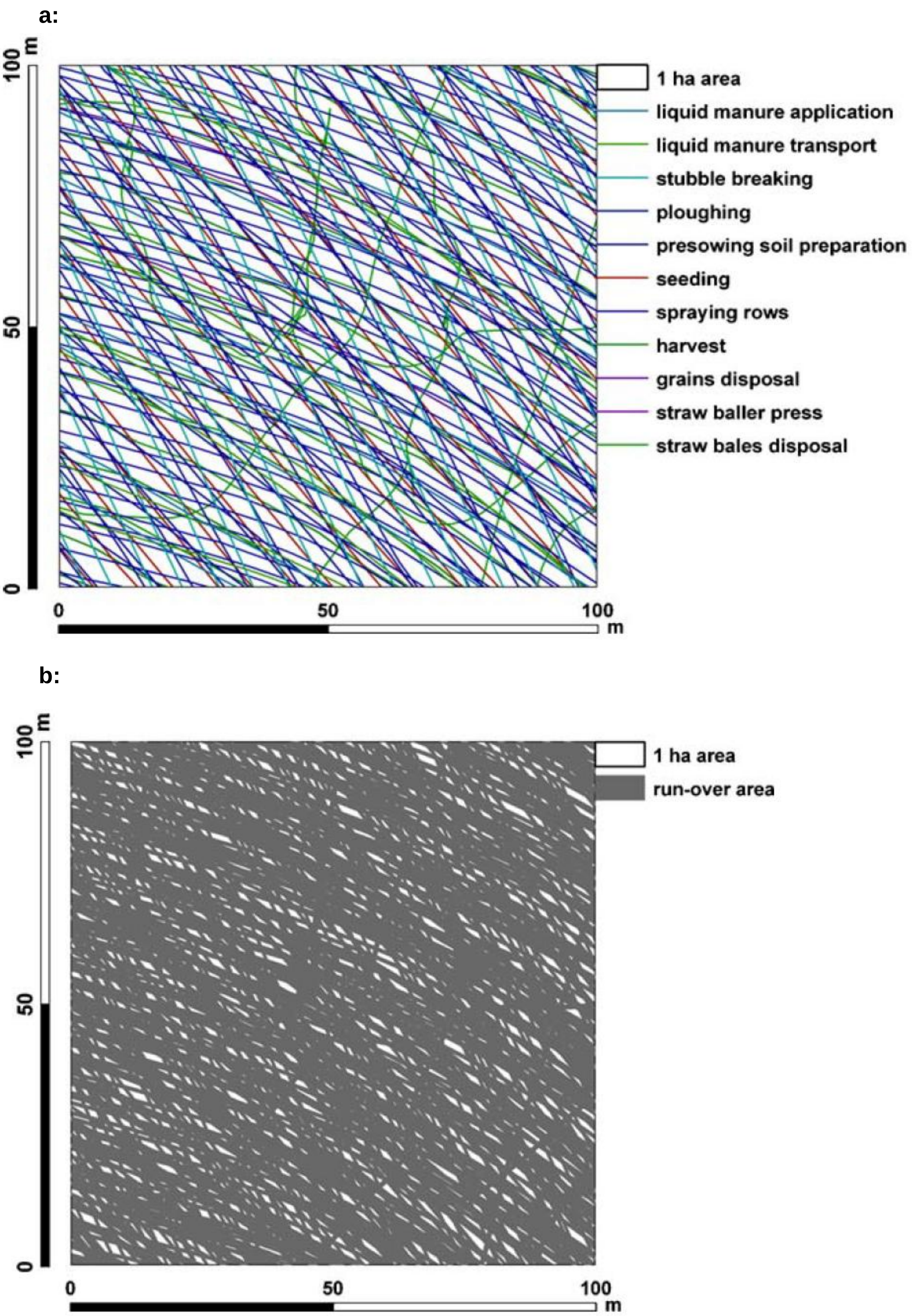

Figure 2.8 - Representation of machinery passes for conventional soil tillage during one cropping season a: machine movements in the field and b: total run-over area (1 ha^2)

(Source adapted from: Kroulík *et al*, 2009)

2.4 Low ground pressure tyres

Chamen *et al.* (2015) identified the use of low ground pressure tyres (low inflation pressure) and the adoption of Controlled Traffic Farming as methods to avoid soil compaction. Using low inflation pressure tyres can reduce soil compaction and increase crop yields compared to higher (standard) tyre inflation tyres (Hamza and Anderson, 2005). Low inflation pressure tyres change the distribution of stresses at the tyre-soil interface. Raper *et al.* (1995) found that low inflation pressures increased the footprint of the tyre and concentrated more of the load towards the outside of the tyre whilst higher inflation pressures concentrated more of the load in the centre of the tyre. Low inflation pressures reduced stresses in the topsoil at 100 mm depth but did not influence soil stresses in the subsoil (>300 mm depth). However load increases did increase subsoil stresses (Arvidsson and Keller, 2007). This is in agreement with previous research by Söhne (1953) cited by Chamen *et al.* (2015) and Lamandé and Schjønning (2011) who suggested that tyre contact pressure was responsible for topsoil stresses and load was responsible for those at depth. However Arvidsson and Keller (2007) go on to state that soil stress is always a function of soil conditions, tyre properties, load and inflation pressure.

Radial tractor tyres have now largely replaced crossply (bias-ply) tyres due to their increased traction performance and reduced compaction effect due to a larger soil contact area (Raper, 2005). Increases in contact area have been measured to be between 30 and 46% higher for radial tyres compared to the equivalent sized bias-ply tyres (Soane *et al.,* 1980). Contact stresses in the soil below a tyre can be considerably higher than the tyre inflation pressure (Arvidsson and Keller, 2007). This is due to the stiffness of the tyre carcass (Koolen and Kuipers, 1983) which increases the ground pressure from tyres with low inflation pressures (Sharma and Pandey, 1996). If a tyre had a thin flexible wall the tyre inflation pressure would be equal to the contact stress (Koolen and Kuipers, 1983). Michelin (2014) developed a low inflation tyre using this concept known as 'Ultraflex Technology' which has increased the length of the thin tyre side wall as shown in Figure 2.9 which has allowed the tyres to run at lower inflation pressures suitable for field and road use.

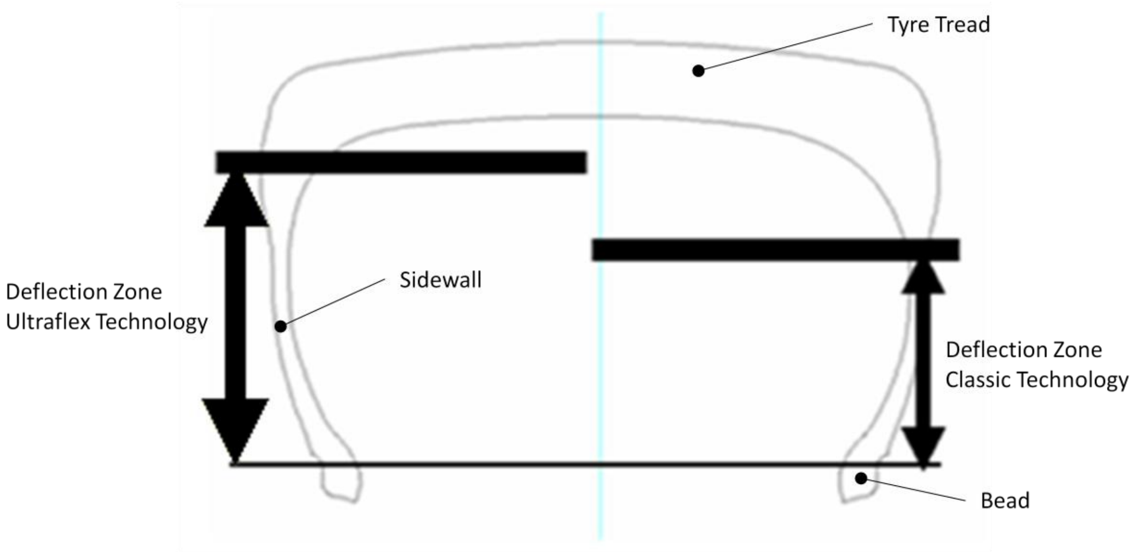

Figure 2.9 - Cross section through an agricultural tyre showing the increased length of deflection zone due to Ultraflex Technology compared to Classic Technology

(Source adapted from: Michelin, 2014)

2.5 Tracked agricultural vehicles

Tracked vehicles were thought by Jansson and Johansson (1998) to produce a lower ground pressure than wheeled vehicles, but they found that the measured soil parameters after trafficking by a wheeled vehicle and a tracked vehicle on a forest soil were similar except in the top 50 mm of soil where the tracked vehicle had increased soil bulk density and the wheeled vehicle decreased bulk density. The wheeled vehicle formed deep ruts which they considered a risk to waterlogging and erosion. When comparing the effect on soil compaction from rubber tracks and wheels in a soil bin study at Cranfield University, UK, Ansorge and Godwin (2007) also found that tracks reduced surface rut depth but also found that penetrometer resistance was lower in the subsoil under tracks than under wheeled systems. They also found that a simulated 'plough pan' at 200-300 mm depth protected the subsoil under the rubber track system whereas the tyre system pushed the pan into the subsoil. In a randomised plot experiment on a clay soil near Rome, Italy, Pagliai *et al.* (2003) found that penetration resistance was significantly lower between 0-350 mm under a wheeled vehicle after one pass compared to under a tracked vehicle but after four passes the penetration resistance was lower under the tracked vehicle for 0-150 mm depth.

Low ground pressure tyres and tracks reduce the risk of compaction by increasing the ground contact area for a given load (Keller *et al.*, 2002). The calculated mean soil contact pressure is less for a track than for a tyre (Ansorge and Godwin, 2007) and it could be expected that it produces less stress in the soil. However stress distribution under a tracked system may not be uniform due to the stress pulses from the idler wheels which increase on the front idler when pulling an implement (Alakukku *et al.*, 2003). Track loads are applied for longer and vehicle vibrations are more easily transmitted into the soil due to reduced dampening by the suspension compared to a wheeled vehicle (Ansorge and Godwin, 2007). This may explain why there is often little difference in the soil compaction effect between tracks and wheels as reported by Alakukku *et al.* (2003). Smith (2016) found that pressure distribution was not uniform along the length of the rubber track of a Challenger MT765 resulting in higher pressures being applied to the soil for a longer period of time than for tyres. Bygdén *et al.* (2004) found that the use of steel tracks in a Swedish forest reduced soil rut depth by 40% compared to tyres. However metal tracks are difficult to manoeuvre and vehicles are slow and not allowed on public roads (Pagliai *et al.*, 2003). An advantage of rubber tracks is that they can be used on the highway but they have a more uneven weight distribution under the track on soft surfaces than steel tracks due to belt tension effects and idler distribution (Ansorge and Godwin, 2007). As the edges of the track are flexible the stress is more concentrated toward the centre of the tracks (Alakukku *et al.*, 2003). A correctly inflated low ground pressure tyre will give an evenly distributed contact pressure which reduces soil compaction risk and increases traction efficiency (Alakukku *et al.*, 2003).

The use of tracks and low ground pressure tyres seek to reduce soil compaction risk by distributing the vehicle load over a larger contact area, but soil compaction risk can also be reduced by management of field traffic (Controlled Traffic Farming) to reduce the area of the field trafficked. In grain-cropping systems, 'random' traffic practices can cover in excess of 85% of the field area, but a well designed Controlled Traffic Farming system can reduce this area to less than 15% (Antille *et al.*, 2016).

2.6 Controlled Traffic Farming

Controlled Traffic Farming (CTF) is the term used for a field traffic system that restricts agricultural machinery to traffic lanes that are separate from distinct crop zones (Gasso *et al.*, 2014) and uses navigation and auto-steer technology (Gasso *et al.*, 2013). Highly accurate (possible positioning error <20 mm (Sun *et al.*, 2010)) RTK-GPS (Real Time Kinematic Global Position System) keeps farm vehicles to the 'sacrificial' tracks year upon year allowing the crop zones in-between to remain untrafficked. This reduces field soil damage and improves crop yields (Jensen *et al.*, 2012). A CTF system is designed to eliminate soil compaction in the cropping zone (by the removal of field traffic) thereby reducing the need for deep tillage operations, giving reductions in tillage draft force requirement meaning reduced power per hectare (Taylor, 1983). It can also improve tractive efficiency (the ratio of output power at the drawbar to input power of the tyres or tracks (Li *et al*, 2009)) leading to improved timeliness of field operations and reduced runoff due to increased soil water infiltration rates (Taylor, 1983). Ideally CTF systems require all machinery to have the same working width so that traffic lanes occupy the least amount of area and all machinery is capable of being guided by navigation systems (Galambošová *et al.,* 2017). The diverse range of agricultural machinery and road traffic width restrictions in the UK and Europe means that there is no universal CTF track layout. As the combine harvester is usually the most expensive piece of equipment to replace, the most popular solution is an 'OutTrac' system where all other machinery is adapted or replaced to run the same track gauge and the combine harvester runs on its own track gauge as shown in Figure 2.10. Other popular systems are TwinTrac (vehicles with a narrower gauge straddling adjacent passes of vehicles with a wider gauge) and AdTrac (the narrower gauge using one track of the wider gauge) (Hargreaves *et al.*, 2016). The tracked areas associated with well designed CTF systems are around 15% in contrast to over 85% associated with conventional Random Traffic Farming (RTF) systems (Antille *et al.*, 2016). The lack of compatibility of working widths between the different agricultural equipment used in the field was considered the main reason for the non adoption of CTF (Tullberg, 2010) but Galambošová *et al.* (2017) implemented a CTF system using existing equipment (without modification) on a 16 ha site at Slovak University of Agriculture in Kolinany and reduced the area trafficked by vehicles by 50%. They showed that improved soil conditions associated with a reduction in soil bulk density in the CTF untrafficked crop zones could improve yields by up to 0.5 t ha^{-1} if a RTF system was converted to CTF. Godwin *et al.* (2017) calculated, using 2016 UK grain prices, that the 0.61 t ha^{-1} increase in yields from a 15% CTF system compared to a conventional RTF system would pay for the annual costs for three RTK guidance systems if the area farmed was 168 ha or above.

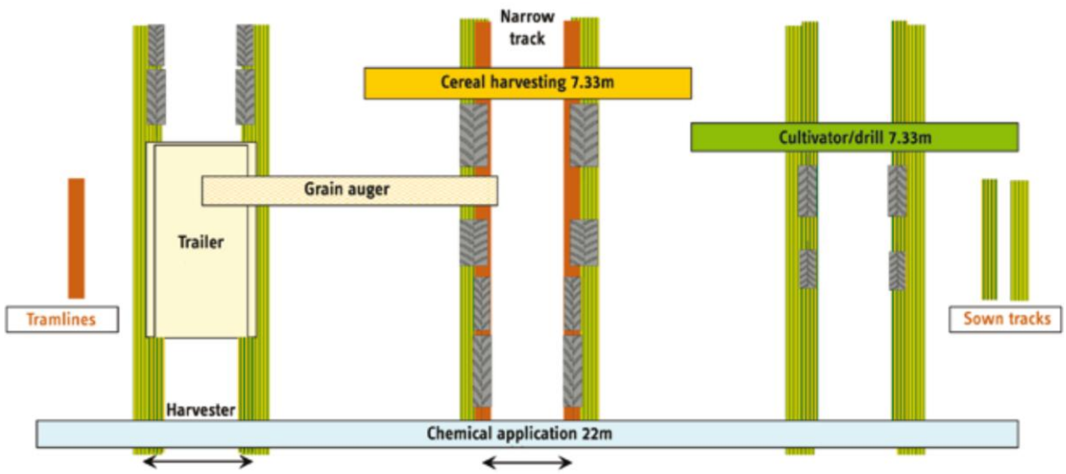

Figure 2.10 - Typical CTF OutTrac layout

(Source adapted from: Roberts, 2010)

2.7 Tillage systems

Tillage is an important part of a cropping system and together with other components such as crop rotation, crop choice, nutrition, crop protection and harvesting must be tailored to local environmental and climatic conditions in order to produce the maximum crop yield (Boone, 1988). It is used to remove biological, physical and chemical limitations within soils to provide conditions that are favourable for good crop establishment and growth (Morris *et al.*, 2010). The aim is to produce a good seedbed that allows good germination by increased soil warming and soil to seed contact and reduced soil resistance for seedlings and root development (Hallett and Bengough, 2013). Braim *et al.* (1992) found that barley roots in ploughed soil were longer than those in soil that been shallow cultivated or direct drilled. Tillage, whilst beneficial for the growing plant may be detrimental to seedling establishment due to poor seed to soil contact. This can be improved by consolidation of the soil by rolling the surface of the soil to provide sufficient pressure to pack soil around the seed but not compact the soil to an extent that it would impede root growth of the plant (Hallett and Bengough, 2013). Tillage can be used to incorporate crop residues and nutrients and destroy weeds (Godwin, 2014) as well as loosening compaction to improve structure providing improved soil aeration and water infiltration (Sommer and Zach, 1992). A loosened soil (good tilth) that is supplied by capillary water is favourable to plant growth as it provides a good supply of both oxygen and water (Sinnott, 1935). Field operations, especially during harvest, influence the structure of the soil and distribution of crop residues which, together with the needs of the next crop, will determine the tillage requirement. This will differ dependent upon climate, soil type and cropping system (Boone, 1988).

Conventional tillage in the UK consists of primary cultivation that inverts the soil using a mouldboard plough to a depth around 200 mm followed by secondary cultivation (often by use of a tine, disc or rotary cultivator) to prepare a seedbed. Discs break down clods produced by the ploughing and smaller aggregates are made from following with tines or a harrow (Morris *et al.*, 2010; Hallett and Bengough, 2013). This system provides accelerated soil drying and warming and is used on soils with drainage problems associated with traffic compaction. It is effective in breaking disease and weed cycles by burying the surface residues (Morris *et al.*, 2010). Crop pathogens can over-winter on crop residues and infect the new crop (Conway, 1996). Tillage incorporates crop residues into the soil, which stimulates soil microbial activity that suppresses the activity of pathogens reducing the primary incolulum. This retards the development of foliar and soil borne diseases (Conway, 1996). Mouldboard ploughing mechanically destroys weeds and buries weed seeds throughout the tilled layer reducing germination and growth of those seeds that are buried deeper (Peigné *et al.*, 2007).

Cultivation of soil can degrade soil especially by erosion and is not a new problem. It was a contributing factor in the decline in several early civilisations including those of Greece and Rome (Montgomery, 2012). Long-term use of a conventional inversion tillage system can lead to accelerated erosion by wind and water runoff because it leaves the soil bare. The 1930s 'Dust Bowl' in the USA where an extended drought caused the topsoils of the southern plains to blow away highlights how plough based cultivations can make topsoil vulnerable to erosion (Huggins and Reganold, 2008). The 'lost' soil particles take nutrients and pesticides from the soil and pollute streams, rivers and other water bodies. Ploughing reduces the soil organic matter content of the soil due to mineralisation and together with the repeated breaking of the soil aggregates leads to decline in soil structure making the soil more susceptible to erosion, compaction and capping (Lal *et al*, 2007).

Continuous cycles of ploughing in a cropping system can produce a compacted layer (known as 'plough pan') in the soil (Mallory *et al.*, 2011) that forms immediately below the tilled layer at the boundary between the disturbed and undisturbed soil (Lucas *et al.*, 2000; Morris *et al.*, 2010). Mouldboard ploughing involves running two tractor wheels from one side of the tractor in the open furrow during the operation which produces high stresses in the subsoil (Keller, 2004). The compacted plough pan forms from pressure exerted on the undisturbed soil by the wheels and smearing from the base of the plough running along the furrow especially if the soil is wet (Moebius-Clune *et al.*, 2016; Hillel, 2004; Wiseman *et al.*, 1993). Repeated cultivation at the same depth compacts the plough pan to a high bulk density that is a barrier to crop roots and reduces water infiltration limiting water movement through the soil profile (Morris *et al.*, 2010; Keller, 2004). This requires deep loosening periodically using a sub-soiler (Morris *et al.*, 2010) but this makes the soil susceptible to re-compaction from subsequent field traffic (Sommer and Zach, 1992). Soane *et al.* (1986) found that trafficking of soil that was deep loosened and then ploughed led to significant re-compaction of the subsoil and soils that were ploughed and then deep loosened had a greatly reduced soil surface bearing capacity.

Non-inversion tillage (reduced tillage) is an alternative to conventional mouldboard ploughing and is seen as a means of reducing energy and time inputs to a cropping system. Reduced tillage requires fewer machine passes to produce an acceptable seedbed and fuel cost and time taken are reduced (Warner *et al.,* 2016). Košutić *et al.* (2005) found that using non-inversion tillage (tine) reduced the power needed for cultivation by 37.5% compared to a mouldboard plough system on a silty loam soil in Croatia. Arslan *et al.* (2014) found that reducing the depth of tine tillage from 250 to 100 mm reduced maximum draft force from 127 kW to 47 kW which reduced tractor fuel consumption by 25%. Reduced tillage has been able to replace mouldboard plough based systems as broad-spectrum herbicides have removed the need to bury weeds (Triplett and Dick, 2008). Figure 2.11 shows the relationship of tillage systems to tillage intensity as described by Morris *et al.* (2010).

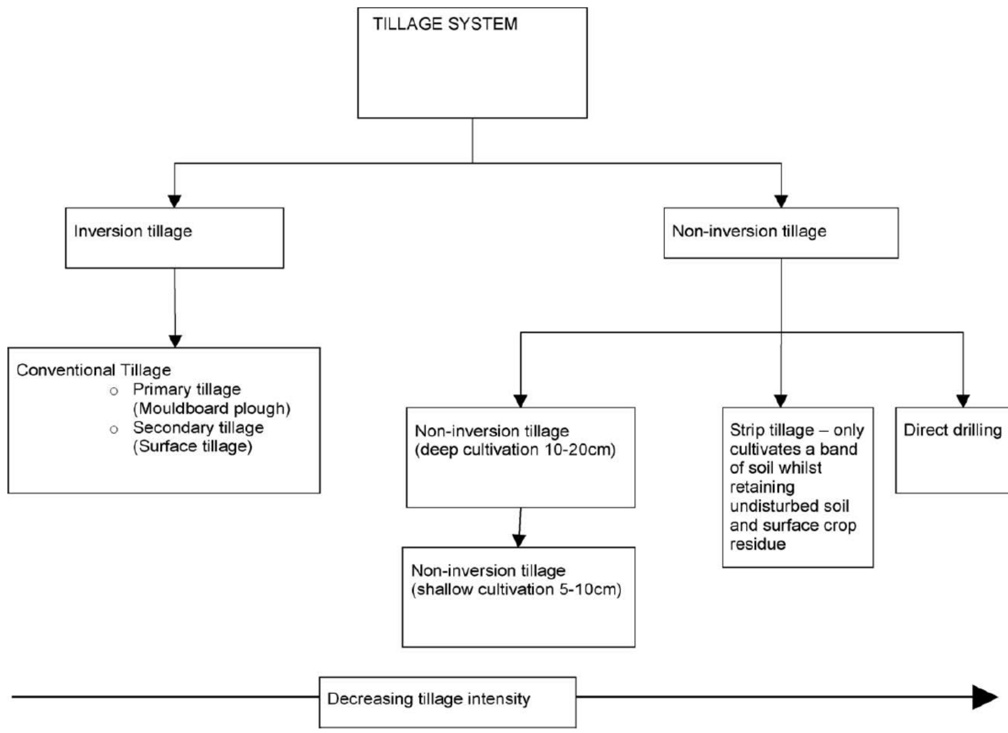

Figure 2.11 - Tillage systems in relation to tillage intensity

(Source adapted from: Morris *et al.*, 2010).

Conservation Agriculture is based on the three principles of minimising tillage (known as conservation tillage), maintaining year round soil cover and using diverse crop rotations and cover crops to reduce agrochemical inputs and losses (Jones *et al.*, 2006; Reicosky and Saxton, 2007). It seeks to promote biological processes in and on the soil which protect soil and water and allow for sustainable high crop yields (Jones *et al.*, 2006). The aim of conservation tillage is to minimise soil disturbance preferably by direct drilling (no-till) but if necessary using non-inversion tillage with either discs or tines avoiding mouldboard ploughing (Jones *et al.*, 2006). Conservation tillage retains a minimum of 30% soil surface cover by crop residues (Peigné *et al.*, 2007) whilst partially mixing some residues with the small amount of disturbed soil which aids soil moisture retention and reduces soil erosion (Reicosky and Saxton, 2007).

Non-inversion tillage implements are frequently equipped with tines that lift and shatter the soil to remove compaction and concave discs that create a fine tilth by cutting and mixing soil clods and surface residues. The soil is then levelled and packed by trailing press wheels (Morris *et al.*, 2010). Figure 2.12 illustrates how the reduction in tillage associated with adopting conservation tillage reduces the amount of vehicular traffic needed to establish crops and therefore reduces not only the cost associated with establishment but also reduces the intensity of traffic on the soil. Although reduced cultivation equipment reduces the amount of vehicular traffic, the high energy input is often not much less than for mouldboard ploughing and large tractors are required. However, they do have a high output and one driver can cultivate soil ready for drilling, at a rate of up to 6 ha per hour, using a 6 metre wide implement (Davies and Finney, 2002).

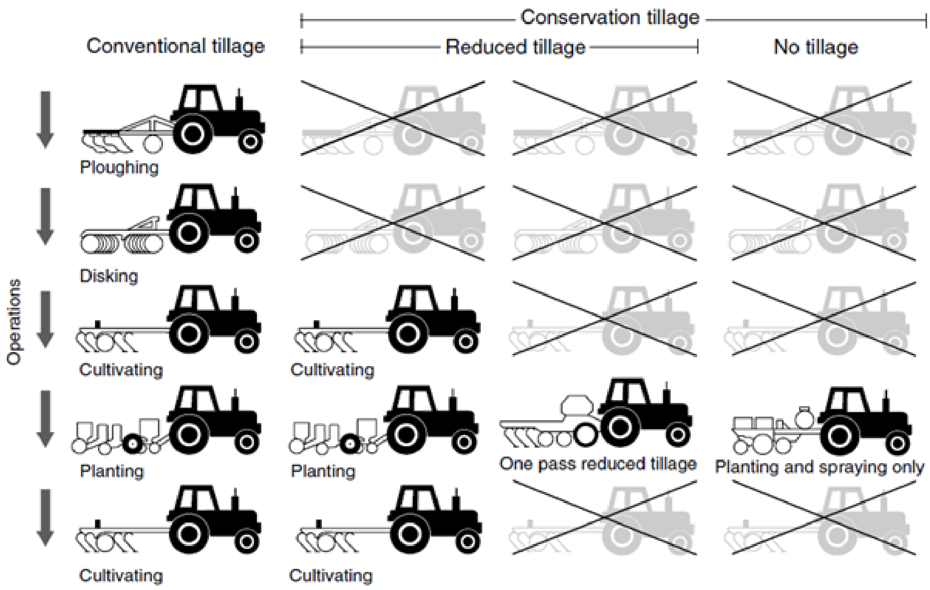

Figure 2.12 - The reduction in field traffic associated with conservation tillage

(Source adapted from: Hallett and Bengough, 2013)

In the UK reduced tillage is used for more than 40% of arable land but only 5% of arable land is no-till (Godwin, 2014: after Knight *et al.,* 2012) compared to over 20% of agricultural land in the USA (Hallett and Bengough, 2013). Despite the benefits of non-inversion tillage many farmers are reluctant to discontinue a plough based system due to fears of reduced yields, reluctance to adopt new technology or peer pressure that reduced tillage fields appear to be badly managed due to retention of surface crop residues (Jones *et al.*, 2006).

No-tillage machines are specialised equipment that can be seen by farmers as a cost restraint. However this can be less important if the purchase of no-till equipment coincides with the need to replace existing equipment (Llewellyn *et al.*, 2012). Tebrugge (2001) cited by Soane *et al.* (2012) calculated that fuel costs using a plough based system were 6.5 times higher, machinery investment 1.63 times higher and maintenance costs were 4 times higher than for a no-till system. Ingram (2010) reported that unlike some North American and European countries England had no policy or subsidies to support implementation of reduced tillage practices. This may be a reason for the low uptake of no-till in the UK. Additionally, there is a lack of technical knowledge in advisory bodies to support farmers and the transition to reduced tillage relies mainly on support from the commercial interests of machinery and chemical companies (Ingram, 2010). Soane *et al.* (2012) consider that the uptake of no-till in Europe relies heavily on the management of soil compaction, effective weed control and successful crop residue handling and will continue to be affected by fuel, machinery and herbicide costs. Plough based systems are still needed in the production of root crops and the adoption of direct drilling is dependent on suitable soils and effective drills (Tivy, 1990).

It is generally accepted that no-till decreases the susceptibility of soil to erosion from wind and rainfall runoff compared to conventionally tilled soils because soil surfaces are covered with crop residues rather than being left bare (Soane *et al.,* 2012). Runoff is also reduced, by increased soil infiltration, as these residues protect the soil surface from raindrop impact reducing surface capping, retaining the stability of near surface aggregates and the continuity of vertical earthworm burrows from the surface to the sub soil (Soane *et al.,* 2012). This increase in macro pore stability and connectivity, together with the increased herbicide use associated with no-till systems can lead to raised levels of pollutants getting into the groundwater (Herrick, 2000).

Weed populations associated with no-till are different than those after mouldboard ploughing. Perennial grass weeds become more dominant as their dormancy and germination is affected by their seed retention near the surface rather than being buried (Soane *et al.,* 2012). Low efficacy of herbicides applied in low temperatures or when applications are followed by high rainfall may mean that additional herbicide applications are required. In the UK, black grass (*Alopecurus myosuroides*), Italian ryegrass (*Lolium perenne L*.) and wild oats (*Avena fatua*) have been identified as having resistance to herbicides and additional cultural control of delayed autumn drilling, crop rotation and cover crops are necessary to reduce weed problems (Jarvis and Woolford, 2017; Soane *et al.,* 2012).

Harvest crop residues are left on the soil surface in reduced tillage systems and can affect crop establishment (Freer, 2006). Retaining crop residues on the soil surface can increase the occurrence of diseases such as Eyespot (*R. herpotrichoides*) and Leaf Spot (*S. tritici*) where new plants are infected by splash dispersal of inoculums (Morris *et al.*, 2010). The retention of crop residues on the soil surface can sustain large slug populations that can cause considerable damage to winter sown wheat and barley seedlings (Soane *et al.,* 2012). The presence of crop residues from the previous crop on the surface of the soil during drilling, can lead to “hair-pinning” (when the surface crop residues become trapped with the seed in the slot formed by the disc of the seed drill opener). The straw produces acetic acid in wet conditions that can kill seeds and seedlings. In dry conditions the straw can prevent the seed from accessing moisture from the soil (Baker, 2007). Russell (1977) suggested that plant residues should be disposed of prior to drilling to prevent poor germination due to toxic substances produced by straw decomposition. Morris *et al.* (2010) reported that the effect of poor establishment due to straw residue can reduce yields by up to 50%. Baker (2007) considers the presence of surface residues advantageous as the associated increases in earthworm activity enhances the soil structure in no-till soils. Additionally, if the crop residues cover the seed slot after closing they can reduce the loss of soil moisture, which is beneficial to germination and seedling growth. Freer (2006) found that the poorest wheat establishment was associated with soils that had the largest amount of loose surface residue and recommended that when using a disc drill (the Väderstad Spirit used for this research is a disc drill) crop stubble should be left as long as possible to reduce soil surface residue cover. Taller stubble over 300 mm high can block coulters and tines causing uneven seed placement and reduced establishment under large clumps of crop residues (Morris *et al.*, 2010). Tillage can be used to incorporate crop residues into the soil (Godwin, 2014) and the partial mixing of crop residues using small disturbances to the soil can improve soil moisture retention and reduce soil erosion (Reicosky and Saxton, 2007). To successfully incorporate crop residues using reduced cultivation, the combine harvester should be capable of chopping and spreading the residues across the full width of the header (Carter *et al.*, 2003). Shorter straw cereal varieties together with improved combine straw chopper design allows straw to be finely chopped and spread over the soil, promoting faster decomposition by increasing the surface area of the straw that is in contact with the soil. Finely chopped straw also reduces occurrences of drilling machine blockages during sowing (Blake *et al.*, 2003). Problems associated with crop residues can be reduced by removal of straw by bailing but this can limit the erosion protection associated within reduced tillage systems (Townsend *et al.*, 2016). Removal of straw from the field is a balance between timeliness of bailing and carting, as well as the value of the straw against the potential loss of nutrients to the soil (Carter *et al.*, 2003) and reduction in soil organic matter (Townsend *et al.*, 2016). The additional field operations needed can increase the potential for soil compaction due to the additional field traffic by tractors, balers, loaders and trailers. Trailers can weigh up to 25 tonnes which can cause compaction in the top 300 mm of the soil profile. Damage to the soil can be reduced by keeping the straw trailer to tramlines or reducing the area trafficked by using bale collectors which remove the need for loaders (Nicholson *et al.*, 2014).

Crop yields from no-till systems may be reduced in climates with cold springs and on heavy or poorly drained soils (Lal, 2007). On poorly drained soils the use of strip tillage can provide the benefits of a tillage system by cultivating the planting row to remove residues, reducing soil moisture and warming the soil whilst retaining residue on the no-till inter-rows (Licht and Al-Kaisi, 2005; Jones *et al.*, 2006).

Cannell *et al.* (1978) assessed available experimental evidence in order to classify the suitability of land in Britain to repeated direct drilling of combinable crops. The areas that were identified as being most suitable for direct drilling tended to be in the east of the country and are closely associated with the major cereal growing areas in Britain. Figure 2.13 shows the areas of Britain that were considered suitable for direct drilling of combinable crops. The location of Harper Adams University is indicated by the red dot and is located on the border of the category that may produce a risk of lower yields from direct drilling (compared to conventional cultivation).

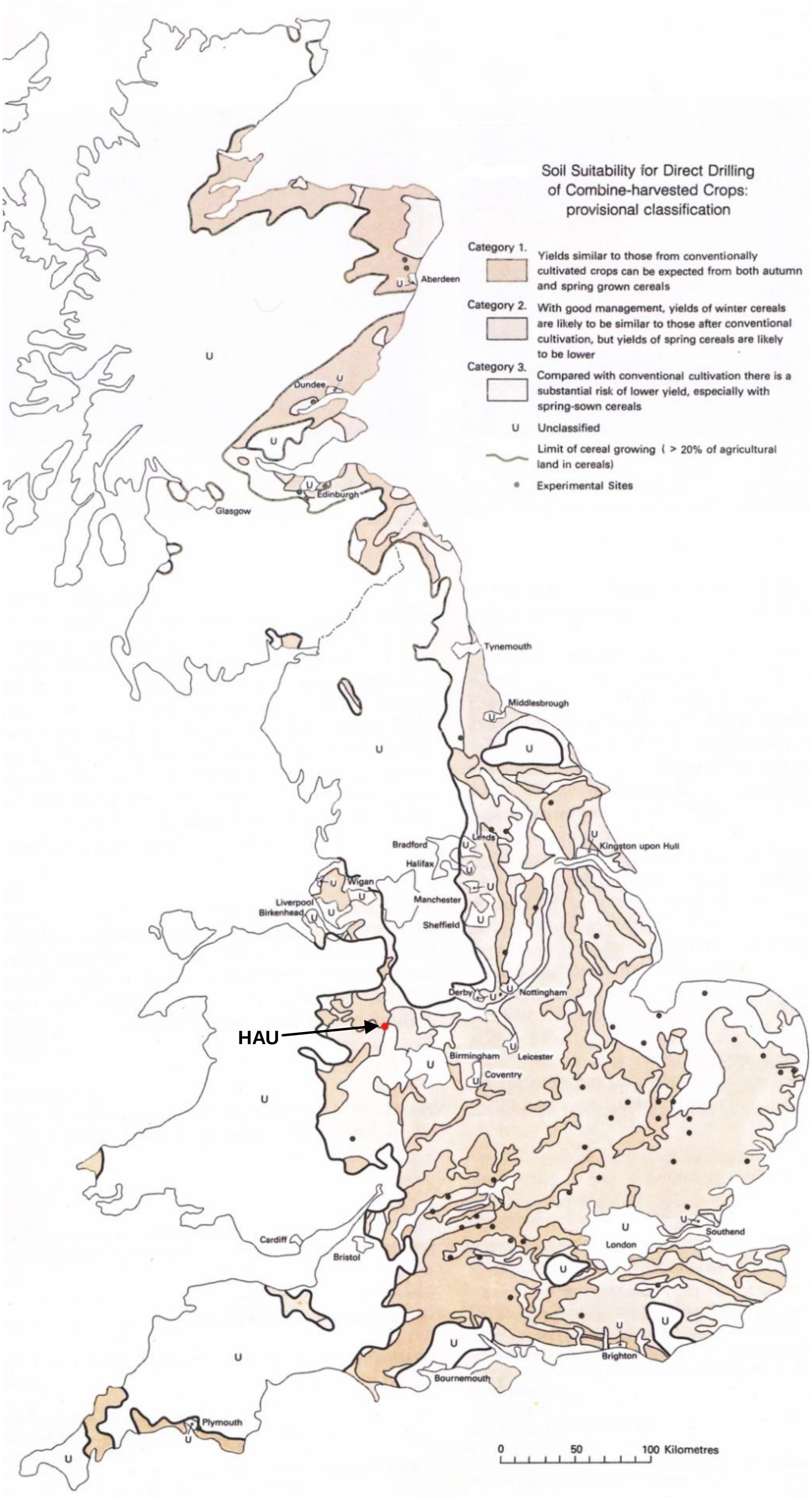

Figure 2.13 - The suitability of UK soils for direct drilling of combinable crops
Red dot indicates the location of Harper Adams University (HAU), Newport, Shropshire.

(Source adapted from: Cannell *et al.*, 1978)

2.8 Compaction and tillage effects on soil thermal properties

Soil obtains heat from the sun but only a fraction of the incoming radiation is absorbed by soil, the rest is reflected or scattered. The radiation absorbed is used in four ways, by being re-radiated back to the sky, used as latent heat in evaporating water, raising the temperature of the surface soil and then dissipated as sensible heat to the air or conducted into the body of the soil (Wild, 1988). Soil temperature is an important physical property of a seedbed that controls seed germination (Hallett and Bengough, 2013) and also affects plant emergence and growth as well as root development. Its distribution within the soil is dependent upon the heat capacity and thermal conductivity of the soil (Rahimi *et al.*, 2013) which controls the exchange of heat energy at the interface between the soil and the atmosphere (Mengistu *et al.*, 2017). The volumetric heat capacity of soil depends upon the composition of the soil (mineral and organic components), water content and bulk density and is defined as the change in soil heat content due to temperature and can be expressed as joules per m^3 per ^oK (Hillel, 2004). The quantity of heat transferred through an area of soil in a given time from a given temperature gradient is known as the soils thermal conductivity (Hillel, 2004). The ability of a soil to conduct heat from one point to another is known as thermal diffusivity which is the ratio of thermal conductivity and heat capacity (Rahimi *et al.*, 2013). The constituents of soil have different thermal conductivities with the values for solids and water being much higher than that of air. Soils with a higher air content (less water) have a lower thermal conductivity (Hillel, 2004).

Any soil management practice that affects the relative proportion of soil, water and air components will affect the thermal properties of the soil (Lipiec and Hatano, 2003). Soil tillage increases the proportion of air to soil particle volumes which reduces the heat capacity of the tilled soil and provides additional air pockets which increases the opportunity of water evaporation promoting quicker soil drying. As the soil dries thermal conductivity will reduce. These dryer soils can warm and cool faster than wet soils (Licht and Al-Kaisi, 2005). Soil compaction improves the contact between the soil particles which increases the heat capacity, thermal conductivity and thermal diffusivity of the soil (Lipiec and Hatano, 2003; Boone, 1988). Compacted soils are slower to warm and cool and have smaller daily fluctuations in soil temperature at the soil surface than loose soils (Lipiec J. 2004). Although a compacted soil will have a lower surface temperature than a looser soil, subjected to the same heat energy, at greater depths they have a higher temperature as found by Lipiec *et al.* (1991). The warmer drier soils (due to tillage) probably contribute to better rooting in seedlings than for compacted soils (Lipiec *et al.*,1991). Increases in soil water content increase heat capacity and reduce soil warming rates (Chesworth, 2008) with aggregated soil having greater thermal conductivity than disturbed soils due to increased continuity of water filled pores (Lipiec and Hatano, 2003).

Soils covered in crop residue reflect more solar radiation than bare soils (due to increased albedo because of their lighter colour (Wolkowski, 2005)), act as an insulating layer and reduce soil water evaporation rates which reduces the rate at which the soil warms (Morris *et al.*, 2010). These wetter and colder soils can delay drilling of crops in spring and lead to delayed germination in no-till systems (Soane *et al.,* 2012). Crop shoots above surface mulches are warmer in the day time due to the reflected solar energy but colder at night due to re-radiation, consequently, the young plants are more susceptible to leaf tip burning and frost damage (Boone, 1988). Strip-tillage can combine the benefits of tillage in the seed row whilst retaining soil residue cover between crop rows. The removal of residues by strip tillage was found by Licht and Al-Kaisi (2005) to increase soil temperature in the crop rows by 1.2 to 1.4^{o}C compared to rows covered in residues. In no-till systems crop residues can be removed from the seeding row, by the use of discs in front of the planting unit, to allow the soil to warm (Wolkowski, 2005). This relies on careful management of the chopping and spreading of the straw by the combine harvester to ensure an even spread of residue across the soil (Morris *et al.,* 2010).

2.9 X-ray Computed Tomography (CT)

Changes to soil dry bulk density can be used to evaluate the effect of soil tillage and vehicular traffic on soil and derive other measures such as soil total porosity, void ratio specific volume and unit weight (Campbell, 1994). Dry bulk density is found by determining the weight of dry soil within a known volume of soil to give an indication of how closely the soil particles are packed (Freitag,1971). In cohesive soils, a widely utilised direct measurement of bulk density method, is the use of an open ended metal cylinder that is hammered or pressed into the soil. The cylinder is then excavated and the soil trimmed flush with the ends of the cylinder. The soil is oven dried and weighed. As the cylinder volume is known the bulk density can be calculated (Freitag,1971; Czyz, 2004). By using the specific gravity of the soil particles the total porosity can be calculated (ratio of non soil volume to the volume of the sample) (Freitag,1971). Both dry bulk density and total soil porosity are commonly used to describe the compaction of soil (Håkansson and Lipiec, 2000) but they are not adequate for accurate assessment of changes in soil makeup (Lipiec and Hatano, 2003) because they do not allow the quantification of pore sizes and distribution within the soil (Campbell, 1994). Compaction is the term used to describe the deformation of soil by vehicular traffic but the stresses on the soil from the tyre produce both volumetric strain (compression) and shear deformation (distortion) of the soil (Berisso *et al.,* 2013). This can make the use of changes to soil bulk density an inadequate indicator for soil structure damage (Chamen *et al.*, 2015) especially as shear stresses can affect pore continuity and subsequent air permeability (Berisso *et al.*, 2013). Soil compaction increases soil strength (Wolkowski, 1990) therefore soil strength measurements, such as shear strength and penetration resistance, can be used to identify changes in soil structure following compaction events (Lipiec and Hatano, 2003). Soil strength can be measured quickly in the field using the shear (field) vane (shear strength) and penetrometer (penetration resistance) (Hoefer and Bachmann, 2012). A shear vane can be used to obtain a direct measurement of soil strength by measuring the torque required to shear the soil along a cylindrical shear surface (Guerif, 1994). It can be used to quickly take a series of readings in moist and wet soils but is not suitable in stony or dry soils (Freitag,1971). Driving the vane into dry soils loosens the soil and reduces its strength which will lead to errors in readings (Guerif, 1994). As compaction is often present in layers within the soil profile, Freitag (1971) considers the shear vane not to be the most suitable instrument for measuring compaction. A penetrometer measures the vertical resistance of the soil to penetration by a cone which gives an indication of the compactness of the soil. Penetration resistance is highly dependent on soil moisture (resistance falls in wetter soils) therefore readings for comparative purposes should be made when soils are near field capacity (Miller *et al.*, 2001). The penetration resistance measured by a penetrometer can be between 2 and 8 times higher than the actual penetration resistance experienced by a plant root tip due to the way the two penetrate the soil. The two are only well correlated when the soil is homogenous (Lampurlanés and Cantero-Martinez, 2003).

Traditionally changes in pore size distribution are indirectly obtained from water retention curves with changes attributed to the total soil volume. Saturated soil samples are drained to increasing water suctions (Dexter and Bird, 2001) with the pore size (dia µm) drained at each suction estimated as 3000 s^{-1} (s= suction in millibars) (Hall *et al.*, 1977). Structural changes are statistically averaged (mean) over the total volume of a sample assuming the soil to be homogeneous and the strain is uniform (Peth *et al.,* 2010). It also assumes that pores are mainly circular and that all pores are continuous and therefore capable of being drained (Hall *et al.*, 1977). The use of water retention curves does not identify the complex changes to soil pore structure due to local differences in the application of stress during wheeling (Peth *et al.,* 2010). Pore systems can be analysed by 2D image analysis of thin slices of undisturbed soil samples as used by Pagliai *et al.* (2003). Samples are dried with acetone and then impregnated by polyester resin before being sliced into thin sections and polished and then analysed with image software such as Image Pro-plus (Pagliai *et al.*, 2003). This method of porosity analysis is time consuming and costly and the technique requires specialist training (Lipiec and Hatano, 2003).

X-ray computed tomography (CT) is a non destructive 3D imaging technique that can effectively be used to measure actual, rather than inferred, soil pore size and distribution (Rab *et al.*, 2014) as well as pore shape, orientation and connectivity (Beckers *et al.*, 2014). X-ray CT can investigate the changes to the soil pore network due to mechanical or hydraulic stresses visualising the form and arrangement of the pore space (Keller *et al.*, 2013). The potential of X-ray CT for use in the soil environment was first demonstrated by Petrovic *et al.* (1982), cited by Helliwell *et al.* (2013), who found a linear relationship between X-ray attenuation coefficient and soil bulk density. X-ray CT derived porosity has been found to be well correlated to soil macro porosity estimated from saturated hydraulic conductivity (Udawatta and Anderson, 2008). Rab *et al.* (2014) found that macro porosity derived by X-ray CT was comparable with porosities obtained using water retention curves but suggested that X-Ray CT was a better method of determining macro porosity at sizes larger than 300 μm diameter. They stated that X-ray CT is a valuable tool for the rapid characterisation of soil porosity with benefits over traditional porosity estimation methods as it provides additional information on the spatial distribution of pores and pore connectivity important in the understanding of soil water dynamics and its effect on plant growth. Kim *et al.* (2010) studied the effect of compaction on a silt loam soil in Missouri, USA using a medical GE Genesis-Zeus X-ray CT scanner. They found that the soil from the compacted treatment had significantly reduced (64%) CT measured porosity compared to the un-compacted soil and that the number of pores reduced by 71% as a result of an increased (8%) bulk density. The differences in the measured parameters between the two soil conditions was greatest between 0-100 mm but was not statistically significant below 200 mm depth. Katuwal *et al.* (2015) compared air transport in a soil with varying organic carbon content, clay content and bulk density measured using established laboratory methods on soil samples from an agricultural field in Silstrup, Denmark with macro porosity measured using X-ray CT. They found that pore size distribution and connectivity was important in air-flow within the soil and there was stronger preferential flow in samples with low macro porosity when pores were less dense and interconnected. The effect of conventional (plough based) tillage and a no-till system on the growth of maize roots was compared on a sandy loam soil using X-ray CT and mercury intrusion porosimetry on farmland in north eastern Italy by Dal Ferro *et al.* (2014). Significant differences (P<0.005) were found where the conventional tillage produced a greater number of smaller pores (100-250 μm) and fewer larger pores (250-500 μm) than the no till treatment at 0-100 mm depth with similar results at 200-400 mm depth with smaller pores (54-250 μm) and larger pores (500-750 μm). No difference in soil micro porosity was detected using the mercury intrusion porosimetry.

X-ray CT uses mathematical reconstructions from attenuation of radiation to produce stacked 2D images to produce 3D models of the soil sample (Vaz *et al.*, 2011) allowing visualisation of changes in pore system structure through the soil profile. The process (illustrated in Figure 2.14) involves a sample (e.g. soil core) being rotated incrementally through 360^o in X-ray beams to produce a series of radiograms which are then algorithmically reconstructed to produce a 3D attenuation map of the sample (Beckers *et al.*, 2014). The intensity of the beams diminish as they pass through the sample (attenuation) and are projected onto a detector which measures the change in energy intensity.

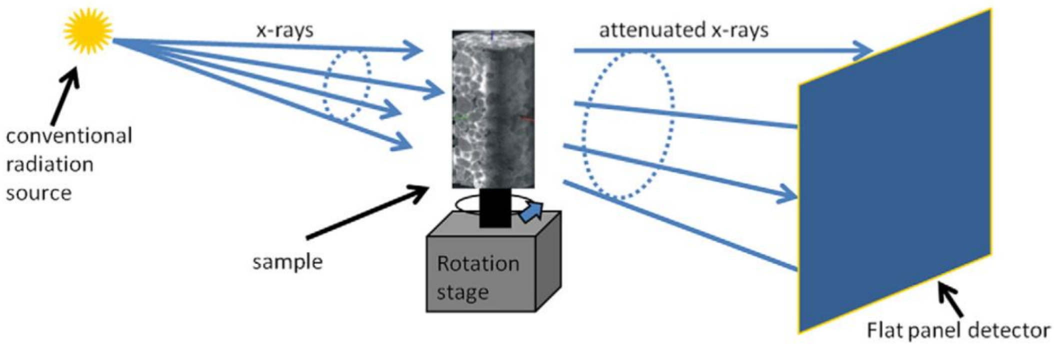

Figure 2.14 - Typical X-ray Computed Tomography cone-beam configuration setup

(Source adapted from: Wildenschild and Sheppard, 2013)

The attenuation coefficient is the characteristic of the material to absorb or scatter a photon and is related to the density of the material (Helliwell *et al.*, 2013). As the sample is rotated successive projections of pixels based on the attenuation are created and these are then reconstructed into cross sectional 2-D images (slice) through the 3-D object (Mooney *et al.*, 2012). Each image is made up of 3-D pixels (voxels) based on the X-ray resolution (Calistru and Jitareanu, 2015). Two or more different elements of the X-ray CT image can be differentiated by the use of segmentation (Taina *et al.*, 2008) therefore in order to detect pore space the reconstructed images are segmented using a threshold tool on an 8-bit greyscale image (Taud *et al.*, 2005). This segmentation utilises the simple histogram (Lamandé *et al.*, 2013) of the grey scale values of the image which has three main phases of pore space, organic material and mineral grains. The threshold tool separates the pore space phase from the organic and mineral phases (Helliwell *et al.*, 2013). Values lower than the threshold are considered air-filled pore space and those above non pore (Kim *et al.*, 2010). As there is a large contrast between the X-ray attenuation of soil solids and soil pores it is relatively easy to quantify soil pore networks (Taina *et al.*, 2008). However a study by Baveye *et al.* (2010) identified that the thresholding of images was affected by user bias. They asked 13 CT experts to threshold the same test images and received porosity estimates that varied between 12.92 and

72.71%. This suggests that for repeatability, manual thresholding should be avoided and an automated thresholding algorithm utilised (e.g. Li) as recommended by Wildenschild and Sheppard (2013). Although automatic thresholding (as used in this research) may still have some observer dependence (Baveye *et al.*, 2010), it is an efficient technique when applied to bimodal grey scale histograms (Taud *et al.*, 2005).

2.10 Growth and development of cereals

Globally, barley is the fifth most produced crop with a mean production for the years 2000 to 2007 estimated by the Food and Agriculture Organisation of the United Nations to be 140 million tonnes (Ullrich, 2011). Oats are an important component of livestock feed and are generally grown in cool moist climates because they are sensitive to dry hot conditions. Annually 21.2 million tonnes of oats are produced making them the sixth most grown cereal worldwide behind maize, wheat, rice, barley and sorghum (Finnan and Spink, 2017). In 2015 the UK planted 1.1 million hectares of barley with a total yield of almost 7.3 million tonnes (winter barley 46%, spring barley 54%), an overall increase of 5.3% upon 2014 yields. An increase of 7.5% in production of winter barley was due to a 4.4% increase in yield to 7.5 t ha^{-1}. Mean UK wheat yield was 8.8 t ha^{-1} with a total yield of 16.2 million tonnes. UK oat yield deceased by 5.1% to 779 thousand tonnes (DEFRA, 2015).

2.10.1 Growth stages of cereal

Cereal growth and development are affected by both soil and climatic variables. The term development relates to the series of stages from germination through to maturity and the rate of development is mainly affected by temperature and photoperiod. Growth is the increase in size of the plant and is determined by factors including nutrient and water availability and light (Wild, 1988). Several growth stage scales can be used to describe the development of cereals, a popular one being Zadoks as used by Yara (Not dated a). This decimal scale is described by Zadoks *et al.* (1974) and key growth stages are shown diagrammatically in Figure 2.15. Zadoks growth stages (GS) describe the visible features of the developing cereal plant from germination through to harvest. The first number describes the major developmental stage (as shown in Table 2.2) and the second number gives finer detail. The code allows easy identification of growth stages to assist growers, chemical manufacturers and scientists to discuss crop management. The Zadoks key is predominately used in UK wheat and barley publications due to the popularity of growing the crops in the UK but the Zadoks scale is also applicable to the life cycle of oats (White, 1995). Figure 2.16 is an example of the Zadoks scale applied to barley and shows when the key stages occur for winter barley sown in October.

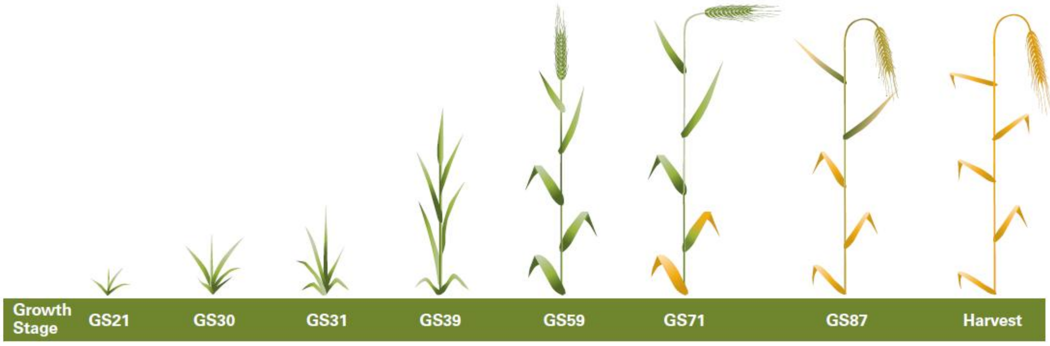

Figure 2.15 - Visual identification of cereal key growth stages based on Zadoks decimal scale

(Source adapted from: AHDB, 2015a)

Table 2.2 - Zadoks major developmental stages

Growth stage (GS)	Description of major stage
GS 00-09	Germination
GS 10-19	Seedling Growth
GS 20-29	Tillering
GS 30-39	Stem Elongation
GS 40-49	Booting
GS 50-59	Ear Emergence
GS 60-69	Flowering
GS 70-79	Milk development
GS 80-89	Dough Development
GS 90-99	Ripening

(Source adapted from: AHDB, 2015a; White, 1995)

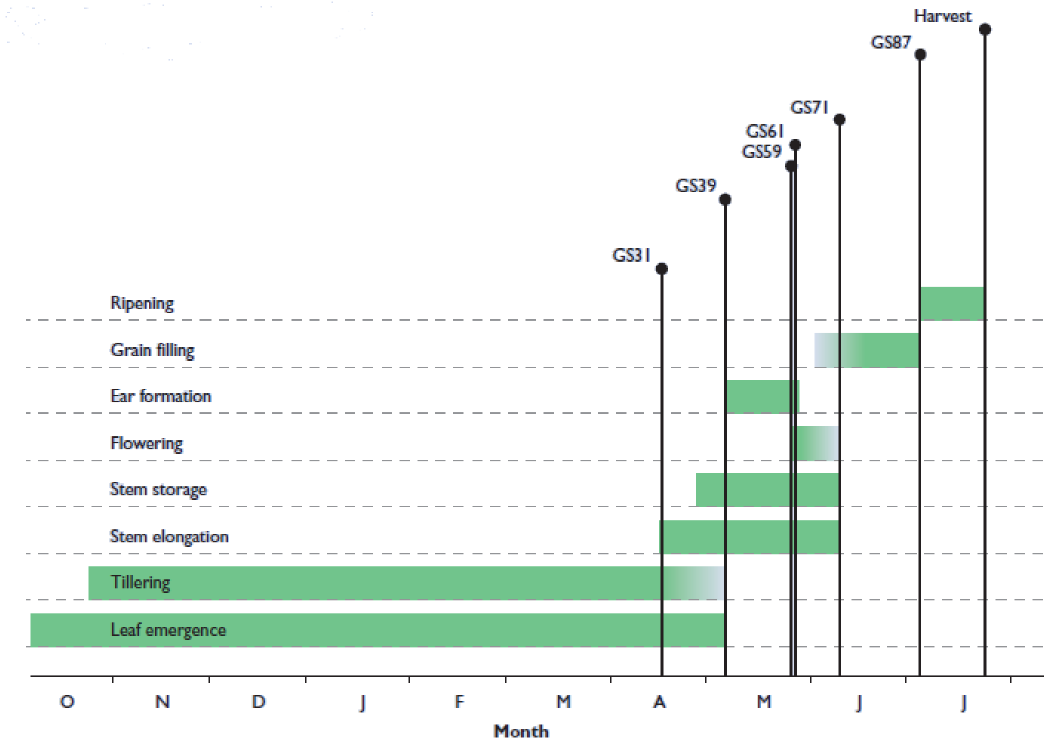

Figure 2.16 - Winter barley development phases

(Source adapted from: HGCA, 2006)

2.10.2 Growth stage benchmarks

Commercial barleys are mainly 2-row or 6-row barley. These are descriptions of the arrangement of the kernels on the head (ear) when viewed down its axis (Briggs, 1978). Barley growth stage benchmarks based on the median values from six UK trial sites for the 2-row variety Pearl (2002 to 2004) are shown in Table 2.3. Cereal benchmarks are a measure of crop progress that indicates good crop performance (AHDB, 2015b). They can be used by growers to evaluate crop performance and determine how best to manipulate crop husbandry (HGCA, 2006) by application of growth regulators, herbicides or fungicides at specific growth stages (Spink *et al.*, 2000). The understanding of the physiology of yield in conjunction with benchmarks for crop growth can be used to identify where yield limiting effects exist (Blake *et al.*, 2006).

Table 2.3 - Benchmark for barley (two-row)

Decimal Code (target date)	Stage	Plants (m^2)	Shoots (m^2)	Ears (m^2)	TGW (g)	Yield (t ha^{-1})	Straw (t ha^{-1})
GS 21 (13 Nov)	Tillering	305					
GS 30 (02 Apr)	Main shoot+3 tillers		1180				
GS 61 (26 May)	Grain filling start						
GS 87 (05 Jul)	Grain filling finish						
Harvest (26 Jul)				775	46	8.8	6.4

(Source adapted from: HGCA, 2006)

2.10.3 Cereal root growth

Roots provide mechanical support of the cereal plant but their fibrous root size and distribution within the soil is important for nutrient and water absorption and therefore crop yield. Root growth and development can be affected by soil chemical and biological properties and soil physical properties such as soil strength, bulk density, macro porosity, soil water content and aeration (Fageria, 1992). The size and efficiency of the root system is essential to supply the crop canopy with sufficient water to drive evaporation for transpiration, although root length is more important than root mass as it determines the soil volume available to supply water (Baker and Bland, 1994). Barley growth is affected by low pH soils. In the UK soils at pH 6.5 are best (Wiseman *et al*, 1993) with acid soils limed to pH 6-7 (Briggs, 1978). Prolonged waterlogging can prevent grain germination and kill roots. Cereal roots will not penetrate into soil which is below permanent wilting point (Brouwer and Flood, 1995) or grow into waterlogged soil (due to lack of oxygen). Wet soils in spring are slow to warm (Briggs, 1978) although compaction increases thermal conductivity that is beneficial to spring plant growth (Czyz *et al.*, 2001). Root growth is influenced by the availability of nutrients which also affects the root:shoot dry matter ratio

(Briggs, 1978). The early development of the cereal root structure is illustrated in Figure 2.17. Following germination the primary root is formed along with two pairs of secondary rootlets known as seminal roots. The plumule grows upwards and forms a tube-like structure above ground from which the true leaf appears. Once photosynthesis has started the plant development becomes independent of the seed (Wiseman *et al*, 1993). Adventitious roots develop from stem nodes (also called nodal roots) and are important for establishment as they transport more water than the smaller diameter seminal roots (Fageria and Moreira, 2011).

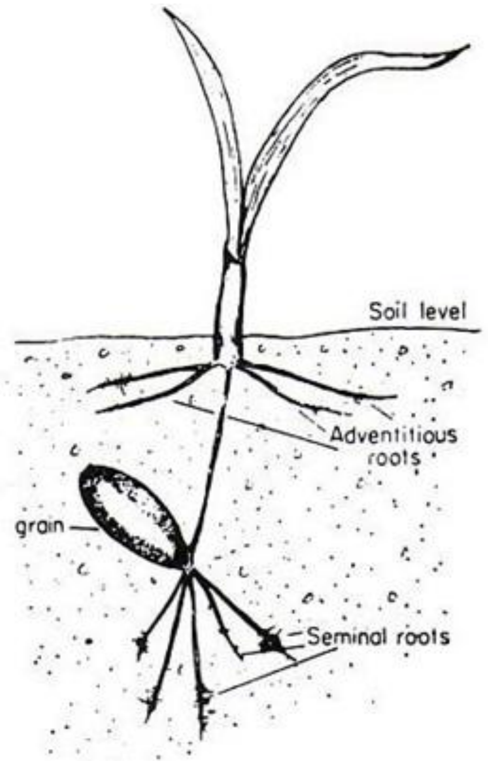

Figure 2.17 - Developing cereal plant

(Source adapted from: Wiseman *et al*, 1993)

Root length and dry weight are more easily determined than other root system properties and are often used in studies. Root growth influences nutrient and water supply and therefore yield. Although root length positively correlates to yield, root dry weight is a better predictor of stem dry weight and yield (Fageria and Moreira, 2011). Czyz *et al.* (2001) found that barley yield was '*significantly positively correlated with total root mass'*. When nitrogen supply is low, plants produce proportionally more root dry weight than shoot dry weight when compared to plants with adequate nitrogen supplies (Fageria and Moreira, 2011). Shortage of other nutrients or water produces the same effect but carbohydrate shortage produces an opposite effect (Wilson, 1988).

2.10.4 Cereal tillers

Tillers are lateral axillary shoots off the main stem (lateral stem in oats) (Brouwer and Flood, 1995) and form between GS 20 and GS 29 (White, 1995). In wheat, tiller emergence stops after ear emergence, but in some barley and oat cultivars this can continue after ear (panicle) emergence (Brouwer and Flood, 1995). Many secondary tillers are formed in barley but only a few live to produce grain spikes. Early tillers are more likely to survive and higher nutrient availability can reduce tiller mortality (Smith *et al.*, 1999). In high yield cultivars of oats increased tillering can protect against unfavourable environmental conditions. A large number of unproductive tillers in wheat has only a small effect on the growth of the productive tillers (Brouwer and Flood, 1995). Good root development aids tiller survival. As late tillers have reduced nodal roots they are more prone to dieback. Low nitrogen supply and water availability during the tillering period reduces tiller numbers and survival rates. Factors affecting nitrogen uptake include soil pH, temperature and anaerobic conditions (Smith *et al.*, 1999). Tiller survival determines the number of ears m^{-2} which is an important component of yield (HGCA, 2006).

2.10.5 Crop yield

Crop yield is the economic part of the cereal crop that is used for animal or human consumption. Soil physical and chemical properties affect crop yield but climatic variations in solar radiation, temperature and moisture supply also influence yield (Fageria, 1992). Cereal yield is dependent on the contributions of the yield components and can be expressed as: grain yield = ears m^{-2} x grains ear^{-1} x mean grain weight (Blake *et al.*, 2006; Fageria, 1992). Unlike barley and wheat, which have ears, the grain in oats is contained in a number of spikelets arranged on branches which form a panicle (White, 1995). Barley yield is less dependent on grain size than grain numbers, which are a function of grains per spike and spikes m^{-2} (Smith *et al.*, 1999). The number of ears m^{-2} is a result of final numbers of fertile shoots which is influenced by tiller production and survival. Křen *et al.* (2014) reported than barley final yield was not only dependant on tiller numbers but also on tiller size and strength and the number of grains per spike. Barley maximum shoot numbers occur at stem extension (GS 30) and the main tiller mortality period is between GS 30 and flowering (GS 59) (Blake *et al.*, 2006). Budakli Carpici and Celik (2012) showed by path coefficient analysis that harvest index, spike number per m^{-2} and grains per spike had ranked percentage direct effects on barley yield of 72%, 48% and 28% respectively. Path coefficient analysis is a statistical method of testing cause and effect relationships by splitting correlation coefficients into direct and indirect effects and can be used to study the interrelationship between components of yield and their effect on final yield (Budakli Carpici and Celik, 2012). The seeding rate and number of tillers influences the number of spikes whilst the number of grains per spike is more influenced by apical development. Factors such as temperature and nutrient and moisture availability affect apical growth (Smith *et al.*, 1999). This will affect the efficiency of photosynthesis during grain filling affecting final yield (Yara, not dated b). Barley awns are particularly important during the grain filling period as they provide 80% of the photosynthesis to the ear (Yara, not dated b and Thorne, 1973). However the flag leaf and penultimate leaf are important for grain filling in oats and rice (Brouwer and Flood, 1995). Wheat yields are reduced by insufficient water at tillering and grain filling stages (Akram, 2011). Water stress at anthesis can reduce yield in barley (Aspinall, 1966) and wheat because it reduces pollination which leads to lower grain numbers (Akram, 2011).

2.10.6 Harvest Index

Harvest Index is the ratio between grain yield and total crop weight (dry) at harvest (Equation 1.1). The ratio is variable between crops and varieties (AHDB, 2015b) with modern intensively cultivated cereal crops having values of between 0.4 and 0.6 (Hay, 1995). Plant breeders have been successful in increasing the harvest index of modern cereal varieties (AHDB, 2015b). The increased grain yield of these newer varieties is associated with shorter straw length and their increased harvest index but they also reach anthesis earlier and intercept more light during grain filling than older varieties (Wild, 1988).

$$\text{Harvest Index (\%)} = \frac{\text{weight of grain (t)}}{\text{total crop weight (t)}} \times 100$$

Equation 1.1

A crops total above ground dry matter is known as its biological yield and the economically useful part (e.g. grains for cereal) of this is known as the economic yield. The relationship between economic yield and harvest index is shown in Equation 1.2. This shows that to increase economic yield requires an increase in either total dry matter or harvest index (Fageria, 1992).

$$\text{Economic yield} = \text{biological yield} \times \text{harvest index}$$

Equation 1.2

Total above ground biomass is an indicator of final yield as confirmed by Sandaña and Pinochet (2011) who found a significant relationship (R^2=0.99) between biomass at harvest and grain yield. They stated that harvest index was largely unaffected by soil stress conditions including nutrient deficiencies (i.e. phosphorus, nitrogen and sulphur), aluminium toxicity and compaction. It was suggested that yield was therefore not affected by partitioning of biomass but as a result of biomass accumulation. This is not in agreement with Smith, E. (2016) who found a significant difference in harvest index (P=0.011) between traffic treatments (CTF=51%, LTP=48% and STP=47%) and suggested that the increased harvest index could be due to lower soil moisture.

There is a linear relationship between crop biomass produced and the amount of photosynthetically active radiation (PAR) intercepted by a crop. The slope of this relationship represents the crops radiation use efficiency. Crop yield can be expressed as a product of the solar radiation intercepted (RI), the radiation use efficiency (RUE) and harvest index (HI) as shown in Equation 1.3 (Sandaña and Pinochet, 2011).

$$\text{Yield (g m}^{-2}\text{)} = \text{RI (MJm}^{-2}\text{)} \times \text{RUE (gMJ}^{-1}\text{)} \times \text{HI (g g}^{-1}\text{)}$$

Equation 1.3

Crop yield can only be estimated by this (solar driven) relationship when the crop has adequate water to allow stomata to remain open which allows transpiration and CO^2 uptake to be close to the environmental limits. When the crop is subjected to water stress, yield will be related to the water that is transpired (Azam-Ali, 2013).

2.10.7 Crop rotation and cover crops

Conservation agriculture is an important strategy that combines diverse crop rotations and cover cropping with minimising soil tillage to sustainably manage soils, by enhancing soil quality and avoiding soil degradation, with an aim of increasing agricultural yields (Abdollahi and Munkholm, 2014; Jones *et al.*, 2006). Cover crops can increase soil organic matter content especially when used in conjunction with no-till farming systems (Nascente *et al.*, 2013).

A rotation is a cropping system where two or more different crops are grown in a fixed sequence which may also include a period in grass (lay) (Wiseman *et al.*, 1993). The benefits of a rotation for the farming business can include spreading the workload associated with planting and harvesting over a longer period of time, managing soil water and crop residues and having more than one crop to sell (Cook and Weller, 2004). Continuous cereal production is practiced by many farms and is possible due to herbicides that control weeds and improved fungicides to control disease (Wiseman *et al.*, 1993). It has economic advantages when local conditions are particularly suited to cereal production (Cook and Weller, 2004) and offers lower labour and capital costs compared to livestock or root crop farming (Cook and Weller, 2004). Wheat crops grown consecutively can be prone to damage from soil and residue borne disease, some of which can be partly controlled by seed dressings and fungicide applications, for example tan spot caused by *Pyrenophora tritici-repentis* or eyespot by *Tapesia yallundae* (Kirkegaard *et al.*, 2008). Barley and wheat are more resistant than oats to cereal cyst nematode *Heterodera avenae* which makes oats unsuitable for continuous production (Wiseman *et al.*, 1993). The take-all disease *Gaeumannomyces graminis var tritici*, a significant disease in wheat worldwide requires the use of a 'break crop' for control (Kirkegaard *et al.*, 2008). Break crops of oats, which is mostly immune from *Gaeumannomyces graminis var tritici (White, 1995),* have been shown to dramatically reduce levels of take-all in subsequent wheat crops. However, the yields in the wheat have not always been improved, as the oat residues can have a phytotoxic effect on wheat (Kirkegaard *et al.*, 1996). Popular combinable break crops in the UK are oilseed rape, peas and beans (Wiseman *et al.*, 1993). Wheat yields following *brassica* break crops are higher than after other broadleaf break crops due to suppression of wheat disease by allelochemicals mainly isothiocyanates. Cereal pathogens are highly sensitive to isothiocyanates released by oil seed rape (Kirkegaard *et al.*, 2008).

Cover crops are usually grown between two cash crops in place of leaving the soil fallow (Gabriel *et al.*, 2013) and are traditionally used to cover the ground protecting the soil from erosion (Dabney *et al.*, 2001) and to reduce nutrient leaching into water bodies (Chen and Weil, 2010). They are also able to suppress weeds and reduce crop damage from disease and insects (Fageria *et al.*, 2005). Suppression of weeds by cover crops can be due to shading or competition for water and nutrients as well as an allelopathic influence from the cover crops and their residues (Fageria *et al.*, 2005). Cover crops used include cereals and grasses, brassicas and legumes which have different properties and it is necessary to select the species or mix of species according to the function that the cover crop is required to deliver (AHDB, 2015c). Legume cover crops, in association with nitrogen fixing bacteria, fix nitrogen from the atmosphere into a form that the succeeding crop can use after the breakdown of the legume (Clark, 2007; Hartwig and Ammon, 2002). Non legume plants such as grasses and oil seed rape use residual soil nitrogen (NO_3) and prevent it from leaching from the soil (Fageria *et al.*, 2005; Hartwig and Ammon, 2002). Legume and grass mixtures can be used for both fixing and retaining nitrogen reducing the demand for additional nitrogen application for the succeeding crop (Clark, 2007). Winter cover crops have been found to decrease soil bulk density and penetration resistance and brassica cover crops may alleviate soil plough pan (Abdollahi *et al.*, 2014). Burr-Hersey *et al.* (2017) investigated the ability of cover crops to alleviate soil compaction by 'bio-drilling' using X-ray Computed Tomography. They found that radish *Raphanus sativus* and black oat *Avena strigosa* where able to penetrate compacted soil leading to improvement in soil structure by changing soil pore size distribution. Cover crops can be planted prior to harvest into the main crop or after harvest and are usually killed off before the next crop is planted (Hartwig and Ammon, 2002). Cover crops are often killed of using glyphosate but mechanical methods such as rolling, mowing, undercutting or partial rototilling are used by many farmers wishing to reduce chemical use (Fageria *et al.*, 2005).

2.11 Previous research carried out on the Harper Adams University Traffic and Tillage Trial

A randomised 3x3 factorial trial (three traffic systems (Random Traffic Farming - standard tyre inflation pressure (STP), Random Traffic Farming - low tyre inflation pressure (LTP) and Controlled Traffic Farming (CTF) and three tillage systems (deep (250mm), shallow (100mm) and no till)) with four replicated blocks was established at Harper Adams University in September 2012 after a normalisation year. For normalisation, a mouldboard plough/power harrow treatment was applied uniformly to all plots to allow the field site to stabilise after the installation of a gravel back-filled drainage system at 13 m spacing. This was followed by subsoiling operations to a depth of 0.6m (this was the maximum depth achievable due to the equipment capabilities) to remove any compaction layer that may have been formed by previous field use and to provide uniform conditions for crop production (Smith *et al.*, 2012). Winter wheat was then drilled and the resulting harvest showed good uniformity in wheat yield with a coefficient of variation of 6% (Godwin *et al.*, 2015). The first trial crop of winter wheat (*Triticum aestivum* var. *Duxford*) with the three tillage x three traffic treatments was planted in November 2012. Crop establishment was determined at GS11/12 (January 2013) using a quadrant method to determine plants m^{-2}. Data analysis found no significant effect from the traffic and tillage treatments on establishment. Photographic crop assessment at GS37/39 and immediately prior to harvest showed visual evidence of limited establishment in primary wheel ways and non-uniformity in the no-till plots. There was no significant difference found in combine harvest yields as a result of the interaction of tillage and traffic treatments at 5% probability level. The CTF treatment produced the highest mean yields (7.7 t ha^{-1}). CTF shallow tillage treatment had the highest yield of 8.3 t ha^{-1} which was 14% higher than the mean of the other treatments (7.4 t ha^{-1}) and higher by 15% (1.1 t ha^{-1}) than the standard tyre inflation pressure (STP) deep tillage mean yield (not significant at 5% probability level). STP - zero tillage treatment had the lowest mean yield of 6.8 t ha^{-1} (Smith *et al.*, 2014; Godwin *et al.*, 2015). These results suggest that (i) avoiding soil compaction through the use of a Controlled Traffic System can produce higher winter wheat yields and (ii) soil compaction produced by Random Traffic Farming and not subject to remedial tillage can reduce yields.

Smith, E. (2016) found that there was no significant differences in establishment of winter wheat and winter barley in the traffic or tillage treatments (P>0.05). The use of low inflation pressure tyres increased combine harvest yield of winter wheat by 4% but reduced yield of winter barley by 2% compared to standard inflation pressure tyres although these differences were not significant. Zero tillage significantly reduced the combine harvest yield of winter wheat (P<0.001) compared to deep and shallow tillage treatments but tillage had no significant effect on the combine harvest yield of winter barley (P=0.857).

Smith, E. (2016) measured soil bulk density, penetration resistance and hydraulic conductivity on the traffic and tillage plots. Vehicular traffic significantly increased soil bulk density (P=0.001) but there was no significant differences in soil bulk density or penetration resistance between the low inflation pressure and standard inflation pressure treatments. Hydraulic conductivity was significantly (P<0.001) higher in the untrafficked soil in the CTF plots compared to the wheelways. The effect of the traffic and tillage treatments in the Large Marsh trial on soil aggregate stability was investigated by Abell (2016). Deep tillage significantly (P=0.020) reduced the proportion of stable aggregates (77.8%) compared to zero tillage (87.5%) but there was no significant effect from traffic. Deep tillage significantly (P=0.049) increased water infiltration rate compared to zero tillage treatments and traffic decreased water infiltration (STP w treatments were significantly (P=0.014) lower than the untrafficked CTF ut treatments). Smith, E. (2016) also found that traffic significantly (P < 0.001) decreased water infiltration compared to untrafficked treatments and that deep tillage treatments had significantly (P = 0.009) greater water infiltration rates than shallow and zero tillage treatments. Abell (2016) also found that the soil organic matter was not significantly different between the traffic and tillage treatments.

Smith, V.L. (2016) investigated the effect of the traffic and tillage treatments upon earthworm density. Earthworm numbers were found to be significantly higher (P=0.004 in autumn and P<0.001 in winter) in the zero tillage treatments compared to the deep tillage treatments. This was thought to be because soil disturbance was lower in the zero tillage treatments and that tillage is known to be destructive to earthworm burrows and habitat. Ahmed *et al.* (2016) studied the effect of the traffic and tillage treatments upon nematode assemblages. They found that *Acrobeloides* (bacteria feeding) were significantly (P< 0.050) more abundant in the shallow tillage treatments than in the deep or zero tillage treatments. *Meloidogyne* (root knot nematode) and *Pratylenchus* (root lesion nematode), had significantly higher numbers in the zero tillage treatments compare to the tilled treatments (P<0.0001).

2.12 Literature review conclusion

To increase the productivity of modern cropping systems and reduce production costs has required agricultural machinery to become more powerful and therefore heavier. Soil degradation due to compaction from this machinery is a major problem for agriculture and affects an area of 68 million ha globally of which 33 million ha is in Europe. When a stress is applied to a soil in excess of the soil's strength, compaction occurs. This increases the bulk density of the soil, as a result of a reduction in soil porosity, reducing the proportion of large to small pores. This change in pore structure affects soil strength and thermal conductivity and reduces soil aeration, which decreases crop root and shoot growth, leading to reduced nutrient use efficiency that affects growth and reduces yield. The degree of compaction of a soil from agricultural machinery depends upon the stress applied by the vehicle tyre, the strength of the soil and the soil moisture. Wet soils are less able to resist compaction and increases in soil moisture lead to increased soil compaction.

Uncontrolled agricultural field traffic (Random Traffic Farming (RTF)) is a common feature of modern farming which can lead to in excess of 85% of a field being trafficked annually by agricultural vehicles. Controlled Traffic Farming (CTF) is a field traffic system that restricts agricultural machinery to sacrificial traffic lanes whilst leaving separate crop zones free from traffic. Well designed CTF systems require all machinery to have matched working widths and rely on the use of navigation and auto-steer technology but they can restrict the area of a field that is trafficked by vehicle tyres to 15%. The lack of adoption of controlled traffic management systems in the UK is thought to be due to non compatibility of machinery working widths but there can be beneficial increases in crop yield using existing farm equipment by using a controlled traffic system. Where field traffic is necessary, the use of low ground pressure systems (low inflation pressure tyres or tracks) can reduce the risk of soil compaction by increasing the ground contact pressure for a given load. Researchers have found that low inflation pressure (LTP) tyres can reduce soil compaction and increase crop yields compared to using standard inflation pressure tyres. Stresses under LTP tyres have been found to reduce soil stresses in the top 100 mm of the soil but they do not influence stresses in the subsoil below 300 mm.

Tillage is an important component of modern cropping systems that is used to remove biological, chemical and physical limitations within the soil to provide better conditions for crop establishment and growth. To produce the maximum crop yield tillage must be tailored to the local environmental and climatic conditions. Tillage is used to incorporate crop residues and nutrients into the soil, destroy weeds and improve soil aeration and water infiltration. Long term use of inversion tillage can lead to soil degradation by erosion.

This can be by wind or water runoff, the latter can also lead to pollution of water bodies by pesticides and nutrients. Repeated cultivations at the same depth can lead to plough pan, a region of high bulk density below the cultivation depth, that forms a barrier to crop roots and limits water infiltration. Plough pan removal requires deep loosening of the soil which reduces the bearing capacity of the soil and leaves the soil at risk of further compaction from agricultural traffic. Non-inversion tillage (reduced tillage) can be used as an alternative to mouldboard ploughing as the use of broad-spectrum herbicides has removed the need to bury weeds. Minimising tillage, maintaining year round soil cover and employing diverse crop rotations (the three principles of Conservation Agriculture) promotes biological processes in the soil that allows sustainable high crop yields. In the UK reduced tillage is used on 40% of arable land but only 5% of arable land is under no-till (direct drilling) compared to 20% in the USA. The susceptibility of soil to erosion is reduced under no-till systems, as runoff is reduced and infiltration is increased, due to increased macro pore stability and connectivity. However crop yields in climates with cold springs or on heavy or poorly drained soils can be reduced for no-till systems. The main areas associated with cereal growing in the east of the UK are most suited to no-till cereal farming.

This literature review highlighted the importance of good soil structure to provide suitable conditions for high crop yields and that the most important feature of soil structure is soil porosity. Soil porosity is usually calculated from bulk density and soil pore size distribution by means of water desorption or mercury intrusion. Although these methods have given a good understanding of the nature of soil porosity they are indirect methods that describe porosity. The use of image analysis on thin soil sections can provide information on pore size, shape, orientation and connectivity but is not only difficult but also time consuming. Although there is a quantity of research on soil structure connecting good structure to crop yields or soil water transport, there seems to be little information on what is a good structure from its actual properties. The development of X-ray CT in the use of soil analysis has allowed measurement of soil pore size and distribution as well as pore shape, orientation and connectivity to be relatively quick. Much of the previous X-ray CT research has concentrated on developing the technique in soil analysis especially around the technical problems associated with segmenting the images. Studies on soil compaction and tillage has mainly been focussed on 'two field' studies. It is believed that this research is the first time that X-ray CT has been used to measure the properties of soil from a long-term traffic and tillage trial.

Previous research by Smith, E. (2016) on the traffic and tillage plots on Large Marsh at Harper Adams University found no significant differences in establishment of winter wheat and winter barley in the traffic or tillage treatments (P>0.05). Although not significant, yields were increased in the low inflation pressure tyres treatments compared to standard inflation pressure tyre treatments for winter wheat (4%) but decreased for winter barley (2%). Zero tillage significantly (P<0.001) reduced the combinable yield of winter wheat compared to deep and shallow tillage treatments but was not significantly different for winter barley. Soil physical properties measured were soil bulk density, penetration resistance and hydraulic conductivity. Vehicular traffic significantly increased soil bulk density (P=0.001) but there was no significant differences in soil bulk density or penetration resistance between the low inflation pressure and standard inflation pressure treatments. Hydraulic conductivity was significantly (P<0.001) higher in the untrafficked soil in the CTF plots compared to the wheelways.

2.13 Identified research gap

The literature has identified that improvement in the productivity of modern cropping systems has led to agricultural soils being degraded by soil compaction. This has led to reductions in crop yield. Tillage is used to improve soil properties to increase yields but can also lead to soil degradation. Controlled Traffic Farming and the use of low inflation pressure tyres are identified as strategies to reduce the impact of agricultural traffic on soils. A reduction in tillage intensity, including no-till systems, can improve the structure of soils. There are few studies that have investigated the long term effect of traffic and tillage interactions on soil properties and crop yield. Although earlier work on this trial identified benefits from Controlled Traffic Farming and low inflation pressure tyres (not significant) compared to random traffic farming with standard inflation pressure tyres for crop yields, this was only based on two years of winter crop data. There is no data on how the traffic and tillage treatments affect spring crop growth and yield. It has also not been possible to access how repeated annual application of the traffic and tillage treatments and their interactions affect soil physical properties and crop growth and yield. There was insufficient data years to access the effect of annual weather fluctuations on crop yields. The effect of traffic and tillage on crop establishment, growth and yield was studied by Smith, E. (2016) but did not include analysis on root development and its relationship to biomass in response to the traffic and tillage treatments. Smith, E. (2016) measured soil physical properties by the indirect methods of soil bulk density, penetration resistance and soil water infiltration. There is no data on soil porosity (particularly micro porosity), soil pore distribution or connectivity changes due to the traffic and tillage treatments or how these changes may relate to crop growth and yield.

Chapter 3 General methodology

3.1 Introduction

This chapter describes the configuration of the long term traffic and tillage trial based at Harper Adams University since 2011, the equipment used and the methods involved in the application of the traffic and tillage treatments and the drilling of the crops. The detailed methodologies for the experiments and studies carried out during the three years of this research (2015-2017) are detailed in the appropriate chapters (i.e. Chapters 4, 5 and 6).

3.2 Harper Adams University traffic and tillage trial

In 2011, a long-term study was set up at Harper Adams University, Shropshire, UK (Figure 3.1) to investigate the effect of three traffic systems (Random Traffic Farming - standard tyre inflation pressure (STP), Random Traffic Farming - low tyre inflation pressure (LTP) and Controlled Traffic Farming (CTF)) for soils managed with three tillage systems (deep (250 mm), shallow (100 mm) and no-till) on soil properties, crop yield and energy requirements.

Figure 3.1 - Map of the United Kingdom showing the location of Harper Adams University

(Source adapted from: Google, 2018)

The experimental work was conducted on a 3.12 ha portion of a field known as Large Marsh (Figure 3.2) with a sandy loam soil mainly Claverley, with small areas of Olerton and Salwick series soils (Beard, 1988). This long term trial was designed to enable a full arable rotation to be studied (the first five years crops being winter wheat, winter barley, winter barley, winter cover crop, spring oats and spring wheat).

Figure 3.2 - Harper Adams University, Shropshire. UK: Looking South East. Large Marsh field trial area outlined in red

(Source adapted from: Commission Air Ltd, unpublished, 2015)

Large Marsh field at Harper Adams University was selected for the long term traffic and tillage experiment because of its relative uniformity and location. Historically it had been split into 3 different fields with a total area of 8.51 ha. In September 2011 Kristof *et al.* (2012) measured soil electromagnetic conductivity (using a DUALEM-2S) to determine soil texture and elevation, to evaluate the three areas of the field for spatial variability (Figure 3.3). This work indicated that area A had the lowest variability in soil texture with little elevation change and hence the study was sited in this part of the field. The randomised 3x3 factorial study (three tillage x three traffic) with four replicated blocks was established on part A of Large Marsh field (area outlined in red at Figure 3.2) in September 2012 after a normalisation year. For normalisation, a mouldboard plough/power harrow treatment was applied uniformly to all plots to allow the field site to stabilise after the installation of a c.1m deep, 13m spaced back-filled pipe drainage system followed by subsoiling operations to a depth of 0.6m, to remove any deep compaction (Smith *et al.*, 2014). Winter wheat was then drilled and the resulting harvest showed good uniformity in wheat yield with a 6% coefficient of variation (Godwin *et al.*, 2015).

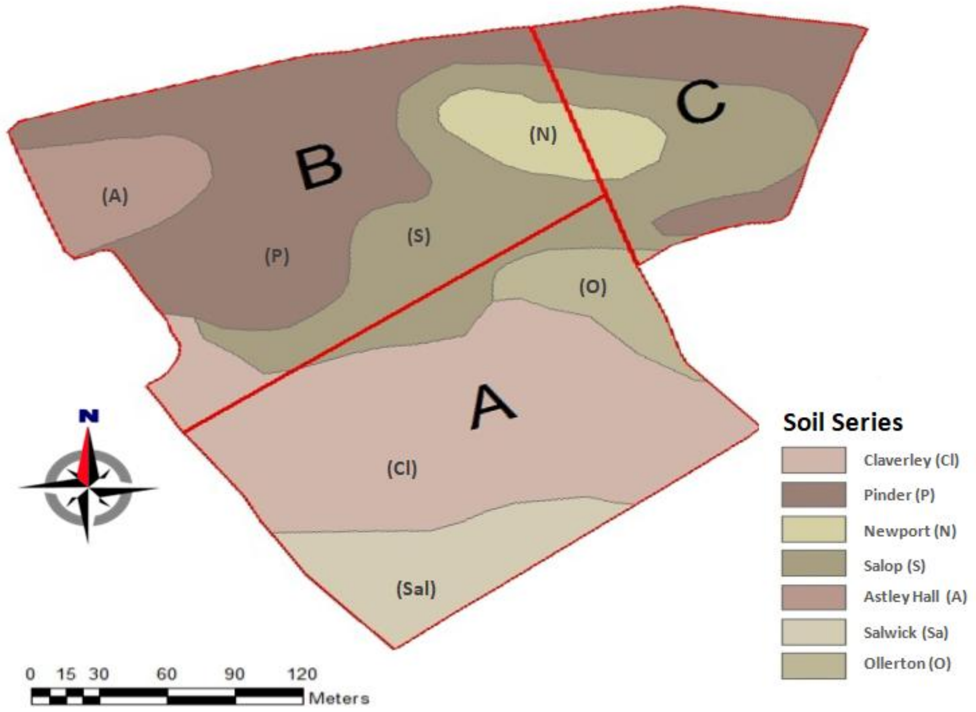

Figure 3.3 - Soil series distribution for Large Marsh field, Harper Adams University

(Source adapted from: Kristof *et al.*, 2012)

3.3 Field - Block and plots layout

3.3.1 Plot plan

The three tillage (deep, shallow, zero) x three traffic (Random Traffic Farming STP (standard tyre inflation pressure), Random Traffic Farming LTP (low tyre inflation pressure), CTF - Controlled Traffic Farming) trial with four replicated blocks each containing nine plots nominally 4m wide by 80m long and with randomised treatments were as follows:

1. STP Deep Tillage	4. LTP Deep Tillage	7. CTF Deep Tillage
2. STP Shallow Tillage	5. LTP Shallow Tillage	8. CTF Shallow Tillage
3. STP Zero Tillage	6. LTP Zero Tillage	9. CTF Zero Tillage

The four trial replication blocks were arranged as shown in Figure 3.4. Block 4 had to be offset from blocks 1-3 to avoid the surface inlet of a historical land drain. The nine treatments were randomly allocated plots as shown in Figure 3.5. Plots were numbered from right to left with a spare plot between each block. For the years 2015-2017 these three spare plots were allocated different tillage depths and were used to set tillage and drilling machinery and to check drilling depths prior to applying the treatments to the trial plots.

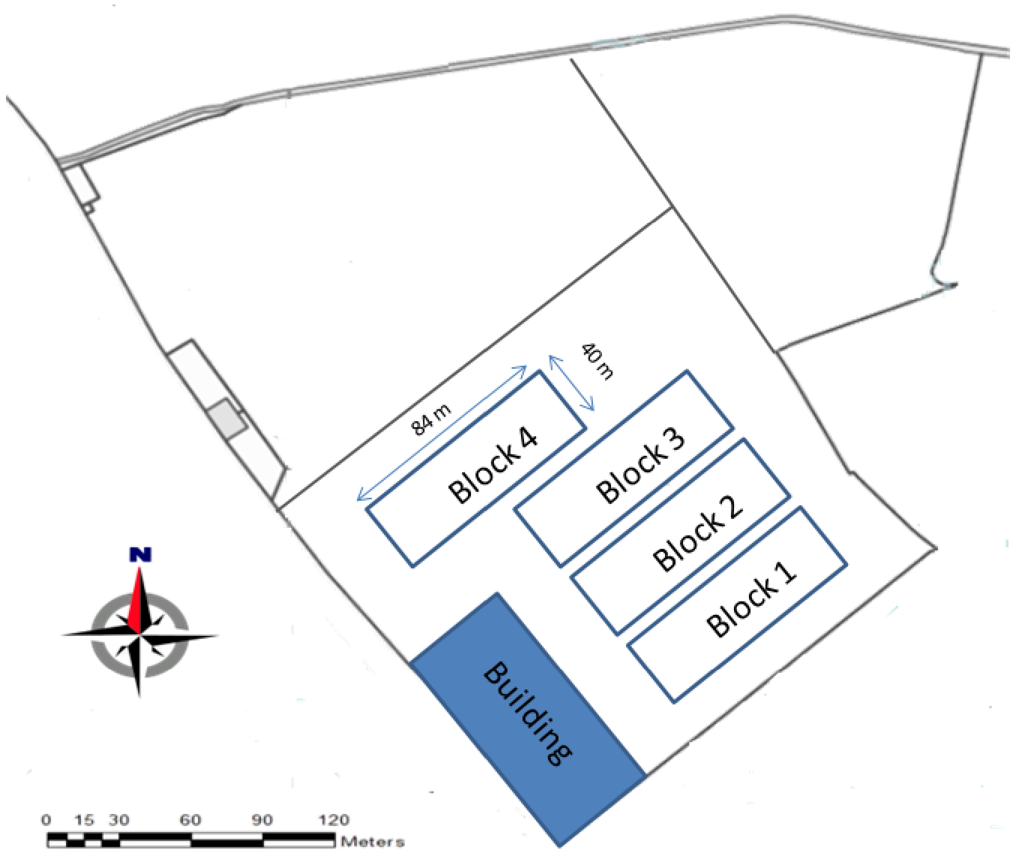

Figure 3.4 - Schematic of the arrangement of the four trial replication blocks on Large Marsh field

Block 4	Plot 36	CTF	Deep
Block 4	Plot 35	LTP	Shallow
Block 4	Plot 34	CTF	Zero
Block 4	Plot 33	STP	Shallow
Block 4	Plot 32	LTP	Deep
Block 4	Plot 31	STP	Deep
Block 4	Plot 30	LTP	Zero
Block 4	Plot 29	STP	Zero
Block 4	Plot 28	CTF	Shallow
	Spare 3		Zero
Block 3	Plot 27	LTP	Shallow
Block 3	Plot 26	LTP	Zero
Block 3	Plot 25	STP	Deep
Block 3	Plot 24	CTF	Zero
Block 3	Plot 23	STP	Shallow
Block 3	Plot 22	CTF	Deep
Block 3	Plot 21	LTP	Deep
Block 3	Plot 20	STP	Zero
Block 3	Plot 19	CTF	Shallow
	Spare 2		Shallow
Block 2	Plot 18	STP	Deep
Block 2	Plot 17	CTF	Deep
Block 2	Plot 16	LTP	Zero
Block 2	Plot 15	STP	Zero
Block 2	Plot 14	CTF	Zero
Block 2	Plot 13	STP	Shallow
Block 2	Plot 12	LTP	Shallow
Block 2	Plot 11	CTF	Shallow
Block 2	Plot 10	LTP	Deep
	Spare 1		Deep
Block 1	Plot 9	STP	Shallow
Block 1	Plot 8	CTF	Shallow
Block 1	Plot 7	LTP	Zero
Block 1	Plot 6	STP	Zero
Block 1	Plot 5	LTP	Shallow
Block 1	Plot 4	CTF	Deep
Block 1	Plot 3	CTF	Zero
Block 1	Plot 2	LTP	Deep
Block 1	Plot 1	STP	Deep

Figure 3.5 - Traffic and tillage treatment configuration for the four replicated blocks

3.4 Trial traffic and tillage treatments

The protocol for applying the traffic and tillage treatments was changed in 2015 from that used by the previous researcher due to equipment availability. The protocol described here is applicable to years 2015-2017 but differences applicable to the previous research is highlighted.

A Massey Ferguson 8480 tractor (Figure 3.6) was used for applying all the traffic and tillage treatments and drilling the crops each year. Total vehicle weight was 12.55 tonnes (weight distribution: front axle 5.55 tonnes, rear axle 7.00 tonnes) with a track width of 2.05 metres. Previous research had used the Massey Ferguson 8480 tractor to apply the additional compaction treatments (detailed in 3.5.1) but a Cat Challenger MT765C (Figure 3.7) tracked tractor was used to apply the tillage treatments and the crop drilling operations (Smith, E., 2016). An investigation by Smith, E. (2016) found that the Cat Challenger MT765C produced consistently lower soil pressures compared to using MachXBib and AxioBib tyres and concluded that the use of Cat Challenger MT765C tracked vehicle would complement the low inflation pressure tyres. The Cat Challenger MT765C was not available to use for this research. The use of the tracked tractor before 2015 meant that the primary wheelways in all traffic treatment plots (CTF, LTP and STP) had benefitted from low ground pressure running gear (Smith *et al.*, 2014). The use of the Massey Ferguson 8480 tractor to apply the tillage treatments and the crop drilling operations from 2015 onwards would allow the standard inflation pressure to be used for all compaction applied to the STP to better represent a Random Traffic standard tyre pressure farming system. As Controlled Traffic Farming is a management strategy intended to minimise compaction of soil (Gasso *et al.*, 2014) it was decided to leave the CTF plots with a low ground pressure treatment for the wheelways. This would enable comparisons to be made with the findings of the previous researcher and between Controlled Traffic Farming low inflation tyre pressure and Random Traffic low inflation tyre pressure to measure the effect on soil properties and crop growth by controlling traffic. Similarly a comparison could be made between Random Traffic low inflation tyre pressure and Random Traffic standard inflation tyre pressure to measure differences due to tyre inflation pressure. The trial design would not allow the CTF plots to have both low inflation tyre pressure and standard tyre inflation pressure treatments which is recommended for future studies. The Massey Ferguson 8480 was fitted with Michelin Axiobib tyres (IF 650/85 R38 TL 179D, rear and IF 600/70 R30TL 159D, front). Tyre pressures were set to 1.2 bar front, 1.5 bar rear for STP plots and 0.7 bar front and rear for LTP and CTF plots. Prior to 2015 the tyres used were Michelin MachXbib tyres (600/70 R28 front and 650/85 R38 rear) with the same tyre pressures as used with the Axiobib tyres. (Smith *et al.*, 2014). In 2015 the navigation of the tractor was provided by a Trimble FmX integrated display unit (Trimble, 2018a) connected to a Trimble EZ-Steer steering system (Trimble, 2018b). The EZ-Steer was replaced in autumn 2015 by an in-vehicle auto-steer system.

Figure 3.6 - Massey Ferguson 8480 (216.3 kW [290 HP]; 12.5 tonne) tractor

Figure 3.7 - Caterpillar Challenger MT765C tractor

(Source adapted from: Misiewicz, unpublished, 2012)

3.4.1 Traffic treatments

Traffic treatments (compaction) were applied with the Massey Ferguson 8480 tractor. The number of vehicle passes applied and plot area covered simulated real farm traffic systems (Smith *et al.*, 2013; Smith, E., 2016) based on the findings of Kroulik *et al.* (2009) and were designed to represent the total area and intensity of field trafficking that could reasonably be expected on a field due to the operations of agricultural vehicles associated with cereal production in a growing season. The constraints of the trial plot sizes led to 30% of the CTF plots being wheeled. It is expected that a farm using a CTF system could reasonably expect a lower percentage wheeled area. Chamen (2015) reported that the usual maximum width for CTF systems is 12 metres, restricting soil wheeled area to 13%.

The application of traffic treatments in the trial plots is shown diagrammatically at Figure 3.8. Table 3.1 shows the areas of traffic treatment per vehicle pass. The front and rear tractor tyre from one side of the tractor created each compaction treatment pass. The area of the random traffic plots (both standard and low inflation pressure) subjected to wheeling was 75% for deep, 60% for shallow and 45% for zero tillage plots. As the controlled traffic plots only had wheeling from the tillage and drilling applications and no extra traffic treatments applied, the area wheeled was 30% of the plot.

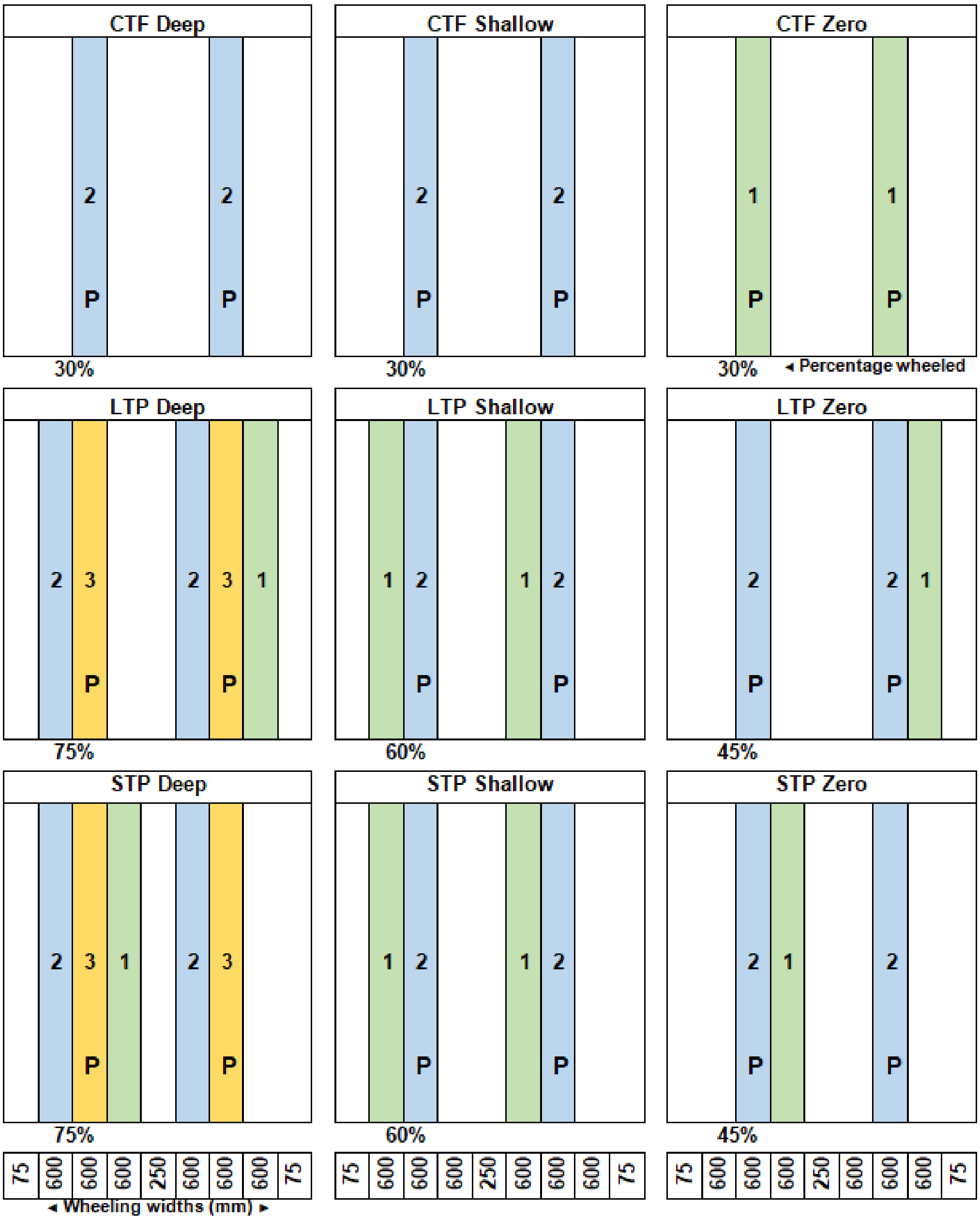

Figure 3.8 - Trial plot compaction plan showing percentage area and widths of traffic treatments for the nine treatments plots.
Coloured strips represent traffic wheelings; central numbers the nominal tractor passes; letter P the primary wheelways

Table 3.1 - Area of plot covered by traffic treatments (%)

	STP and LTP				CTF			
Tillage/Passes	1	2	3	Total	1	2	3	Total
Deep	30	30	15	**75**	0	30	0	**30**
Shallow	30	30	0	**60**	0	30	0	**30**
Zero	15	30	0	**45**	0	30	0	**30**

The desired level of traffic treatment detailed by Figure 3.8 and Table 3.1 was achieved in two parts. Each treatment plot has a pair of 'primary' wheelways (indicated by the letter P in Figure 3.8 which received compaction from the tractor when carrying out tillage and drilling operations. This accounts for all the traffic treatment in the CTF plots (Table 3.1). In order to simulate the extra traffic due to random traffic farming expected in real world farming, extra traffic treatments were applied to the STP and LTP traffic plots using the protocol given in Appendix A. For winter crops this was carried out in the autumn after the previous harvest. The autumn traffic treatments were applied in August 2014 (previous researcher) for the 2015 crop and 20th August 2015. As a cover crop was drilled in autumn 2015 (Section 6.3.3) it was decided to add a smaller additional traffic treatment in Spring 2016 to simulate the extra operations likely to be associated with the establishment of a cover crop. The protocol used is given in Appendix A. In 2016 the crop rotation dictated a move to spring crops and hence the compaction treatment was applied 28th March 2017. The estimated soil moisture (using the method in Section 3.9) at the time of the traffic and tillage treatments was 20th August 2015 (13%), 5th April 2016 (21%) and 28th March 2017 (21%) (National Rivers Flow Archive, 2019).

3.4.2 Cultivation equipment and settings

The deep and shallow tillage treatments were applied using a 4 m wide Väderstad Topdown, a high intensity multipurpose cultivator (Väderstad, Not dated a), pulled by the Massey Ferguson 8480 tractor along the primary wheel ways (Figure 3.9). A Caterpillar Challenger MT765C tractor was used prior to 2015. The tillage tines were set to 250 mm (deep tillage) and 100 mm (shallow tillage) depth on “spare 1” and “spare 2” plots respectively. Implement depths were set using packers on the hydraulic rams and depth markers (Figure 3.10). Tillage depths were checked using a wooden rule pushed into the tine slots in the soil and the equipment settings were adjusted as necessary prior to carrying out the cultivation treatments. The 14 standard tines had 270 mm spacing and the front discs were set to 50 mm depth. The protocol used is given in Appendix A.

Figure 3.9 - Väderstad 4 metre wide Topdown cultivator pulled by the Massey Ferguson 8480 tractor

Figure 3.10 - Implement depth settings on the Väderstad Topdown left: indicators and right: packers

3.5 Crop drilling

The crops used in this research (January 2015 - December 2017) and in the previous research (September 2011 - September 2014) are detailed in Table 1.1. The rotation was intended to follow a continuous cereal production system with a combinable break crop as described by Wiseman *et al.* (1993). To reduce the infection risk from 'take-all' (Cotterill and Sivasithamparam, 1988) a break crop of oilseed rape (*Brassica napus*) was drilled in autumn 2014 but failed to establish due to very wet conditions (Smith, 2015. Pers. Comm.). As a result a replacement second winter barley (*Hordeum vulgare* var. Cassia) crop was planted 20th October 2014. Expected difficulties with combine harvesting the crop and capturing the yield with the Claas Dominator 85 combine harvester meant that an oilseed break crop could not be planted in 2015/2016. To provide a suitable break from wheat and barley a TerraLife-N-Fixx cover crop was planted 3rd September 2015 followed by spring oats (*Avena sativa* var. Aspen) planted 25th April 2016. Break crops of oats, which is mostly immune from *Gaeumannomyces graminis var tritici* have been shown to dramatically reduce levels of take-all *(White, 1995)*. Spring wheat (*Triticum aestivum* var. Mulika) was planted 4th April 2017.

Each crop was drilled using a Väderstad Spirit pneumatic seed drill (Väderstad, Not dated b) pulled by the Massey Ferguson 8480 along the primary wheel ways (Figure 3.11). A Caterpillar Challenger MT765C tractor was used prior to 2015. The Spirit drill has 24 seed coulters however the outside coulters were blocked to prevent seed placement. This provided a gap between plots to aid manual combine harvest guidance. Wheel track eradicator tines were fitted to the Spirit drill. These were lifted out of the soil during drilling of the zero tillage (no-till) plots to preserve their no-till status. The drill settings for each tillage system was set on the three spare plots to check seed depth and soil packing prior to drilling the trial plots. The cover crop was drilled 3rd September 2015 (40 kg ha^{-1}), spring oats 25th April 2016 (350 seed/m^2 +30% for no-till plots) and spring wheat 4th April 2017 (400 seed/m^2 +30% for no-till plots). The protocol used is given in Appendix A.

Figure 3.11 - Väderstad 4 metre Spirit drill pulled by the Massey Ferguson 8480 tractor

3.6 In field crop row identification

GPS technology (Trimble FmX integrated display unit (Trimble, 2018a)) was used to apply the traffic and tillage treatments (and crop drilling). Each of the 36 trial plots had its own AB line down the centre. All in-field survey/experimental work used this centre (AB) line as the datum. After crop emergence the boundaries of each plot were identified by counting the crop rows and placing a marker before row 1, at the centre point between rows 11 and 12 and after row 22 (each plot contained 22 rows). The crop row numbering in each plot was from East to West.

3.7 Agronomy

Agronomic and application recommendations were provided by Hodges and Moss (H.L. Hutchinson Ltd). Fertilisers, herbicides and fungicides were applied to all trial plots along perpendicular (to plot length) tramlines spaced at 24 metre intervals. This provided equal application of inputs and trafficking to all trial plots. Additionally the application tramlines provided pedestrian access to the plot interiors avoiding trial crop damage. Fertiliser, herbicide and fungicide applications for the three years of this research are given in Appendix B.

3.8 Weather data

Harper Adams University has a fully automated Meteorological Monitoring System (MMS) that records rainfall, temperature, wind speed and direction, solar radiation and soil temperatures (Harper Adams University, 2010). Live and historical data is available for research on the Harper Adams University intranet (Harper Adams University, 2018). Mean monthly rainfall for Harper Adams University for the seasons (September to August) 2011/12 to 2016/17 are shown in Table 3.2. The season 2011-12 was wettest with an annual rainfall of 885 mm which was 26% higher than the 705 mm annual mean for the six years. April 2012 was particularly wet with 175 mm of rainfall which was 257% higher than the April mean of 49 mm. June, July and September 2012 had 75%, 106% and 178% higher rainfall than the monthly mean rainfall of 64, 72 and 37 mm respectively. Season 2016 had 34% less rainfall than the six year mean with April to August 2017 having 48% less rainfall than the six year mean for the same period.

Table 3.2 - Mean monthly rainfall at Harper Adams University for the seasons 2011/12 to 2016/17 (September - August)

	Mean monthly rainfall (mm) 2011-2017					
Season/Month	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
September	23	103	11	19	43	22
October	36	56	58	64	39	23
November	70	88	67	85	59	76
December	93	114	61	67	84	27
January	58	64	100	51	105	47
February	21	59	89	25	21	56
March	19	59	33	61	78	56
April	175	13	14	16	61	14
May	48	91	59	59	56	43
June	112	31	60	51	86	42
July	148	67	50	57	55	57
August	82	40	82	105	59	2
Season total	**885**	**785**	**685**	**660**	**747**	**465**

3.9 Estimating soil water content for field operations

This research investigates the cumulative effects of annual traffic and tillage treatments on soil properties and crop yields. The nature of the research so far has not allowed a continuous monitoring of soil properties that would make it possible to identify changes in soil properties due to a single traffic or tillage treatment event. The application of traffic and tillage treatments relied on the availability of external equipment and technicians which restricted the time available to carry out the application of traffic, tillage and drilling operations. Therefore there was not time to carry out surveys of soil water content during these operations due to the size of the trial plots. Smith, E. (2016) measured gravimetric soil moisture content and found no significant differences is soil moisture content suggesting that the moisture content in all treatments would be the same during the application of traffic treatments. It is recommended that future research could include the continuous monitoring of soil water content to identify any differences in water content between the treatments and any moisture variation due to heterogeneous vertical soil compaction as suggested by the literature. Negi *et al.* (1981) found that the optimum soil moisture for maximum compaction of a sandy loam in experimental plots was 23% (+/-3%).

The United Kingdom Meteorological Office produces monthly estimates of soil water deficit for Great Britain produced using the United Kingdom Meteorological Office rainfall and evaporation calculation system (MORECS 2.0) (Hough and Jones, 1997) which is included in the Monthly Hydrological Summaries provided by The National Hydrological Monitoring Programme (NHMP) available from the National Rivers Flow Archive (2019). The data is provided for 40 x 40 km squares based on the Ordnance Survey National Grid (Hough and Jones, 1997) and relates to soil deficits for grass cover. The available water content (AWC) used by MORECS 2.0 is calculated for grass as 133 mm (Hough and Jones, 1997). The soil moisture deficit at field capacity (FC) = 0 mm (Piwowarczyk *et al.*, 2011) and the soil moisture deficit at permanent wilting point (PWP) is 133 mm. The percentage soil moisture volume at FC for a fine sandy loam soil = 23.3% and at PWP = 6.3% (i.e. volumetric AWC = 17%) as shown in Figure 4.13. For every 10 mm water deficit for grass reported by MORECS 2.0 volumetric water content in a sandy loam soil reduces by 1.28%. Using the reported MORECS 2.0 water deficit for the Harper Adams University area for a particular time, it is possible to estimate the soil moisture content in Large Marsh soil at that time (see Section 3.4.1). The use of meteorological data relies on assumptions and approximations which can affect the accuracy of soil water storage calculations (Marshall, 1959).

3.10 Statistical analysis and confidence level

Statistical analysis of data was conducted using Genstat 18th Edition and Microsoft Excel. Details of the functions used are in the relevant methodologies in Chapters 4, 5 and 6. Voorhees (1991) suggested that the moving away from the 95% confidence level in crop studies was becoming more prevalent as it more reflected the decisions made in real world farming situations. This view was shared by Godwin *et al.* (2015) who thought that '*over rigorous statistical significance*' could hinder the adoption of beneficial soil management techniques and therefore used a 90% confidence level in presenting their results. As means are the most important outcome of investigations, Webster (2007) recommends that standard error of means should be reported so that the reader can make an informed decision on whether the results are significant. This report uses *P*-values, standard error of the means (SEM) and coefficient of variance (%CV) to aid interpretation of the results with statistical significance reported at the 95% confidence level.

Chapter 4 Soil physical properties: In-field measurements

4.1 Introduction

Compaction of agricultural soils by heavy machinery is a major problem and accounts for the degradation of an area of 33 million ha of soil in Europe (Kroulik *et al.*, 2009). Graves *et al.* (2015) estimate that soil compaction costs UK agriculture £181 million per year in lost yields. Tillage to remove traffic induced soil compaction can be more of a problem than soil compaction as it can result in soil structure degradation and erosion (Lal *et al.*, 2007; Montgomery, 2012). Ploughed soils have been found to have reduced microbial biomass such as fungi, earthworm and beetle populations (Stoate *et al.*, 2009). Reduced tillage is considered to be a solution for this problem (Tullberg *et al.*, 2007). Chamen *et al.* (2015) identify the use of low ground pressure tyres and the adoption of controlled traffic farming as methods to avoid soil compaction.

The effects of the traffic and tillage treatments used in this research on the soil aggregate stability and water infiltration rates have been studied by other researchers (Section 2.11). Due to time constraints these were not repeated in this research as it was considered that a repeat of these experiments would not add additional knowledge.

Dry bulk density is a means of identifying changes in soil compaction and total soil porosity in response to vehicular traffic and the mechanical effect of tillage operations (Campbell, 1994). Bulk density is the mass of solid matter for a given volume of soil and is used to determine the ratio of soil particles to pore space (Lewis, 2008). Soil compaction increases soil strength which increases penetration resistance for crop roots (Wolkowski, 1990). Soil strength can be measured quickly in the field using the shear (field) vane (shear strength) and penetrometer (penetration resistance). As a penetrometer measures vertical and horizontal stresses, both shear vane and penetrometer methods can be used to measure the soil horizontal stress component which is changed permanently by loads applied to soil (Hoefer and Bachmann, 2012).

The previous researcher Smith, E. (2016) measured soil penetration resistance and dry bulk density in an un-replicated study in the traffic and tillage plots for the first experimental year (2013). This was followed by a replicated study in July 2014 after the trial plots had received the 2nd (n=2) annual traffic and tillage treatment application. Bulk density measurements were collected for 100 mm sections to a depth of 300 mm. Bulk density in the STP 2 pass wheelings was found to be higher than in the LTP 2 pass wheelings but this was not significant (*P*=0.75). The deep tillage treatments had a significantly lower (*P*=0.042) bulk density (1.57 Mg m^{-3}) than the shallow (1.66 Mg m^{-3}) and zero (1.65 Mg m^{-3}) tillage treatments.

4.2 Research hypothesis and objectives

The hypothesis for this research was that after repeated applications of vehicular traffic, soil compaction is increased as measured by bulk density, penetration resistance and shear strength and that by using Controlled Traffic Farming, low inflation pressure tyres and reduced tillage systems soil bulk density, penetration resistance and soil shear strength are decreased.

The objectives were:

1. To determine changes in soil shear strength, penetration resistance and bulk density after five (n=5) applications of the three traffic treatments (wheeled using standard tyre inflation pressures, wheeled using low tyre inflation pressures and untrafficked) and three tillage treatments (deep (250 mm), shallow (100 mm) and zero tillage (no-till)).

2. To determine the effect of the traffic and tillage treatments on crop dry biomass.

4.3 Methodology

In 2011, a long-term study was set up on the Large Marsh field at Harper Adams University, UK to investigate the effect of three traffic systems (Random Traffic Farming - standard tyre inflation pressure (STP), Random Traffic Farming - low tyre inflation pressure (LTP) and Controlled Traffic Farming (CTF)) and three tillage systems (deep (250 mm), shallow (100 mm) and zero (no-till)) on soil properties, crop yield and energy requirements (Smith, E., 2016). The soil is a sandy loam, mainly Claverley, with small areas of Olerton and Salwick (Beard, 1988). The methodology for applying the treatments is described in Chapter 3.

This chapter details the results of indicative in-field methods used to measure soil physical properties i.e. soil bulk density, soil shear strength and penetration resistance. This methodology is different from Smith, E. (2016) in that the trial plots had been subjected to more applications (n=5) of the traffic and tillage treatments and a shear vane was used to collect additional data on soil shear strength. Resolution in bulk density data was increased by reducing the 100 mm core length used by Smith, E. (2016) to 50 mm core length (see Section 4.1).

Collectively they are companion data for the X-ray CT data detailed in Chapter 5. They were taken concurrently and from the same locations as the undisturbed soil cores used for X-ray CT.

4.3.1 Sample location

Spring oats were drilled 25 April 2016 at a row spacing of 167 mm with a seed rate of 350 seeds m^{-2} (+ 30% on zero tillage plots). To compare untrafficked and trafficked treatments within each plot would have required a minimum of 72 cores (i.e. one from each main wheelway and one from an untrafficked area in each of the 9 treatments x 4 replications). Constraints by the availability of the X-ray CT equipment and required scan time for each core meant that this number of samples could not be accommodated. However, as CTF ut had been subjected to the same treatments as LTP ut and STP ut, and CTF w had been subjected to the same trafficking as for LTP w it was possible to reduce this number to 36. This would still allow comparison of soil properties between LTP w and STP w and between trafficked and untrafficked treatments subjected to the three tillage treatments. It would also show the effect of the three tillage systems only in the untrafficked (CTF ut) treatments.

A total of 36 soil cores (one from each plot = 9 treatments x 4 replications) were taken 08 August 2016 from untrafficked centres (crop rows 17-18) in the Controlled Traffic Farming (CTF ut) plots (n=12) and from the main wheelway (crop rows 11-12) in the Random Traffic Farming - standard tyre inflation pressure (STP w) (n=12) and Random Traffic Farming - low tyre inflation pressure (LTP w) (n=12). **Note**: suffixes used in this chapter are ut - untrafficked, w - wheeled, deep - deep tillage, shallow - shallow tillage and zero - zero tillage. Samples taken from CTF ut zero have not been subjected to traffic or tillage and therefore could be used as a reference point for the purposes of analysis.

To allow correct use of measurement equipment, above ground crop biomass was removed from the sample locations to give a bare soil surface. As biomass is a measure of a crop's response to its environment (Sylvester-Bradley *et al.*, 1985), in this case the applied traffic and tillage treatments, the results are discussed in this chapter.

4.3.2 Measurements

4.3.2.1 Soil cores

An undisturbed soil core was taken from the centre of the plant sampling areas as shown in Figure 4.1 (36 plots = 9 treatments x 4 replications) using an Eijkelkamp 04.15.SB soil core sampler (Figure 4.2) with sample liners of ø50 mm x 300 mm length in accordance with Eijkelkamp (not dated). All soil core samples were stored in the PVC liner with cap fitted (an example is shown at Figure 4.2) standing upright in the dark at 4°C to avoid drying out and to reduce compositional changes to the soil by retarding biological activity (Paetz and Wilke, 2005). The action of the soil corer during sample taking and the storage of the cores on their bases loosened the soil at around 275-300 mm depth affecting porosity measurements. Analysis was therefore conducted on data between 0-250 mm. The soil cores were used for the X-ray CT scanning described in Chapter 5 and then used for soil bulk density measurements.

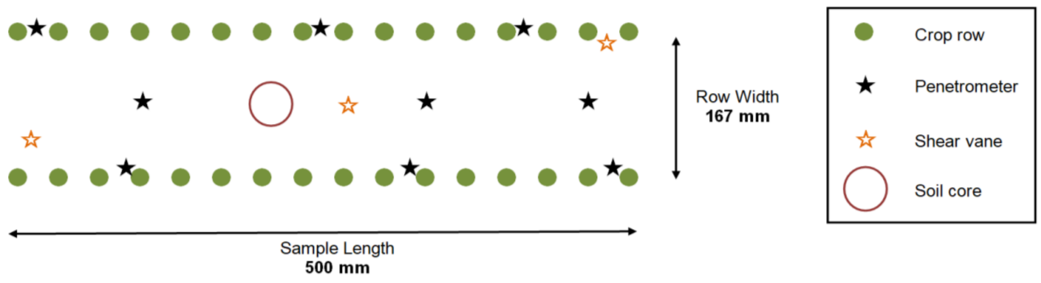

Figure 4.1 - Schematic of sampling locations relative to crop rows

Figure 4.2 - Eijkelkamp 04.15.SB soil core sampler (left) and undisturbed soil core in PVC liner (right)

4.3.2.2 Bulk density and soil porosity

After the X-ray CT scanning of the soil cores was complete (Chapter 5) the soil cores were then used to measure bulk density measurements at 0-50, 50-100, 100-150 150-200 and 200-250 mm depths. This would enable direct comparisons to be made to the results of X-ray CT analysis (Chapter 5). This provided more resolution to changes in bulk density than the work carried out by Smith, E. (2016) who collected data in 100 mm lengths. The soil cores were cut into 50 mm length sections using a jig and saw (Figure 4.3). Several methods of partitioning the soil for the bulk density measurements were investigated. Due to drying of the soil during storage after X-ray CT scanning, the soil cores were predisposed to breakage whilst being removed from the PVC tube. Marking and then separating by cutting the PVC tube with a knife was difficult because the tube was not robust enough for the pressure needed and again lead to breakage of the cores. Using the saw allowed cutting through the tube and soil core together without breakage but needed the bespoke jig (Figure 4.3) to guide the saw blade to produce a flat face on the soil sections to allow accurate determination of soil volumes. Soil samples were dried at 105^{o}C for 48 hours in accordance with the standard ISO DIS 11272:1998 (Determination of dry bulk density) as described by Wilke (2005) and weighed. Equation 4.1 was used to calculate the bulk density of each sample. Using bulked soil samples (from the bulk density soil samples) from the centre of each of the four trial blocks, soil particle density was measured by the Graduated Cylinder Method (two replications) as described by Estefan *et al.* (2013). Using equation 4.2 soil particle density were found to be 2.54 g cm^{-3}. This value is in agreement with the findings of Rose (1991) cited by Rühlmann *et al.* (2006) who found the particle density of arable sandy loam soils at Rothamsted, Saxmundham, Wellesbourne and Woburn (UK) to range between 2.49–2.70 g cm^{-3}. Soil porosity for all samples was calculated using Equation 4.3 (these porosities are discussed in Chapter 5).

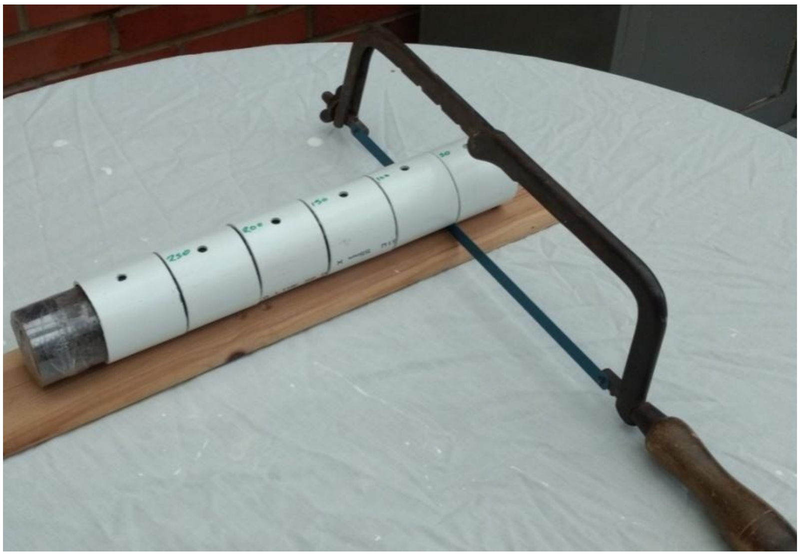

Figure 4.3 - Jig and saw used to section cores into 50 mm lengths

$$\text{Soil bulk density (g cm}^{-3}\text{)} = \frac{\text{oven dry weight of soil (g)}}{\text{volume of soil (cm}^{3}\text{)}}$$

Equation 4.1

$$\text{Soil particle density (g cm}^{-3}\text{)} = \frac{\text{oven dry weight of soil (g)}}{\text{volume of solids (cm}^{3}\text{)}}$$

Equation 4.2

$$\text{Soil porosity (\%)} = 1\text{-}\left(\frac{\text{soil bulk density (g cm}^{-3}\text{)}}{\text{soil particle density (g cm}^{-3}\text{)}}\right)$$

Equation 4.3

4.3.2.3 Shear vane

A shear vane can be used to measure the shear strength of soil. It is driven into the soil and rotated which causes the soil to shear along the surface of the generated cylindrical surface. It can be used at successive depths without removal (Gill and Vanden Berg, 1968). The rectangular shear vane used had a height/diameter = 2, as shown in Figure 4.4 and the dimensions were height (H)=36 mm and diameter (D)=18 mm. The torque wrench in Figure 4.4 (ADS 25) range 5-25 N m with an accuracy of +/-3% (Torqueleader, 2014) was used with the shear vane to obtain torque readings which were used to calculate shear stress (soil strength) using Equation 4.4 (for rectangular vane of H/D = 2) where t = shear torque (N m) and D = diameter of shear vane = 0.018 m (A.S.T.M., 2002). Readings were taken at 100, 200 and 300 mm depth from three positions as shown in

Figure 4.1 (36 plots = 9 treatments x 4 replications) and at a spacing greater than 80 mm to avoid interference in readings due to horizontal soil disturbance (Sulaiman, 2015).

$$\text{shear strength (Pa)} = \frac{6t}{7\pi D^3}$$

where: t = shear torque (N m) and D = diameter of shear vane (0.018 m)

Equation 4.4

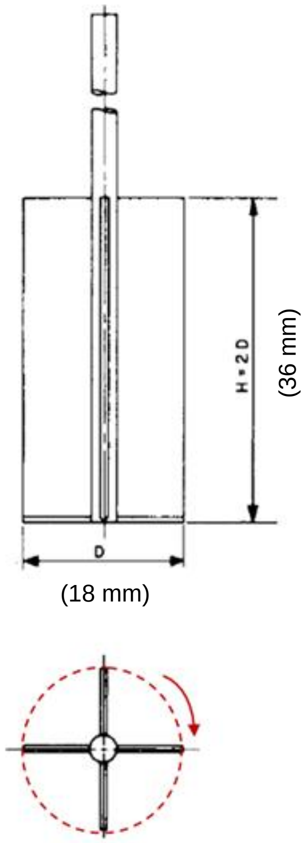

Figure 4.4 - Rectangular shear vane (H=2D) dimensions ø18 x 36 mm height red dotted line indicates generated shear surface due to rotation (left) and shear vane torque wrench ADS 25 *range 5-25 N m* (right)

(left: Source adapted from: A.S.T.M., 2002)

4.3.2.4 Penetration resistance

Soil penetrometer measurements were taken using an Eijkelkamp 06.15 penetrologger set (Figure 4.5) following the guidance in Eijkelkamp (2000). For each plot sample area nine readings (3 from each of the two crop row and 3 from between rows in the sample area) were taken as shown in Figure 4.1 (36 plots = 9 treatments x 4 replications) using the 1 cm^2 base area cone (60º top angle). Penetration resistance readings are affected by soil moisture so measurements were taken when the soil was near field capacity as recommended by Miller *et al.* (2001). Soil sampling at field capacity (defined as the amount of water held in a draining soil 48 hours after being saturated (Ward and

Robinson, 2000) or the soil water content at the soil matric potential of -0.03 MPa (Kirkham, 2005)) is satisfactory for intrasite comparisons (MAFF (1982).

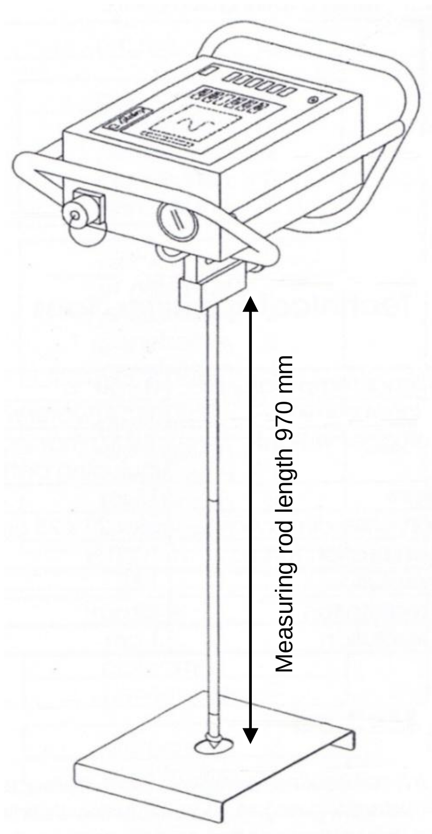

Figure 4.5 - Eijkelkamp 06.15 penetrologger set

(Source adapted from: (Eijkelkamp, 2000)

4.3.2.5 Soil moisture content

At the time of collecting the soil core samples, soil volumetric water content was measured by Time-domain reflectometry using a Spectrum Field Scout TDR 100 soil moisture meter (serial no: 67-050), fitted with 200 mm rods (Figure 4.6). It was intended to measure the gravimetric water content of the soil cores when calculating the bulk densities and therefore replicated measurements were not taken using the TDR 100. However the soil cores were retained in archival cold storage after scanning for several weeks for re-scanning should it have been needed. The soil cores were found to have lost moisture during this period making gravimetric water content measurement of no benefit.

Figure 4.6 - Spectrum Field Scout TDR 100 soil moisture meter

(Source adapted from: Österreichische Bundesforste, 2019)

4.3.2.6 Spring oats biomass

To ensure that the soil cores could be collected and all soil measurements completed in advance of the combine harvest all aboveground spring oat crop growth was collected 25th July 2016 using hand shears from the two rows (500 mm length) that formed the boundaries of the sample areas as shown in Figure 4.1 (36 plots = 9 treatments x 4 replications). At this time the oat crop was at GS 83. Samples were oven dried at 80^{o} C for 24 hours as described by Jones (2000) and then weighed.

4.3.3 Statistical analysis

Genstat 18th Edition (VSN International, 2015) was used for statistical analysis of data using two-way analysis of variance (ANOVA) for independent data (i.e. fixed depth data for bulk density, penetration resistance, shear strength and biomass). For related data (i.e. incremental depth data) repeated measures ANOVA was used for bulk density, penetration resistance and shear strength. Regression analysis used simple linear regression with groups. Post hoc tests were used to determine significant differences in means when the calculated probability was <0.05 (Tukey's test for traffic and tillage and the Bonferroni test for traffic x tillage integration) at 5% probability.

4.4 Results and discussion

4.4.1 Bulk density

The bulk density means for the traffic and tillage treatments (50 mm intervals) between 0-250 mm depth are shown in Figure 4.7 and their calculated probability (*P*-value) and standard error of the means (SEM) from two-way ANOVA analysis are given in Table 4.1. Bulk density was lower in CTF ut treatments at all depths (significantly lower at 50-100 (P<0.001) and 200-250 mm (P=0.001) depth) than traffic treatments (Table 4.1). There was no significant difference in bulk density between STP w and LTP w treatments. Figure 4.7 a shows a more compacted zone between 100-150 mm depth in the STP w and LTP w treatments. This may have been a pan associated with the shallow tillage (100 mm depth) which can also be seen at 100-150 mm depth in Figure 4.7 b. This was in agreement with the findings of Riley *et al.* (1994) and Rydberg (1986) as reported by Rasmussen (1999), who found similar increases in bulk density at 100-150 mm depth (just under shallow tillage depth). Compared to the zero tillage treatments, tillage tended to decrease bulk density in the upper part of the soil profile and increase bulk density lower down. This was likely to be because of the recompaction of soil after tillage as the tilled soil had lost structural strength and was unable to support vehicle traffic (Horn *et al.,*1995). There was no significant interaction between the traffic and tillage treatments at any depth.

Table 4.1 - Calculated probability (*P-value*) and standard error of the means (SEM) for bulk density means between 0-250 mm depth (50 mm intervals) for the traffic and tillage treatments

	Depth (mm)									
	0-50		**50-100**		**100-150**		**150-200**		**200-250**	
	p	SEM	p	SEM	p	SEM	p	SEM	p	SEM
Traffic	0.072	0.030	<0.001	0.025	<0.001	0.023	0.330	0.032	0.001	0.011
Tillage	0.033	0.030	0.141	0.025	0.093	0.023	0.397	0.032	0.030	0.011
Traffic x Tillage	0.323	0.053	0.176	0.042	0.091	0.039	0.950	0.055	0.097	0.019
%CV	8.3		3.1		5.4		7.7		2.8	

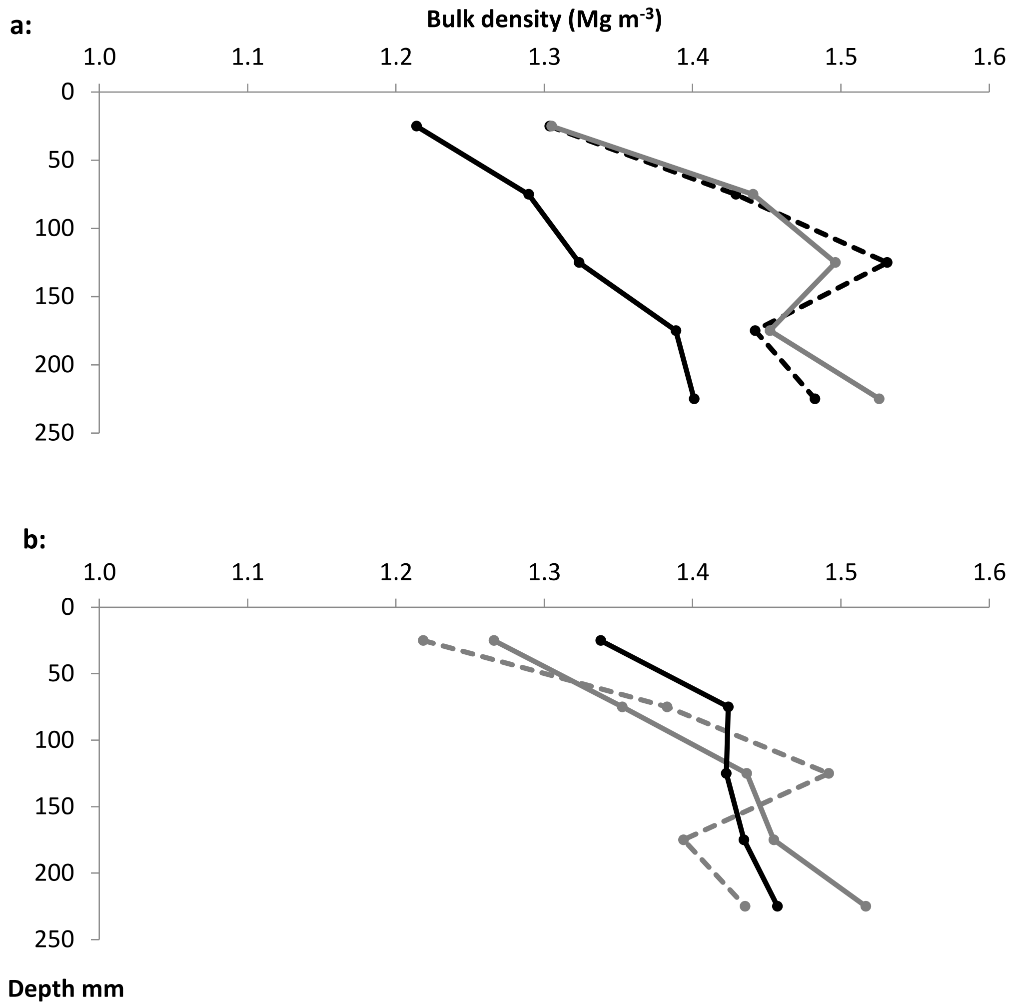

Figure 4.7 - Bulk density (Mg m^{-3}) means for traffic and tillage treatments (50 mm intervals) between 0-250 mm depth
a: traffic means (Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)
b: tillage means (Lines: solid grey - deep, dash grey - shallow, solid black - zero)

Repeated measures ANOVA analysis (0-250 mm depth) showed that CTF ut treatment bulk densities were significantly lower (P<0.001) than STP w and LTP w treatments (Table 4.2). The increase in bulk density with depth was significant (P<0.001). This was also found by Smith, E. (2016). The depth x tillage interaction was significant (P=0.010). There was no significant interaction between the traffic and tillage treatments.

Table 4.2 - Repeated measures ANOVA for bulk density (Mg m^{-3}) 0-250 mm depth

Bulk density (Mg m^{-3}) 0-250mm depth			
Treatment	*P*-value	SEM	CV%
Traffic	<0.001	0.011	6.4
Tillage	0.165	0.011	
Traffic x Tillage	0.150	0.020	
Depth	<0.001	0.015	
Depth x Traffic	0.147	0.026	
Depth x Tillage	0.010	0.026	
Depth x Traffic x Tillage	0.263	0.044	

Figure 4.8 shows the bulk density (Mg m^{-3}) means for the traffic and tillage treatments (0-250 mm depth). Deep tillage decreased bulk density between 50 and 150 mm depth (Figure 4.8 a). The vehicle traffic increased bulk density at similar rates (with STP w being higher than LTP w) compared to values in CTF ut zero treatments. There was a drop in bulk density at 150-200 mm depth in both LTP w and STP w treatments. A similar recompaction effect by the traffic treatments with shallow tillage was apparent (Figure 4.8 b) when compared to CTF ut zero (Figure 4.8 c). There was an increase in bulk density for both traffic treatments at 100-150 mm depth especially for the LTP w treatment possibly due to a pan under the tillage tool. As a pan occurs below the tine depth a similar pan could not be seen in the deep tillage treatment results as the bulk density measurements were only taken to 250 mm depth (see Section 4.3.2.1) which was the same as deep tillage depth. In the zero tillage treatments the bulk density was increased by vehicle traffic with LTP w having higher values than STP w. The peak bulk density value occurred at 50-100 mm for LTP w and 100-150 mm for STP w.

Two-way ANOVA analysis of the bulk density means for the traffic and tillage treatments for 0-250 mm depth are shown in Table 4.3. The bulk density mean in the untrafficked (CTF ut) treatments (1.32 Mg m^{-3}) was significantly (P<0.001, SEM=0.0113, %CV=2.8) lower than for the trafficked treatments (LTP w and STP w, 1.44 Mg m^{-3}). There was no significant difference between the LTP w and STP w means. Although tillage is used to reduce the bulk density of soil, the effect is temporary and the soil settles and returns to its former bulk density (Lampurlanés and Cantero-Martinez, 2003). This may be why there was no significant difference between the means for the tillage treatments. There was no significant interaction between the traffic and tillage treatments. The mean soil bulk density for all treatments was within the 1.3 to 1.45 Mg m^{-3} optimum mean bulk density range (for 0-300 mm soil depth) for maximum corn yields identified by Negi *et al.* (1981).

Table 4.3 - Bulk density means (Mg m^{-3}) for traffic and tillage treatments 0-250 mm depth

Bulk density (Mg m^{-3}) means				
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	1.33	1.31	1.33	1.32^{a}
LTP w	1.41	1.42	1.48	1.44^{b}
STP w	1.47	1.42	1.44	1.44^{b}
Mean	1.40	1.38	1.42	

(**Note**: Means not followed by the same letters are significantly different from each other)

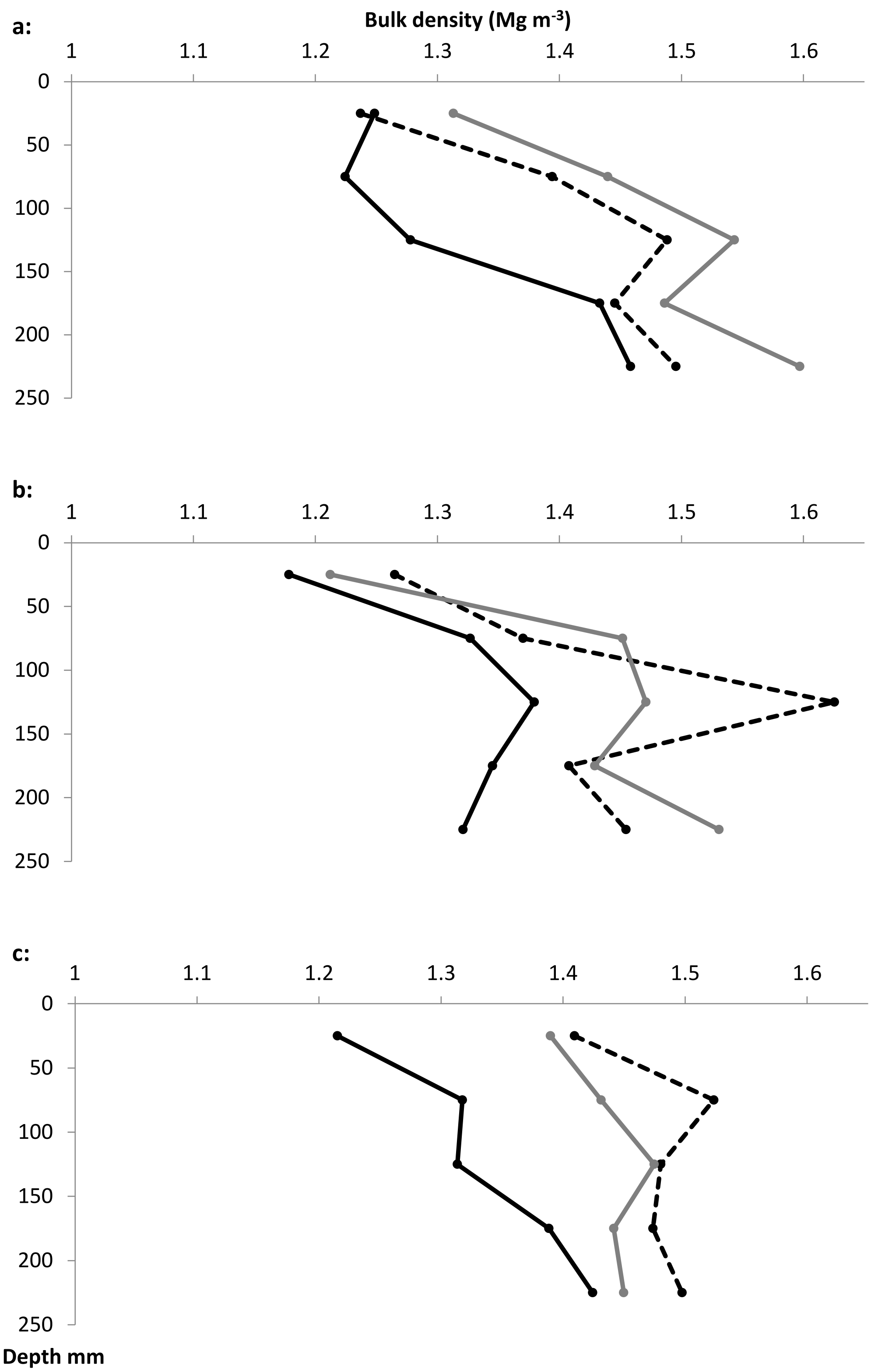

Figure 4.8 - Bulk density (Mg m^{-3}) means for the traffic and tillage treatments (0-250 mm depth)
a: deep tillage, b: shallow tillage and c: zero tillage
(Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)

As expected from the literature (e.g. Lipiec *et al.*, 2003a) traffic increased soil bulk density compared to the untrafficked (CTF ut) treatments (significantly for 50-100 (P<0.001), 200-250 (P=0.001) and 0-250 mm (P<0.001) depths). There was no significant difference in bulk density between the LTP w and STP w treatments. This would confirm that using a

Controlled Traffic Farming system to remove vehicular traffic from a large portion of the field was a sensible way to avoid soil compaction. However when field traffic was necessary, the use of low inflation pressure tyres may not be effective at reducing soil compaction (at 0-250 mm depth on a sandy loam soil) compared to standard inflation pressure tyres when using a vehicle comparable to the one used in this experiment (12.5 tonnes). The bulk density means, for 0-250 mm depth, were all between the optimum 1.3 and 1.45 Mg m^{-3} associated with higher yields, as identified by Negi *et al.* (1981), suggesting that the field soil bulk density was not high enough to severely limit crop yield.

4.4.2 Shear vane

Figure 4.9 shows the soil shear strength means from 100, 200 and 300 mm depth combined to show the changes soil shear strength with depth. Soil shear strength was significantly lower (P<0.001) in the untrafficked (CTF ut) treatments than in the wheeled (STP w and LTP w) treatments at all three depths. Although not significantly different from STP w, LTP w treatments resulted in lower soil shear strength throughout the soil profile. Tillage significantly reduced soil shear strength at 100 mm depth (P<0.001) and reduced soil shear strength in CTF ut treatments at all three depths. The effect of tillage on soil shear strength can be seen to extend below the depth of the tillage tines (100 mm for shallow and 250 mm for deep) at the 300 mm depth (Figure 4.9). Both tillage means at this depth are higher than the zero tillage mean (0.33 MPa) which was lower (P= 0.081) than the mean soil shear strength for deep tillage (0.40 MPa). This was likely due to the action of the tillage reducing the bearing capacity of the tilled soil for subsequent vehicular traffic as found by Yavuzcan *et al.* (2002), allowing deeper penetration of soil stresses than in the zero tilled treatments. Soils are susceptible to recompaction after loosening especially if trafficked within a few days of the operation (Spoor, 2006). The shear vane ANOVA analysis at each reading depth (100, 200 and 300 mm) is given in Appendix C.

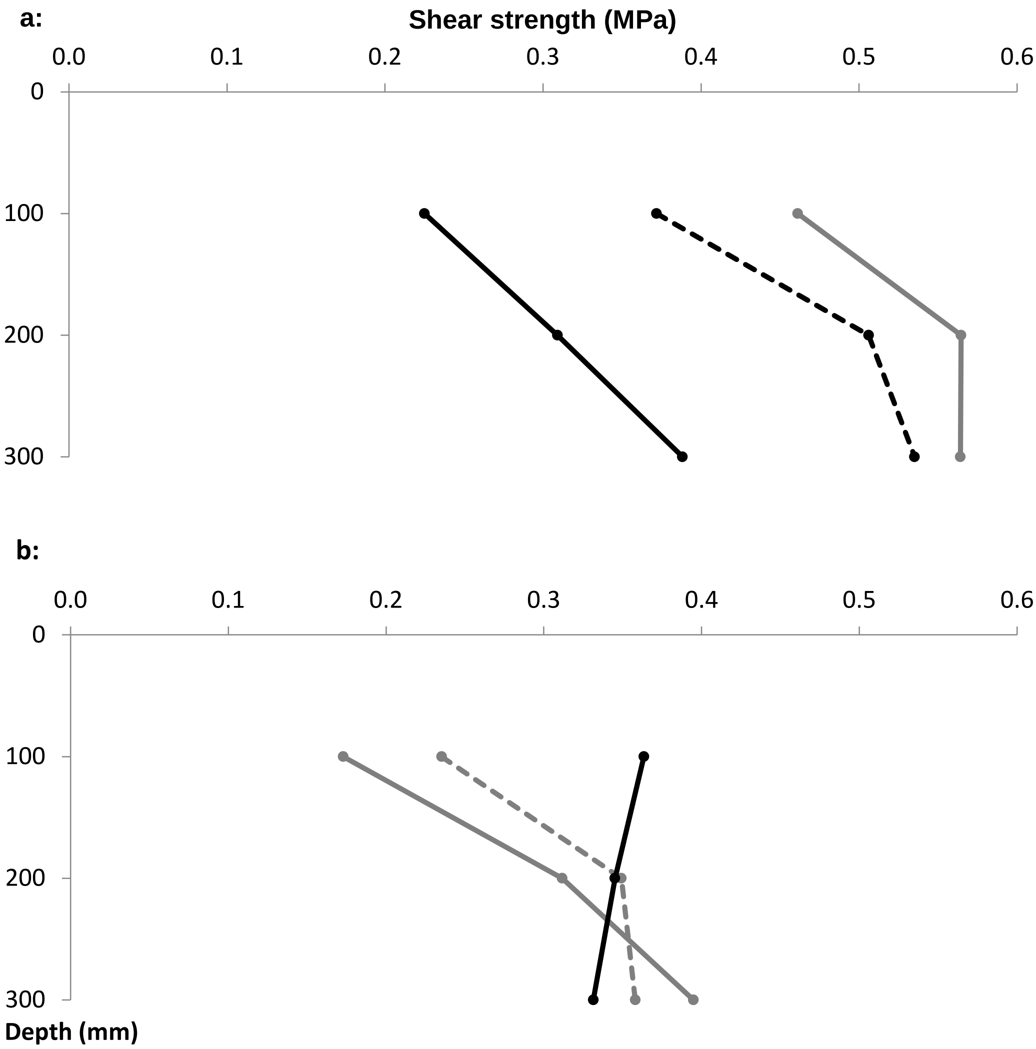

Figure 4.9 - Soil shear strength means (100, 200 and 300 mm depth)
a: traffic means (Lines: solid black - CTF ut, dash black - LTP w, solid grey - STP w)
b: tillage means (Lines: solid grey - deep, dash grey - shallow, solid black - zero)

The shear strength means for the traffic and tillage treatments (100 mm intervals) between 0-300 mm depth are shown at Figure 4.10 and their calculated probability (*P*-value) and standard error of the means (SEM) from two-way ANOVA analysis are given in Table 4.4. Deep tillage reduced soil shear strength in the untrafficked treatments at all depths (compared to CTF ut zero) and in the wheeled treatments at 100 mm depth (Figure 4.10 a). The soil shear strength increased at 200 mm depth signifying traffic compaction (the compaction effect was lower in the LTP w treatments than in STP w) and continued to increase below the tillage depth to 300 mm. A similar effect was seen in the LTP w shallow tillage treatments (Figure 4.10 b) but in the STP w treatments the soil shear strength (being higher than LTP w at 100 and 200 mm depth) declined after 200 mm. This would indicate that standard inflation pressure tyres produce more stress in the soil near the surface than low inflation pressure tyres as reported by Raper (2005). Although the low inflation pressure tyres may have produced lower soil stresses, the compaction effect was distributed further down into the soil profile than the standard tyre inflation pressure tyres. Figure 4.10 c shows that the effect from traffic (higher shear strength) acts higher in the profile due to higher initial soil strength due to no tillage. At 200 mm depth soil shear strength was similar for LTP w and STP w treatments. At 300 mm LTP w treatments had soil shear strength values similar to untrafficked treatments but STP w treatments were similar to the 200 mm value (0.39 MPa). To get a more reliable curve for each set of data and determine how far below the tillage depths that the compaction effect continued it would be necessary to repeat the experiment to a greater depth and with smaller increments. At 300 mm depth the shear strength in the STP w deep tillage (0.477 MPa) treatments was significantly (P=0.041) higher than CTF ut shallow tillage (0.262 MPa), CTF ut deep tillage (0.280 MPa), LGP w zero tillage (0.303 MPa) and CTF ut zero tillage (0.307 MPa) treatments. This was possibly due to recompaction at this depth due to vehicular traffic following the deep tillage as previously identified by Yavuzcan *et al.* (2002). Repeated measures ANOVA analysis (0-300 mm depth) showed that CTF ut treatment soil shear strength was significantly lower (P<0.001) than STP w and LTP w treatments (Table 4.5). Soil shear strength in the deep tillage treatments was significantly lower (P=0.030) than for zero tillage treatments. The increase in soil shear strength with depth was significant (P<0.001).

Table 4.4 - Calculated probability (*P-value*) and standard error of the means (SEM) for shear strength means between 0-250 mm depth (50 mm intervals) for the traffic and tillage treatments.

	Depth (mm)					
	100		200		300	
	p	SEM	p	SEM	p	SEM
Traffic	<0.001	0.021	<0.001	0.017	<0.001	0.019
Tillage	<0.001	0.021	0.235	0.017	0.081	0.019
Traffic x Tillage	0.770	0.036	0.162	0.029	0.041	0.033
%CV	28.1		17.1		18.3	

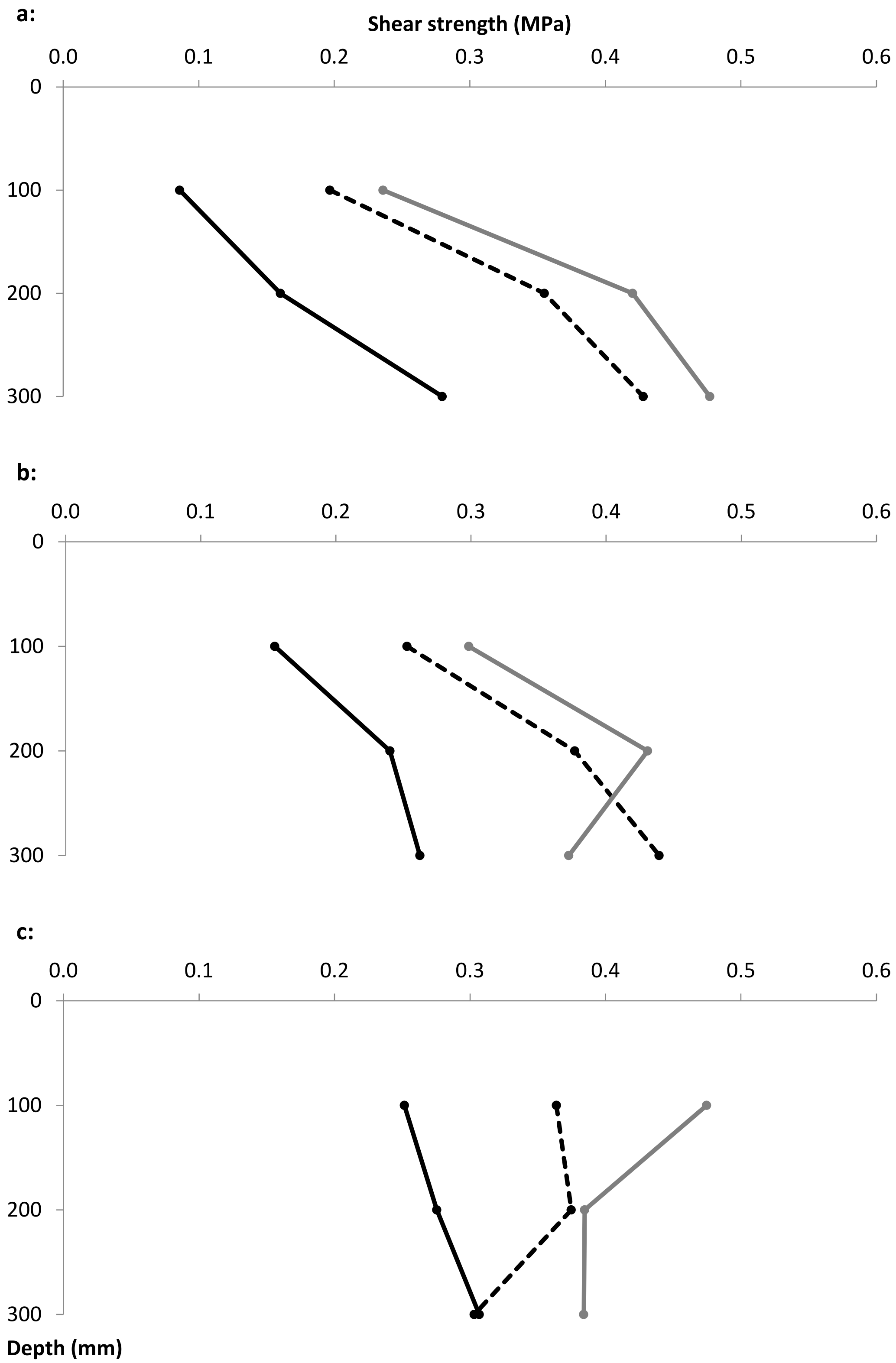

Figure 4.10 - Shear strength means for the traffic and tillage treatments a: deep tillage, b: shallow tillage and c: zero tillage
(Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)

Table 4.5 - Shear strength (MPa) 0-300 mm depth

	Shear strength (MPa) 0-300 mm depth			
Treatment	*P*-value	SEM	LSD	CV%
Traffic	<0.001	0.013	0.039	17.4
Tillage	0.030	0.013	0.039	
Traffic x Tillage	0.318	0.023	0.068	
Depth	<0.001	0.009	0.028	
Depth x Traffic	0.318	0.019	0.055	
Depth x Tillage	<0.001	0.019	0.055	
Depth x Traffic x Tillage	0.067	0.032	0.096	

Soil strength is dependent upon soil compactness. As soil is compacted particles move closer together which results in higher binding forces. Additionally, structural weakness within the soil, because of cracks and flaws associated with soil porosity, diminishes as the soil porosity decreases due to increases in soil compaction (Guerif, 1994). This may explain why tillage decreased soil strength at 100 mm depth as it would introduce more flaws in the soil structure whilst increasing soil porosity. Similarly, the increase in soil strength in the traffic treatments would be associated with a reduction in soil porosity. The use of a shear vane in this experiment gave soil strength comparisons at three (100, 200 and 300 mm) depths. This may not have given sufficient resolution to identify layers of compaction within the profile as identified by Freitag (1971).

4.4.3 Penetration resistance

Figure 4.11 shows the penetration resistance means for the traffic and tillage treatments and associated repeated measures ANOVA statistical output given in Table 4.6. The penetration resistance means (MPa) for traffic and tillage treatments between 0-450 mm depth are in Table 4.7. Readings were significantly (P<0.001) higher (LTP w 25% and STP w 24%) in the traffic treatments than in untrafficked but there was no significant difference between STP w and LTP w (Figure 4.11 a). Schjønning *et al.* (2016) found that lower tyre pressures produced lower stresses in the upper soil profile resulting in lower penetration resistance but for deeper layers penetration resistance was correlated to vehicle load. This is consistent with the findings of other soil compaction researchers as reported by Raper (2005). The effect of lower tyre inflation pressure on soil compaction in the upper soil profile can be seen between the higher penetration resistance in the STP w treatments compared to LTP w treatments from 0-170 mm but between 250-350 mm depth LTP w treatments have the higher penetration resistance. This may be due to variations in soil moisture and/or soil structure due to previous compaction treatments at succeeding vehicular traffic events. Wheeled traffic in agricultural soils have been found to produce heterogeneous vertical soil compaction and the effect of this on root growth has rarely been studied (Pfeifer *et al.*, 2014). Penetration resistance values where similar between the LTP w and STP w treatments between 350-450 mm depth which is consistent with soil stresses produced axle load (Raper, 2005).

Penetration resistance was 11 % higher in deep tillage treatments than for shallow tillage treatments (*P*=0.089). This difference was due to the low penetration resistance mean (1.77 MPa) in the CTF ut (untrafficked) shallow tillage treatments (Table 4.7) which was 24% lower than the mean for CTF ut deep treatments. The statistical analysis did not show a significant difference between shallow and zero tillage but the effect of depth was significant (*P*<0.001). Figure 4.11 b shows that tillage intensity did not affect penetration resistance between 0-150 mm (i.e. they were the same for deep and shallow). At 150 mm depth, penetration resistance in the deep tillage treatments continued to increase at a higher rate (0.5 MPa per 55 mm increase in depth) than for shallow and zero tillage which increased but at a lower rate (0.5 MPa per 64 and 77 mm increase in depth respectively). This deeper compaction in the deep tillage treatments agrees with the findings of Soane *et al.* (1986) that deep tillage reduced the bearing capacity of soil leading to recompaction often worse than before tillage.

The 50 mm interval penetration resistance ANOVA for depths 0-50, 50-100, 100-150, 150-200 and 200-250 mm are shown at Table 4.8. Penetration resistance in untrafficked (CTF ut) treatments was significantly lower than STP w and LTP w treatments at depths 50-250 mm (*P*<0.001) and STP w treatments only at 0-50 mm depth (*P*=0.014). Tillage significantly reduced penetration resistance compared to zero tillage at depths 0-150 mm. At 150-200 mm depth only shallow tillage treatments had significantly lower penetration resistance than zero tillage treatments. Deep tillage produced the highest penetration values at 200-250 mm depth which were significantly higher than for shallow tillage treatments. There was no significant interaction between the traffic and tillage treatments at any depth.

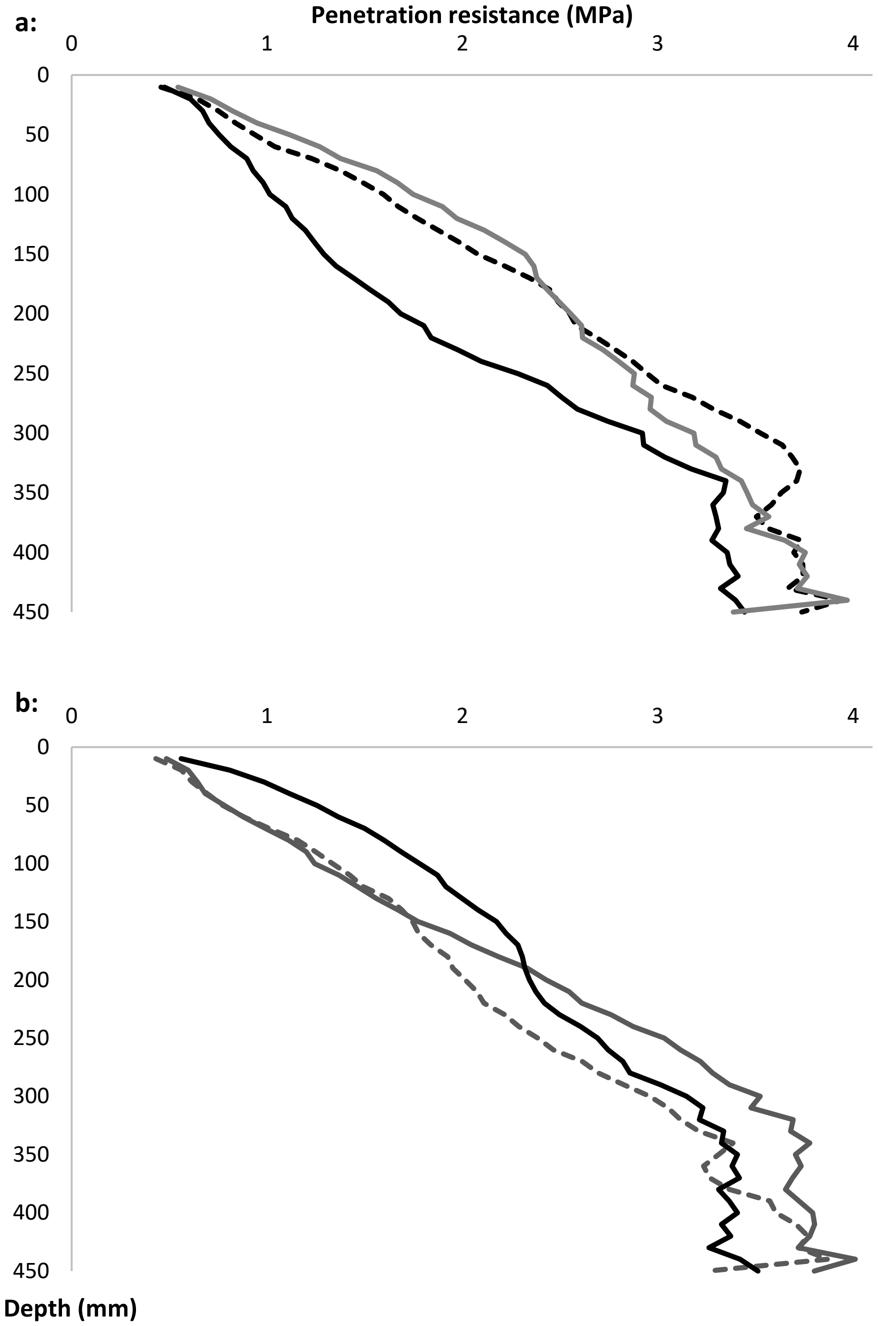

Figure 4.11 - Penetration resistance (MPa) Traffic and Tillage 0-450 mm depth
a: traffic means (Lines: solid black - CTF ut, dash black - LTP w, solid grey - STP w)
b: tillage means (Lines: solid grey - deep, dash grey - shallow, solid black - zero)

Table 4.6 - Repeated measures ANOVA (10 mm intervals) for penetration resistance (MPa) 0-450 mm depth

	Penetration resistance (MPa) 0-450 mm depth			
Treatment	*P*-value	SEM	LSD	CV%
Traffic	<0.001	0.083	0.242	18.7
Tillage	0.089	0.083	0.242	
Traffic x Tillage	0.315	0.143	0.419	
Depth	<0.001	0.076	0.233	
Depth x Traffic	0.076	0.154	0.474	
Depth x Tillage	0.015	0.154	0.474	
Depth x Traffic x Tillage	0.162	0.266	0.821	

Table 4.7 - Penetration resistance means (MPa) for traffic and tillage treatments 0-450 mm depth

	Penetration resistance (MPa) means			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	2.34	1.77	2.16	2.09[a]
LTP w	2.59	2.49	2.75	2.61[b]
STP w	2.66	2.57	2.54	2.59[b]
Mean	2.53	2.27	2.48	

(**Note**: Means not followed by the same letters are significantly different from each other)

Table 4.8 - Penetration resistance means (MPa) for traffic and tillage treatments 0-250 mm depth

	Penetration resistance means (MPa) 0-250 mm depth				
Treatment/Depth (mm)	0-50	50-100	100-150	150-200	200-250
CTF ut	0.643[a]	0.928[a]	1.191[a]	1.526[a]	2.000[a]
LTP w	0.726[ab]	1.347[b]	1.876[b]	2.410[b]	2.775[b]
STP w	0.829[b]	1.525[b]	2.104[b]	2.447[b]	2.725[b]
P-value	0.014	<0.001	<0.001	<0.001	<0.001
Deep	0.638[a]	1.085[a]	1.567[a]	2.186[ab]	2.765[b]
Shallow	0.615[a]	1.127[a]	1.596[a]	1.901[a]	2.216[a]
Zero	0.945[b]	1.587[b]	2.008[b]	2.296[b]	2.519[ab]
P-value	<0.001	<0.001	<0.001	0.026	0.006
Traffic x Tillage *P*-value	0.227	0.806	0.780	0.447	0.875
SEM	0.041	0.062	0.081	0.098	0.110
%CV	19.6	16.8	16.2	16.0	15.2

(**Note**: Means not followed by the same letters are significantly different from each other)

The effect of the traffic and tillage treatment interactions on penetration resistance between 0-450 mm depth is shown at Figure 4.12. Penetration resistance means in the LTP w and STP w deep treatments were similar 2.59 and 2.66 MPa respectively (Table 4.6) and higher than CTF ut deep (2.34 MPa). Their rate of increase in penetration resistance with depth was also similar (i.e. 0.5 MPa per 57 mm increase in depth, R^2 = 0.864 and R^2 = 0.956 respectively). At 300-350 mm depth penetration resistance values stopped increasing in the traffic treatments down to 450 mm depth (Figure 4.12 a). This may indicate that the soil strength at this point was strong enough to prevent any more soil compaction (penetration resistance 3.5-4.0 MPa). Penetration resistance in the traffic treatments subjected to shallow tillage showed uniform increases from 0-450 mm depth (Figure 4.12 b). LTP w and STP w had similar values and the rate of increase was 0.5 MPa per 57 mm increase in depth (R^2 = 0.968). This rate of increase in penetration resistance in the wheeled treatments (LTP w and STP w) is the same as under the deep tillage treatments. Penetration resistance increased at a lower rate (37%) in the CTF ut shallow tillage treatments (i.e. 0.5 MPa per 78 mm increase in depth, R^2 = 0.985). The CTF ut shallow mean (1.77 MPa) was noticeably lower than for all the other traffic x tillage treatments (Table 4.6) and contributed to the difference (P=0.089) between the means for CTF ut (2.09 MPa) and LTP w and STP w (2.61 and 2.59 MPa respectively). Figure 4.12 c shows that the CTF ut zero tillage treatments had lower penetration than LTP w but they had similar penetration resistance curves. Both increased uniformly until 300-350mm depth when penetration resistance became static at ~3.1 MPa (CTF ut) and ~3.7 MPa (LTP w). STP w had a similar rate of increase as the other two traffic treatments but only increased uniformly until 150 mm depth (2.8 MPa). Penetration resistance was then static until 300 mm depth where it increased gently until 450 mm depth. Arvidsson and Keller (2011) confirmed that as soil water content increased, soil penetration resistance decreased. Compaction decreases soil pore size which increases soil capilliary water capacity altering soil moisture (Badalíková, 2010). The small pores hold water at field capacity but this is not necessarily available to the crop due to structural and aeration issues (Warkentin, 1971). This localised soil moisture may be a reason why the penetration resistance values below 150 mm in the STP w zero tillage treatments stopped increasing with depth. Danfors (1994) found that low inflation pressure tyres generally produced less compaction than higher inflation pressures but some deviations were likely to be due to soil variations.

Soil compaction, as measured by penetration resistance, was significantly increased by vehicle traffic as identified in the literature. Increases in penetration resistance may affect crop growth and yield because crop root growth decreases. Significant decreases in root growth occur when penetration resistance exceeds 2 MPa. However, roots can continue growing in soils with high penetration resistance if they use the biopores retained in well structured soil such as no-till soils (Lampurlanés and Cantero-Martinez, 2003). Previous research has found that lower inflation pressure tyres have been found to produce lower stresses in soil near the surface and that load is the contributing factor in stresses in the lower profile (Raper, 2005). This was confirmed by the reduced penetration resistance in the LTP w treatments compared to the STP w treatments between 0-170 mm depth and the similar penetration resistance values for the LTP w and STP w treatments between 350-450 mm depth. The use of a penetrometer gave better resolution for soil strength measurement than the shear vane as it took a penetration resistance reading at 10 mm intervals down to 450 mm depth. As the readings are highly dependent upon the soil moisture at the time of the readings (Miller *et al.*, 2001) it can be difficult to relate the results to the bulk density readings which are largely independent of moisture content.

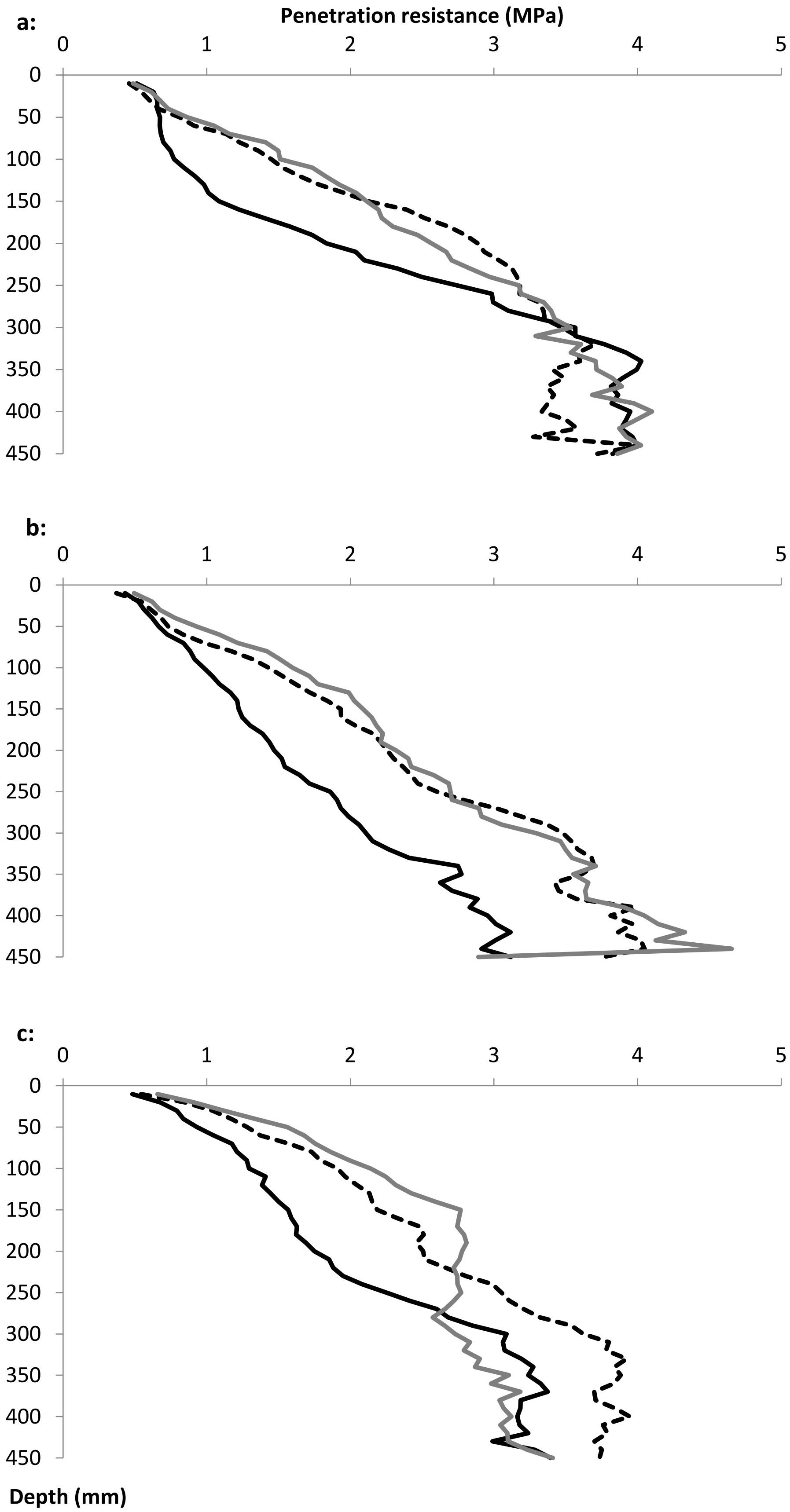

Figure 4.12 - Penetration resistance (MPa) for Traffic x Tillage 0-450 mm depth a: deep tillage, b: shallow tillage and c: zero tillage
(Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)

4.4.4 Soil moisture

Mean soil volumetric water content measured using the TDR 100 soil moisture meter was 23% (n=10). This corresponds to the upper limit of the field capacity range for a fine sandy loam soil as indicated (Figure 4.13) by Ward and Robinson (2000). Gravimetric soil moisture content could not be measured (see Section 4.3.2.5). Smith, E. (2016) previously measured gravimetric soil moisture content for this traffic and tillage trial and found no significant differences in soil moisture content due to the traffic (P=0.985) or tillage (P=0.367) treatments suggesting that any soil structural changes due to the treatments had not affected the soil moisture content. Although not significant, soil water content was higher in the tilled treatments than in the no-till treatments which is not as expected by Fageria (1992) who stated that soil water content is greater in no-till soils due to reduced evaporation. However, as tillage can break the capillary system by forming a layer of coarse loose material at the soil surface (Sinnott, 1935) water loss at the soil surface would be reduced in the tillage treatment plots.

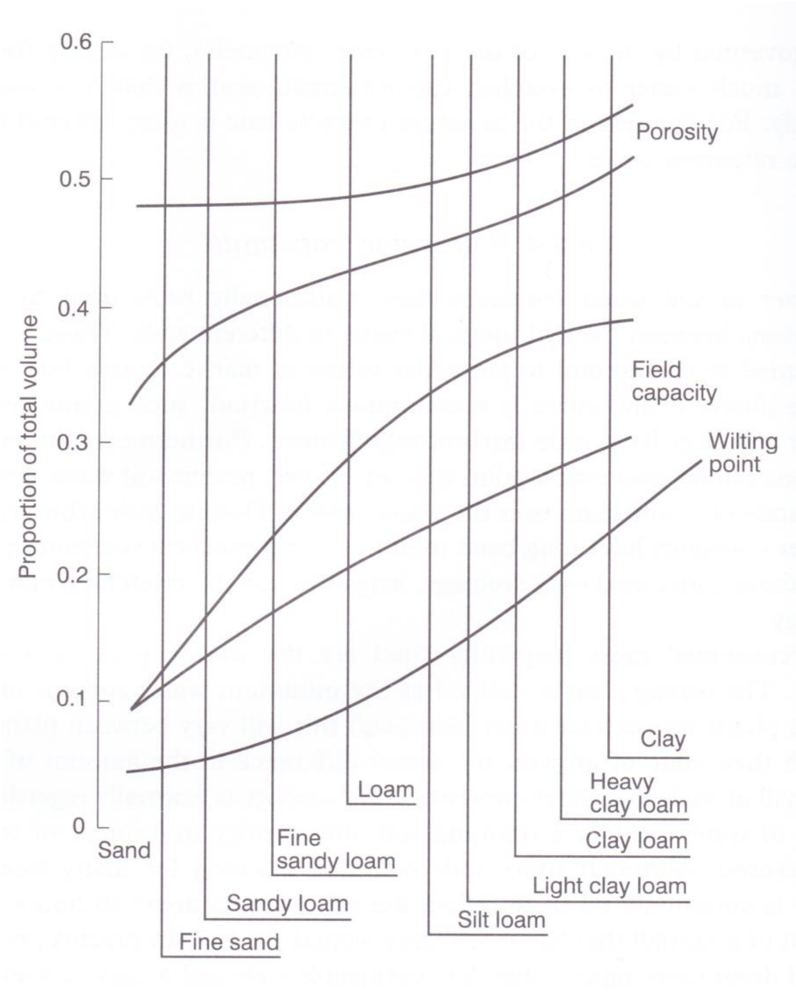

Figure 4.13 - Total porosity, field capacity and wilting point in different soils

(Source adapted from: Ward and Robinson, 2000).

4.4.5 Crop biomass

The means of the total above ground spring oat biomass taken from the sample locations are shown in Table 4.9. Both deep and shallow tillage increased biomass in all traffic treatments and this was significantly higher than zero tillage treatments (P<0.001). This difference was likely due to the reduced biomass in the STP w and LTP w wheelways (43% and 52% respectively compared to CTF ut zero) that had not received any tillage. Increasing tillage depth increased biomass but this was not statistically significant. The low biomass from the LTP w zero treatments contributed to the significant difference between LTP w and CTF ut treatments (P=0.049).

Table 4.9 - Spring oat biomass (t ha^{-1})

	Biomass (t ha^{-1})			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	10.17	9.58	8.99	9.58^{b}
LTP w	9.91	9.05	4.33	7.76^{a}
STP w	9.82	9.31	5.16	8.10^{ab}
Mean	9.97^{b}	9.31^{b}	6.16^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other)

4.4.5.1 The relationship between soil bulk density and spring oat biomass at GS 83

Soil strength and bulk density are used to describe soil compaction and researchers such as Rosenberg and Willits (1962) cited by Saini (1980) have found correlation between them and crop yields on the same soil. Correlations tend to break down when comparisons are made between compaction and crop yields on different soils or on the same soil but with varying soil conditions (Saini, 1980). The relationship between mean soil bulk density and spring oat biomass (at GS 83) was investigated using simple linear regression with groups (tillage and traffic).

The linear regression models for the tillage means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 4.14. The 0-50 mm depth data was best fitted by three separate lines (Figure 4.14 a) accounting for 50.5% of the variance (P<0.001). Biomass was reduced as soil bulk density increased in the shallow and zero tillage treatments. An increase in soil bulk density in the deep tillage treatments resulted in an increase in biomass. This was not as expected. The maximum bulk density in the deep tillage treatment was not particularly high (1.4 Mg m^{-3}) and similar to the optimum soil density for root growth and yield identified by Czyz *et al.* (2001). It is possible that an increase in bulk density above 1.4 Mg m^{-3} would have resulted in a reduction in biomass. The increase in biomass in the deep tillage treatments, at the 0-50 mm depth, due to increased bulk density could have been as a result of better plant establishment resulting from consolidation of soil around the seed (Hallett and Bengough, 2013). The zero tillage line was significantly different from the deep tillage line (*tP*=0.023) highlighting that zero tillage resulted in lower biomass at all bulk densities above 1.2 Mg m^{-3}.

The depths 50-100,100-150,150-200 and 200-250 mm all had a similar model as follows. The 50-100 mm depth data was best fitted by three parallel lines (Figure 4.14 b) accounting for 43.6% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002). The 100-150 mm depth data was best fitted by three parallel lines (Figure 4.14 c) accounting for 37.6% of the variance (*P*<0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*<0.001). The 150-200 mm depth data was best fitted by three parallel lines (Figure 4.14 d) accounting for 32.5% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002). The 200-250 mm depth data was best fitted by three parallel lines (Figure 4.14 e) accounting for 35.5% of the variance (*P*<0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002). These models (Figure 14.14 b-e) showed that an increase in bulk density slightly decreased biomass (deep, shallow and zero tillage) at 50-100 and 100-150 mm depth and slightly increased biomass at 150-200 and 200-250 mm depth. Deep and shallow tillage treatments resulted in significantly more biomass than the zero tillage treatment. This was probably due to the decreased establishment in the zero tillage plots as shown in Table 6.15.

Seehusen *et al.* (2014) indicated that it was the condition in the upper soil layer that had greatest influence on yield. The linear regression models (Figure 4.14) indicate that soil compaction (measured by soil bulk density) between 0-50 mm does reduce biomass, possibly through increased resistance to root penetration (Wolkowski, 1990). However there is often limited correlation between crop growth and bulk density due to the influence of pore size distribution (Campbell, 1994) and the models show that tillage increases biomass independently of soil bulk density. This may be explained by changes in soil pore size and distribution and the corresponding effect of soil moisture and aeration as identified by previous researchers (Wolkowski, 1990).

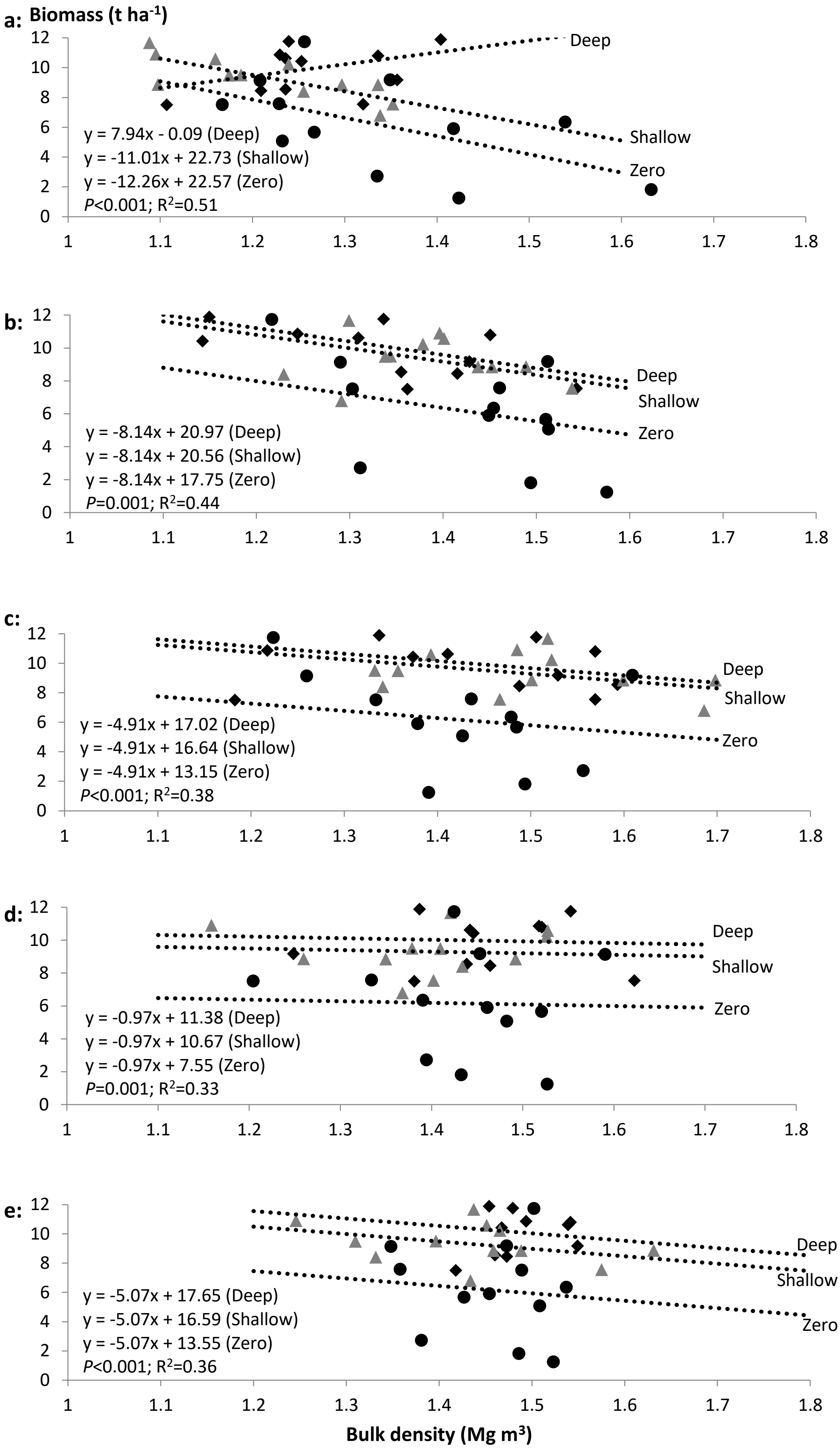

Figure 4.14 - Linear regression analysis (with tillage groups) of the relationship between bulk density (Mg m^{-3}) and spring oat biomass (t ha^{-1}) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth

(Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

The linear regression models for the traffic means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 4.15. The 0-50 mm depth data was best fitted by three separate lines (Figure 4.15 a) accounting for 35.9% of the variance (*P*=0.002). The CTF ut line was significantly different from the LTP w line (*tP*=0.006). As soil bulk density increased in the CTF ut treatments biomass increased. This may have been due to increased consolidation of soil around the seed by increased soil bulk density promoting better seed germination (similar to Figure 14.14 a). Alternatively, the effect could have been caused by leverage in the model as most CTF ut values are grouped closely together with an outlier (x=1.4, y=11.88). An increase in soil bulk density in the two wheeled treatments (STP w and LTP w) resulted in a decrease in biomass as identified in the literature (Czyz, 2004).

At 50-100 mm depth the data was best fitted by a single line (Figure 4.15 b) accounting for 19.5% of the variance (*P*=0.001). This showed that an increase in soil bulk density resulted in reduced biomass irrespective of traffic treatment. There was no significant model for 100-150 (*P*=0.325), 150-200 (*P*=0.341) and 200-250 mm depth (*P*=0.364) shown at Figures 14.15 c-e.

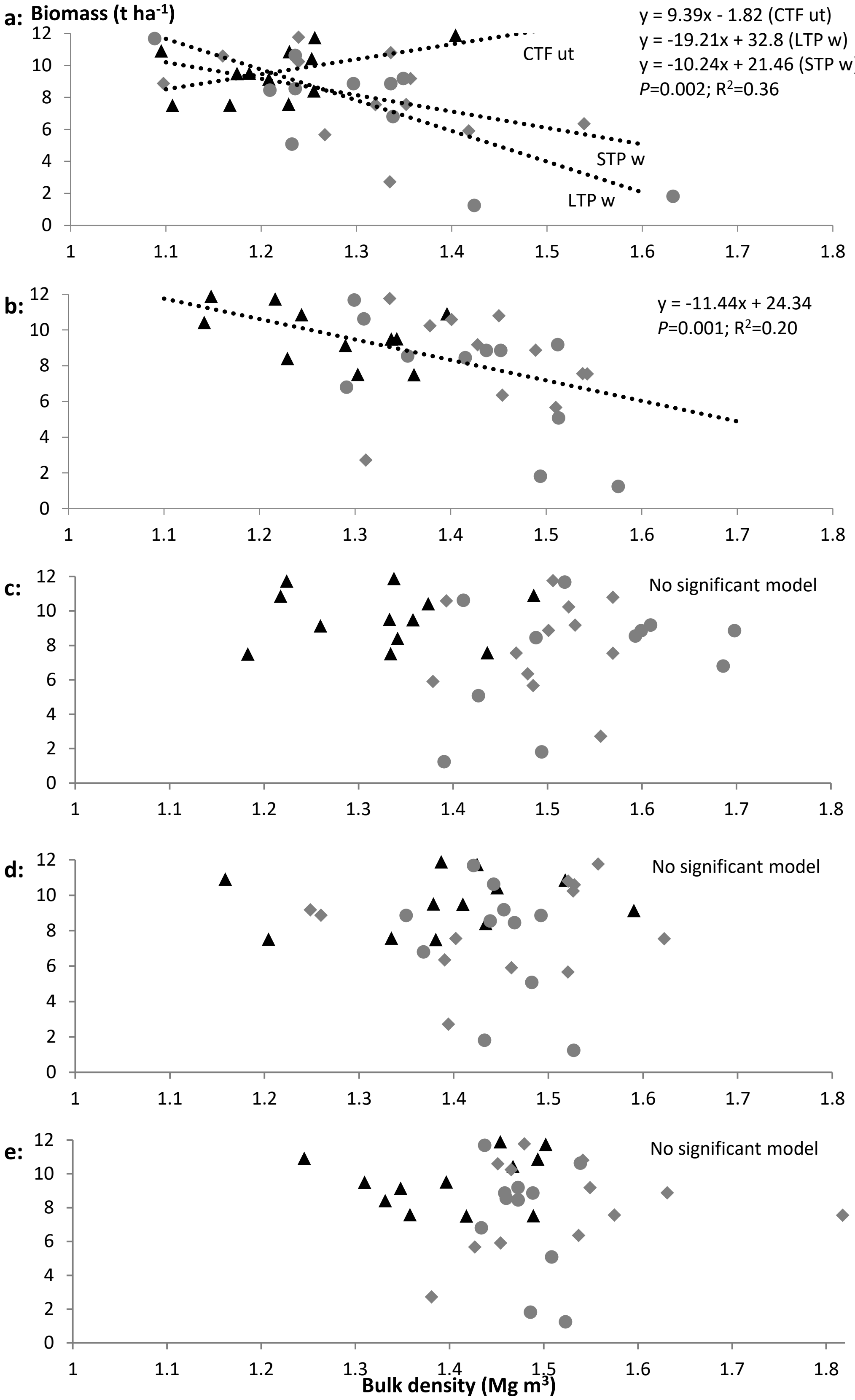

Figure 4.15 - Linear regression analysis (with traffic groups) of the relationship between bulk density (Mg m^{-3}) and spring oat biomass (t ha^{-1}) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth

(Markers: triangle black - CTF ut, circle grey - LTP w , diamond grey - STP w)

4.4.5.2 The relationship between soil shear strength and spring oat biomass at GS 83

The relationship between mean soil shear strength and spring oat biomass (at GS 83) was investigated using simple linear regression with groups (tillage and traffic). The linear regression models for the tillage means for 100, 200 and 300 mm depths are shown at Figure 4.16. The 100 mm depth data was best fitted by three parallel lines (Figure 4.16 a) accounting for 32.5% of the variance (*P*=0.001). The model showed that as soil strength increased there was a small reduction in biomass indicating that increases in shear strength up to 0.6 MPa at 100 mm depth have little effect upon biomass. The zero tillage line was significantly different from the deep tillage line (*tP*=0.002) and shallow tillage line (*tP*=0.005). This was similar to the results in Figure 4.14 b-e which showed that deep and shallow tillage treatments resulted in significantly more biomass than the zero tillage treatment. The models for 200 mm model (Figure 4.16 b) was similar to the 100 mm model. The 200 mm depth data was best fitted by three parallel lines (Figure 4.16 b) accounting for 32.4% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002). For the 300 mm depth the data was best fitted by three parallel lines (Figure 4.16 c) accounting for 32.7% of the variance (*P*=0.001). Unlike Figure 4.16 a and b, an increase in soil shear strength was associated with a small increase in biomass. The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002).

Unlike the relationship between soil bulk density and biomass (for tillage) at 0-50 mm depth (Figure 4.14 a) which showed that an increase in soil bulk density reduced biomass, an increase in soil shear strength (at 100, 200 and 300 mm depth) had little effect on biomass. This was similar to the soil bulk density and biomass results from 50-250 mm (Figures 4.14 b-e). As compaction is often present in layers within the soil profile, it is possible that the readings at 100, 200 and 300 mm did not measure any compaction that might affect biomass (i.e. 0-50 mm; Figure 4.14 a). This would agree with Freitag (1971) who considers the shear vane not to be the most suitable instrument for measuring compaction. Deep and shallow tillage treatments resulted in significantly more biomass than the zero tillage treatment irrespective of the soil shear strength at any of the three depths.

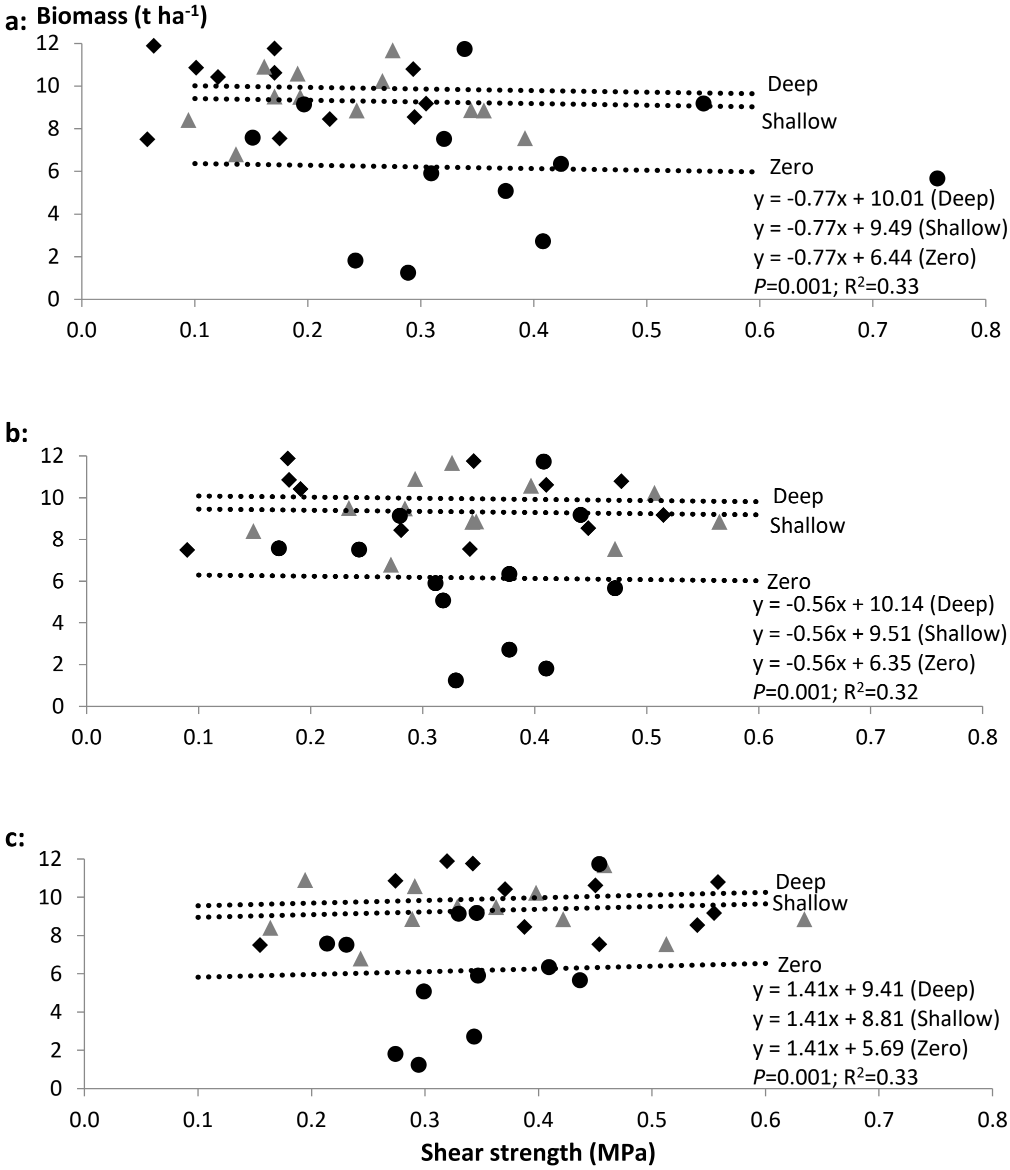

Figure 4.16 - Linear regression analysis (with tillage groups) of the relationship between shear strength (MPa) and spring oat biomass (t ha^{-1}) at a:100, b:200, c:300 mm depth (Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

The linear regression models for the traffic means for 100, 200 and 300 mm depths are shown at Figure 4.17. The 100 mm depth data was best fitted by a single line (Figure 4.17 a) accounting for 11.4% of the variance (P=0.025). The model showed there was a decrease in biomass associated with an increase in soil shear strength that was more pronounced than that for the data grouped for tillage (Figure 4.16 a) however the model only accounted for 11.4% of the variance compared to 33% for the tillage model. The single line model suggests that an increase in soil shear strength resulted in reduced biomass irrespective of traffic treatment. There was no significant model for the 200 mm depth (P=0.262).

At the 300 mm depth the data was best fitted by three parallel lines accounting for 15.3% of the variance (P=0.001). An increase in soil shear strength was associated with an increase in biomass. The CTF ut line was significantly different from the LTP w line (tP=0.014) and STP w line (tP=0.022) indicating that biomass was significantly reduced by increased soil shear strength at 300 mm due to vehicular traffic. Figure 4.17 showed that soil shear strength tended to be lower in the CTF ut treatments at all three depths.

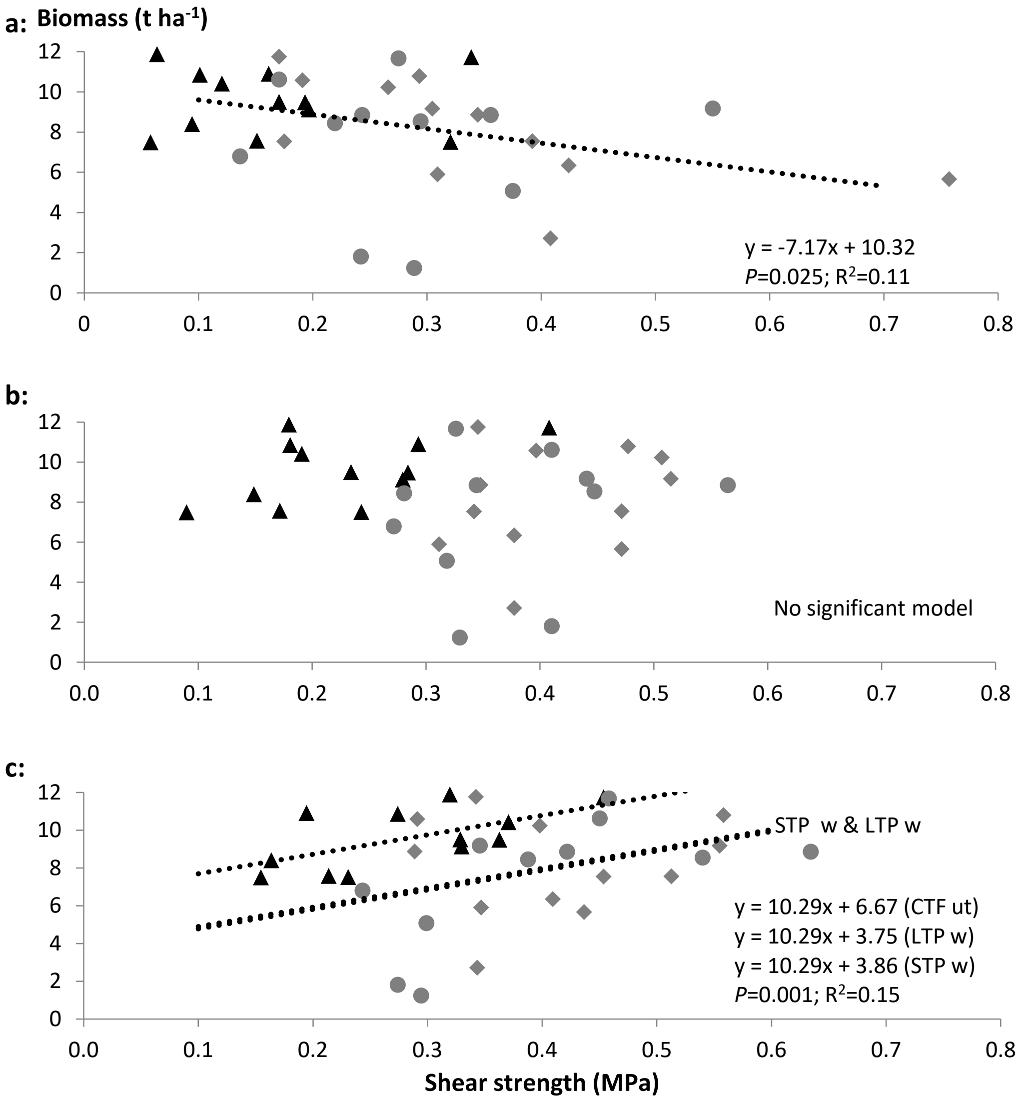

Figure 4.17 - Linear regression analysis (with traffic groups) of the relationship between shear strength (MPa) and spring oat biomass (t ha^{-1}) at a:100, b:200, c:300 mm depth (Markers: triangle black - CTF ut, circle grey - LTP w , diamond grey - STP w)

4.4.5.3 The relationship between soil penetration resistance and spring oat biomass at GS 83

The relationship between soil penetration resistance and spring oat biomass (at GS 83) was investigated using simple linear regression with groups (tillage and traffic). The linear regression models for the tillage means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 4.18. The 0-50 mm depth data was best fitted by three parallel lines (Figure 4.18 a) accounting for 46.7% of the variance (*P*<0.001). There was no significant difference between the lines therefore a single line ($y = -8.51x + 14.71$) could be used to describe the fit which accounted for 44.7% of the variance. This single line model predicts that at 0-50 mm depth an increase in bulk density of 0.5 Mg m^{-3} biomass would decrease by 4.26 t ha^{-1}. The depths 50-100,100-150,150-200 and 200-250 mm all had similar models as follows. The 50-100 mm depth data was best fitted by three parallel lines (Figure 4.18 b) accounting for 32.7% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*=0.002) and shallow tillage line (*tP*=0.008). The 100-150 mm depth data was best fitted by three parallel lines (Figure 4.18 c) accounting for 32.7% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (t*P*=0.003). The 150-200 mm depth data was best fitted by three parallel lines (Figure 4.18 d) accounting for 32.6% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002). The 200-250 mm depth data was best fitted by three parallel lines (Figure 4.18 e) accounting for 32.4% of the variance (*P*=0.001). The zero tillage line was significantly different from the deep tillage line (*tP*<0.001) and shallow tillage line (*tP*=0.002). Except for the 0-50 mm depth, the models (Figure 4.18 b-e) would indicate that biomass was largely unaffected by changes in penetration resistance between 50-250 mm depth.

According to Shah *et al.* (2017) soil with penetration resistance approaching 2 MPa restricts root growth and that above this limit roots are unable to grow. This might explain the drop in biomass in the zero tillage treatments between 50-100 mm depth (Figures 4.18 b and c) but does not seem to hold true below 100 mm (Figures 4.18 d and e) as some penetration resistance values were in excess of 2 MPa for the tillage treatments and biomass slightly increased with increasing penetration resistance. This may be due to the presence of continuous pore systems produced in the tilled soils as described by Ehlers *et al.* (1983) allowing better root growth and consequently better biomass production.

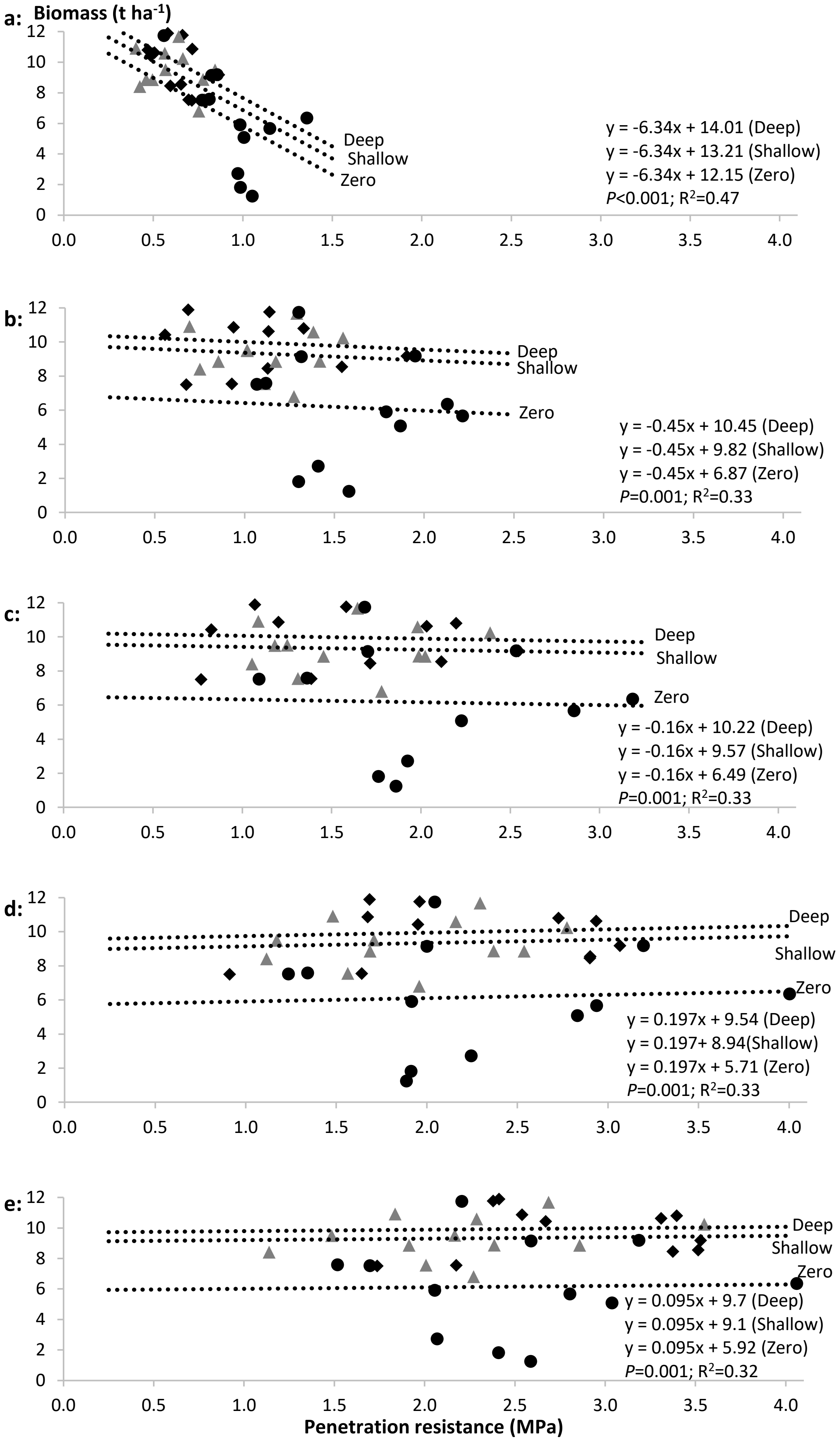

Figure 4.18 - Linear regression analysis (with tillage groups) of the relationship between penetration resistance (MPa) and spring oat biomass (t ha^{-1}) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth

(Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

The linear regression models for the traffic means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 4.19. For 0-50 mm depth the data was best fitted by three separate lines (Figure 4.19 a) accounting for 48.1% of the variance (P<0.001). All three lines showed that as penetration resistance at 0-50 mm depth increased biomass decreased. There was no significant difference between the lines therefore a single line (y = -8.51x + 14.71) could be used to describe the fit accounting for 44.7% of the variance (as determined for Figure 4.18 a). The 50-100 mm depth data was best fitted by a single line (Figure 4.19 b) accounting for 12.8% of the variance (P=0.018). This single line model predicts that an increase in bulk density of 0.5 Mg m^{-3} at 50-100 mm depth decreases biomass by 1.29 t ha^{-1}. The data could not be fitted by a significant model for 100-150 (P=0.137), 150-200 (P=0.801) and 200-250 mm depths (P=0.807). The analysis would indicate that biomass was not affected by increased penetration resistance due to traffic below 100 mm depth.

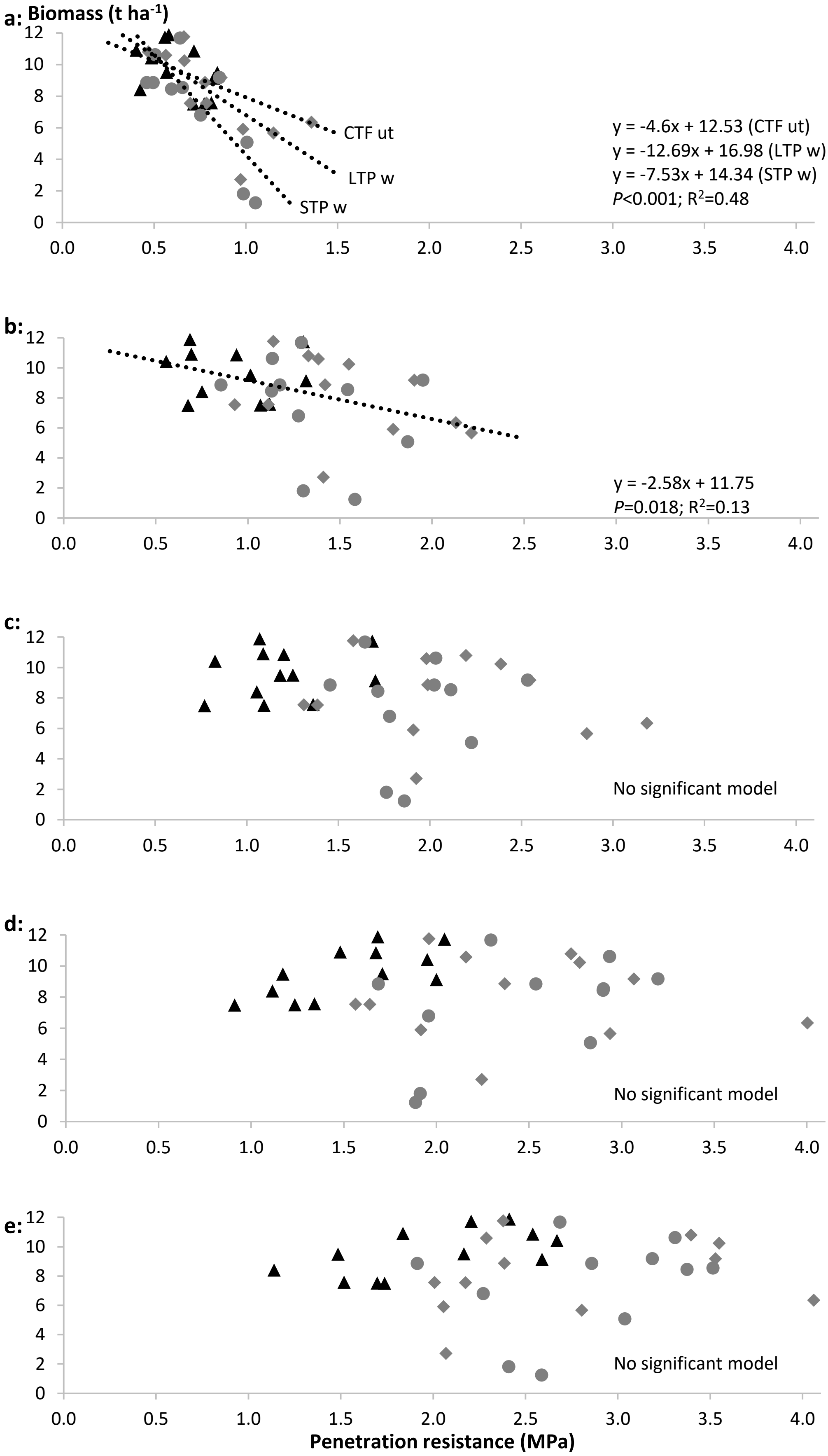

Figure 4.19 - Linear regression analysis (with traffic groups) of the relationship between penetration resistance (MPa) and spring oat biomass (t ha^{-1}) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth
(Markers: triangle black - CTF ut, circle grey - LTP w , diamond grey - STP w)

4.5 Conclusion

The objectives for this part of the research were:

1. To determine the changes in soil shear strength, penetration resistance and bulk density due to the traffic and tillage treatments.

2. To determine the effect of the traffic and tillage treatments on crop biomass.

Vehicular traffic significantly (P<0.001) increased soil bulk density between 0-250 mm depth compared to untrafficked treatments (CTF ut). The was no significant differences in mean bulk densities for the trafficked treatments (LTP w and STP w). There was no significant difference between the mean soil bulk density (0-250 mm depth) of the tillage treatments. The mean soil bulk densities for all treatments were between 1.33 and 1.45 Mg m^{-3} identified by Negi *et al.* (1981) as being optimum for maximum corn yields. These results indicate that to avoid increasing soil bulk density field traffic should be avoided. Tillage is known to reduce bulk density temporarily and then the soil returns to its former bulk density. This may account for there being no significant difference in bulk density being found between the tillage treatments.

Vehicular traffic significantly (P<0.001) increased soil shear strength (0-300 mm depth) compared to untrafficked treatments (CTF ut). Generally the LTP w treatments had lower soil shear strength than the STP w treatments but there was no significant difference in the soil shear strength for the two tyre inflation pressure treatments. Deep tillage significantly (P=0.030) decreased soil shear strength compared to the zero tillage treatments.

Readings were significantly (P<0.001) higher (LTP w 25% and STP w 24%) in the traffic treatments than in untrafficked (CTF ut) but there was no significant difference between STP w and LTP w. There was no significant difference in penetration resistance between the tillage treatments . At 150 mm depth, penetration resistance in the deep tillage treatments continued to increase at a higher rate than for shallow and zero tillage. This deeper compaction in the deep tillage treatments agrees with other researchers findings that deep tillage can reduce the bearing capacity of soil leading to recompaction by subsequent vehicle traffic.

The results show that vehicular traffic increases the bulk density, shear strength and penetration resistance of soil. The use of Controlled Traffic Farming to avoid field traffic is therefore a sensible way of reducing soil bulk density, soil shear strength and penetration resistance. The use of low inflation pressure tyres did not show any significant reduction in these measured parameters and therefore their use may not be effective at reducing compaction between 0-250 mm depth.

Biomass was significantly (P<0.001) reduced in the zero tillage treatments compared to the deep and shallow tillage treatments. This may be due to the presence of continuous pore systems in the tilled soils as described by Ehlers *et al.*(1983) allowing better root growth and consequently better biomass production. Regression analysis of soil bulk density and biomass showed that at 0-50 mm depth, an increase in bulk density was associated with an increase biomass in the deep tillage treatments and an decrease in biomass in the shallow and zero tillage treatments. An increase in bulk density was associated with an increase biomass in the CTF ut treatments and a decrease in biomass in the LTP w and STP w treatments. These differences was not apparent at depths between 50-250 mm depth suggesting that the top 50 mm was important to biomass possibly affecting plant establishment. As identified in the literature, increases in biomass in the deep tillage and CTF ut treatments associated with increases in bulk density may be due to better seed to soil contact increasing establishment rate. Regression analysis showed that increases in penetration resistance between 0-50 mm depth were associated with relatively large reductions in biomass. Below this depth changes in biomass due to increases in penetration resistance was smaller. This supports the results from the bulk density and biomass regression that suggests that the strength of the soil in the top 50 mm due to compaction affects biomass possibly due to reduced establishment. As identified in the literature, high soil strength can restrict development of the seedling root reducing plant establishment.

Relating to the hypothesis (Section 4.2) the results confirmed that vehicular traffic increases soil bulk density, shear strength and penetration resistance and that Controlled Traffic Farming is an effective strategy to avoid field traffic and therefore reduce soil bulk density and strength. The use of low inflation pressure tyres was not found to be effective at reducing soil bulk density and strength compared to using standard tyre inflation pressures. Tillage was found to significantly increase biomass. The physical properties of the soil in the top 50 mm of the soil was important to biomass possibly because of the negative effect of higher bulk density and soil strength on plant establishment.

Chapter 5 Soil physical properties: X-ray Computed Tomography

5.1 Introduction

The system of pores within the soil provides the means of transport for air and water (Eden *et al.*, 2011) and necessary nutrients for the growing plant. Soil compaction has a larger effect on large soil pores (Berisso *et al.*, 2012) and reduces the proportion of large to small pores (Kim *et al.*, 2010) that can affect the whole soil profile (Troldborg *et al.*, 2013). The reduction in macro porosity from soil compaction can be sufficient to restrict root survival (Rab *et al.*, 2014) leading to the reduction in crop yield (Czyz, 2004). However, roots can grow along boundaries between soil peds avoiding the root restriction implied by bulk density (Lampurlanés and Cantero-Martinez, 2003). Measurement of soil dry bulk density can be used to determine the effect of vehicular traffic on soil compaction and total soil porosity, but it cannot quantify pore sizes and pore distribution within the soil. Pore size distribution can be estimated by draining a wetted undisturbed soil sample under increasing moisture tensions to produce a soil moisture release curve based on a capillary model associated with pore diameter (Brewer, 1976). Dexter (2004) used the inflection point on the water retention curve as an indication of soil quality but stated that the curves could not be used to give accurate information about soil pore distribution due to the unknown effect from pore connectivity.

X-ray Computed Tomography (CT) uses mathematical reconstructions from attenuation of radiation to produce stacked 2D images to produce 3D models of a soil sample (Vaz *et al.*, 2011). This 3D imaging technique can be used to measure soil pore size and distribution (Rab *et al.*, 2014) allowing visualisation of changes in pore system structure through the soil profile. The process involves a sample (soil core) being rotated incrementally through 360^{o} in X-ray beams. The intensity of the beams diminish as they pass through the sample (attenuation) and are projected onto a detector which measures the change in energy intensity. As the sample is rotated successive projections of pixels based on the attenuation are created and these are then reconstructed into cross sectional 2-D images (slice) through the 3-D object (Mooney *et al.*, 2012). Each image is made up of 3-D pixels (voxels) based on the X-ray resolution (Calistru and Jitareanu, 2015). To detect pore space the reconstructed images are segmented (Taud *et al.*, 2005) using a threshold tool on an 8-bit greyscale image. Values lower than the threshold are considered air-filled pore space and those above are considered solid matter (Kim *et al.*, 2010).

5.2 Research hypothesis and objectives

The hypothesis for this research was that soil macro porosity is reduced by soil compaction due to vehicular traffic as measured by percentage soil porosity, pore size distribution and connectivity and that by using Controlled Traffic Farming, low inflation pressure tyres and reduced tillage systems, soil compaction is reduced and soil macro porosity increased.

The objectives were to use X-ray Computed Tomography:

1. To determine the changes in soil porosity resulting from three traffic treatments (wheeled using standard tyre inflation pressures, wheeled using low tyre inflation pressures and untrafficked) and three tillage treatments (deep (250 mm), shallow (100 mm) and zero tillage (no-till)).

2. To determine the effect of the traffic and tillage treatments on soil pore distribution, pore connectivity and pore circularity.

3. To determine the relationship between X-ray CT derived porosity and soil bulk density derived porosity.

5.3 Methodology

In 2011, a long-term study was set up on the Large Marsh field at Harper Adams University UK to investigate the effect of three traffic systems (Random Traffic Farming - standard tyre inflation pressure (STP), Random Traffic Farming - low tyre inflation pressure (LTP) and Controlled Traffic Farming (CTF)) and three tillage systems (deep (250 mm), shallow (100 mm) and zero (no-till)) on soil properties, crop yield and energy requirements. The soil is a sandy loam, mainly Claverley, with small areas of Olerton and Salwick (Beard, 1988). The methodology for applying the treatments is described in Chapter 3.

This chapter details the results of an X-ray Computed Tomography study undertaken in 2016 to measure soil properties of undisturbed soil cores. It is a companion study to the study described in Chapter 4. Spring oats were drilled 25 April 2016 at a row spacing of 167 mm with a seed rate of 350 seeds/m^2 (+ 30% on zero tillage plots). Soil core samples were taken in August 2016 from unwheeled centres (crop rows 17-18) in the Controlled Traffic Farming (CTF ut) plots and from the main wheelways (crop rows 11-12) in the

Random Traffic Farming - standard tyre inflation pressure (STP w) and Random Traffic Farming - low tyre inflation pressure (LTP w).

Note: suffixes used in this chapter are ut - untrafficked, w - wheeled, deep - deep tillage, shallow - shallow tillage and zero - zero tillage. Samples taken from CTF ut zero have not been subjected to traffic or tillage and therefore could be used as a reference point for the purposes of analysis.

5.3.1 Soil cores

An undisturbed soil core was taken from the centre of the plant sampling areas (Figure 4.1) using an Eijkelkamp soil core sampler (Figure 4.2) with sample liners of ø50 mm x 300 mm length in accordance with Eijkelkamp (Not dated). Results found by Rab *et al.* (2014) confirmed that a ø50 mm soil core did not have significant soil compaction around its edge and was a suitable size to use in X-ray CT studies of micro porosity. The volumetric soil moisture content was 23% (equivalent to field capacity, see Figure 4.13) at the time the cores were collected. All soil core samples were stored in the PVC liner with cap fitted (an example is shown at Figure 4.3) standing upright in the dark at 4^{o}C to avoid drying out and to reduce microbial activity.

5.3.2 X-ray scanning

The soil cores were scanned using a Phoenix v|tome|x m X-ray microfocus CT system (The University of Nottingham, Not dated) at the Hounsfield Facility, the University of Nottingham, UK as used by Burr-Hersey *et al.* (2017) to investigate soil bulk density effects on cover crop development. The X-ray scanning was carried out by staff of the Hounsfield Facility. Figure 5.1 (centre) shows a soil core mounted vertically supported by a PVC tube. This was a typical X-ray Computed Tomography cone-beam configuration setup (Wildenschild and Sheppard, 2013) as shown in Figure 2.13. When in operation X-rays are emitted from the source (right) and pass through the sample which rotates incrementally through 360^{o}. Attenuated X-rays are collected by the flat panel detector (left).

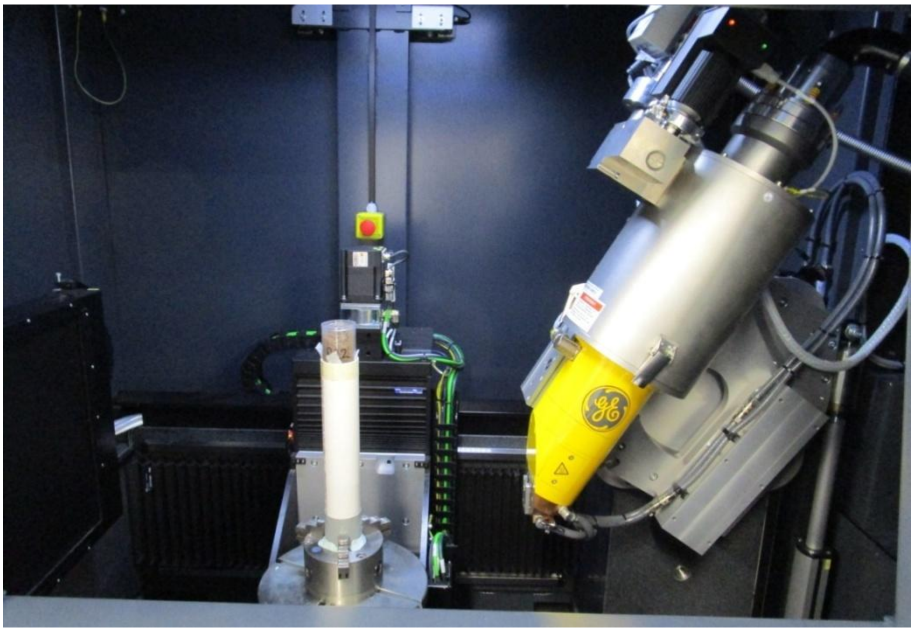

Figure 5.1 - Phoenix v|tome|x m X-ray microfocus CT system

The CT system parameters were 160 KV, 180 µA, 200 ms detector time and 72 µm resolution. As this was a comparative study the compromise between resolution, sample size and CT scanner beam time was considered acceptable as higher resolutions produce a smaller field of view and can miss pore structure information (see also Section 5.5) due to heterogeneity in the larger sample (Peng *et al.*, 2012). In order to cover the full length of the core, three scans were required, 0-100 mm, 100-200 mm and 200-300 mm depth. Scan files were exported as volume files. The three volume files were combined using VG Studio MAX 2.0 software (Figure 5.2) and the resultant 3D X-ray attenuation maps exported as top view (cross sectional area) tiff files.

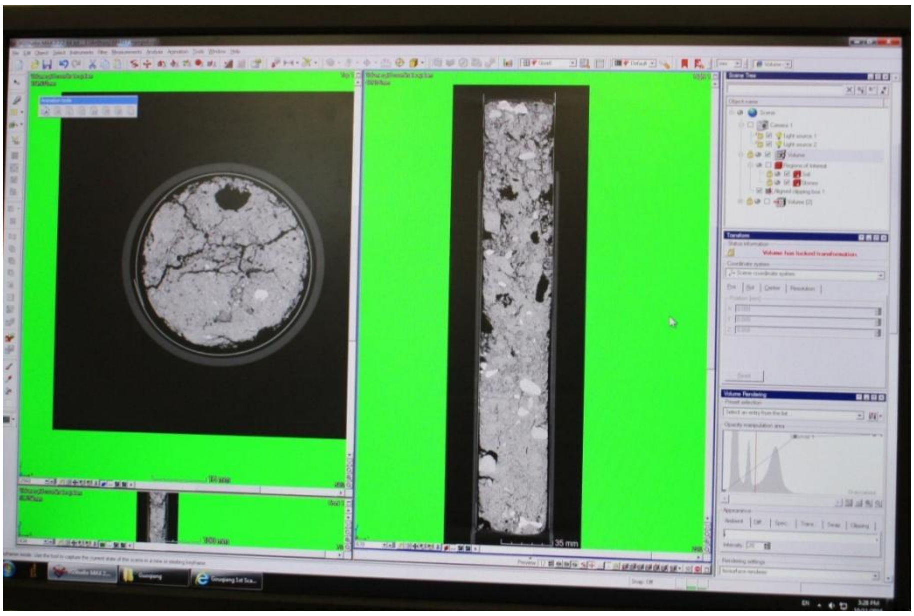

Figure 5.2 - Top view (left) and side view (right) of combined X-ray CT scans in VG Studio

5.3.3 Image analysis

Stacked images were analysed using ImageJ version 1.50i (Rasband, 2009). An area of interest 400 pixel (28.8 mm) x 400 pixel in the centre of the images was selected (Figure 5.3) and the exterior of the images discarded to reduce any effect from beam hardening and deformation from the soil core tool. Beam hardening is a brightening of the objects image around the outer edges produced by greater attenuation of lower energy photons relative to high energy photons. The effect can be reduced by use of a filter between the x-ray source and the sample (Helliwell *et al.*, 2013; Rab *et al.*, 2014). Soil pore space was selected by segmenting (Figure 5.4) using the Li thresholding algorithm (Figure 5.5) based on Li and Tam, (1998) on binary images. Values below the threshold were identified as pore space. The ImageJ 'Analyse Particles' function analyses the pore space for all of the stacked images and outputs data as a spreadsheet containing the calculated total number of pores, total porosity area, mean pore size and mean pore circularity for each image slice. The full ImageJ pore space analysis procedure used is given in Appendix D and is similar to that used by Rachman *et al.* (2005) in a macro porosity study.

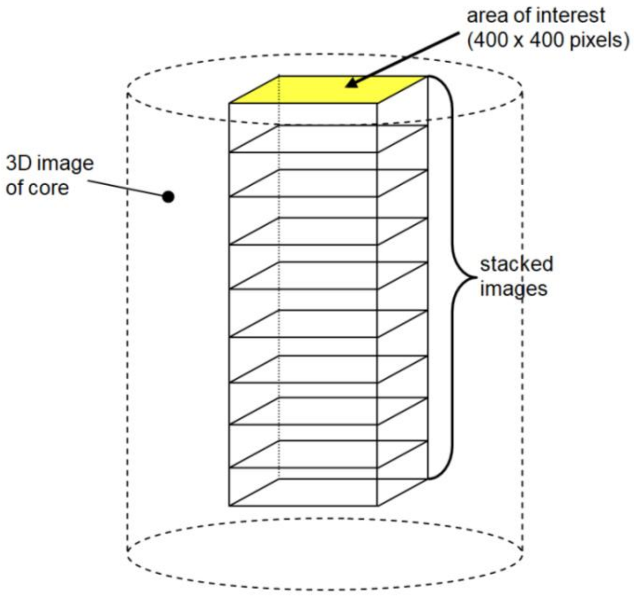

Figure 5.3 - Area of interest selected in stacked images (400 x 400 pixels)

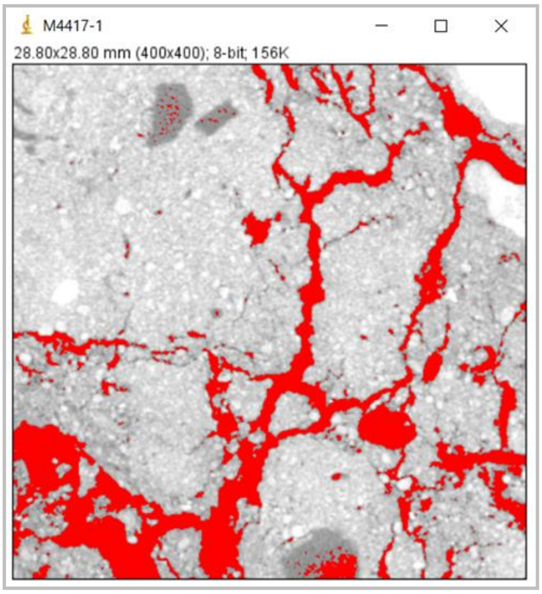

Figure 5.4 - Soil pore space selection on binary image (red) using thresholding

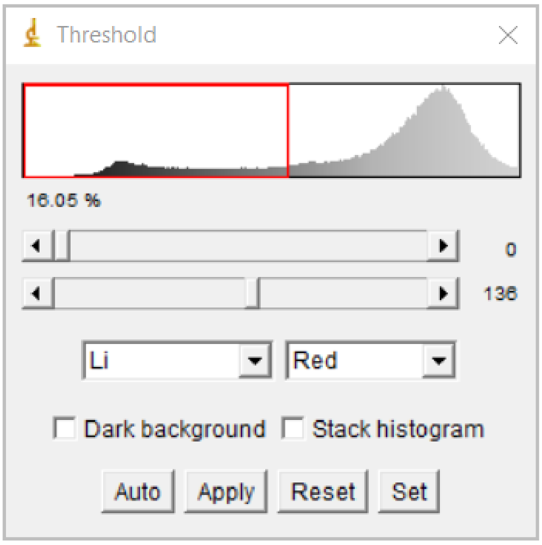

Figure 5.5 - Segmenting using the Li thresholding algorithm
Histogram portion in red box represents pore space

Pore circularity is a measure of how circular pores are in the scan image (a function of perimeter and area as described by Equation 5.1) and has a value of between 0-1 (no units). It is an important parameter for describing soil pore shape (Guo *et al.*, 2018). Pores nearing circular having values closer to 1 (Kim *et al.*, 2010). Pores of 1 or 2 voxels in size return a circularity value of 1 because they are so small. They are more likely to be image 'noise' caused by image mottling from fluctuations in image density from one image to the next (Schmidt *et al.,* 2012). To prevent this noise skewing the results of the circularity analysis all circularity data of pore size 4 voxels and below were excluded.

$$\text{Pore circularity} = 4\pi \times \frac{\text{area}}{(\text{perimeter})^2}$$

Equation 5.1

Changes in soil bulk density, due to compaction, provides information about the total change in the volume of pores in soil but does not account for changes in the distribution of these pores or their connectivity (Alaoui *et al.*, 2011). Pore space connectivity is a measure of structure complexity related to independent pore paths (Pierret *et al.*, 2002). It is difficult to determine the connectivity of macro pores in the field but it can be estimated by using infiltration measurements (Green *et al.*, 2003). In X-ray CT, pore connectivity is provided by measuring the fraction of segmented pore space that has pore voxels that are connected face to face based on the six-connected neighbourhood criterion as illustrated by Figure 5.6 (Houston *et al.*, 2013). VG Studio MAX 2.0 was used to determine the percentage of the pores in each core connected from the surface downwards (between 0 and 250 mm depth) using the 'Volume Analyser' function (the Volume Graphics Quick Method procedure used is given in Appendix D).

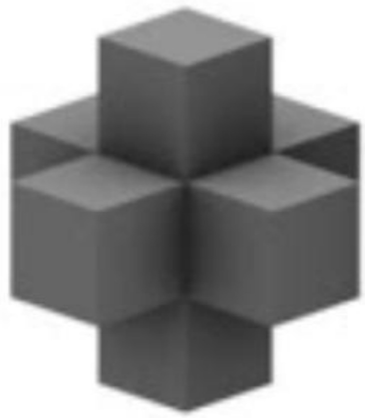

Figure 5.6 - Six-connected voxel connectivity

(Source adapted from: Heinzl *et al.*, 2018)

5.3.4 Statistical analysis

Genstat 18th Edition (VSN International, 2015) was used for statistical analysis of data as described in Section 4.3.3.

5.4 Results and discussion

The action of the soil corer during sample taking and the storage of the cores on their bases loosened the soil at around 275-300 mm depth affecting porosity measurements. In addition some samples were slightly (10-15 mm) shorter than the 300 mm liner length therefore all X-ray CT analysis was conducted on soil core data between 0-250 mm depth.

5.4.1 X-ray CT sample images

The sample images in Figure 5.7 are of vertical cross sections produced from the X-ray CT attenuation maps using the ImageJ software. They illustrate the differences in soil structure between cores from the nine different traffic and tillage sample areas. The deep tillage CTF ut core had a more open structure, illustrating the loosening of the soil by the action of the tillage tine, whilst the STP w deep and LTP w deep showed evidence of possible re-compaction after tillage from vehicular traffic as found by Soane *et al.* (1986). The shallow tillage images showed a more open structure in the upper zone (0-60 mm) only, reflecting the effect of the reduced tillage depth. Unlike in the STP w and LTP w deep tillage treatments, the STP w and LTP w shallow tillage treatments did not indicate recompaction in this upper horizon.

The soil structure around 150 mm depth in the STP w shallow and LTP w shallow images had horizontal cracking as also found by Munkholm *et al.* (2003) and the lack of pore space indicating a platy structure (Munkholm *et al.*, 2003). These pressure induced cracks and lack of voids are associated with agricultural machinery traffic on arable soils and often occur just below the wheel rut and below the tilled layer in the plough pan (Kooistra and Tovey, 1994). Repeated wheeling of soil leads to homogenisation of the soil structure by rearrangement of the soil particles perpendicular to the soil surface by shearing (Horn *et al.*,2003) forming a platy structure with thin elongated pores (Pagliai *et al.*, 2003). The horizontal cracks are a de-loading effect on the soil particles after the passage of the vehicle wheel (Kooistra and Tovey, 1994). The zero tillage STP w and LTP w images showed a more dense structure throughout the profile with the presence of horizontal cracks. This was as expected as the results of the bulk density measurements (Section 4.4.1) indicated that the bulk density in the zero traffic treatments was increased by vehicular traffic. Smith, E. (2016) found that the bulk density in the zero tillage treatments was higher than in deep and shallow tillage treatments.

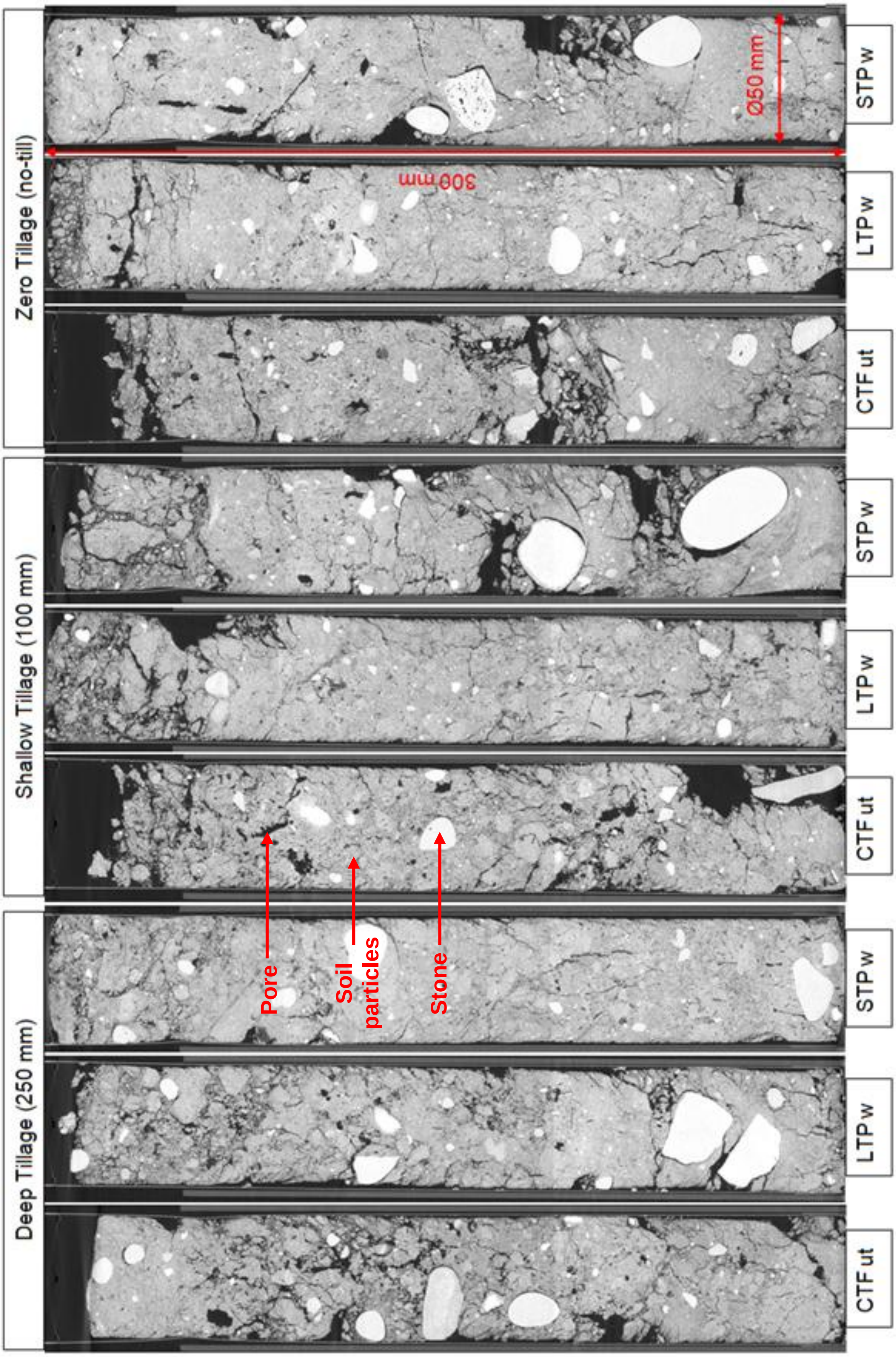

Figure 5.7 - Side view X-ray CT images through centre of soil cores produced using ImageJ software
Pores are shown as black, soil particles as grey and stones as white in the images.

5.4.2 X-ray CT measured percentage porosity

Figure 5.8 shows the CT measured mean porosity for the nine treatments for 0-250 mm depth. The comparison of deep tillage treatments (Figure 5.8 a) illustrates the significant difference in porosity (*P*=0.006, SEM=1.253) between unwheeled (CTF ut) and trafficked (STP w and LTP w) treatments (Table 5.1). Porosity in the three treatments was above 20% at the surface but STP w and LTP w values steadily reduced to around 7% at 120 mm depth and then remained constantly low down to 250 mm. The porosity in the CTF ut treatments remained high (25%) until 120 mm depth and then reduced gradually to 15% at 200 mm depth and remained at this porosity until 250 mm depth. Soane *et al.* (1986) demonstrated that deep tilled soils lacked the strength to support vehicle traffic and consequently were susceptible to re-compaction often worse than previous to cultivation. This effect can be seen in the low percentage porosity in the curves from STP w and LTP w with STP w being more compacted than LTP w. The CTF ut percentage porosity remained between 20-30% between 0-120 mm depth and then reduced steadily to 10% at 220 mm and remained at this porosity to 250 mm depth. The percentage porosity curves in the shallow tillage treatments (Figure 5.8 b) were similar to each other in value and form as reflected in the mean values in Table 5.1. The action of the tillage increased porosity between 0-50 mm compared to the even porosity (10-20%) between 50-250 mm. LTP w and CTF w porosity curves were less variable in form than STP w. Percentage porosity decreased quickly in the zero tillage treatments for STP w and LTP w (Figure 5.8 c). LTP w had the lowest porosity (5-10%) with STP w having more variability with areas of increased porosity throughout the profile. CTF ut treatments had better percentage porosity (15%) but had areas of increased porosity at 150 mm and 250 mm which may have been due to remnants of historical field management or the result of heterogeneous vertical soil compaction as indicated by Pfeifer *et al.* (2014).

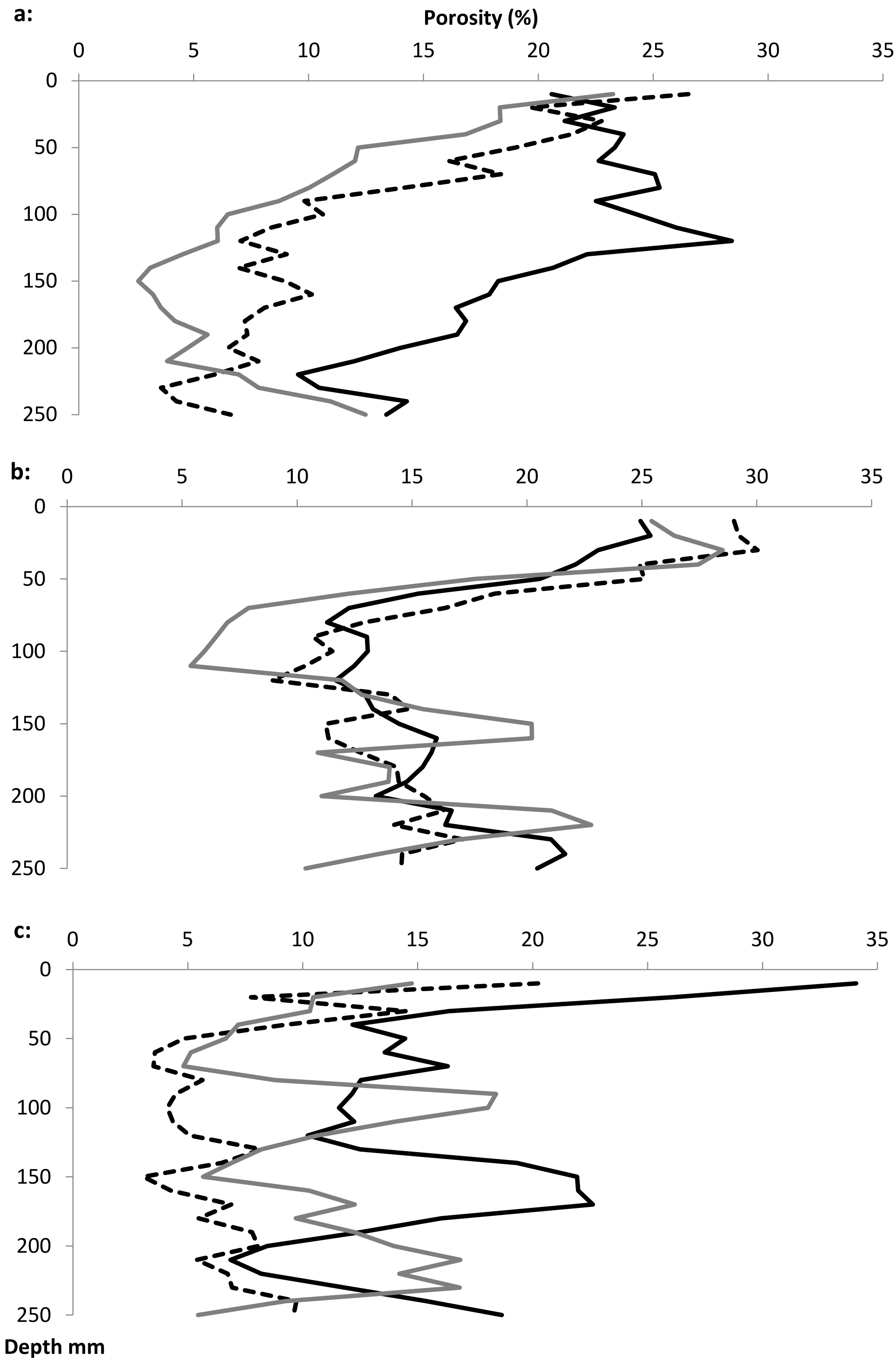

Figure 5.8 - X-ray CT measured porosity (%) for traffic and tillage treatments a: deep tillage, b: shallow tillage, c: zero tillage
(Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)

The results of the repeated measures ANOVA analysis of the CT measured porosity (0-250 mm depth in 50 mm increments) are given in Table 5.1. Statistical analysis of the CT measured porosity for 0-50, 50-100, 100-150, 150-200 and 200-250 mm soil depths is given in Appendix C. Percentage porosity was significantly higher in CTF ut treatments

(46%) than LTP w and STP w treatments. Deep tillage increased porosity in the CTF ut treatments from 15.4% in CTF ut zero (control) to 19.5% and in LTP w treatments from 7% (LTP w zero) to 11.5%. In STP w treatments deep tillage reduced porosity from 10.8% (STP w zero) to 8.9%. Shallow tillage had little effect on porosity in the CTF ut plots but resulted in the maximum porosity for LTP w and STP w plots (16.5% and 15.4% respectively) similar to the CTF zero porosity of 15.4%. This indicates that on unwheeled soil, shallow tillage was unnecessary but on trafficked soil it was the most suitable tillage for returning porosity to levels comparable to untrafficked soil.

Table 5.1 - CT-measured mean porosity (%) 0-250 mm depth

	CT measured porosity (%)			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	19.5	16.5	15.4	17.1[b]
LTP w	11.5	16.5	7.0	11.7[a]
STP w	8.9	15.4	10.8	11.7[a]
Mean	13.3[ab]	16.2[b]	11.1[a]	

(Traffic: *P*=0.006, SEM=1.25; Tillage: *P*=0.029, SEM=1.25; %CV=35.8)

(**Note**: Means not followed by the same letters are significantly different from each other)

Changes in percentage porosity was significant with depth ($P<0.001$) and depth x tillage ($P<0.001$). The top 50 mm of the soil profile was likely to have been affected by the action of the Topdown discs during tillage (deep and shallow) and the drilling operation. It was also likely to have been more influenced by weather and microbial action than lower parts of the soil profile (Kay and VandenBygaart, 2002). This was illustrated by the larger porosity levels in the 0-50 mm depth section shown in Figure 5.9. Below this level the porosity within the soil profile decreased under deep tillage. In the shallow tillage treatments, after an initial drop in porosity between 0-50 and 50-100 mm, porosity increased with depth. Porosity remained constant in zero tillage treatments below the 0-50 mm depth.

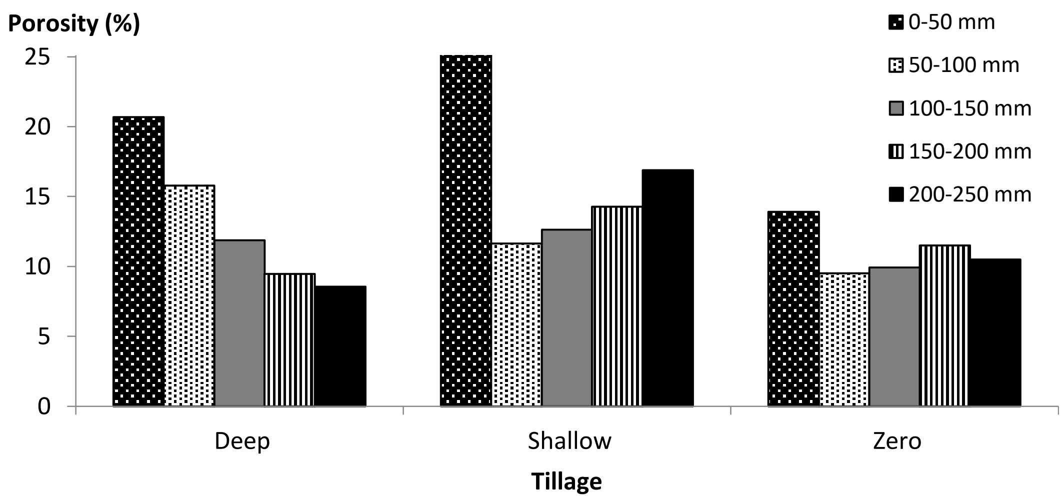

Figure 5.9 - The effect of tillage treatments and soil depth on CT measured porosity (%) means (0-250 mm depth in 50 mm intervals)

Soane *et al.* (1986) and Yavuzcan *et al.* (2002) found that soil that had been deep tilled had reduced bearing capacity and was easily recompacted which is illustrated by the reduction in porosity with depth for the deep tillage treatment (Figure 5.9). The soil in the shallow tillage treatments was tilled to 100 mm depth, therefore the soil below this depth would have retained its bearing capacity similar to that of the untilled soil which is indicated by an absence in soil compaction (no reduction in soil porosity).

Table 5.1 shows the significant differences in X-ray CT mean porosity between traffic and tillage treatments between 0-250 mm depth. To investigate significant differences with depth ANOVA analysis was carried out at 50 mm intervals and the mean porosity for the traffic and tillage treatments are presented in Table 5.2.

Zero tillage treatment mean porosity was significantly (P=0.007, SEM=2.3) lower (45%) than porosity in the shallow tillage treatments (Table 5.2 a). This can be attributed to the low porosity in the trafficked treatments (LTP w 9.9% and STP w 11.3 %) which were 45 and 52% lower respectively than in the untrafficked CTF ut (20.6%) treatments. Although not significantly higher than the deep tillage treatments, shallow tillage produced the highest soil porosities with LTP w treatments having the highest porosity (27.6%) which was 34% higher than for the CTF ut zero tillage (no traffic and no tillage treatment) mean (20.6%). X-ray CT porosity in the LTP w (10.7%) and STP w (9.5%) treatments were significantly (P<0.001, SEM=1.22) lower (36 and 43% respectively) than in the CTF ut (16.7%) treatments at 50-100 mm depth (Table 5.2 b). Deep tillage treatments had 15.8% porosity which was significantly (P=0.004, SEM=1.22) higher (66%) than the zero tillage treatments (9.5%). The lowest percentage porosity was in the LTP w zero tillage treatments (4.3%). CTF ut deep tillage treatments had the highest porosity (24.0%) which was significantly higher than the porosities in the STP w treatments and CTF ut shallow tillage and LTP w zero tillage treatments (P=0.006, SEM=2.11). Although there was no significant difference in tillage means at 100-150 mm depth (Table 5.2 c), CTF ut deep tillage porosity (23.1%) was 51% higher than for CTF ut zero tillage (15.3%) and was higher (P=0.052, SEM=3.06) than LTP w zero tillage (5.4%) and STP w deep tillage (4.4%). The reduction in porosity in the deep tillage treatments due to traffic (65 and 81% for LTP w and STP w respectively) compared to CTF ut (23.1%) was a contributing factor in the significantly (P=0.003, SEM=1.77) lower porosity in the traffic treatment means (LTP w 8.4%, STP w 8.9%) compared to CTF ut treatments (17.1%). At 150-200 mm depth (Table 5.2 d) there was also a reduction in porosity in the deep tillage traffic treatments (LTP w 52% and STP w 74%) compared to the mean porosity in the CTF ut treatments (16.3%). This reduction (probably due to recompaction) was the main reason that deep tillage treatment mean porosities were lower (P=0.069, SEM=1.39) than shallow tillage treatment porosity and that traffic treatment mean porosities (LTP w 9.4%, STP w

10.0%) were significantly (*P*=0.005, SEM=1.39) lower than in the CTF ut treatments (15.9%). Interestingly shallow tillage had the highest porosities in the three traffic treatments between 150-250 mm depth with the mean porosities being similar in the untrafficked and trafficked treatments at 150-200 mm depth (13.7-15.1%, Table 5.2 d) and at 200-250 mm depth (15.4-17.0%, Table 5.2 e). These depths are well below the effective working depth of the shallow tillage tines (100 mm). The shallow tillage treatment porosity means were significantly higher (*P*=0.015, SEM=1.94) than the deep tillage treatment means at 200-250 mm depth (Table 5.2 e). This was again due to the reduction in porosity (LTP w 53% STP w 32%) in the deep tillage traffic treatments compared to CTF ut. Deep tillage produced the same mean porosity as zero tillage in the untrafficked (CTF ut) treatments at 150-200 and 200-250 mm depth.

Table 5.2 - X-ray CT measured percentage porosity means 0-250 mm depth (50 mm intervals)

a: Porosity (%) 0-50 mm depth

Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	22.4	23.2	20.6	22.1
LTP w	21.9	27.6	11.3	20.3
STP w	17.8	25.1	9.9	17.6
Mean	20.7^{ab}	25.3^{b}	13.9^{a}	

b: Porosity (%) 50-100 mm depth

Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	24.0	13.0	13.2	16.7^{b}
LTP w	13.8	14.0	4.3	10.7^{a}
STP w	9.6	7.9	11.0	9.5^{a}
Mean	15.8^{b}	11.6^{ab}	9.5^{a}	

c: Porosity (%) 100-150 mm depth

Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	23.1	13.0	15.3	17.1^{b}
LTP w	8.1	11.7	5.4	8.4^{a}
STP w	4.4	13.2	9.1	8.9^{a}
Mean	11.9	12.6	9.9	

d: Porosity (%) 150-200 mm depth

Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	16.3	15.1	16.3	15.9^{b}
LTP w	7.9	13.7	6.5	9.4^{a}
STP w	4.3	14.0	11.7	10.0^{a}
Mean	9.5^{a}	14.3^{b}	11.5^{ab}	

e: Porosity (%) 200-250 mm depth

Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	11.9	18.3	11.4	13.9
LTP w	5.6	15.4	7.7	9.6
STP w	8.1	17.0	12.5	12.5
Mean	8.6^{a}	16.9^{b}	10.5^{ab}	

(**Note**: Means not followed by the same letters are significantly different from each other)

5.4.3 The relationship between X-ray CT measured porosity and spring oat biomass at GS 83

The relationship between mean X-ray CT measured porosity and spring oat biomass (at GS 83) was investigated using simple linear regression with groups (tillage and traffic). The linear regression models for the tillage means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 5.10.

The 0-50 mm depth data was best fitted by three separate lines (Figure 5.10 a) accounting for 50.2% of the variance (P<0.001). The model showed that at 0-50 mm depth biomass increased at a rate of 1.4 t ha^{-1} in the zero tillage treatments and 0.4 tha^{-1} in the shallow treatments for every 5% increase in X-ray CT measured porosity. Biomass in the deep tillage treatments decreased by 0.6 t ha^{-1} every 5% increase in X-ray CT measured porosity. The zero tillage line was significantly different from the deep tillage line (tP=0.004). The models for 50-100, 100-150 and 150-200 mm depths had a similar form to the model for 0-50 mm depth indicating that biomass increased in the shallow and zero tillage treatments but decreased in the deep tillage treatments. For the 50-100 mm depth (Figure 5.10 b) the data was best fitted by three separate lines accounting for 40.0% of the variance (P<0.001). There was no significant difference between the lines. For the 100-150 mm depth (Figure 5.10 c) the data was best fitted by three separate lines accounting for 52.9% of the variance (P<0.001). The zero tillage line was significantly different from the deep tillage line (tP=0.004). For the 150-200 mm depth (Figure 5.10 d) the data was best fitted by three separate lines accounting for 58.0% of the variance (P<0.001). The zero tillage line was significantly different from the deep tillage line (tP<0.001). The model for the 200-250 mm depth (Figure 5.10 e) was different from the models at the other depths. The data was best fitted by three parallel lines accounting for 41.1% of the variance (P<0.001). Biomass in all the tillage treatments increased by 0.6 t ha^{-1} every 5% increase in X-ray CT measured porosity at 200-250 mm depth. The zero tillage line was significantly different from the deep tillage line (tP<0.001) and the shallow tillage line (tP=0.014). This model suggests that an increase in X-ray CT measured porosity at 200-250 mm depth increased biomass and that biomass in the tillage treatments was significantly more than in the zero tillage treatments.

As expected the models for 0-200 mm depths show that biomass increase was associated with an increase in X-ray CT measured porosity for the zero and shallow tillage treatments. However this was not seen for the deep tillage treatments where an increase in porosity was associated with a decrease in biomass. Although the X-ray CT measured porosity is a measure of the soil macro porosity (see Section 5.5) it does not give an indication of pore continuity and pore size distribution which are the main characteristics of macro pores that influence the flow of water, nutrients and oxygen as well as providing pathways for root growth (Pierret *et al.*, 2002).

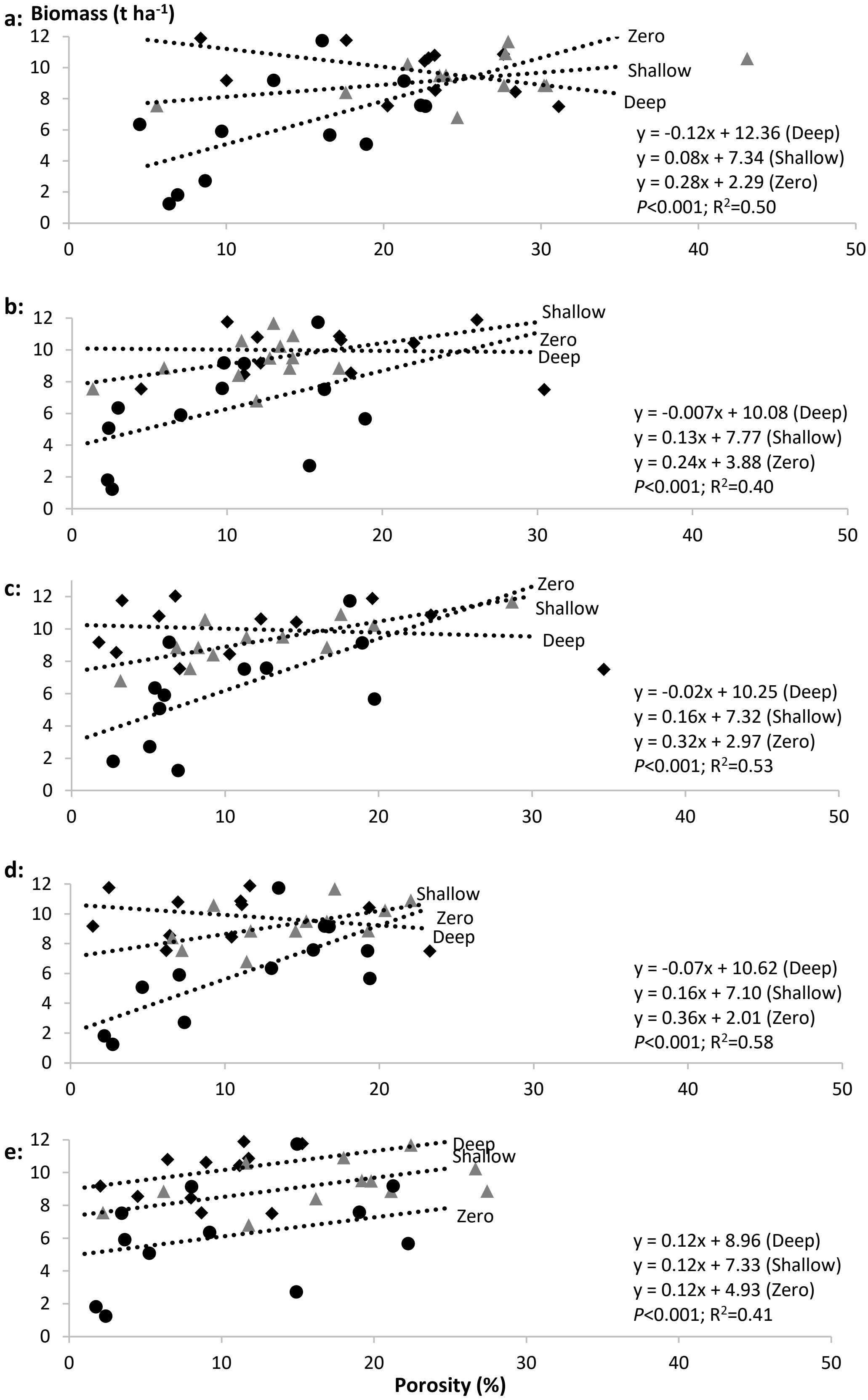

Figure 5.10 - Linear regression analysis (with tillage groups) of the relationship between porosity (%) and spring oat biomass (t ha^{-1}) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth
(Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

The linear regression models for the traffic means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 5.11. For 0-50 mm depth the data was best fitted by three separate lines (Figure 5.11 a) accounting for 27.6% of the variance (P=0.010). The model showed that as the X-ray CT measured porosity increased at 0-50 mm depth biomass increased in the traffic treatments (STP w and LTP w) but decreased in the untrafficked CTF ut treatments. This was similar to the model for tillage at 0-50 mm (Figure 5.10 a) where an increase in X-ray CT measured porosity was associated with a decrease in biomass. The decreases in biomass in the deep tillage and CTF ut treatments, with increases in porosity may have been due to the effect of poor seed to soil contact, reducing establishment (Hallett and Bengough, 2013) or a change in pore size distribution affecting water, nutrient and air flow, affecting plant growth (Pierret *et al.*, 2002). The LTP w line was significantly different from the CTF ut line (tP<0.019). For the 50-100 mm depth (Figure 5.11 b) the data was best fitted by three separate lines accounting for 24.9% of the variance P=0.017. The LTP w line was significantly different from the CTF ut line (tP<0.024). The model was different to the 0-50 mm depth model. In the CTF ut and the STP w treatments an increase in X-ray CT measured porosity was associated with a small difference in associated biomass. There was a large increase in biomass associated with an increase in X-ray measured porosity (2.15 t ha^{-1} for an increase of 5% X-ray CT measured porosity). This would indicate that the pore size distribution in the LTP w treatments was different to that in the CTF ut and STP w treatments. For the 100-150 mm depth (Figure 5.11 c) the data was best fitted by a single line (P=0.040). Although a significant model it only accounted for 9.2% of the variance. An increase in X-ray CT measured porosity at 100-150 mm was associated with a moderate increase in biomass. Below this depth the data could not be fitted by a significant model (150-200 depth (P=0.102) and 200-250 mm depth (P=0.089)).

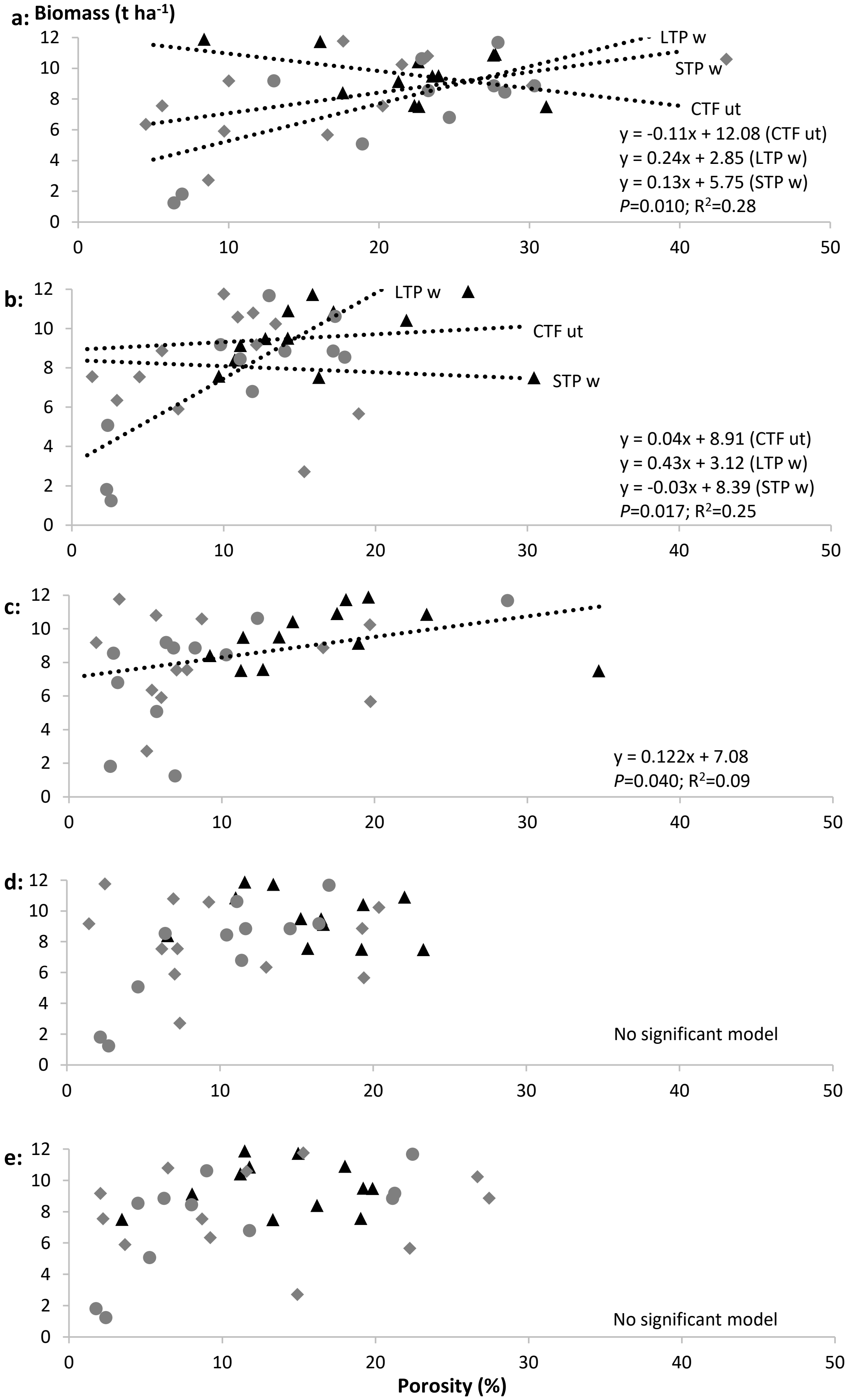

Figure 5.11 - Linear regression analysis (with traffic groups) of the relationship between porosity (%) and spring oat biomass (t ha^{-1}) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth
(Markers: triangle black - CTF ut, circle grey - LTP w , diamond grey - STP w)

5.4.4 Mean number of pores and mean pore size

Repeated measures ANOVA for 0-250 mm depth (Table 5.3) showed that shallow tillage treatments produced 48% more pores than deep tillage treatments (*P*=0.075, SEM=61.2). There was no significant difference in the number of pores between the tillage (*P*=0.075) or the traffic (*P*=0.433) treatments or for their interaction (*P*=0.378).

Table 5.3 - X-ray CT-measured mean number of pores (0-250 mm depth)

	Mean number of pores 0-250 mm depth			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	508	601	600	570
LTP w	421	731	335	496
STP w	338	540	495	458
Mean	422	624	477	

(**Note**: Means not followed by the same letters are significantly different from each other)

Two-way analysis of variance (ANOVA) for 50 mm intervals between 0-250 mm depth, found that there was a significant difference in mean pore size at 150-200 and 200-250 mm depth (Tables 5.4 and 5.5) due to traffic treatments. Mean pore size LTP w (0.139 mm^2) was significantly (*P*=0.012, SEM=0.023) lower (43%) than CTF ut (0.245 mm^2) at 150-200 mm depth (Table 5.4). The biggest contribution to this difference was in the zero tillage treatments where LTP w was 55% lower than in the CTF ut treatments. Although tillage was not statistically significant there was a reduction in mean pore size in the CTF ut treatments compared to zero tillage with pore size decreasing with increasing tillage depth (22% and 42%) for shallow and deep tillage respectively). This may be due to the decreasing number of earthworms associated with tillage on the trial plots as found by (Smith, V.L., 2016).

Table 5.4 - CT-measured mean pore size (150-200 mm depth)

	Pore size (mm^2) 150-200 mm depth			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	0.181	0.243	0.310	0.245[b]
LTP w	0.144	0.133	0.141	0.139[a]
STP w	0.143	0.253	0.170	0.189[ab]
Mean	0.156	0.210	0.207	

(**Note**: Means not followed by the same letters are significantly different from each other)

Table 5.5 - X-ray CT-measured mean pore size (200-250 mm depth)

	Pore size (mm^2) 200-250 mm depth			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	0.132	0.245	0.122	0.166[ab]
LTP w	0.125	0.093	0.145	0.121[a]
STP w	0.271	0.303	0.318	0.297[b]
Mean	0.176	0.214	0.195	

(**Note**: Means not followed by the same letters are significantly different from each other)

Repeated measures ANOVA for 0-250 mm depth found that there were no significant differences for mean pore size or mean number of pores (0-250 mm depth) due to the traffic (P=0.337) and tillage (P=0.915) treatments but depth was found to have had a significant effect (pore size: P<0.001, SEM=0.027 and number of pores: P=0.011, SEM=32.6). The interaction between traffic and tillage was not significant (P=0.651).

5.4.4.1 The relationship between X-ray CT measured pore size, number of pores and soil depth

The relationship between mean X-ray CT measured pore size, number of pores and soil depth was investigated using simple linear regression with groups (tillage and traffic). The linear regression models for the traffic and tillage mean pore size for 0-250 mm depth are shown at Figure 5.12. For the traffic means, the data was best fitted by three separate lines (Figure 5.12 a) accounting for 60.4% of the variance (P=0.016). The LTP w and STP w lines were not significantly different to the CTF ut line (tP=0.436 and 0.454 respectively). There was a simpler significant model of a single line (y = -0.001x + 0.383 as shown for tillage in Figure 5.12 b) which still accounted for 56.7% of the variance (P<0.001). For the tillage means, the data was best fitted by a single line (Figure 5.12 b) accounting for 61.1% of the variance (P<0.001). The linear regression for both groups (traffic and tillage) shows that mean pore size decreases with depth and the rate of decrease is not significantly affected by traffic or tillage treatment. Rab *et al.* (2014) also found that soil pore size decreased with depth.

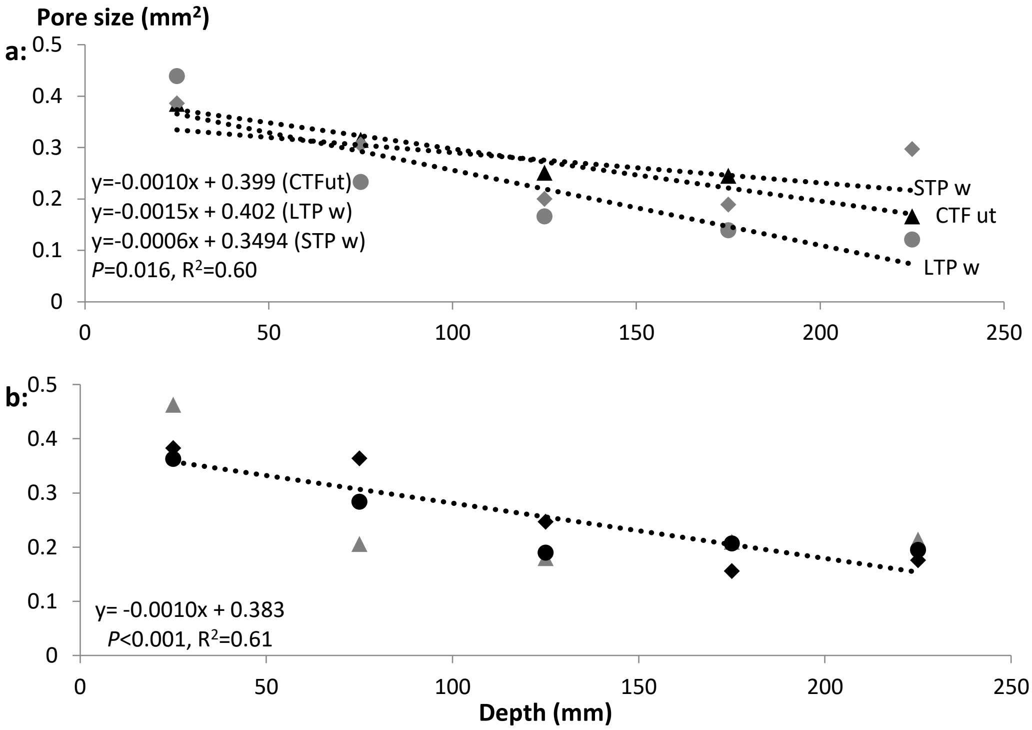

Figure 5.12 - Linear regression analysis of the relationship between soil depth (mm) and mean pore size (mm^2) a: for traffic group b: for tillage group
(Markers - Traffic: triangle black - CTF ut, circle grey - LTP w, diamond grey - STP w
Tillage: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

The linear regression models for the traffic and tillage mean number of pores for 0-250 mm depth are shown at Figure 5.13. For the traffic means, the data was best fitted by three parallel lines (Figure 5.13 a) accounting for 69.2% of the variance (*P*=0.001). The CTF ut line was significantly different from the LTP w line (*tP*=0.035) and the STP w line (*tP*=0.004). The model shows that the number of soil pores increases with soil depth. The rate of change is the same for all three traffic treatments but the number of soil pores is significantly higher in the untrafficked treatments (CTF ut) at all depths. For the tillage means, the data was best fitted by three separate lines (Figure 5.13 b) accounting for 76.1% of the variance (*P*=0.002). The deep tillage line was significantly different from the shallow tillage line (*tP*=0.016) and the zero tillage line (*tP*=0.080). The model shows that the number of pores increased with depth at a similar rate for shallow and zero tillage with shallow tillage having a higher number of pores at all depths. The number of pores in the deep tillage treatments slightly decreased with depth. The mean pore size in all of the tillage treatments decreased equally with depth and the number of pores in the deep tillage treatment decreased with depth. This would indicate that the soil in the deep tillage treatment became more compact (less porosity) with depth (as identified in Figure 5.9). This supports the findings of Soane *et al.* (1986) that deep tillage reduces the bearing capacity of soil leading to recompaction by subsequent vehicle traffic. The reason for the reduction in porosity in the deep tillage treatments was a reduction in the number of pores rather than a reduction in mean pore size.

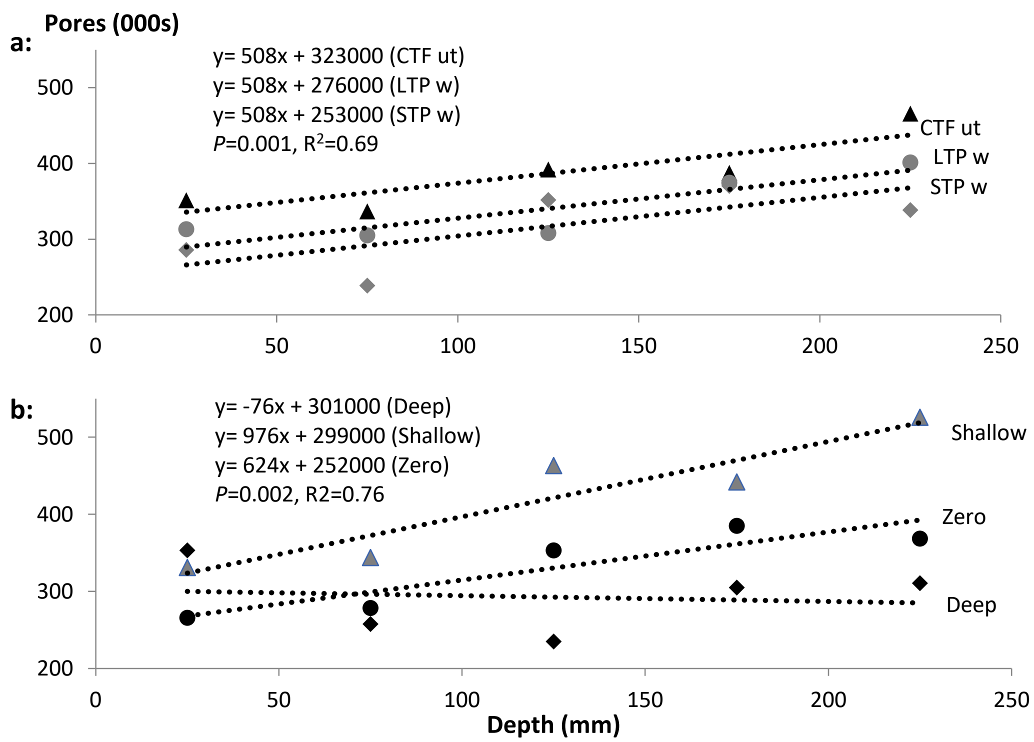

Figure 5.13 - Linear regression analysis of the relationship between soil depth (mm) and number of pores a: for traffic group b: for tillage group
(Markers - Traffic: triangle black - CTF ut, circle grey - LTP w, diamond grey - STP w
Tillage: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

5.4.4.2 The relationship between X-ray CT measured pore size and the number of pores

The relationship between mean X-ray CT measured pore size and number of pores was investigated using simple linear regression with groups (tillage and traffic) and the models are shown at Figure 5.14. For the traffic treatments, the data was best fitted by three parallel lines (Figure 5.14 a) accounting for 52.1% of the variance (*P*=0.011). The CTF ut line was significantly different from the LTP w line (*tP*=0.025) and the STP w line (*tP*=0.016). For the tillage treatments, the data was best fitted by three separate lines (Figure 5.14 b) accounting for 52.7% of the variance (*P*=0.032). The shallow and zero tillage lines were not significantly different to the deep tillage line (*tP*=0.224 and 0.157 respectively). The models confirm (as indicated in Figures 5.12 and 5.13) that as mean pore size decreases the number of pores increases in all treatments except deep tillage. The tillage model (Figure 5.14 b) shows, that for deep tillage, the number of pores is unaltered by changes in mean pores size.

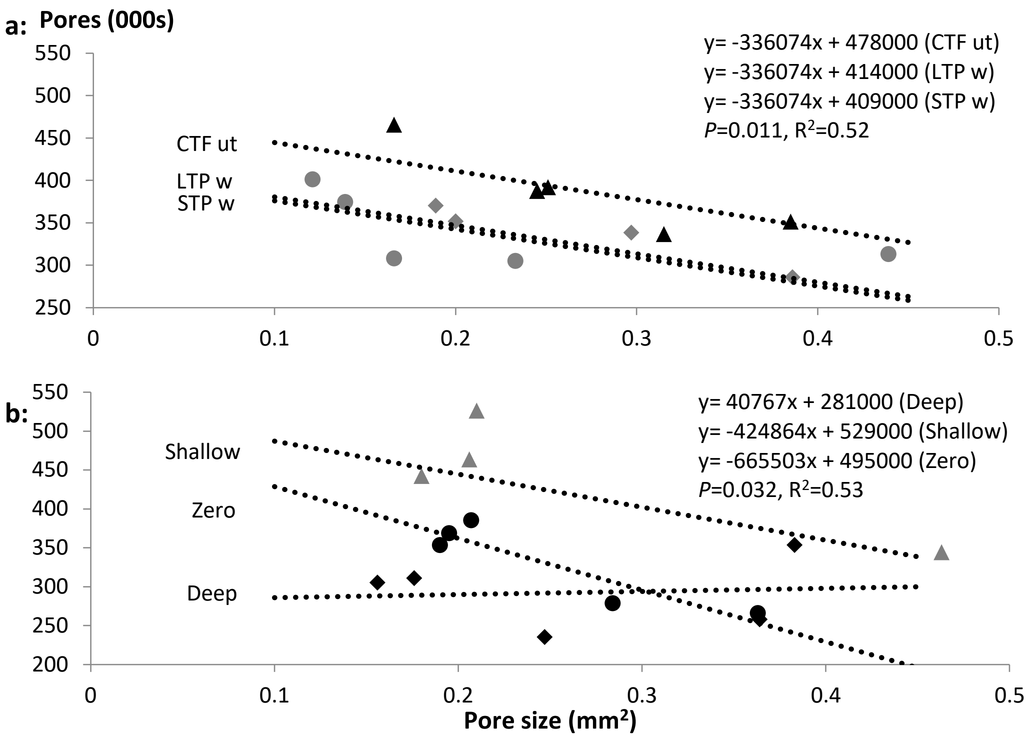

Figure 5.14 - Linear regression analysis of the relationship between mean pore size (mm^2) and number of pores a: for traffic group b: for tillage group
(Markers - Traffic: triangle black - CTF ut, circle grey - LTP w, diamond grey - STP w
Tillage: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

5.4.5 The relationship between X-ray CT measured mean pore size and spring oat biomass at GS 83

The relationship between mean X-ray CT measured mean pore size and spring oat biomass (at GS 83) was investigated using simple linear regression with groups (tillage and traffic). The linear regression models for the tillage means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths are shown at Figure 5.15. At all five depths the data was best fitted by three parallel lines. The models accounted for 32.4% (0-50 mm, P=0.001, Figure 5.15 a), 32.7% (50-100 mm, P=0.001, Figure 5.15 b), 32.5% (100-150 mm, P=0.001, Figure 5.15 c), 36.6% (150-200 mm, P<0.001, Figure 5.15 d) and 32.9% (200-250 mm, P=0.001, Figure 5.15 e) of the variance. In each model, the zero tillage line was significantly different from the deep tillage line (tP<0.001) and the shallow tillage line (tP=0.002 except 150-200 mm where tP=0.001). The models showed that a change in mean pore size was associated with a small change in biomass (increase 0-50 mm depth, decrease 50-100, 100-150 and 200-250 mm depths). At 150-200 mm depth the model (Figure 5.15 d) indicated that biomass had a higher rate of increase associated with an increase in mean pore size at this depth. All models indicate that tillage increased biomass compared to the zero tillage treatments.

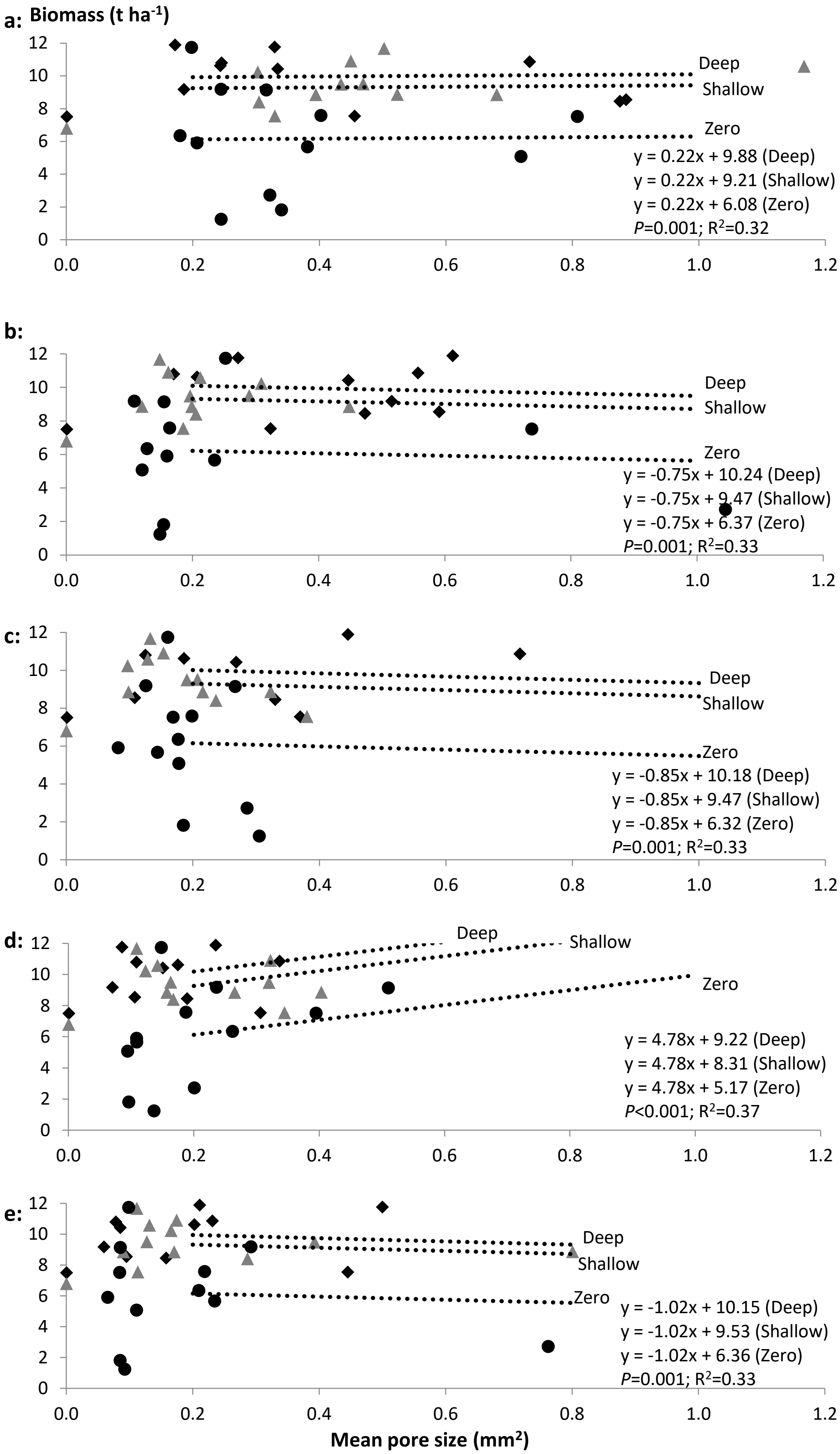

Figure 5.15 - Linear regression analysis (with tillage groups) of the relationship between mean pore size (mm^2) and spring oat biomass ($t\ ha^{-1}$) at a:0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth

(Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

There was no significant linear regression models for the traffic means for 0-50, 50-100,100-150,150-200 and 200-250 mm depths which indicated that biomass was not affected by changes in mean pore size between 0-250 mm depth due to traffic. The data is not presented.

With the possible exception of 150-200 mm depth for tillage (Figure 5.15 d) the linear regression models indicated that biomass was not affected by changes in mean pore size. The lack of significant regression models for traffic treatments would also indicate that changes in mean pore size did not affect biomass. Although mean pore size may be useful in describing changes in soil structure due to compaction from vehicular traffic and changes due to depth (Section 5.4.4), the regression analysis suggests the use of X-ray CT mean pore size for examining the effect of traffic and tillage on crop growth is limited.

5.4.6 Pore size distribution

Tillage increases soil total porosity but its effect on the pore size distribution depends on the soil type (Lipiec *et al.*, 2006). Schjønning and Rasmussen (2000) found that on a sandy and a silt loam soil that had been direct drilled for 4-6 years the volume of macro pores in the top 200 mm was lower than soil that had been under continuous cultivation but the opposite was found for a sandy loam soil. Pore size distribution and connectivity affects water infiltration rates and subsequently available water for the crop. In no-tilled soil, a greater contribution to infiltration is from macro pores made by crop roots and soil fauna whilst in tilled soils infiltration is more affected by inter-aggregate porosity (Lipiec *et al.*, 2006). The use of pore size distribution allows comparison between treatments that attempts to describe the complexity of the soil structure with depth that cannot be seen using percentage porosity (Nimmo, 2004). Pore size distribution is used to define soil pore structure and is one of the most relevant soil structure characteristics that affects crop growth (Cary and Hayden, 1973).

Figure 5.16 show the mean pore size distribution cumulative frequency in the CTF ut plots under the three tillage treatments (0-250mm depth, 50 mm intervals). As the CTF ut cores were taken from unwheeled areas the results show the differences in pore size distribution due to tillage only. The top 50 mm of the soil profile was likely to have been affected by the action of the Topdown discs during tillage (deep and shallow) and also the drilling operation and is illustrated by the similarity of pore size distribution curves for the deep and shallow tillage treatments at 0-50 mm depth (Figure 5.16 a). The zero tillage treatments had a larger range of pore sizes than the tilled treatments and this was possibly due to the influence of weather and microbial action (Kay and VandenBygaart, 2002) and macro pores created by crop roots and soil fauna (Lipiec *et al.*, 2006) on the untilled soil. Chan (2001) reported that no-tilled soils have higher populations of macropores than tilled soils. The difference in mean pore size frequency between tillage treatments became more marked at 50-100 mm depth (Figure 5.16 b). The action of the tillage tines at this depth removed the larger pores (compared to zero tillage treatments) resulting in a pore size frequency for shallow tillage treatments concentrated at 0.2 mm^2. Conversely the deep tillage increased the pore size starting at 0.4 mm^2 and concentrated at 0.53 mm^2 for deep tillage treatments. Pore size frequency for zero till treatments was more distributed between 0.15 mm^2 and 0.56 mm^2 with the mean size being 0.33 mm^2. Mangalassery *et al.* (2014) had similar results with pores in tilled soils (0.52 mm^2) twice as big as pores in zero tilled soils (0.27 mm^2). Deep tillage treatments produced larger pores between 100-150 mm depth (Figure 5.16 c) with mean pore size frequency ranging from 0.28 to 0.7 mm^2. Although this depth was below the shallow tillage depth of 100 mm there was still a noticeable effect when compared to zero tillage. The shallow tillage had two pore size frequency peaks at 0.16 and 0.23 mm^2 whilst zero tillage mean pore size frequency was more evenly distributed between 0.1 and 0.38 mm^2. Both tillage treatments produced curves of mean pore size frequency between 0.2 to 0.3 mm^2 whilst zero tillage has a range of mean pore size from 0.12 to 0.52 mm^2 at 150 to 200 mm depth (Figure 5.16 d). Although this depth is at the lower end of the deep tillage depth (250 mm) it is interesting that the effect on pore size distribution is the same as for shallow which depth is only 100 mm. The zero tillage again had a greater range and mainly larger pore sizes than in the tilled treatments. This could have been an effect from the tillage treatments reducing porosity in the soil or earthworm activity increasing porosity in the zero tillage plots. As pores are enclosed by aggregates it is apparent that the larger the soil aggregates the larger the pores. Breaking of aggregates releases smaller aggregates into pore space making smaller pores (Lebron *et al.*, 2002). Deep and zero tillage had a greater number of smaller pore sizes (< 0.2 mm^2) than shallow tillage (mean pore size 0.2 to 0.4 mm^2) at 200-250 mm depth (Figure 5.16 e). Pore sizes in the shallow tillage treatments where twice the size as those produced in the deep tillage treatments.

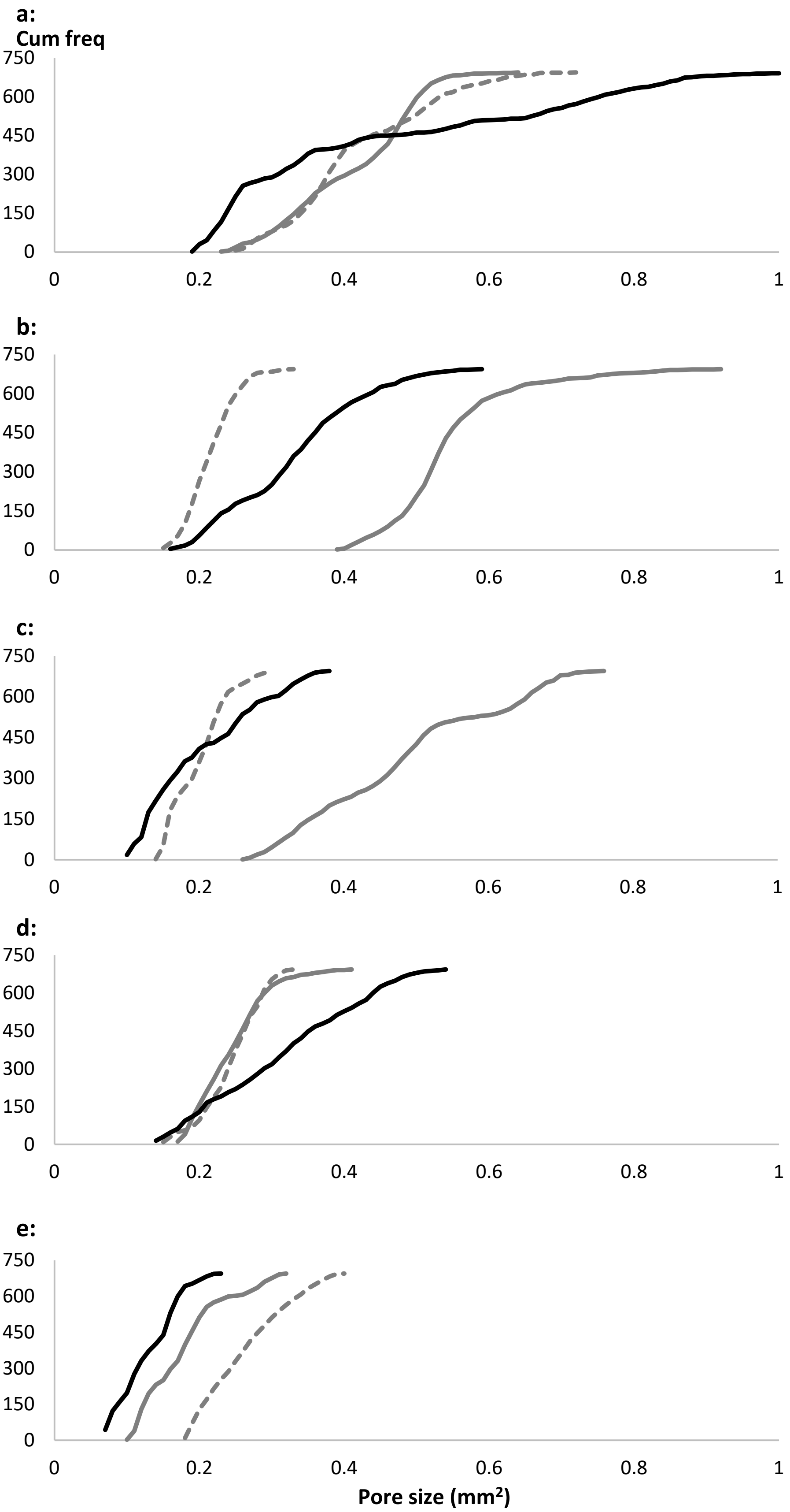

Figure 5.16 - X-ray CT measured mean pore size (mm^2) cumulative frequency in untrafficked (CTF ut) treatment plots
a: 0-50, b: 50-100, c: 100-150, d: 150-200, e: 200-250 mm depth
(Lines: solid grey - deep, dash grey - shallow, solid black - zero tillage)

The interaction between deep tillage and traffic on mean pore size frequency (0-250 mm depth) is shown at Figure 5.17-1. LTP w treatments had a larger spread of mean pore sizes (ranging from 0.3 to 1 mm^2) at 0-50 mm depth (Figure 5.17-1 a) than CTF ut treatments (0.2 to 0.5 mm^2). The pore sizes in the STP w treatment were between 0.2 and 0.3 mm^2 smaller than the bulk of the mean pores sizes in the CTF ut treatments. This may indicate that the STP w treatments had a compaction effect on the soil reducing the mean size of pores. Smaller pores are created during soil compaction at the expense of larger pores (Richard *et al.*, 2001). At 50-100 mm depth (Figure 5.17-1 b) all three treatments have a reasonably normal distribution curve but CTF ut treatments contain larger mean pore sizes (0.4-0.9 mm^2) than the trafficked treatments (STP w and LTP w) which had similar distributions of 0.2 to 0.5 mm^2. STP w and LTP w treatments also had similar distributions at 100-150 mm (0.1-0.3 mm^2, Figure 5.17-1 c) and 150-200 mm (0.1-0.2 mm^2, Figure 5.17-1 d) depths again probably due to a recompaction effect of traffic on deep tilled soil (Soane *et al.*, 1986). CTF ut had a distribution of larger mean pore sizes than STP w and LTP w at 100-150 mm (0.25- 0.75 mm^2) and 150-200 mm (0.18-0.4 mm^2) depths. The pore size distribution for the LTP w treatments at 200-250 mm depth (Figure 5.17-1 e) was similar to at 100-150 and 150-200 mm depths whereas the mean pore sizes for STP w where larger (0.1-0.6 mm^2) than for LTP w and CTF ut (0.1-0.3 mm^2). This would suggest that the compaction effect from vehicular traffic extended as far as 250 mm depth in the LTP w treatments but to only 200 mm depth in the STP w treatments. Over the full profile Figure 5.17-1 shows that STP w had more of a compaction effect on the soil than LTP w at 0-100 mm depth, a similar effect at 100-200 mm depth and a lesser (or no) effect at 200-250 mm. From 50 mm depth, mean pore size in the CTF ut treatments became progressively smaller with each depth interval.

The interaction between shallow tillage and traffic on mean pore size frequency (0-250 mm depth) is shown at Figure 5.17-2. Unlike the pore size frequencies for the deep tillage and traffic treatments (Figure 5.17-2) there is little evidence of recompaction in the traffic treatments between 0-100 mm (shallow tillage depth was 100 mm). Minimum tilled soils have a more distinct vertical pore system than conventionally tilled soils which makes them more resistant to the principal stress and therefore more resistant to compaction (Horn and Lebert, 1994). Interestingly at all depths except 50-100 mm the STP w treatments had the greatest range of mean pore sizes. LTP w and CTF ut had similar frequency curves (mainly 0.25-0.6 mm^2) at 0-50 mm (Figure 5.17-2 a) with CTF ut having a greater number of smaller mean pores. STP w pore sizes were evenly distributed between 0.28 to 0.95 mm^2. CTF ut treatments had a small range in pore sizes (1.8-0.22 mm^2) at 50-100 mm depth (Figure 5.17-2 b). STP w had wider distribution between 0.12-0.28 mm^2 and LTP w treatment pore sizes range from 0.12 to 0.35 mm^2. From 100-250 mm depth LTP w treatments had smaller mean pore sizes than the untrafficked CTF ut treatments suggesting there was some compaction at this depth from the LTP w traffic treatment. There was a similar effect in the STP w treatments but there was also a range of pore sizes larger than CTF ut treatments. This is unlikely to be due to the action of earthworms as it could reasonably be expected to see a similar effect in the LTP w and CTF ut treatments.

Figure 5.17-3 shows the range in mean pore size distribution in the soil (0-250 mm) in the zero tillage treatments and would have therefore not had any tillage treatments applied. In the top layer (Figure 5.17-3 a 0-50 mm depth) LTP w traffic treatments had a pore size distribution between 0.1 to 1.0 mm^2. The untrafficked treatments (CTF UT) had a similar distribution but the smallest pores where 0.2 mm^2. The STP w treatments had a greater number of smaller mean pores (0.15 to 0.35 mm^2) and very few mean pores over 0.5 mm^2. This was possibly due to compaction from trafficking which was not apparent in the LTP w treatments. The majority of soil pores in the LTP w treatment at 50-100 mm depth (Figure 5.17-3 b) ranged between 0.5 and 0.2 mm^2. STP w treatments had a peak in mean pore size distribution at 1.5 mm^2 larger than LTP w but unlike the LTP w there was a small distribution in all sizes up to 1.0 mm^2. Untrafficked (CTF ut) treatments had a nearer to normal distribution ('s' shaped) of mean pore sizes from 0.2 to 0.6 mm^2. At 100-150 mm soil depth (Figure 5.17-3 c) there was a close correlation in pore size frequency between the trafficked (LTP w and STP w) and untrafficked (CTF ut) treatments indicating that pore mean size distribution at this depth was not affected by traffic. Conversely the traffic effect on soil mean pore size frequency was evident between 150-200 mm depth (Figure 5.17-3 d) with LTP w treatments producing a peak at 0.13 mm^2 and STP w treatments at 0.15 mm^2. Untrafficked treatments (CTF ut) had a wider distribution of sizes between 0.13 and 0.55 mm^2. Figure 5.17-3 e shows that CTF ut and LTP w treatments had similar large peaks in small pore sizes (0.07-0.2 mm^2) at 200-250 mm depth which are less numerous in the STP w treatments. STP w treatments had a wider range of pore sizes than LTP w and CTF ut treatments.

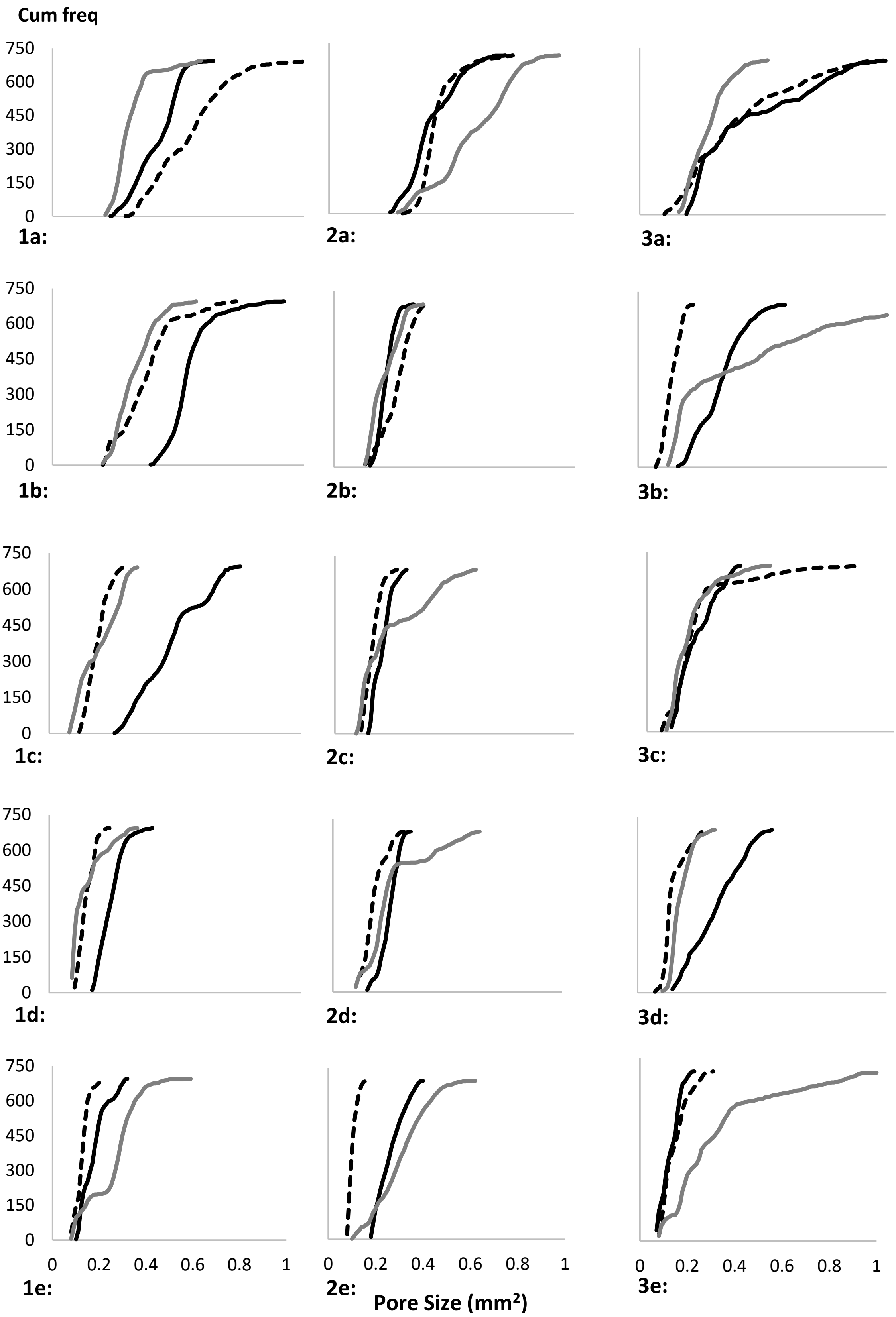

Figure 5.17 - X-ray CT measured mean pore size (mm^2) cumulative frequency in 1: deep, 2: shallow and 3: zero tillage treatment plots
a: 0-50, b:50-100, c:100-150, d:150-200, e: 200-250 mm depth
(Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)

Deep tillage increased the pore size distribution between 50-150 mm depth whilst shallow tillage had a smaller size distribution that was constant over the same depth range (Figure 5.16 b and c - no traffic). The combination of traffic and tillage showed that there was little difference in pore distribution between 50-200 mm depth between deep and shallow tillage treatments wheeled by LTP and STP tyres (Figure 5.17-1 and 5.17-2). Although deep tillage had a larger pore size distribution than shallow tillage in untrafficked soils, traffic reduced the pore size distribution to values similar to that of shallow tillage. This suggests that deep tillage is no better than shallow tillage at increasing soil pore size distribution in wheeled soils and therefore is unnecessary. Figure 5.17-2 (shallow tillage) shows that soil mean pore size distribution was largely unchanged by the addition of vehicular traffic.

5.4.7 X-ray CT measured pore connectivity

The transport and storage of water and nutrients in soil is related to soil porosity and is dependent on pore geometry and size distribution for water storage. The pore size distribution and connectivity within the pore network control the hydraulic properties of the soil (Kumar *et al.*, 2010). Changes to soil porosity due to soil compaction affects pore connectivity and consequently soil aeration, permeability and soil transport processes (Kooistra and Tovey, 1994). The use of bulk density as a measure of soil compaction does not necessarily give an indication of the effect of compaction on crop performance as soil pore geometry and connectivity can be different dependant on soil management e.g. tillage (Alaoui *et al.*, 2011). Table 5.6 shows the mean pore connectivity (%) for the traffic and tillage treatments (0-250 mm). There was no significant difference (P=0.090) between the pore connectivity for the traffic treatments. Pore connectivity in the CTF ut treatments (93%) was higher than in the LTP w treatments (91%) and the STP w treatments (80%). The LTP w treatments had 12% greater pore connectivity compared to STP w treatments. The lower mean pore connectivity for the STP w treatments was due to three outliers (as can be seen in Figure 5.15) possibly due to layers of reduced porosity (compacted layer) within the soil profiles as follows: 60% (deep tillage, reduced porosity layer at 235 mm depth), 25% (shallow tillage, reduced porosity layer at 85 mm depth) and 53% (zero tillage, reduced porosity layer at 180 mm depth). Pore connectivity values for the other samples (n=33) were above 80%. As the permeability of soil water depends on macro pore space connectivity, any reduction in connectivity due to soil compaction will have a corresponding reduction in soil water flow (Schäffer *et al.*, 2007). Gebhardt *et al.* (2006) found that when coarse textured soils (including sandy loam soils) with low initial bulk densities where subjected to loads associated with agricultural field traffic they suffered large decreases in porosity but the decrease in macro porosity was relatively low and consequently changes in saturated hydraulic conductivity were not observed. They also found that fine textured soils with similarly low bulk densities, had a lower percentage of macro pores than coarse textured soils and when subjected to the same loading, lost all of their macro pores due to compaction. As this research trial was based on a sandy loam soil, this may explain why no significant differences were found between the soil pore connectivity due to the traffic treatments. Table 5.6 shows that as tillage intensity increased soil pore connectivity increased although this was not significant (P=0.584). This does not agree with Plaza-Bonilla *et al.* (2018) who stated that long term use of no-till changes the physical properties of the soil because of increased soil fauna and root activities that increase the proportion and connectivity of macro pores. There was no significant interaction between the traffic and tillage treatments for pore connectivity (P=0.992). Gebhardt *et al.* (2006) state that macro porosity in coarse textured soils is mainly determined by texture and therefore tends to persist after trafficking with high loads. This may explain why the connectivity was high (93% in untrafficked soil) and only reduced to 80% in the soil trafficked using the STP tyres.

Table 5.6 - X-ray CT measured pore connectivity (%) means for the traffic and tillage treatments 0-250 mm depth

	Pore connectivity (%)			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	95	94	89	93
LTP w	94	91	86	91
STP w	83	78	79	80
Mean	91	88	85	

5.4.8 Pore circularity

The geometry of the soil macro pores gives an indication of their origin or method of formation (Perret, 1998). Rachman *et al.* (2005) found that soil macro pores under row crops were significantly (<0.010) more circular than macro pores in a grass hedge probably due to better soil aggregation, root activity and the effect from soil fauna affecting the pore perimeters (circularity is a function of pore area and perimeter) in the grass hedge. Macro pores produced by earthworms (e.g. *Lumbricus terrestris)* are usually vertical and can extend to 2 metres in depth and it can be expected that their circularity would not change with depth (Perret, 1998).

Figure 5.18 shows the pore circularity means for the traffic and tillage treatments. Repeated measures ANOVA for 0-250 mm depth (50 mm intervals) found no significant differences in pore circularity due to the traffic and tillage treatments but depth, depth x tillage were significant (P=0.003 and P=0.050 respectively).

It was expected that the soil pores in zero tillage treatments would have been more circular that those in the tillage treatments due to the action of earthworms. Pores in the zero tillage treatments were more circular than for the deep tillage treatments but the shallow tillage treatments had similar pore circularity to those in the zero tillage treatments. This would suggest that the deep tillage treatments were more damaging to soil aggregation and/or that soil fauna activity was reduced in the deep tillage treatments. Rachman *et al.* (2005) also found that macro pores tended to be more circular deeper in the soil than at shallow depths. This is probably because the larger the pore size the less likely they are to be round (Li *et al.*, 2016) and mean pore size decreases with depth (Rab *et al.*, 2014). The results in Figure 5.18 tended to agree with this but the change in pore circularity with depth was not uniform down through the profile.

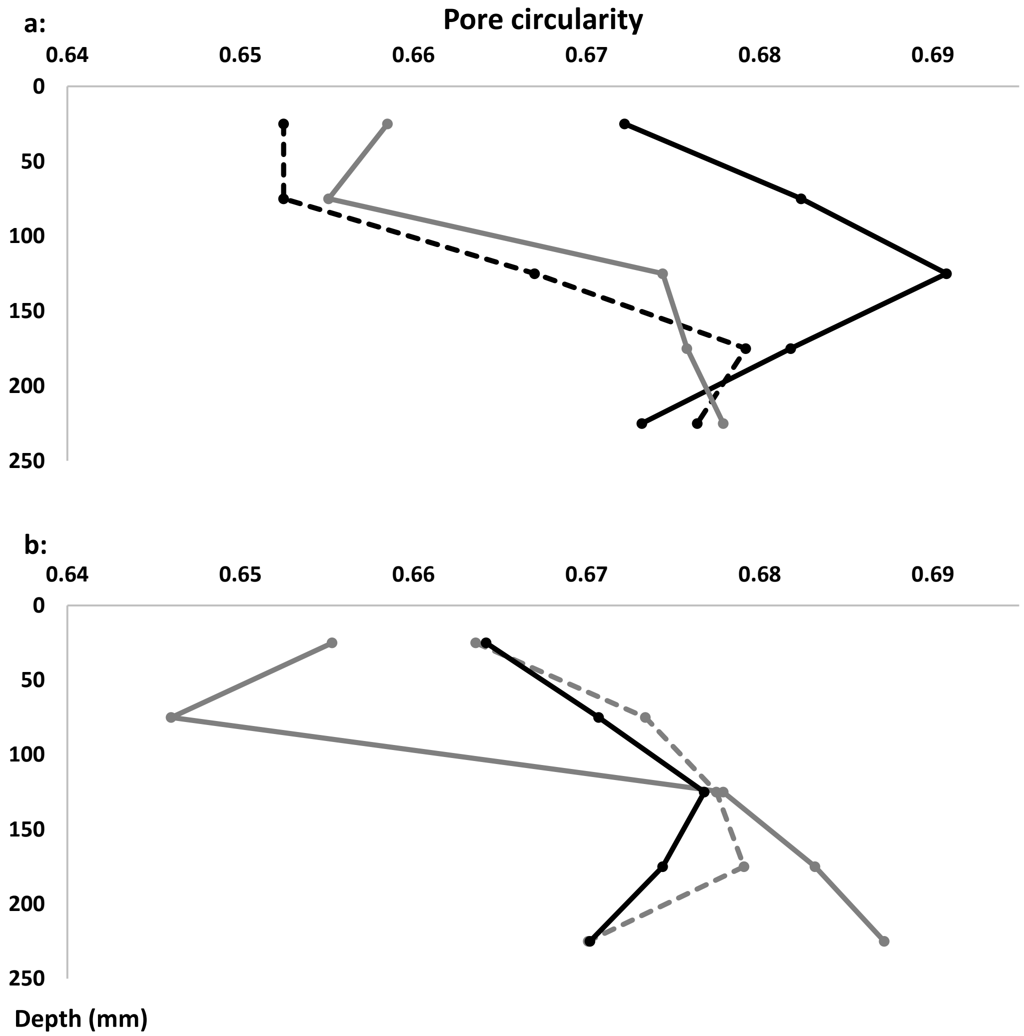

Figure 5.18 - Pore circularity for the traffic and tillage treatments
a: traffic means (Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)
b: tillage means (Lines: solid grey - deep, dash grey - shallow, solid black - zero)

Circularity was significantly higher for untrafficked (CTF ut) treatments (*P*=0.009) than the wheeled (LTP w and STP w) treatments at 50-100 mm depth (Figure 5.18 a and Table

5.7). This may have been due to the action of soil volumetric strain and shear deformation under the tyres in the two traffic treatments, as identified in the literature (Berisso *et al.*, 2013). Deep tillage had significantly lower circularity (*P*=0.018) than shallow and zero tillage treatments (Figure 5.18 b and Table 5.7). There was no significant differences between the traffic and tillage treatments for pore circularity at any of the other depths (i.e. 0-50, 100-150, 150-200 and 200-250 mm).

Table 5.7 - Pore circularity traffic and tillage means (50-100 mm depth)

	Mean circularity			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF ut	0.67	0.69	0.69	0.68[b]
LTP w	0.64	0.65	0.66	0.65[a]
STP w	0.63	0.67	0.66	0.66[a]
Mean	0.65[a]	0.67[b]	0.67[b]	

(**Note**: Means not followed by the same letters are significantly different from each other)

At 100-150 mm depth the LTP w treatment mean (0.667) was lower (*P*=0.075) than the CTF ut mean (0.691). The STP w mean (0.674) was slightly higher than LTP w but was not significantly different from LTP w or CTF ut means. The significant differences *P*=0.033) in the traffic and tillage interaction are shown at Figure 5.19. At this depth circularity in the CTF ut treatments was 0.69 and was not affected by tillage. Increasing tillage decreased circularity in the LTP w treatments but increased circularity in STP w treatments. LTP w deep and STP w zero treatments had significantly lower circularity than all the other treatments. There was no significant differences between the traffic and tillage interaction for pore circularity at any of the other depths (i.e. 0-50, 50-100, 150-200 and 200-250 mm).

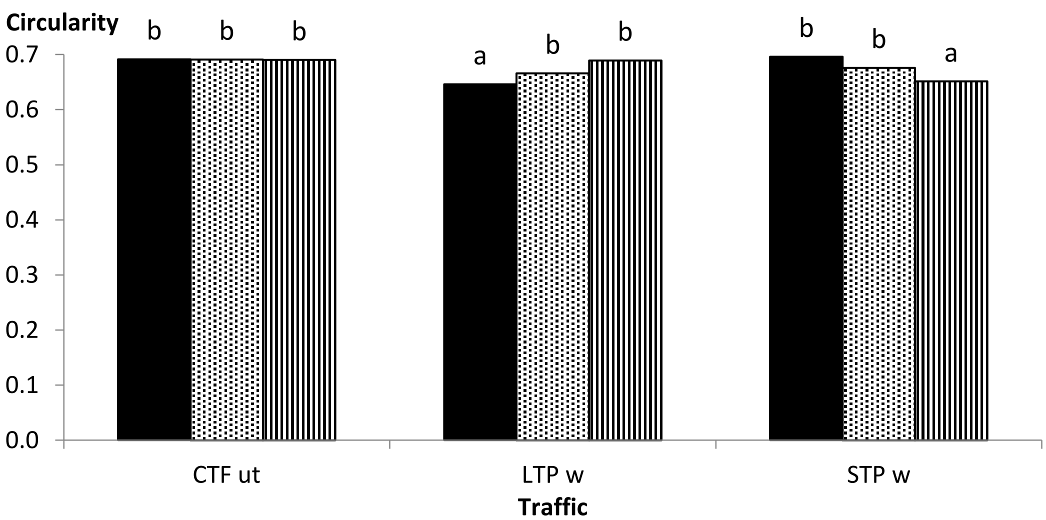

Figure 5.19 - Pore circularity traffic and tillage means (100-150 mm depth)
(Columns: black deep, black dots shallow and black stripes zero tillage)
(**Note**: Means not followed by the same letters are significantly different from each other)

5.5 The relationship between X-ray CT derived porosities and bulk density derived soil porosity

The soil total pore space is all of the pore space between soil particles and aggregates (Estefan *et al.*, 2013) and is defined as the ratio of non-solid volume to total volume of a soil sample (Horton *et al.*, 1994) and can be calculated using the soil bulk density using Equation 4.3. It is generally accepted that the percentage porosity derived from the X-ray CT is lower than porosity measured by physical methods as found by Vaz *et al.* (2011) who also reported that even at an X-ray scan resolution as low as 3.7 µm, CT derived porosities still underestimate total soil porosity. There is a trade off between achievable X-ray resolution and soil sample size. This may be due to the physical capabilities of the scanner (Vaz *et al.*, 2011) or scan time and cost constraints. High resolution scans reduce the field of view to as little as a few millimetres (Vaz *et al.*, 2011) and as a consequence results cannot be indicative of the variance in structure of larger samples due to the heterogeneous nature of soil (Munkholm *et al.*, 2013).

This research used X-ray CT to make comparisons between the different traffic and tillage treatment effects on soil physical properties. The low soil porosity values (<5%) in Figure 5.8 are much lower than the >50% total soil porosities identified by Hall *et al.* (1977). These values for the X-ray CT derived soil porosities, although acceptable for between treatment comparisons, do not reflect actual soil total porosity due to the limitation of the X-ray CT resolution.

When the X-ray CT derived soil porosities for each traffic system were taken away from the corresponding bulk density derived porosities it gave a constant of 31% porosity as shown in Table 5.8. A linear regression analysis between bulk density derived soil porosity and X-ray CT derived porosity is shown at Figure 5.20. Using the X-ray CT derived porosity (y) calculated from the fitted regression equation $y=0.96x - 29.62$ (where x = bulk density derived porosity) the mean difference between the bulk density derived porosity and X-ray CT derived porosity was 31.3% (minimum value 30.7% and maximum value 31.8%).

Table 5.8 - Comparison of mean bulk density and X-ray CT derived porosities (%) for a sandy loam soil 0-250 mm depth

		Porosity (%) 0-250 mm		
Traffic	**Tillage**	BDp	CTp	BDp - CTp
CTF ut	Deep	47.8	19.5	28.3
	Shallow	48.5	16.5	32.0
	Zero	47.6	15.3	32.2
	Mean	48.0	17.1	**30.8**
LTP w	Deep	44.4	11.4	33.0
	Shallow	44.0	16.5	27.5
	Zero	41.9	7.0	34.9
	Mean	43.4	11.7	**31.8**
STP w	Deep	42.0	8.8	33.1
	Shallow	44.2	15.4	28.8
	Zero	43.4	10.8	32.6
	Mean	43.2	11.7	**31.5**

(BDp = bulk density derived porosity, CTp = X-ray CT derived porosity)

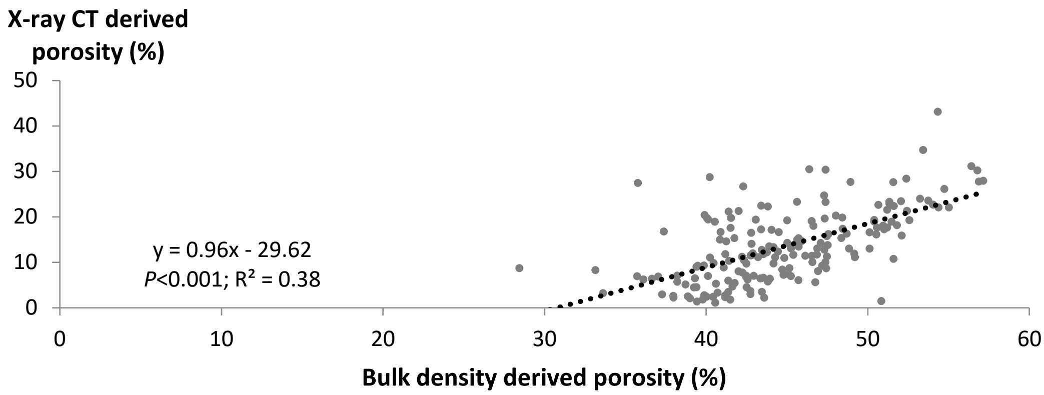

Figure 5.20 - Linear regression analysis of the bulk density derived porosity and X-ray CT derived porosity 0-250 mm depth (n=180)

This 31% constant equated to water filled pore space identified by Hall *et al.* (1977) (Figure 5.21) for the topsoil of a sandy loam which is equivalent to the percentage of pores below 30 µm diameter indicated by Russell (1977) for a light sandy loam soil. This showed that the X-ray CT porosities related to air filled pore space (macro porosity) and that adding 31% to the X-ray CT porosities it was possible to relate X-ray CT derived porosities to physical soil porosities for a sandy loam soil. Kim *et al.* (2010) also found that CT derived porosity was highly correlated to macro porosity because most of the porosity detected by their CT scanner was in the macro pore range. They also found a high correlation between measured saturated hydraulic conductivity and macro porosity indicating that more pores allowed greater transmission of water when the pores were water filled and therefore higher gas transmission rates if the pores were air filled.

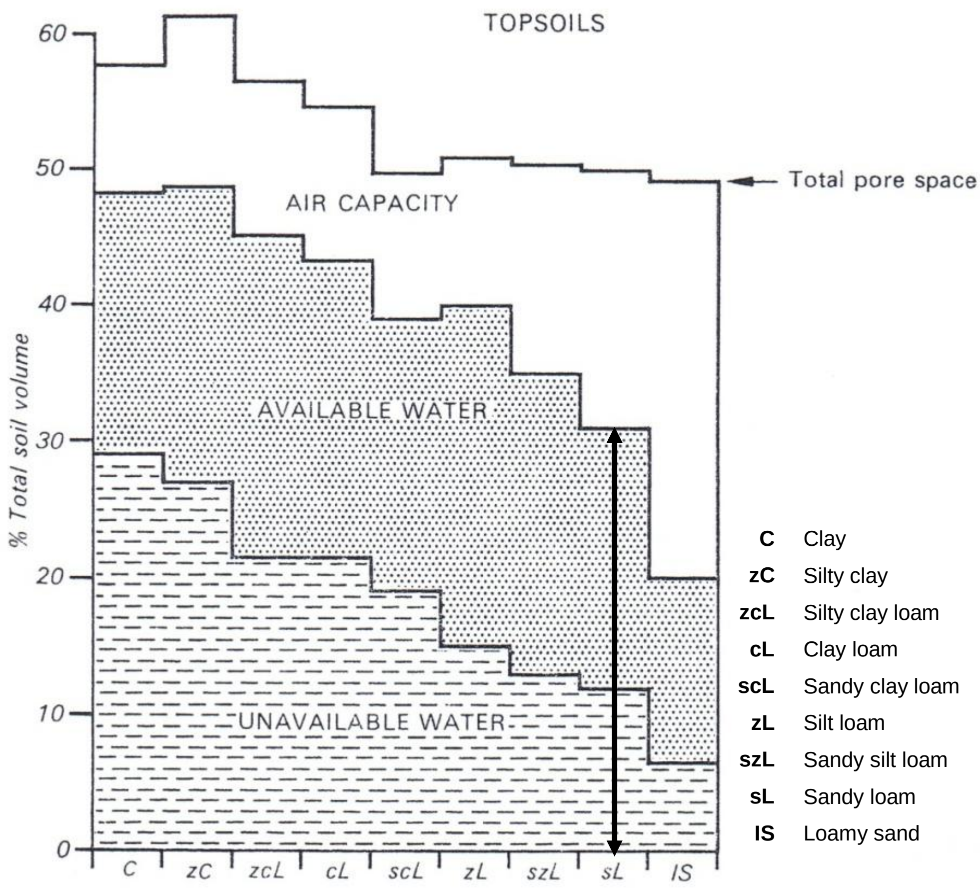

Figure 5.21 - Air capacity and water retention for certain particle-size classes in topsoils
(Black arrowed line indicates the constant 31% porosity difference between X-ray CT and bulk density derived porosities)

(Source adapted from: Hall *et al.*, 1977)

The comparison between the bulk density derived porosity and the X-ray CT derived porosity confirmed that the X-ray CT resolution (72 µm) used was able to capture all porosity above the size boundary between macro and meso pores. The X-ray CT porosity measured, equated to the soil macro porosity (this is air filled porosity when the soil is at field capacity) which is important for soil water, air and nutrient distribution to the crop (Kay and VandenBygaart, 2002; Cary and Hayden, 1973).

5.6 Conclusion

The objectives for this part of the research were to use X-ray Computed Tomography:

1. To determine the changes in soil porosity resulting from the traffic and tillage treatments.

2. To determine the effect of the traffic and tillage treatments on soil pore distribution, pore connectivity and pore circularity.

3. To determine the relationship between X-ray CT derived porosity and soil bulk density derived porosity.

Vehicular traffic significantly (*P*=0.006) reduced soil macro porosity compared to untrafficked treatments. Deep tillage increased soil porosity in untrafficked treatments but subsequent vehicular traffic significantly (*P*=0.006) decreased soil porosity compared to untrafficked treatments (CTF ut). Shallow tillage had little effect on porosity in the CTF ut plots but resulted in the maximum porosity for LTP w and STP w plots (16.5% and 15.4% respectively) similar to the CTF ut zero porosity of 15.4%. This indicates that on unwheeled soil, shallow tillage was unnecessary but on trafficked soil, it was the most suitable tillage for returning porosity to levels comparable to untrafficked soil.

Shallow tillage treatments had 48% more soil pores than in the deep tillage treatments but this was not significant. The ANOVA analysis found that traffic had no significant effect on the number of soil pores but the linear regression analysis found that there were significantly more pores in the untrafficked (CTF ut) treatments than in the LTP w and STP w treatments at all depths (0-250 mm). The number of soil pores significantly increased and the mean soil pore size significantly decreased with depth. A reduction in pore numbers in the deep tillage treatments at depth indicated that recompaction after deep loosening of the soil was associated with a reduction in pore numbers rather than mean pore size.

Although deep tillage had a larger macro pore size distribution than shallow tillage in untrafficked soils, traffic reduced the macro pore size distribution to values similar to that of shallow tillage. This suggests that deep tillage is no better than shallow tillage at increasing soil macro pore size distribution in wheeled soils and therefore is unnecessary.

There were no significant differences between the pore connectivity for any of the treatments. The literature suggests that macro porosity in coarse textured soils is determined by the texture of the soil and persists after trafficking with heavy loads. Consequently, there were no significant differences in pore connectivity due to traffic on this sandy loam soil.

Pore circularity means were not significantly different for the traffic and tillage treatments. Deep tillage pores were less circular than for zero and shallow tillage suggesting that deep tillage was more damaging to soil aggregation due to shear deformation or that there was less soil fauna activity in the deep tillage treatments.

As expected regression analysis showed that the relationship between percentage soil porosity and biomass in the top 50 mm of soil mirrored that found for bulk density. For tillage, as soil porosity decreased there was an associated increase in biomass in the deep tillage treatments and decrease in biomass in the shallow and zero tillage treatments. Similarly, for traffic, as soil porosity decreased there was an associated increase in biomass in the CTF ut treatments and a decrease in biomass in the LTP w and STP w treatments.

A comparison of physical soil porosities calculated from bulk density measurements and X-ray CT derived porosities found that for a sandy loam soil, the X-ray CT derived porosities corresponded to the air filled pore space (macro pore) within the soil. In addition when a constant of 31% porosity was added to the CT derived porosity for each traffic system it gave the value of the total physical porosity calculated from the bulk density. This constant equated to water filled pore space identified by previous researchers. Although the resolution of the X-ray CT used did not allow total porosity of the soil to be examined, it was successful in quantifying the macro porosity, pore size distribution and connectivity which are important physical properties of the soil in relation to water flow and soil aeration necessary for plant growth.

Relating to the hypothesis (Section 5.2) the results showed that vehicular traffic significantly reduced soil macro porosity irrespective of tyre pressure used indicating that using low inflation pressure tyres is not effective at reducing soil compaction as measured by soil porosity. Deep tillage increased soil porosity in the untrafficked (CTF ut) treatments but subsequent traffic significantly decreased porosity. Shallow tillage resulted in the maximum soil porosity in the traffic treatments similar to those in the CTF ut zero treatments. However the percentage porosity in the CTF ut treatments was unaffected by shallow tillage. These results suggest that if field soil is untrafficked, such as in a Controlled Traffic Farming system, then tillage is unnecessary. If soil has had vehicular traffic then shallow tillage is the most appropriate tillage to increase soil porosity. The analysis of the pore size distribution showed that deep tillage was not as effective as shallow tillage at increasing pore size distribution in trafficked soil also suggesting that shallow tillage should be there preferred tillage operation on trafficked soil. The traffic and tillage treatments had no significant effect on soil pore connectivity or circularity.

Chapter 6 Crop growth and yield experiments

6.1 Introduction

In 2012, Smith *et al.* (2014) identified variations in combine harvested wheat yields due to tillage and traffic treatments. Tillage was found to have an effect on yield between CTF shallow and CTF no-till treatments (P<0.05) and CTF shallow and STP deep tillage (P<0.10). All no-till treatments had lower mean yields (Godwin *et al.*, 2015). Good seed germination can result from slightly compacted soil due to increased contact between seed and soil (DeJong-Hughes *et al.*, 2017). This could be the reason that a crop emergence survey at GS11/12 found a reasonably uniform establishment. Later visual analysis (GS37/39) found variations in growth and uniformity (Smith *et al.*, 2014). These results suggest that the traffic and tillage treatments did not affect crop establishment but did affect the growth and yield of the wheat crop.

6.2 Research hypothesis and objectives

The hypothesis for this research was that soil compaction from vehicular traffic reduces crop establishment, growth and yield as measured by plant establishment, number of tillers, root mass and components of yield and that by using Controlled Traffic Farming, low inflation pressure tyres and reduced tillage systems, crop yields can be increased.

The objectives were:

1. To measure the response of crops during early growth and subsequent yield (over a three year crop rotation) from three traffic treatments (Random Traffic Farming wheeled using standard tyre inflation pressures, Random Traffic Farming wheeled using low tyre inflation pressures and Controlled Traffic Farming wheeled using low tyre inflation pressures) and three tillage treatments (deep (250 mm), shallow (100 mm) and zero tillage (no-till)).

2. To determine the effect of varying tillage depth and traffic intensity on crop growth and yield over a three year cereal crop rotation.

3. To measure the effect of the traffic and tillage treatments on the amount of combine harvest residues left on the surface of the soil prior to drilling.

6.3 Methodology

6.3.1 Introduction

This chapter details the results of crop growth and yield analysis over the three crop rotations: Section 6.3.2 - Year 1 winter barley (2014/15), Section 6.3.3 Year 2 winter cover crop, Section 6.3.4 - Year 2 spring oats (2015/16) and Section 6.3.5 - Year 3 spring wheat (2016/17). The methodology for applying the treatments is described in Chapter 3 - General Methodology.

There were three different crop experiments in Year 1. The winter barley growth and yield study was an experiment based upon traffic intensity sampling which was missing from the hand harvest transect study that was based upon a sampling protocol undertaken by Smith, E. (2016). The hand harvest transect study allowed comparisons to be made between wheeled and untrafficked areas within the CTF plots. Combine harvest of the experimental plots provided the yields based on traffic x tillage system. After evaluating the first year results and analysis, there was a change in protocol (as described in Section 6.3.4) which allowed a more flexible transect survey based on row data that could be used to measure the effects of all traffic treatments within the STP and LTP plots as well as comparisons between wheeled and untrafficked areas within the CTF plots. This meant that only two crop surveys, rather than three, were needed in Year 2 and 3 (i.e. transect by row and combine harvest). Damage to the Year 2 cover crop (described in Section 6.3.3) meant that no experiments were carried out on the cover crop. In Year 3 there was an additional crop residue experiment.

6.3.2 Year 1 - Winter barley

Three separate crop studies were undertaken in Year 1 and the methodology is detailed as follows: Year 1 - Winter barley growth and yield study in Section 6.3.2.1, Year 1 - Winter barley hand harvest in Section 6.3.2.2 and Year 1 - Winter barley combine harvest in Section 6.3.2.3.

The crop was a two row winter barley (*Hordeum vulgare* var. Cassia) planted 20th October 2014 at a density of 226 kg ha^{-1} at a depth of 40 mm and row spacing 167 mm using a 4 metre Väderstad Spirit pulled by a Cat Challenger MT765C (Smith, 2015. Pers. Comm.). The seed was supplied by Wynnstay (Agriculture Supplies) Ltd. It had a broad spectrum single purpose seed treatment (Kinto®) with 60 g/l prochloraz and 20 g/l triticonazole (active ingredients) to control loose smut caused by *Ustilago nuda,* covered smut caused by *Ustilago hordei,* seedling blight caused by *Microdochium nivale a*nd foot rot caused by *Fusarium* spp*.* (BASF, 2013).

6.3.2.1 Year 1 - Winter barley growth and yield study (traffic intensity sampling)

In an attempt to quantify the variations previously identified visually by Smith *et al.* (2014), a growth analysis survey was carried out on the 2014/2015 winter barley crop. This investigated the effects that the soil treatments had on the early development of winter barley and links with the subsequent replicate yield analysis to determine whether the soil compaction and tillage treatments affected establishment, root development and the ability of the crop to access water and nutrients. It also allowed comparisons to be made between the treatments effect on the winter wheat crop (2012/2013) and winter barley (2014/2015).

The aim of the winter barley growth and yield analysis study was to determine whether the traffic and tillage treatments had an effect on barley early growth and final yield by comparing crop growth and development at GS 30, and components of yield at harvest.

Early growth samples (whole plant) were taken at GS 30 and hand harvest samples were taken immediately prior to combine harvest (22-26 July 2015). Samples for both early growth and harvest were selected from areas in each plot subjected to different intensities of wheeling as shown in Table 6.1 (e.g. samples taken from the STP and LTP deep plots consisted of one from a wheel track subjected to one vehicle pass and one from a wheel track subjected to three passes). Where plots had more than one possible location for samples to be taken, the left-hand location was selected. Sampling was completed for each block before sampling the next to ensure that any differences within the results due to sampling time would be between blocks rather than between plots. The number of samples per plot is shown in Table 6.1 (total per block n=14: x 4 replications n=56).

Table 6.1 - Plot treatments: sample identification

Traffic	Tillage	Sample Location (vehicle passes)	No of samples per plot
STP and LTP	Deep	1 and 3	2
	Shallow	1	1
	Zero	1	1
CTF	Deep	0 and 2	2
	Shallow	1 and 2	2
	Zero	2 and 2	2

Figure 6.1 shows the position and number of treatment passes (the numbers in the coloured boxes represent the number of vehicle passes e.g. one pass represents

compaction applied by one pass of the front and rear wheel on one side of the tractor) in the treatment plots. The letter P indicates the primary wheelways in each plot that are trafficked during tillage, drilling and harvest operations. Wheel track widths were 0.6m. Centrelines of compaction treatments were identified in the field using flexicanes (Figure 6.2).

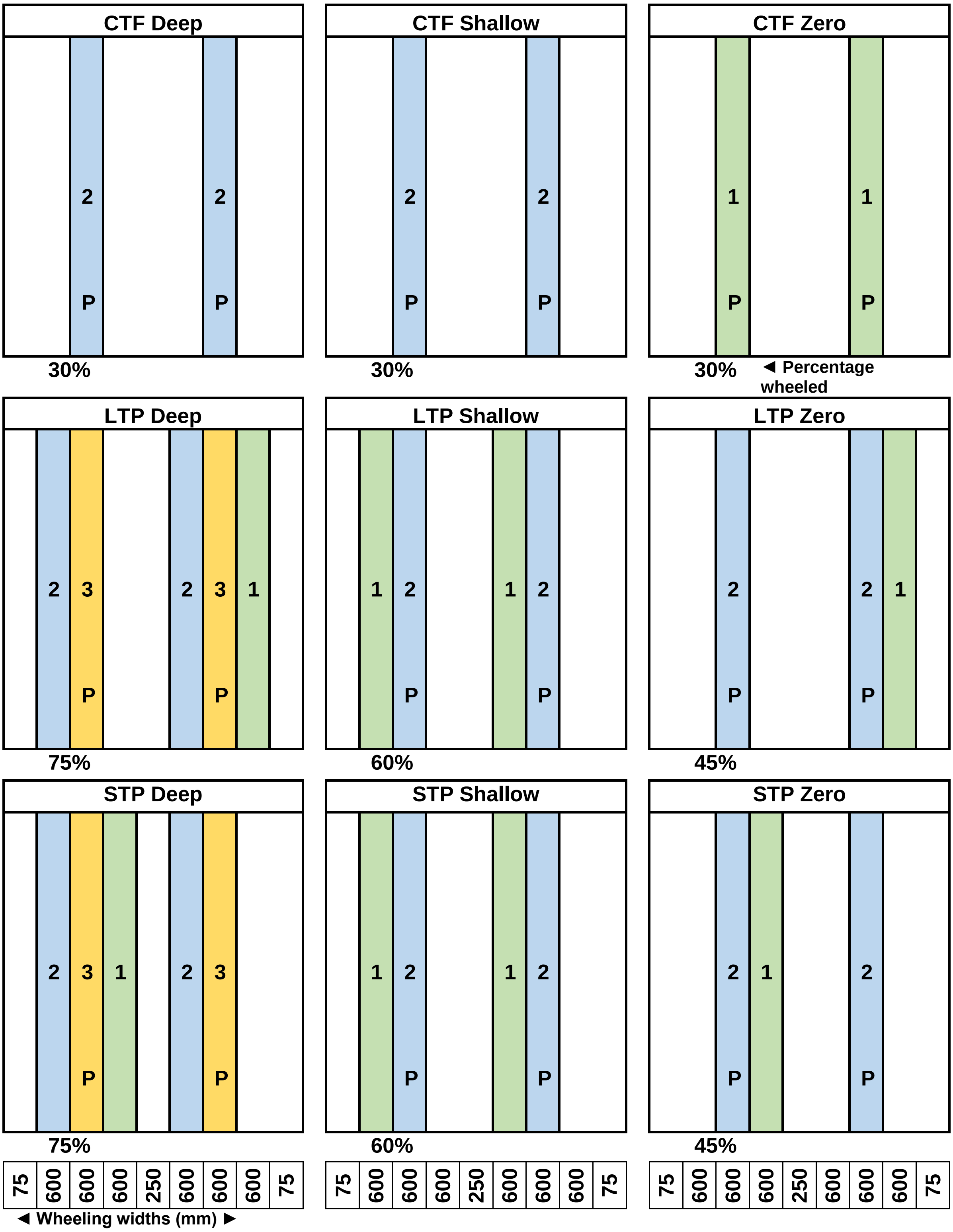

Figure 6.1 - Trial plot compaction mapping

Figure 6.2 - Centrelines of compaction treatments identified using flexicanes
(plots run left to right and flexicanes run parallel to 1st fertiliser/herbicide spray tramline across plots)

The early growth sampling (GS 30) took place at the start of April 2015. This was selected as it was the end of the tillering phase and before the start of stem extension. Sylvester-Bradley *et al.* (1985) suggests that this is the best time to count tillers as it is when tiller numbers are at their maximum. The samples were whole plants taken from two adjacent 500 mm rows at a distance of one metre from the 1st sprayer tramline as shown in Figure 6.3a (i.e. one linear metre) using a 500 mm measure (Figure 6.3b). This is the optimum method and size for cereal sampling recommended by Hudson (1939) cited by Sylvester-Bradley *et al.* (1985). To ensure that the sample was representative of the traffic treatment, the centre line of the sample coincided as closely as possible with the centre line of the wheel track (samples for un-trafficked treatments were taken 300 mm from the centre line of the CTF plots). The plant roots were gently washed to remove soil particles before plants and stems were counted and roots cut from the plant using scissors. All roots and stems in each sample were bagged separately and oven dried at the recommended 80^{o}C for 24 hours as described by Jones (2000) and then weighed. Braim *et al.* (1992) oven dried plant stems and roots at 85^{o}C for 14 hours. Bell and Fischer (1994) suggest that samples should be oven dried at 70^{o}C for 24 hours until a constant weight is reached.

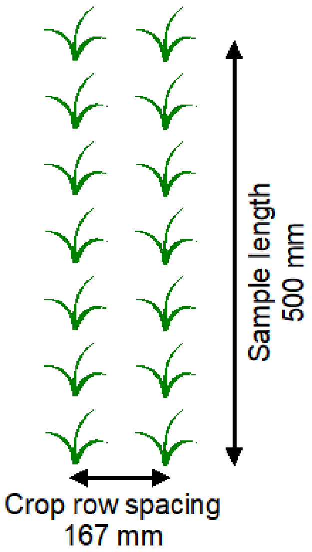

Figure 6.3 - Schematic showing sample selection from two rows of crop (left) and sample selection using 500 mm measure and flexicane (right)

Hand harvest samples were determined by the same method as for early growth (Table 6.1), located adjacent to the previous sample plots (i.e. from two adjacent 500 mm rows at a distance of 1.6 m from the 1st sprayer tramline) and cut with hand shears at ground level. Hand harvest samples were taken immediately prior to combine harvest in July 2015. The heads were removed from the samples with scissors and counted. Heads and straw were dried at 30°C and weighed. Sylvester-Bradley *et al.* (1985) suggested that alternatively, grains can be dried at 100^{o} C for 40 hrs, weighed when cool and dry matter content calculated and converted to 85% dry matter (i.e. 15% moisture content). Heads were threshed using a F. Walter and H. Wintersteiger KG laboratory thresher (Figure 6.4) and then weighed. Grain moisture was measured using a Dickey John Grain Analysis Computer (GAC) 2500-UGMA (Figure 6.5) and the grain weights adjusted to 15% moisture content using Equation 6.1 where mc = moisture content, to remove bias from yield estimation (Bloom, 1985). A Farm-Tec Count-a-matic (Figure 6.6) was used to count grains to calculate the 1000-grain weight.

Figure 6.4 - F. Walter and H. Wintersteiger KG laboratory thresher

Figure 6.5 - Dickey John Grain Analysis Computer (GAC) 2500-UGMA

$$\text{Grain weight at 15\% moisture content (g)} = \frac{\text{100-moisture content}}{85} \times \text{grain weight (g)}$$

Equation 6.1

Figure 6.6 - Farm-Tec Count-a-matic

6.3.2.2 Year 1 - Winter barley hand harvest (transect measurement)

To make comparisons to the previous research (2011-2014) the same methodology was used for taking hand harvest samples as used by Smith, E. (2016). The crop was cut at ground level using hand shears from a 0.3 m wide transect across each plot (4 m width). In the CTF plots the crop was still cut from a 0.3 x 4 m transect but the crop in the wheeled portions was collected separately from the untrafficked portions as shown in Figure 6.7.

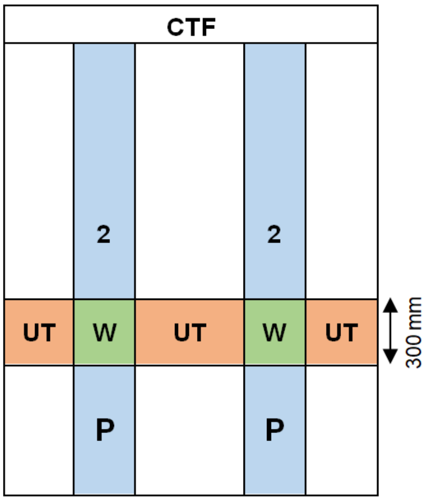

Figure 6.7 - Hand harvest transect across trial plots
(crop in CTF plots was collected separately from wheeled (W) and untrafficked (UT) portions of the transect

Hand harvested crop samples were oven dried at 100°C for 48 hrs, threshed and then weighed as suggested by Sylvester-Bradley *et al.* (1985). Grain moisture was measured using a Dickey John Grain Analysis Computer (GAC) 2500-UGMA and the grain weights adjusted to 15% moisture content using Equation 6.1.

6.3.2.3 Year 1 - Winter barley combine harvest

Combine harvesting of the winter barley took place on the 7th August 2015. Prior to combining, the edges of the trial plots were marked by removing a 1 metre width of crop on the headland side using a BCS Tracmaster 720 power scythe (Figure 6.8). This allowed the combine driver to remove all crop from the headland up to this marked area and to accurately determine the length of each plot for yield analysis.

Figure 6.8 - BCS Tracmaster 720 power scythe

Each trial plot was harvested in sequence (east to west starting at Plot 1) using a Claas Dominator 85 combine harvester with a 4 metre cutter bar (Figure 6.9). After each plot run the tank was emptied using the combine's auger into a specially built hopper (Figure 6.10) suspended from a telehandler and weighed using a Novatech F204TFROKO - 1 tonne strain gauge (Figure 6.11: S/N: 20479) (Novatech, 2017). The weight was recorded and a hectare litre sample was taken using a RDS grain testing flask (part no.: S/HU/182-2-067) and weighed by spring balance (part no.: S/AC/182-2-068). A grain moisture reading was obtained from this sample using a Protimeter Grainmaster grain moisture meter (Figure 6.12). Hectare litre and grain moistures were adjusted to 15% moisture content prior to analysis using Equation 6.1. The hopper was then emptied into a grain trailer for disposal ready for the next plot crop yield measurement.

Figure 6.9 - Claas Dominator 85 combine harvester with a 4 metre cutter bar

Figure 6.10 - Weighing grain with a hopper and 1 tonne load cell

Figure 6.11 - Novatech F204TFROKO 1 tonne strain gauge

Figure 6.12 - Protimeter Grainmaster grain moisture meter

6.3.3 Year 2 - Winter cover crop

Since establishment the traffic and tillage trial had two winter wheat crops followed by two winter barley crops. To reduce the infection risk from 'take-all' required a break crop (Cotterill and Sivasithamparam, 1988). It was not possible to plant an oil seed rape (OSR) crop due to difficulties combine harvesting the crop and capturing the yield with the Claas Dominator 85 combine harvester. A TerraLife-N-Fixx cover crop (a mixture of legumes and non-legumes to fix nitrogen, improve soil health suitable for intensive rotations especially after winter barley (DSV United Kingdom Ltd, 2015)) plant mix was planted 3rd September 2015 at a rate of 40 kg ha^{-1}, 20 mm depth and 167mm row spacing. The seed mix was supplied by DSV United Kingdom Ltd. and consisted of field pea (*Pisum sativum L.*), squarrose clover (*Trifolium squarrosum L.*), persian clover (*Trifolium resupinatum L.*), serradella (*Ornitophus sativus*), phacelia (*Phacelia tanacetifolia*), niger (*Guizotia abyssinica*), buckwheat (*Fagopyrum tataricum*), sunflower (*Helianthus annuus L.*) and common vetch (*Vicia sativa L.*) The cover crop, combined with a follow on spring oats crop, would provide the necessary break. The planting date was later than recommended by the seed supplier (DSV United Kingdom Ltd, 2015) due to non availability of machinery and personnel and then by poor weather. The cover crop mix germinated well but, due to poorly closed drill slots, the newly emerged seedlings were decimated by slugs and birds within a few days and consequently a cover crop was not successfully established. There was therefore, unlikely to have been any detectable effect on soil or water properties and no plant measurements were possible. Any residual cover crop together with barley volunteers were sprayed off using Monsanto Roundup Flex (glyphosate) 12th February 2016 at a rate 2 litres ha^{-1}.

6.3.4 Year 2 - Spring oats

The hand harvest by plot transect used in Year 1 (Section 6.3.2.2) was based on the protocol used by Smith, E. (2016). It was possible to identify the wheelways in the CTF plots so that analysis could be done between wheeled and untrafficked areas in the CTF plots. Difficulties in identifying all the separate traffic treatment areas in the LTP and STP plots had meant that crop measurement in the LTP and STP plots was confined to a single transect across the plots which only gave a mean for these plots as a whole. Year 1 also included the winter barley growth and yield analysis (Section 6.3.2.1) that investigated the effect on the crop growth and development due to the traffic and tillage treatments from samples obtained according to the different traffic intensities within the plots. In an attempt to obtain data similar to that obtained from the two studies in Year 1 from a single experimental design it was decided to carryout analysis of establishment, tillering and yield using a transect method but collecting data by row similar to that used by Hadjichristodoulou (1983) as described in Section 6.3.4.1. Two separate crop studies were undertaken in Year 2 and the methodology is detailed as follows: Year 2 - Spring oats establishment, tillering and hand harvest using row measurements in Section 6.3.4.1 and Year 2 - Spring oats combine harvest in Section 6.3.4.2.

Spring oats (*Avena sativa* var. Aspen) were planted 25th April 2016 at a density of 350 seeds m^{-2} (+ 30% for no-till plots) at row spacing 167 mm using a 4 metre Väderstad Spirit drill. The seed (TGW 34) was supplied by Wynnstay (Agriculture Supplies) Ltd. It had a broad spectrum single purpose seed treatment (Kinto®) with 60 g/l prochloraz and 20 g/l triticonazole (see Section 6.3.2).

6.3.4.1 Year 2 - Spring oats establishment, tillering and hand harvest using row measurements

To allowed for better analysis in the LTP and STP plots than in previous years, field surveys and hand harvest collection was carried out using a 300 mm transect across all plots (Figure 6.13) as described in Section 6.3.2.2 but data and samples were collected by row (22 rows per plot). Spring oats plant emergence was counted on the 18th May 2016 followed by a tiller count from the same transects on the 16th June 2016. Hand harvest samples were collected cutting the oat crop at ground level and bagged by row into oven drying bags (Figure 6.14) 8th to 12th August 2016.

Figure 6.13 - Hand harvest transect - 300 mm width

Crop samples were oven dried at 100^{o}C for 48 hrs (Sylvester-Bradley *et al.*, 1985), the heads were removed from the samples with scissors, counted and then threshed using a F. Walter and H. Wintersteiger KG laboratory thresher (Figure 6.5). The grain was weighed and grain moisture was measured using a Dickey John Grain Analysis Computer (GAC) 2500-UGMA (Figure 6.5) and the grain weights adjusted to 15% moisture content using Equation 6.1.

Figure 6.14 - Dried hand harvest samples (per row) ready for head count and threshing

6.3.4.2 Year 2 - Spring oats combine harvest

The methodology used for Year 2 combine harvest was the same as that described in Section 6.3.2.3. Combine harvesting of the Spring oats took place on the 7th and 8th of September 2016.

6.3.5 Year 3 - Spring wheat

Three separate crop studies were undertaken in Year 3 and the methodology is detailed as follows: Year 3 - Spring wheat establishment and hand harvest using row measurements in Section 6.3.5.1, Year 3 - Spring wheat combine harvest in Section 6.3.5.2 and Year 3 - crop residue in Section 6.3.5.3.

Spring wheat (*Triticum aestivum* var. Mulika) was planted 4th April 2017 at a density of 400 seeds m^{-2} (+ 30% for no-till plots) at row spacing 167 mm using a 4 metre Väderstad Spirit. The seed (TGW 46) was supplied by Wynnstay (Agriculture Supplies) Ltd. It had a broad spectrum single purpose seed treatment (Redigo Pro®) with 150 g/L (13.2% w/w) prothioconazole and 20 g/L (1.8% w/w) tebuconazole (active ingredients) to control seedling blight and stem base browning caused by *Microdochium nivale* and *Fusarium culmorum*, bunt caused by seed- or soil-borne infections of *Tilletia caries,* loose smut caused by *Ustilago nuda fsp tritici* and *U. avenae* and the effect of blue mould (*Penicillium spp*) on germinating cereal seeds (Bayer, 2018).

6.3.5.1 Year 3 - Spring wheat establishment and hand harvest using row measurements

Spring wheat plant emergence was counted on the 5th May 2017. Hand harvest samples were collected cutting the wheat crop at ground level and bagged by row (oven drying bags) 22nd to 29th August 2017. Hand harvest samples were processed as described in section 6.3.4.1 except grain moisture which was measured using a Protimeter Grainmaster grain moisture meter (Figure 6.7). Grain weights adjusted to 15% moisture content using Equation 6.1.

6.3.5.2 Year 3 - Spring wheat combine harvest

Combine harvesting of the spring wheat took place on the 26th September 2017. The methodology used for year 3 combine harvest was the same as that described in section 6.3.2.3.

6.3.5.3 Year 3 - crop residue

Harvest crop residues are left on the soil surface in reduced tillage systems and can affect crop establishment. The poorest crop establishment is associated with soils that have the largest amount of loose surface residue (Freer, 2006). An image analysis experiment was conducted to measure the differences in soil surface residue between the different traffic and tillage treatments to provide an indication of the amount of crop residue incorporation into the soil as a result of the two tillage treatments (deep and shallow). Photographs were taken one day after the cultivation treatments (27th October 2017), of the crop residues enclosed by a rectangular quadrant (500 x 250 mm), placed in the centre of each of the plots between the primary wheelways (qty 36 plots). ImageJ software (Rasband, 2009) was used for image analysis to estimate the percentage of soil surface covered with straw residue (image processing procedure is at Appendix D).

6.3.6 Statistical analysis

Genstat 18th Edition (VSN International, 2015) was used for statistical analysis of data as described in Section 4.3.3. The REML (residual maximum likelihood) method was used for analysis of linear mixed models (Payne, 2003). The t-Test: Two-sample Assuming Unequal Variances function in Excel was used for small sample sizes. The Student's t-Distribution is recommended for comparing means of small samples sizes (Alder and Roessler, 1964).

6.4 Results and discussion

Data analysis from measurement of the research crops is presented in this section in year order. For year 1 there was a standalone winter barley growth and yield study (Section 6.4.1) followed by a hand harvest by transect (6.4.2) and then combine harvest. In year 2, a change in protocol allowed establishment, tillering and hand harvest to be measured as part of one study (6.4.4). Year 2 combine results are in section 6.4.5. The year 3 establishment and hand harvest study is in Section 6.4.6 followed by the combine harvest results (6.4.7). An analysis of soil coverage by crop residue left from year 3 combine harvest is at Section 6.4.8. Combine harvest data from the three years of this research and the two years from previous research is compared in Section 6.4.9. A comparison of hand harvest and combine harvest results is discussed in Section 6.4.10. The relationship between combine harvest yields and rainfall for the years 2013-2017 is explored in Section 6.4.11.

6.4.1 Year 1 - Winter barley growth and yield study

The results from this study are split into two: Section 6.4.1.1 reports the results from the controlled traffic farming (CTF) plots (n=12) and Section 6.4.1.2 compares the results from the LTP and STP plots subjected to one vehicle pass (n=24).

6.4.1.1 Year 1 - Winter barley growth and yield study controlled traffic treatment (CTF) plots

The samples taken in the controlled traffic plots (CTF) were from zero passes (untrafficked) and the primary wheel ways (wheeled). These treatments represent the two extreme compaction treatments from the Year 1 winter barley growth and yield study. The untrafficked zero tillage treatment had not been subjected to tillage or compaction and could be considered as a control treatment.

6.4.1.1.1 Year 1 - Winter barley growth and yield study controlled traffic treatment (CTF) plots - Plants at GS 30

The mean number of plants m^{-2} (at GS 30) in the CTF plots (n=12) subject to the tillage treatments is shown in Table 6.2. The mean number of plants (m^{-2}) in the untrafficked treatments (qty 289) was significantly (*P*=0.002, SEM=14, %CV=19.1) higher (34%) than in the wheeled treatments (qty 216). Mean plant establishment was lowest (qty 201 m^{-2}) in the zero tillage treatments and was significantly lower than in the shallow tillage treatments (*P*=0.004, SEM=17, %CV=19.1) which had the highest establishment (qty 296 m^{-2}). Tillage improved establishment compared to untrafficked zero tillage treatment (control qty 246 m^{-2}) except in the deep tillage wheeled treatments where establishment was 18% lower (qty 202 m^{-2}) probably as a result of soil recompaction after deep tillage as identified in Chapter 4 (Sections 4.4.2 and 4.4.3) and Chapter 5 (Section 5.4.2). There was no significant interaction between the traffic and tillage treatments for plant m^{-2} (*P*=0.132). With the exception of the untrafficked deep and shallow treatments, establishment (at GS 30) was below the recommended benchmark of 305 m^{-2} (HGCA, 2006) for the remaining treatments. Although the benchmark is for establishment recorded at GS 21, the results would indicate that vehicular traffic reduced expected establishment and that in the untrafficked soil, tillage was a management option that could be used to reach benchmark establishment. Reintam *et al.* (2009) found that reduced barley plant numbers was associated with poor seedling emergence on compacted soils. The effect of shallow tillage improving plant establishment in the wheeled areas suggests that the soil structure in the upper profile (0-100 mm) is important for winter barley establishment. This improvement in establishment may be due to increased aeration and warmth in the top layer of soil as suggested by Lipiec *et al.* (2003b).

Table 6.2 - Winter barley plants (m^{-2}) for the traffic and tillage treatments in CTF plots at GS 30

	Plants (m^{-2})			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	317	304	246	289[a]
Wheeled	202	289	157	216[b]
Mean	260[ab]	296[b]	201[a]	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.1.1.2 Year 1 - Winter barley growth and yield study controlled traffic treatment (CTF) plots - Stems at GS 30

Figure 6.15 shows the mean number of stems m^{-2} at GS 30 in the CTF plots. Traffic significantly (*P*<0.001, SEM=41, %CV=12.2) reduced (28%) the mean number of winter barley stems m^{-2} (qty 973) at GS 30 in the CTF plots compared to the untrafficked treatments (qty 1349). The zero tillage treatments mean density (1033 m^{-2}) was significantly (*P*=0.005, SEM=50, %CV=12.2) lower (21%) than for the shallow tillage treatments (qty 1306). The mean number of stems in the wheeled shallow tillage treatment was not significantly different from the means of the three untrafficked treatments suggesting that unlike deep tillage, shallow tillage did not re-compact the soil to an extent that it affected the growth of barley stems. Compared to untrafficked zero tillage treatment mean (qty 1314) the wheeled deep and zero tillage treatment means had 32% (qty 897) and 43% (qty 751) fewer stems respectively and both were significantly lower (*P*=0.007, SEM=70, %CV=12.2) than the stem means in the other treatments. In addition both treatments were below the target benchmark of 1180 stems m^{-2} at GS 30 (HGCA, 2006). The number of stems m^{-2} was related to the number of plants m^{-2} and the number of stems per plant does not seem to have been affected by compaction in the tillage treatments (ranging from 4.2 to 4.4 stems per plant). This ratio was increased in zero tillage plots to 4.7 in wheeled and 5.3 in untrafficked. The coefficient of variation (CV%=12.2) is within the expected range of 10-20% expected from a cereal trial indicating that there were sufficient replications to detect treatment differences (Clewer and Scarsisbrick, 2001).

Reductions in tiller numbers can be due to a reduction in nitrogen supply and low water availability during the tillering period (Smith *et al.*, 1999). This may have been caused by the reduction in root mass (Section 6.4.1.1.3) in the compacted soil of the traffic treatments leading to reduced tiller survival. Shallow tillage improved survival of the tillers but deep tillage did not. This may have been due to soil recompaction caused by subsequent field traffic on low bearing capacity soil, due to deep tillage, as identified by Soane *et al.* (1986). The increase in tillers per plant in the zero tillage treatments is probably due to the reduced plant m^2 (Section 6.4.1.1.1) because winter barley can compensate for reduced establishment by increasing the number of tillers (AHDB, 2015a).

Alternatively, the reduced tiller numbers associated with the higher plant populations may be due to reduced levels of photosynthetically active radiation (PAR) in the lower canopy initiating earlier cessation of tillering (Evers *et al.,* 2006).

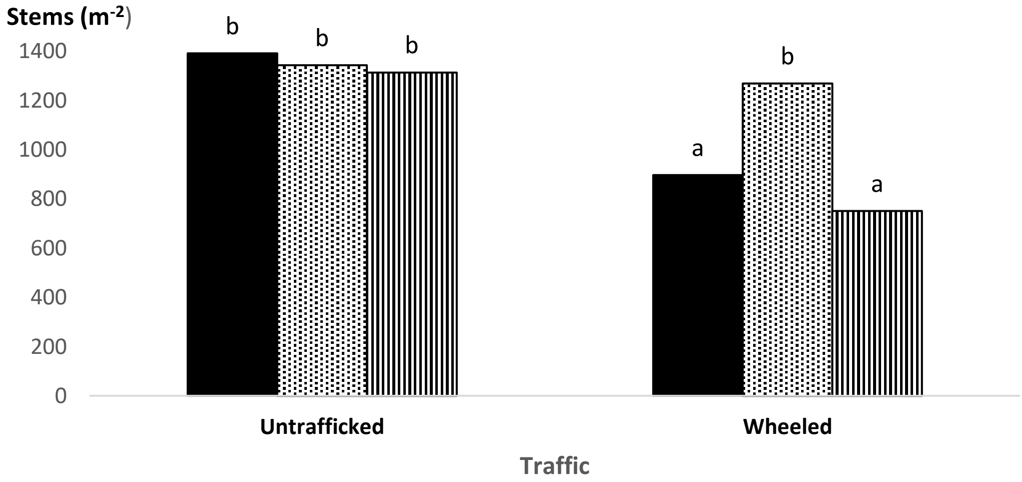

Figure 6.15 - Winter barley stems (m^{-2}) for the traffic and tillage treatments in CTF plots at GS 30
(Columns: black deep, black dots shallow and black stripes zero tillage)
(**Note**: Means not having the same letters are significantly different from each other)

The winter barley stem dry mass means (g) for the traffic and tillage treatments in CTF plots are in Table 6.3. Dry stem mass in wheeled treatments (28.3 g) was significantly (P<0.001, SEM=2.48, %CV=22.9) lower (40%) than the mean (46.8 g) in untrafficked treatments. Zero tillage treatments significantly (P=0.004, SEM=3.04, %CV=22.9) reduced biomass (27.8 g) compared to the deep (40.9 g) and shallow (44.0 g) tillage treatments. Traffic reduced above ground biomass by 63% in the zero tillage treatments (untrafficked zero tillage 40.4 g, wheeled zero tillage 15.1 g). There was no significant difference in mean stem mass (per plant) for the wheeled and untrafficked treatments.

Table 6.3 - Winter barley stem dry mass means (g) the traffic and tillage treatments in CTF plots

	Stem dry mass (g)			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	51.8	48.1	40.4	46.8[a]
Wheeled	29.9	39.8	15.1	28.3[b]
Mean	40.9[b]	44.0[b]	27.8[a]	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.1.1.3 Year 1 - Winter barley growth and yield study controlled traffic treatment (CTF) plots - Roots at GS 30

The winter barley root dry mass means (g) for the traffic and tillage treatments in CTF plots are in Table 6.4. Mean dry root mass in wheeled treatments (9.77 g) was significantly (*P*<0.001, SEM=0.71, %CV=20.8) lower (30%) than the mean (13.89 g) in untrafficked treatments. This could have been due to poorer root penetration due to higher bulk density or attributed to water logging and possibly anaerobic conditions due to associated smaller pore spaces as suggested by the literature (Czyz, 2004). It is also possible that these conditions reduced seed viability and early plant survival reducing plant establishment in the compacted treatments. The presence of anaerobic conditions may have been determined if the field test described by Batey and Childs (1982) for locating anoxic soil had been used. The low dry root mass in the wheeled zero tillage treatment (5.7 g) was the main contribution to this reduction as well as the significant reduction (*P*=0.001, SEM=0.87, %CV=20.8) in root dry mass in the zero tillage treatment (8.6 g) compared to the tillage treatments (deep 13.2 g and shallow 13.8 g). The wheeled zero tillage treatment mean was 50% lower than the mean of the untrafficked zero tillage treatment mean (11.4 g). There was no significant difference in mean root mass (per plant) for the wheeled and untrafficked treatments which would indicate that the differences in total root mass was due to variations in plant establishment rather than root development. Braim (1986) cited by Braim *et al.* (1992) also found little difference in winter barley root mass on a sandy loam soil at the similar growth stage (GS 31) but did find differences at GS 65 due to different tillage treatments.

Table 6.4 - Winter barley root dry mass means (g) the traffic and tillage treatments in CTF plots

	Root dry mass (g)			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	15.6	14.6	11.4	13.9^{a}
Wheeled	10.7	12.9	5.7	9.8^{b}
Mean	13.2^{b}	13.8^{b}	8.6^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.1.1.4 Year 1 - Winter barley growth and yield study controlled traffic treatment (CTF) plots - Root:stem ratio at GS 30

As identified in the literature, growth of leaves and roots are affected by soil compaction as a result of restricted root development and the ability of the plant to access nutrients and water (Grzesiak *et al.*, 2013; Briggs, 1978). This can lead to increases in plant root to stem ratio. The mean root to stem ratio (Table 6.5) was significantly (*P*=0.025, SEM=0.011, %CV=11.6) higher (13%) in wheeled treatments (0.36) than in untrafficked treatments (0.32). Wheeled deep and zero tillage treatments had the largest root to stem ratio means (0.37) which was probably as a result of increased soil compaction (as previously indicated by the lower plant and stem counts). The reduction in root dry mass (30%) in the wheeled (more compacted) soil was lower than the reduction in dry stem mass (40%) which led to the increase (13%) in root:stem (also called root:shoot) ratio. This is in agreement with Hussain *et al.* (1999) and may be due to the decrease in plant density and/or decrease in nutrient availability as reported by Braim *et al.* (1992) and Lucas *et al. (2000*).

Table 6.5 - Winter barley root:stem ratio (dry mass) means for the traffic and tillage treatments in CTF plots

	Root:stem ratio			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	0.31	0.33	0.30	0.32[a]
Wheeled	0.37	0.32	0.37	0.36[b]
Mean	0.34	0.33	0.34	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.1.1.5 Year 1 - Winter barley growth and yield study controlled traffic treatment (CTF) plots - Yield

Deep tillage treatments produced 29% more barley heads than the zero tillage treatments (*P*=0.053, SEM=56, %CV=19.1) as shown in Table 6.6. The shallow tillage treatments had 850 heads m^{-2} (19% more than in the zero tillage treatments) but there was no significant difference in between the means for the tillage treatments. There was no significant difference between the means for the traffic treatments.

Table 6.6 - Winter barley mean number of heads (m^{-2}) for the traffic and tillage treatments in CTF plots (winter barley growth and yield study)

		Heads (m^{-2})		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	963	820	744	842
Wheeled	882	879	683	814
Mean	922	850	713	

(**Note**: Means not followed by the same letters are significantly different from each other)

The barley yield for the different traffic and tillage treatments in the CTF plots (Table 6.7) were not significantly different. The highest yield was 12.37 t ha^{-1} in the wheeled shallow tillage treatment and the lowest yield was 9.14 t ha^{-1} from the wheeled zero tillage treatment. There was no significant difference in thousand grain weight (TGW) due to the traffic and tillage treatments in the CTF plots (untrafficked treatment mean was 54.9 g and the wheeled treatment was 55.7 g). The difference in straw yield in the CTF plots was not significant and ranged from 7.6 t ha^{-1} in the untrafficked deep tillage treatment to 6.21 t ha^{-1} in the wheeled zero tillage (which was slightly under the 6.4 t ha^{-1} benchmark (HGCA, 2006).

Table 6.7 - Winter barley yield (t ha^{-1}) for the traffic and tillage treatments in CTF plots (winter barley growth and yield study)

	Winter barley yield (t ha^{-1})			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	11.91	10.39	11.35	11.22
Wheeled	11.42	12.37	9.14	10.98
Mean	11.67	11.38	10.24	

6.4.1.2 Year 1 - Winter barley growth and yield study LTP and STP one pass treatment

Winter barley establishment (plants m^{-2} at GS 30) was 19% higher (*P*=0.057, SEM= 16.11, %CV=20.3) in the LTP 1 pass treatments (299 plants m^{-2}) than in the STP 1 pass treatments (252 plants m^{-2}). The number of stems was significantly (*P*=0.007, SEM=2.21, %CV=18.1) higher (26%) in the LTP treatments compared to the STP treatments. Plant numbers were responsible for part of the difference in mass but some of the increase was due to a larger mean stem mass per plant (6%) in the LTP treatments (0.157 g) compared to the STP treatments (0.148 g). Total root mass per sample was higher in the LTP treatments (12.69 g) compared to the STP (10.53 g) but the mass per plant was the same (0.042 g) for both treatments indicating that the difference in total root mass between the two treatments was due to plant establishment. There was no significant difference in the TGW or the number of heads m^{-2} between the two treatments. Although there was a 12% higher yield in the LTP 1 pass treatments (13.01 t ha^{-1}) than in the STP 1 pass treatments (11.60 t ha-1) this was not statistically different (*P*=0.161, SEM=0.675, %CV=19).

6.4.1.3 Year 1 - Winter barley growth and yield study comparison to wheat crop 2012

Unlike the results of the wheat crop study 2012 carried out by Smith *et al.* (2014), detailed in Section 6.1, this investigation found differences at early growth stages for the barley crop and no significant differences in yield. This may be due to differences of wheat and barley response to compaction and tillage but is more likely due to rainfall amount. It is probable that if the barley crop had been exposed to the rainfall experienced over the preceding three years (2011-2014) then yields would have been lower and the differences observed at GS 30 would have been translated into similar differences in the yield (Raper, 2005).

6.4.2 Year 1 - Winter barley hand harvest - transects

The results in this section relate to hand harvest samples taken from all plot (n=36) transects (0.3 x 4 m). Section 6.4.2.1 relates to whole transect totals from all traffic x tillage plots (n=36) and section 6.4.2.2 compares the trafficked and wheeled areas in the CTF plots only (n=12).

6.4.2.1 Year 1 - hand harvest (plot measurements)

Table 6.8 shows the traffic and tillage means for the number of heads (m^{-2}), TGW (g), straw ($t\ ha^{-1}$) and yield ($t\ ha^{-1}$) for the winter barley crop hand harvested from the 0.3 x 4 m transects across each trail plot (n=36). There was no difference in the number of heads (Table 6.8 a) produced in the three traffic systems (~900 m^{-2}) but the zero tillage treatments produced significantly (P<0.001, SEM=17.5, %CV=6.7) fewer heads (803 m^{-2}) than deep (944 m^{-2}) and shallow (958 m^{-2}) tillage treatments (15% and 16% respectively). There was an inverse relationship with the TGW means (Table 6.8 b) with the TGW mean in the zero traffic treatments (59.7 g) being significantly (P<0.001, SEM=0.65, %CV=3.9) larger (7%) than the two tillage treatments means (55.8 and 58.9 g for deep and shallow). There was no significant difference in TGW for the traffic treatments. There was no significant differences in mean yield of straw (Table 6.8 c) and grain (Table 6.8 d) from the traffic and tillage treatments. However it is interesting to note that the mean yields (straw and grain) were lowest in the CTF zero tillage plots (least traffic and least tillage treatment). The larger transect hand harvest sample sizes compared to the sample size for the Year 1 winter barley growth and yield study (Section 6.4.1) led to less variable data indicated by the lower %CV values.

Table 6.8 - Winter barley hand harvest (all plots: 0.3 x 4 m transect)
a: number heads (m^{-2}), b: TGW (g), c: Straw (t ha^{-1}) and d: yield (t ha^{-1})

a:		**Heads (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	973	969	751	897
LTP	922	950	837	903
STP	938	956	821	905
Mean	944[b]	958[b]	803[a]	

b:		**TGW (g)**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	55.4	56.9	60.2	57.5
LTP	56.9	55.7	58.1	56.9
STP	55.1	55.1	60.7	57.0
Mean	55.8[a]	55.9[a]	59.7[b]	

c:		**Straw (t ha^{-1})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	5.88	6.26	5.22	5.79
LTP	6.10	6.10	6.11	6.10
STP	6.01	6.01	6.10	6.04
Mean	6.00	6.12	5.81	

d:		**Yield (t ha^{-1})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	11.81	11.75	10.48	11.35
LTP	11.33	11.42	11.21	11.32
STP	11.24	11.20	11.31	11.25
Mean	11.46	11.46	11.00	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.2.2 Year 1 - hand harvest (CTF plots)

Table 6.9 shows the winter barley heads (m^{-2}) for the traffic and tillage treatments in the CTF plots (hand harvest 0.3 x 4 m transect). Traffic significantly (*P*=0.012, SEM=31.4, %CV=12.3) reduced (13%) the number of heads (untrafficked 952, wheeled 825 heads m^{-2}). Both deep and shallow tillage significantly (*P*=0.002, SEM=38.5, %CV=12.3) increased (28%) the number of heads m^{-2} (959) compared to the zero tillage treatments (748).

Table 6.9 - Winter barley heads (m^{-2}) for the traffic and tillage treatments in CTF plots (hand harvest 0.3 x 4 m transect)

		Heads (m^{-2})		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	1049	1022	786	952[a]
Wheelway	869	896	709	825[b]
Mean	959[b]	959[b]	748[a]	

(**Note**: Means not followed by the same letters are significantly different from each other)

The thousand grain weight mean (Figure 6.16) was significantly (*P*=0.009, SEM=0.4, %CV=2.4) lower (3%) in the wheeled treatments (56.7 g) compared to the untrafficked treatments (58.4 g). Tillage significantly (*P*<0.001, SEM=0.5, %CV=2.4) increased the TGW (9% deep: 60.2g, 3% shallow: 56.4 g) compared to the zero tillage treatments (55.4

g). Wheeled deep tillage treatments had significantly lower TGW than all the other treatments (*P*=0.001, SEM=0.7, %CV=2.4).

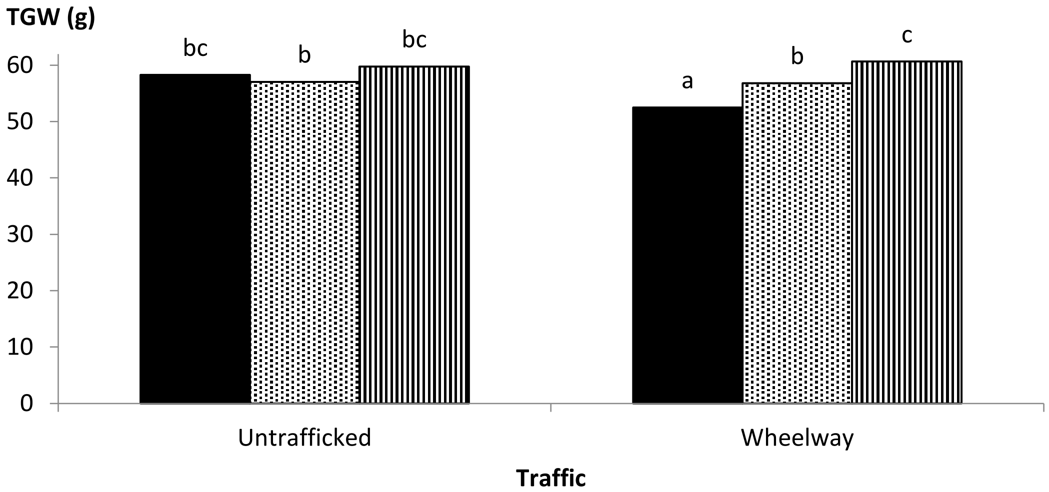

Figure 6.16 - Winter barley TGW (g) for the traffic and tillage treatments in CTF plots (hand harvest 0.3 x 4 m transect)
(Columns: black deep, black dots shallow and black stripes zero tillage)
(**Note**: Means not having the same letters are significantly different from each other)

The straw yield was 5.02 t ha^{-1} in the wheeled treatments (Table 6.10) which was significantly (*P*=0.005, SEM=0.29, %CV=17.7) lower (21%) than in the untrafficked treatments (6.37 t ha^{-1}). The untrafficked deep tillage treatment had the highest straw yield (6.99 t ha^{-1}) and wheeled deep tillage the lowest (4.37 t ha^{-1}).

Table 6.10 - Winter barley straw (t ha^{-1}) for the traffic and tillage treatments in CTF plots (hand harvest 0.3 x 4 m transect)

	Straw (t ha^{-1})			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	6.99	6.69	5.42	6.37^a
Wheelway	4.37	5.68	5.00	5.02^b
Mean	5.68	6.19	5.21	

(**Note**: Means not followed by the same letters are significantly different from each other)

Table 6.11 shows the yield means of winter barley for the traffic and tillage treatments in the CTF plots. Traffic also significantly (*P*=0.004, SEM=0.42. %CV=13) reduced (17%) grain yield (10.19 t ha^{-1}) compared to the untrafficked treatments (12.22 t ha^{-1}). Although not significant, increasing tillage intensity increased yields in the untrafficked treatments from 10.9 (zero) to 12.53 (shallow) to 13.24 t ha^{-1} (deep). As with the straw yield, the untrafficked deep tillage treatment had the highest grain yield (13.24 t ha^{-1}) and wheeled deep tillage the lowest (9.87 t ha^{-1}).

Table 6.11 - Winter barley yield (t ha^{-1}) for the traffic and tillage treatments in CTF plots (hand harvest 0.3 x 4 m transect)

	Yield (t ha^{-1})			
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	13.24	12.53	10.90	12.22^{a}
Wheelway	9.87	10.69	10.00	10.19^{b}
Mean	11.56	11.61	10.45	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.3 Year 1 - Winter barley combine harvest

Table 6.12 shows the mean winter barley combine harvest yields (t ha^{-1}) for the traffic and tillage treatments. The zero tillage treatment mean yield (9.62 t ha^{-1}) was significantly lower (*P*<0.001, SEM=0.225, %CV=7.4) than the deep and shallow tillage means (10.88 and 11.00 t ha^{-1} respectively). Shallow tillage produced the highest yields overall (not significantly different from deep tillage) and especially in the random traffic treatments (LTP and STP) indicating that deep tillage was not required to produce optimum yields. Traffic had no significant effect on yield (*P*= 0.841).

Table 6.12 - Year 1 combine harvest traffic and tillage mean yields (t ha^{-1}) for winter barley

	Yield (t ha^{-1})			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	11.02	10.89	9.82	10.58
LTP	10.96	11.09	9.54	10.53
STP	10.67	11.02	9.49	10.40
Mean	10.88^{b}	11.00^{b}	9.62^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other)

There was no significant differences in grain specific weight mean values due to the traffic and tillage treatments which ranged from 67.2 to 68.4 ha l.

6.4.4 Year 2 - Spring oats establishment, tillering and hand harvest study

The results in this section relate to establishment and tillering counts and the hand harvest samples taken for each crop row from plot transects (0.3 x 4 m). Section 6.4.4.1 relates to whole transect totals from all traffic x tillage plots (n=36) and Section 6.4.4.2 compares the trafficked and wheeled areas in the CTF plots only (n=12). The results from the additional compaction wheelings for 1 (n=24) and 2 (n=8) pass in the STP and LTP traffic plots are compared in Section 6.4.4.3. Note: It was not possible to measure TGW due to shattering of the grain during threshing therefore TGWs for spring oats are not presented.

6.4.4.1 Year 2 - Spring oats establishment, tillering and hand harvest (results for all plots)

The mean spring oat plant establishment (expressed as plants m^{-2}) for each row (1-22) in the nine traffic and tillage treatments are shown in Figure 6.17. There was decreased plant establishment in the primary wheelways (i.e. rows 4-7 and 16-19) which was particularly evident in the CTF and zero tillage treatments (although not all rows were affected equally). STP and LTP traffic treatments had reduced establishment compared to the CTF treatments with the exception of STP shallow.

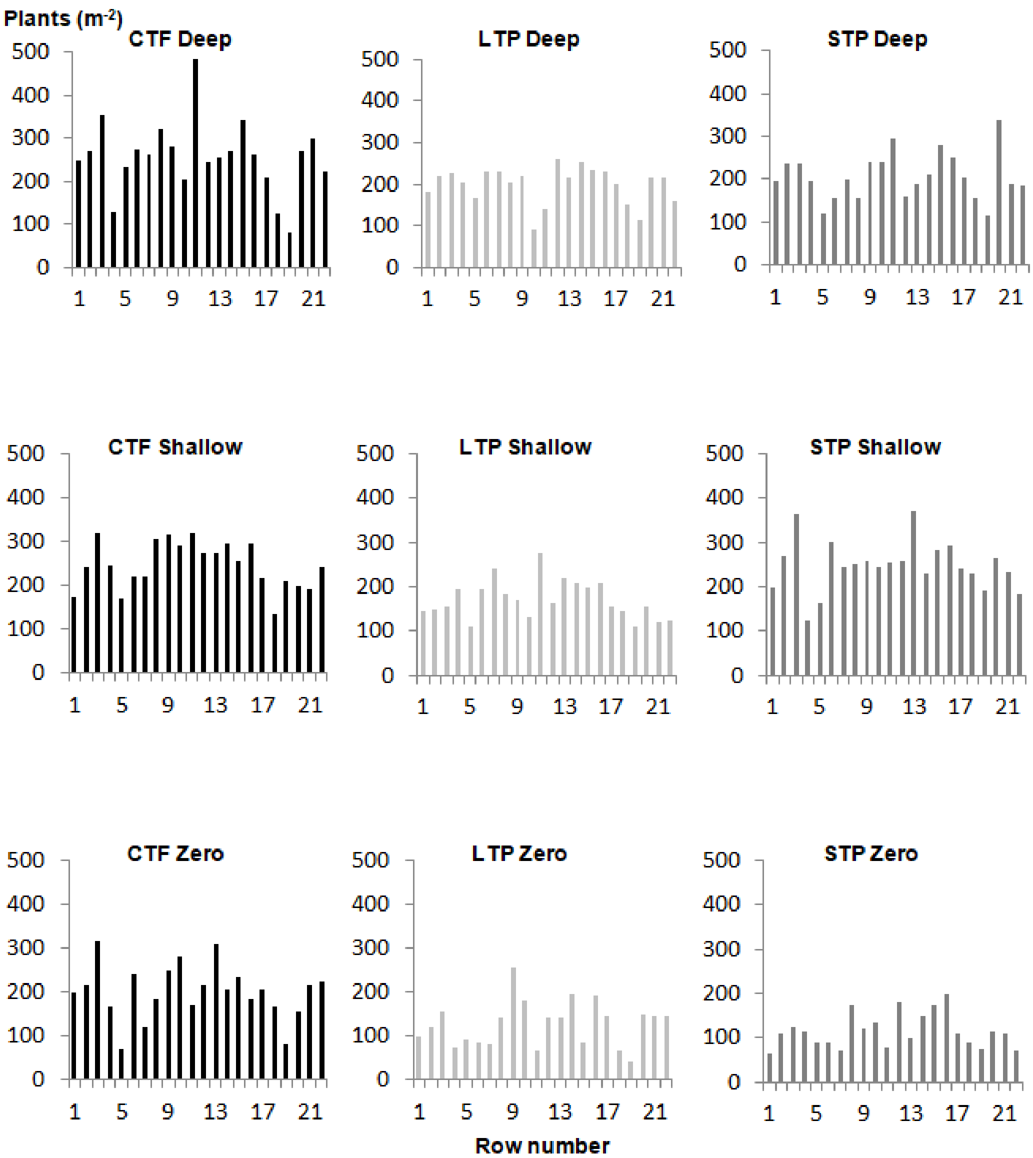

Figure 6.17 - Spring oats establishment by row (m^{-2}) for the traffic and tillage treatments (primary wheelways located at rows 4-7 and 16-19)

Table 6.13 shows the mean spring oat establishment and number of stems at GS 30 (m^{-2}) for the traffic and tillage treatments. As seen visually in Figure 6.21 LTP and STP treatments (Table 6.13 a) had significantly (*P*=0.001, SEM=11.83, %CV=20.9) lower spring oat establishment (190 and 165 respectively) than for the CTF treatment (234). The zero tillage treatment significantly (*P*<0.001, SEM=11.83, %CV=20.9) reduced plant establishment by 33% compared to the deep and shallow tillage treatments. The number of stems at GS 30 (Table 6.13 b) was significantly (*P*<0.001, SEM=19, %CV=11.8) lower (~21%) in the zero tillage treatments compared to the deep and shallow tillage treatments. There were fewer stems m^{-2} (*P*=0.063, SEM=19, %CV=11.8) in the LTP treatments (528) compared to in the CTF treatments (592). STP treatments had 544 stems m^{-2} but this was not significantly different to CTF or LTP treatments.

Table 6.13 - Spring oat means (m^{-2}) for the traffic and tillage treatments for a: establishment and b: stems at GS 30

a:		**Plant establishment (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	257	245	200	234^{b}
LTP	198	171	126	165^{a}
STP	206	248	116	190^{a}
Mean	220^{b}	221^{b}	147^{a}	

b:		**Stems (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	657	584	536	592^{b}
LTP	541	595	449	528^{a}
STP	584	622	427	544^{ab}
Mean	594^{b}	600^{b}	471^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other).

The mean number of panicles m^{-2} for the traffic and tillage treatments is shown at Figure 6.18. The LTP treatments produced significantly (*P*=0.004, SEM=17.7, %CV=11.9) reduced numbers (17%) of panicles m^{-2} (472) than the CTF treatments (566). STP treatments had a mean of 510 panicles m^{-2} but this was not significantly different from the CTF or LTP treatments. Zero tillage treatments had the lowest number of panicles (459 m^{-2}) which was significantly (*P*=0.002, SEM=17.7, %CV=11.9) lower (15 and 17%) than deep (537) and shallow (552) tillage treatments respectively. STP zero tillage treatments produced the lowest number of panicles m^{-2} (377) which was significantly lower (*P*=0.017, SEM=30.7, %CV=11.9) than in the CTF and STP deep and shallow tillage treatments. There was no significant differences in panicle numbers between the other treatments.

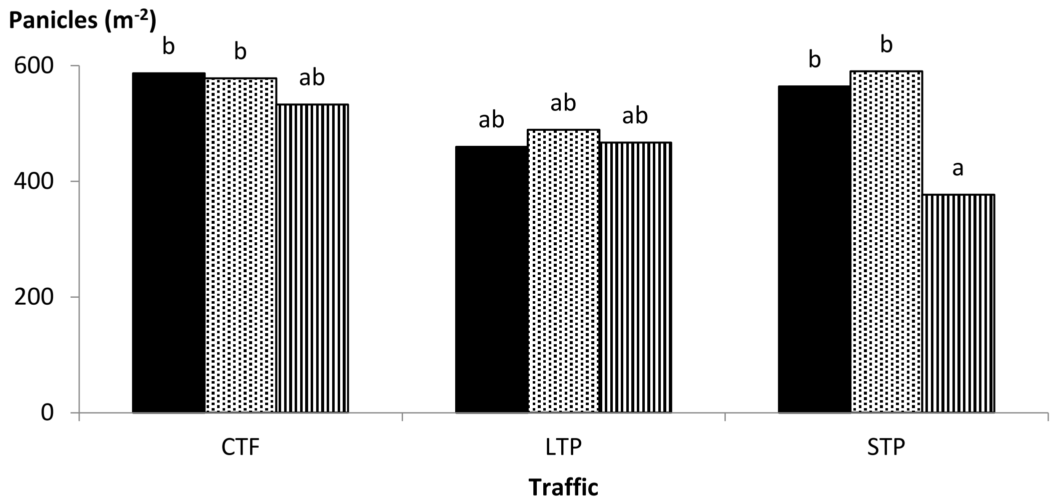

Figure 6.18 - Spring oat panicle means (m^{-2}) for the traffic and tillage treatments
(Columns: black deep, black dots shallow and black stripes zero tillage)
(**Note**: Means not having the same letters are significantly different from each other at the 0.05 probability level)

Similarly to the plant establishment (Figure 6.17), hand harvest mean spring oat yield is presented by row (expressed as t ha^{-1}) for the traffic and tillage treatments at Figure 6.19. The yields are quite variable per row and the reduction in yields in the primary wheelways (rows 4-7 and 16-19) is not as pronounced as for plant establishment. Although the yields for each row are quite varied it is possible to estimate that overall the yields from all treatments are fairly similar with the exception of STP zero tillage which is reduced.

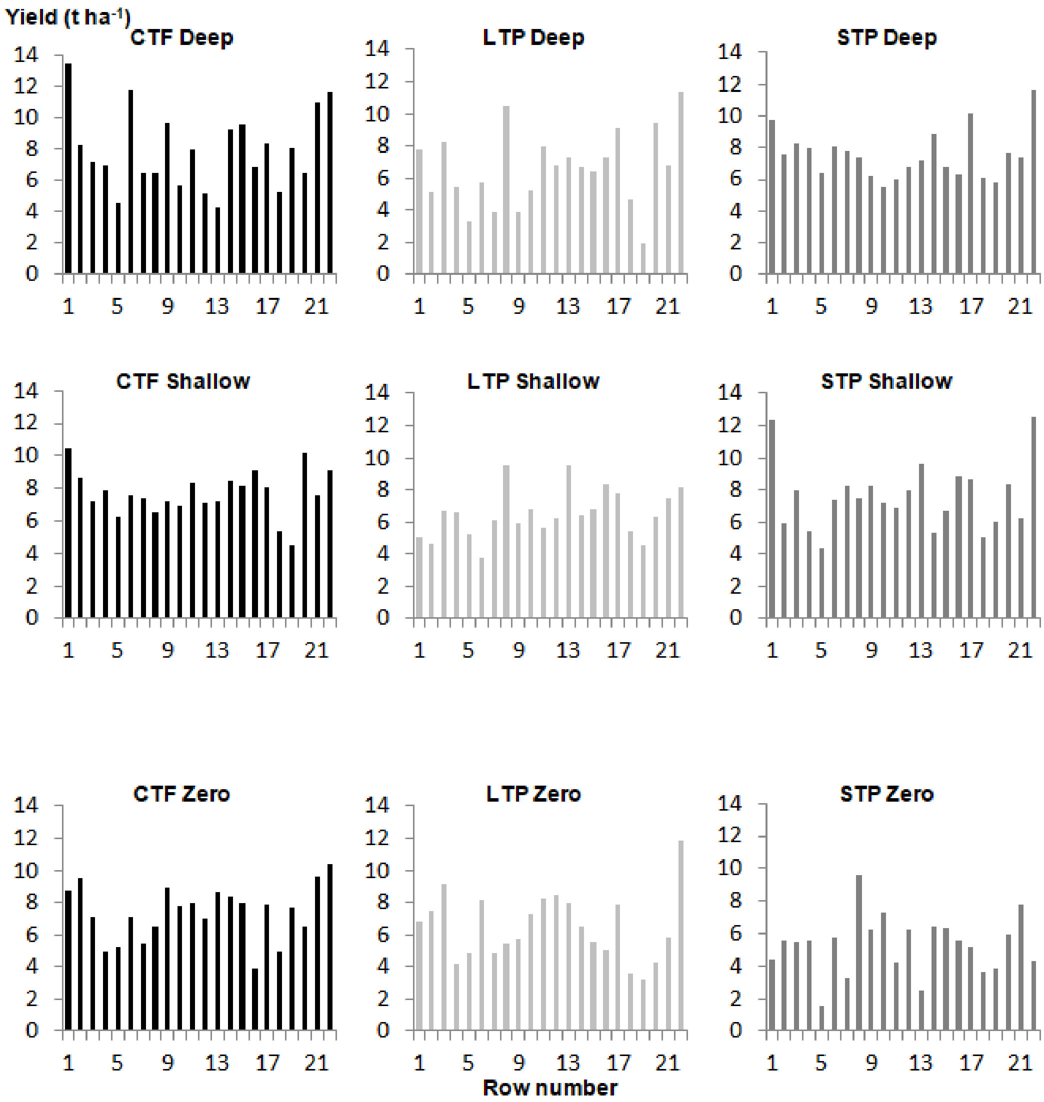

Figure 6.19 - Spring oat yield by row (t ha^{-1}) for the traffic and tillage treatments (primary wheelways located at rows 4-7 and 16-19)

The spring oat mean yields for the traffic and tillage treatments are shown at Figure 6.20. The CTF treatments had the highest yield (7.65 t ha^{-1}) which was significantly (*P*<0.001, SEM=0.199, %CV=9.9) higher than for the trafficked STP and LTP treatments (6.81 and 6.46 t ha^{-1} respectively). Both tillage treatments significantly increased yield (deep 7.35 and shallow 7.22 t ha^{-1}) by 16 and 14% respectively compared to the zero tillage treatment (6.35 t ha^{-1}). STP zero tillage treatments produced the lowest yield (5.32 t ha^{-1}) which was significantly lower (*P*=0.018, SEM=0.345, %CV=9.9) than in the CTF treatments and STP deep and shallow tillage treatments. There was no significant differences in yield between the other treatments.

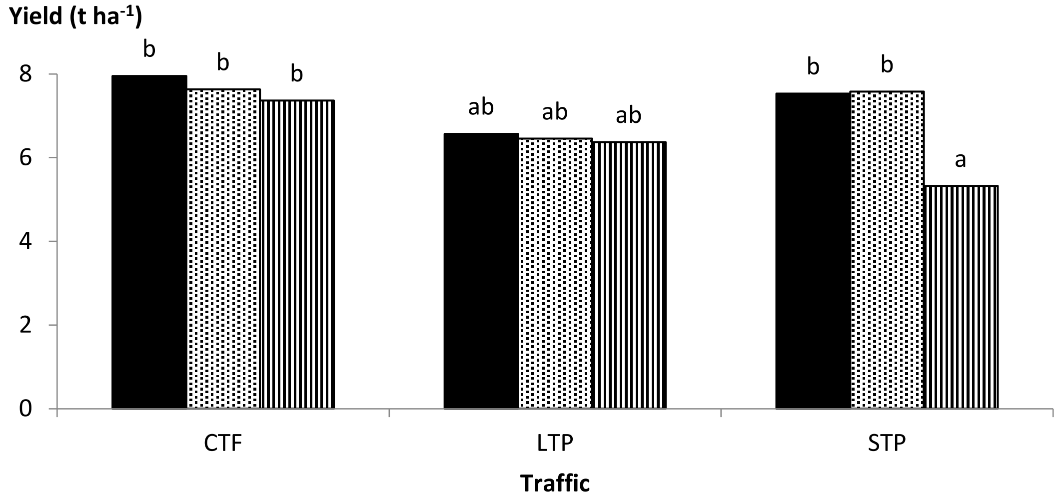

Figure 6.20 - Spring oat yield (t ha^{-1}) for the traffic and tillage treatments
(Columns: black deep, black dots shallow and black stripes zero tillage)
(**Note**: Means not having the same letters are significantly different from each other)

Table 6.16 shows the spring oat means in the untrafficked areas in each plot for the traffic and tillage treatments. It is interesting that there were significant differences in all parameters due to traffic despite the samples being taken from areas that have not been subjected to compaction treatments. This illustrates that wheeled traffic can have a compaction effect on soil that is adjacent to tracks as well as soil directly under the wheel. Plant establishment (Table 6.14 a) was significantly (P=0.003, SEM=13.69, %CV=21.3) lower (28%) in the LTP (186) treatments compared to the CTF treatments (260). Tillage significantly (P=0.003, SEM=13.69, %CV=21.3) increased (37%) plant establishment (245, 244 and 179 plants m^{-2} in deep shallow and zero tillage treatments respectively). Tillage also (P=0.085, SEM=22.6, %CV=12.6) increased (11%) the number of stems m^{-2} (Table 6.14 b) from 578 (zero) to 644 and 641 for deep and shallow tillage treatments. Stem numbers (Table 6.10 b) were 11% lower (P=0.068, SEM=22.6, %CV=12.6) in the LTP (576) treatments compared to the CTF treatments (645). Tillage did not have a significant effect on the number of panicles produced (Table 6.14 c) but the number of panicles in LTP treatments (504 m^{-2}) was significantly (P=0.006, SEM=22.4, %CV=13.7) lower (17%) than in the CTF treatments (606 m^{-2}). There was an equivalent reduction in yield (Table 6.14 d) in the LTP treatments (6.77 t ha^{-1}) which was significantly (P=0.007, SEM=0.31, %CV=14.0) lower (17%) than in the CTF treatments (8.18 t ha^{-1}).

Table 6.14 - Year 2 Spring oat means in the untrafficked areas in each plot for the traffic and tillage treatments
a: establishment (m^{-2}), b: stems (m^{-2}), c: panicles (m^{-2}) and d: yield ($t\ ha^{-1}$)

a:	**Plant establishment (m^{-2})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	291	263	226	260^{b}
LTP	221	190	149	186^{a}
STP	224	279	160	221^{ab}
Mean	245^{b}	244^{b}	179^{a}	

b:	**Stems (m^{-2})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	727	621	589	645^{b}
LTP	588	623	516	576^{a}
STP	618	679	628	642^{ab}
Mean	644^{b}	641^{b}	578^{a}	

c:	**Panicles (m^{-2})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	628	606	585	606^{b}
LTP	531	480	501	504^{a}
STP	579	593	593	588^{b}
Mean	579	560	559	

d:	**Yield ($t\ ha^{-1}$)**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	8.34	8.01	8.20	8.18^{b}
LTP	7.06	6.45	6.81	6.77^{a}
STP	7.70	7.85	8.39	7.98^{b}
Mean	7.70	7.44	7.80	

(**Note**s 1: means not followed by the same letters are significantly different from each other. 2: samples collected from crop rows not under wheelways or compaction treatments)

6.4.4.2 Year 2 - Spring oats establishment, tillering and hand harvest (results for CTF plots)

Table 6.15 shows the spring oats establishment, tillering and hand harvest means in the CTF plots for the traffic and tillage treatments (hand harvest 0.3 x 4 m transect). The samples taken in the controlled traffic plots (CTF) were from zero passes (untrafficked) and the primary wheel ways (wheeled) as shown in Table 6.15. Vehicular traffic significantly (P=0.010, SEM=17.4, %CV=26.11) reduced plant establishment (Table 6.15 a) by 28% from 260 to 188 plants m^{-2}. There was particularly low establishment (153) in the wheeled zero tillage treatments although this was not statistically significant. The number of stems m^{-2} (Table 6.15 b) was also significantly (P<0.001, SEM=19.9, %CV=12.0) reduced (23%) by traffic from 645 to 497 stems m^{-2}. Deep tillage treatments had significantly (P=0.016, SEM=24.3, %CV=12.0) more (22%) stems (631) than the zero tillage treatments (517). Untrafficked deep tillage treatments had the highest density of stems (727 m^{-2}) but 14% of these did not result in panicles (628 panicles m^{-2} Table 6.15 c). There was only a 1-2% difference in the number of stems and resultant panicles for all the other treatments. Despite the reduction in panicle density in the untrafficked deep tillage treatments, wheeled treatments (606) still had significantly (P=0.002, SEM=20, %CV=12.5) fewer (18%) panicles m^{-2} than the untrafficked treatments (497). The reduced number of panicles in the wheeled treatments led to a similar difference in final yield (Table 6.15 d). The mean yield for the untrafficked treatments was 8.18 t ha^{-1} and the yield in the wheeled treatments was significantly (P<0.001, SEM=0.248, %CV=12.0) lower (18%) being 6.74 t ha^{-1}. As might be expected from the yield results, there was a similar difference in straw produced (Table 6.15 e). Wheeled treatments had a significantly (P<0.001, SEM=0.176, %CV=10.7) lower amount (17%) of straw than untrafficked treatments (untrafficked 6.24 and wheeled 5.16 t ha^{-1}).

Table 6.15 - Year 2 Spring oats establishment, tillering and hand harvest means in the CTF plots for the traffic and tillage treatments
a: establishment (m^{-2}), b: stems (m^{-2}), c: panicles (m^{-2}), d: straw (t ha^{-1}) and e: yield (t ha^{-1})

a:		**Plant establishment (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	290	263	226	260^{a}
Wheeled	198	213	153	188^{b}
Mean	244	238	190	

b:		**Stems (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	727	621	589	645^{a}
Wheeled	535	519	444	499^{b}
Mean	631^{b}	570^{ab}	517^{a}	

c:		**Panicles (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	628	606	585	606^{a}
Wheeled	520	531	441	497^{b}
Mean	574	569	513	

d:		**Yield (t ha^{-1})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	8.34	8.01	8.20	8.18^{a}
Wheeled	7.31	7.01	5.88	6.74^{b}
Mean	7.83	7.51	7.04	

e:		**Straw (t ha^{-1})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	6.22	6.27	6.23	6.24^{a}
Wheeled	5.31	5.43	4.74	5.16^{b}
Mean	5.76	5.85	5.48	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.4.3 Year 2 - Spring oats establishment, tillering and hand harvest results for 1 and 2 pass traffic treatments in the STP and LTP plots

Unlike the CTF plots, STP and LTP plots contained extra wheeled compaction treatments to replicate the agricultural vehicle field wheelings associated with random traffic farming identified by (Kroulik *et al.*, 2009). A comparison was made between the 1 pass (using ANOVA) and 2 pass treatments (using a t-Test due to the small number of measurements as 2 pass treatments were only present in the deep tillage treatments) in the STP and LTP plots.

Table 6.16 shows the spring oat means in the 1 pass wheelings for the STP and LTP traffic and tillage treatments. There was no significant difference between the mean establishment for the two traffic systems (Table 6.16 a). Establishment was significantly (P<0.001, SEM=4.72, %CV=26.3) higher in the deep (65 m^{-2}) and shallow (58 m^{-2}) tillage treatments (124 and 100% respectively) than in the zero (29 m^{-2}) tillage treatments. STP zero tillage treatments had the lowest establishment (21 m^{-2}) which was significantly (P=0.017, SEM=6.68, %CV=26.3) lower than the STP deep, LTP deep and STP shallow treatments (68, 62 and 72 m^{-2} respectively). LTP zero tillage treatments had significantly (P=0.017, SEM=6.68, %CV=26.3) lower establishment (37 m^{-2}) than in the STP shallow treatments (72 m^{-2}). The number of stems in the STP zero tillage treatments (Table 6.16 b) was significantly (Traffic x Tillage: P=0.012, SEM=13.9, %CV=17.6) lower than for all the other treatments and was the main reason that the mean for the STP treatments was significantly (P=0.010, SEM=8.0, %CV=17.6) lower than the LTP treatment mean, and that the zero tillage mean was significantly (Tillage: P<0.001, SEM=9.8, %CV=17.6) lower than the means in the deep and shallow tillage treatments. The low number of stems in the STP zero tillage treatments was translated into a comparable low number of panicles m^{-2} (Table 6.16 c) with the number of panicles in the STP zero tillage treatments being significantly (P<0.001, SEM=14.6, %CV=19.7) lower than all the other treatments making the zero tillage mean significantly (P<0.001, SEM=10.3, %CV=19.7) lower than the means of the deep and shallow tillage treatments. The yield in the STP zero tillage treatment (Table 6.16 d) was correspondingly low and was significantly lower than all the other treatments (P=0.002, SEM=0.250, %CV=24.8). Again this made the zero tillage treatment mean significantly (P=0.018, SEM=0.176, %CV=24.8) lower than the deep and shallow tillage treatment means.

Table 6.16 - Year 2 Spring oat means in the 1 pass wheelings for the STP and LTP traffic and tillage treatments
a: establishment (m^{-2}), b: stems (m^{-2}), c: panicles (m^{-2}) and d: yield ($t\ ha^{-1}$)

a:	**Plant establishment (m^{-2})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	62	44	37	48
STP	68	72	21	54
Mean	65^{b}	58^{b}	29^{a}	

b:	**Stems (m^{-2})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	193	183	146	174^{a}
STP	172	190	60	140^{b}
Mean	182^{b}	186^{b}	103^{a}	

c:	**Panicles (m^{-2})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	139	165	165	156
STP	167	198	54	140
Mean	153^{b}	182^{b}	110^{a}	

d:	**Yield ($t\ ha^{-1}$)**			
	Deep	Shallow	Zero	Mean
LTP	2.03	2.16	2.35	2.18
STP	2.28	2.50	0.77	1.85
Mean	2.16^{ab}	2.33^{b}	1.56^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other)

Establishment in the 2 pass wheelings of the deep tillage treatments was 55 m^{-2} in the LTP treatments which was significantly lower (P=0.046) than in the STP treatments (67 m^{-2}). There was no significant differences in the number of stems in the 2 pass wheelings and there was a lower number of panicles (P=0.086) in the LTP (162 m^{-2}) compared to STP treatments (181 m^{-2}).

6.4.5 Year 2 - Spring oats combine harvest

Table 6.17 shows the mean spring oats combine harvest yields ($t\ ha^{-1}$) for the traffic and tillage treatments. The zero tillage treatment mean yield (7.07 $t\ ha^{-1}$) was significantly lower (P<0.001, SEM=0.157, %CV=6.5) than the deep and shallow tillage means (8.90 and 8.91 $t\ ha^{-1}$respectively). The means from the deep and shallow tillage were not significantly different indicating that deep tillage was not required to produce optimum yields. Yields in the CTF treatments was highest for all tillage treatments and the CTF mean (8.60 $t\ ha^{-1}$) was higher (P=0.057, SEM=0.157, %CV=6.5) than for the STP treatments (8.04 $t\ ha^{-1}$). STP zero tillage had the lowest yield (6.70 $t\ ha^{-1}$) which was 27% lower than the highest yield in the CTF deep treatments (9.12 $t\ ha^{-1}$).

Table 6.17 - Year 2 combine harvest traffic and tillage mean yields ($t\ ha^{-1}$) for spring oats

	Yield ($t\ ha^{-1}$)			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	9.12	9.06	7.60	8.60
LTP	8.96	8.86	6.91	8.25
STP	8.61	8.81	6.70	8.04
Mean	8.90^{b}	8.91^{b}	7.07^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other)

The grain specific weight mean (48.3 ha l) for the zero tillage treatments was significantly lower (*P*<0.001, SEM=0.458, %CV=3.2) than for the tillage treatments (51.3 ha l for deep and shallow).

6.4.6 Year 3 - Spring wheat establishment and hand harvest study

The results in this section relate to hand harvest samples taken for each crop row from plot transects (0.3 x 4 m). Section 6.4.6.1 relates to whole transect totals from all traffic x tillage plots (n=36) and section 6.4.6.2 compares the trafficked and wheeled areas in the CTF plots only. The results from the additional compaction wheelings for 1 (n=24) and 2 (n=8) pass in the STP and LTP traffic plots are compared in section 6.4.6.3.

6.4.6.1 Year 3 - Spring wheat establishment and hand harvest (results for all plots)

The mean spring wheat plant establishment (expressed as plants m^{-2}) for each row (1-22) in the nine traffic and tillage treatments are shown in Figure 6.21. There was decreased plant establishment in the primary wheelways (i.e. rows 4-7 and 16-19) which was particularly evident in the CTF and zero tillage treatments (although not all rows were affected equally). LTP deep and shallow tillage had largest and more constant establishment across the plots. CTF and STP zero tillage treatments had the lowest plant establishment. Photographs of plant establishment for the traffic and tillage treatments in block 1 are provided in Appendix E.

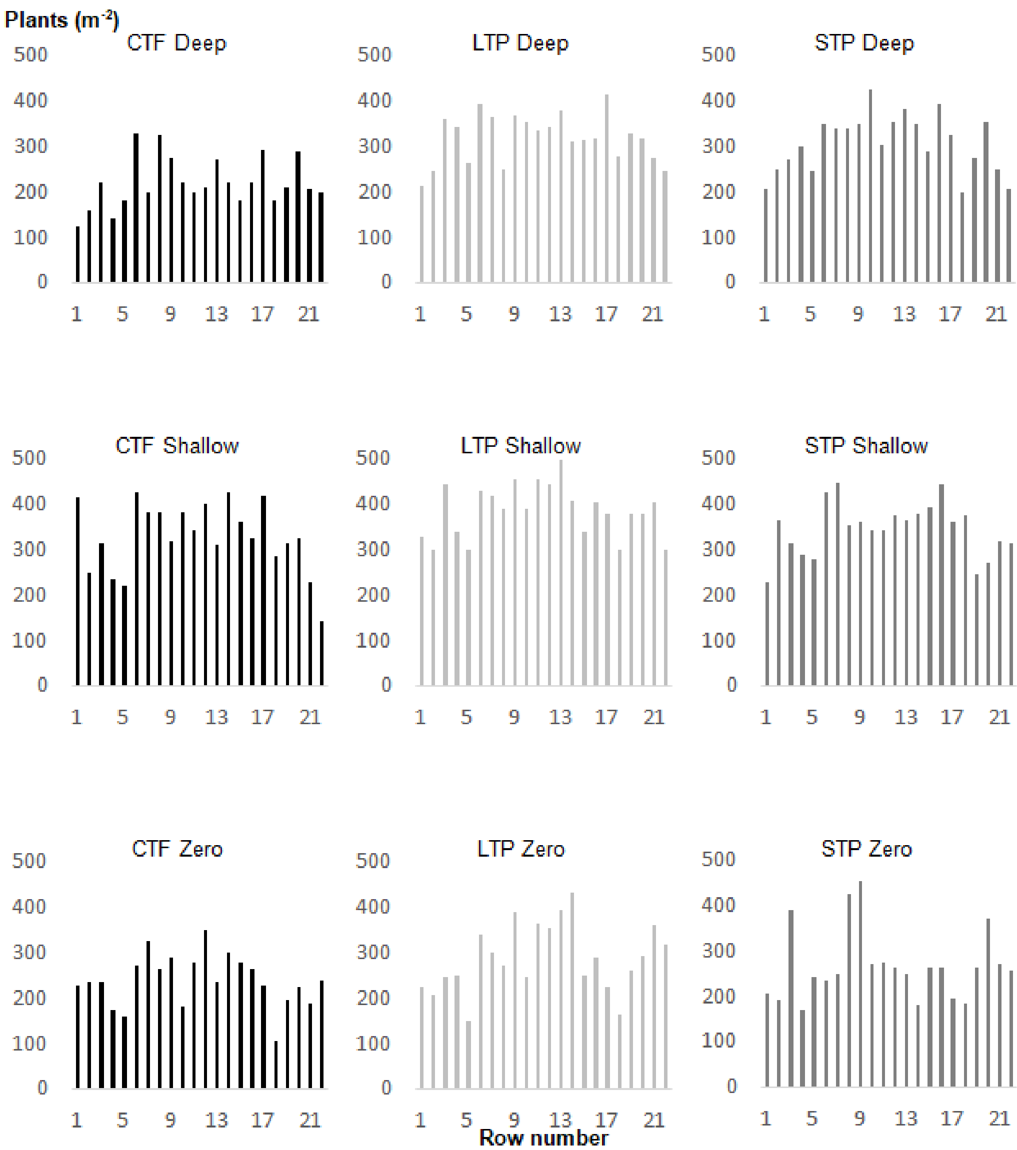

Figure 6.21 - Spring wheat establishment by row (m^{-2}) for the traffic and tillage treatments (primary wheelways located at rows 4-7 and 16-19)

Table 6.18 shows spring wheat means of establishment, number of heads and yield for the traffic and tillage treatments. Spring wheat establishment (Table 6.18 a) was significantly (P=0.032, SEM=23.4, %CV=27.1) increased (34%) in the shallow tillage treatments (353 m^{-2}) compared to the zero tillage treatments (264 m^{-2}). The number of heads (Table 6.18 b) in the shallow tillage treatments (414 m^{-2}) was 13% higher (P=0.095, SEM=16.59, %CV=15) than in the deep and zero tillage treatments (367 m^{-2}). There was no significant difference in TGW between the traffic and tillage treatments (Table 6.18 c). The mean TGW for all of the treatments was 30.2 g which was 34% lower than the TGW of the drilled seed (46 g - Section 6.3.5). STP treatments had 12% higher (P=0.071, SEM=0.1231, %CV=12.5) yield (3.56 t ha^{-1}) than the CTF treatments which had the lowest (3.17 t ha^{-1}) yield (Table 6.18 d). Although the yield in the LTP treatments (3.51 t ha^{-1}) was 11% higher than in the CTF treatments this was not significantly different from either the

CTF or STP means. There was no significant differences in the mean straw yield from the traffic and tillage treatments.

Table 6.18 - Year 3 Spring wheat means for the traffic and tillage treatments a: establishment (m^{-2}) b: heads (m^{-2}) and c: TGW (g) d: yield (t ha^{-1})

a:		**Establishment (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	220	327	239	262
LTP	319	386	287	331
STP	307	345	266	306
Mean	282^{ab}	353^{b}	264^{a}	

b:		**Heads (m^{-2})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	332	397	346	358
LTP	392	425	387	402
STP	377	419	369	388
Mean	367	414	367	

c:		**TGW (g)**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	30.3	28.3	31.7	30.1
LTP	28.9	31.8	31.1	30.6
STP	30.7	29.9	29.5	30.0
Mean	30.0	30.0	30.8	

d:		**Yield (t ha^{-1})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	3.06	3.49	2.96	3.17^{a}
LTP	3.56	3.61	3.35	3.51^{ab}
STP	3.7	3.5	3.47	3.56^{b}
Mean	3.44	3.53	3.26	

(**Note**: Means not followed by the same letters are significantly different from each other).

Table 6.19 shows the spring wheat means in the untrafficked areas in each plot for the traffic and tillage treatments. Unlike year 2 spring oat yield (Table 6.19) CTF treatments (Table 6.19 a) had the lowest plant establishment (267 m^{-2}) and were significantly (*P*=0.032, SEM=26.8, %CV=28.3) lower than the LTP (28%) and STP (23%) treatment means (369 and 347 m^{-2} respectively). Deep tillage treatments (278 m^{-2}) had significantly lower establishment (*P*=0.092, SEM=26.8, %CV=28.3) than the shallow (23 and 20%) and zero tillage treatments (359 and 347 m^{-2} respectively). LTP treatments produced 481 heads m^{-2} (Figure 6.19 b) which was significantly (*P*=0.020, SEM=27.3, %CV=22.2) more (32%) than in the CTF treatments (365 m^{-2}). Deep tillage significantly (*P*=0.009, SEM=22.2, %CV=22.2) reduced the number of heads (357 m^{-2}) by 27% compared to the zero tillage treatments (488 m^{-2}). There was no significant difference in TGW for the traffic and tillage treatments (Table 6.19 c). The yield had corresponding differences to the heads m^{-2} (Table 6.19 d). The CTF treatment mean (3.19 t ha^{-1}) was significantly (*P*=0.030, SEM=0.225, %CV=21.0) lower (21%) than the LTP mean (4.02 t ha^{-1}). The deep tillage treatment mean yield (3.31 t ha^{-1}) was significantly (*P*=0.030, SEM=0.225, %CV=21.0) lower (21%) than the zero tillage mean (4.20 t ha^{-1}).

Table 6.19 - Year 3 Spring wheat means in the untrafficked areas in each plot for the traffic and tillage treatments
a: establishment (m^{-2}), b: heads (m^{-2}) and c: TGW (g) d: yield (t ha^{-1})

a:		**Establishment (m^2)**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	221	328	252	267^a
LTP	336	402	367	369^b
STP	276	346	420	347^b
Mean	278^a	359^b	347^b	

b:		**Heads (m^2)**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	337	392	364	365^a
LTP	393	491	559	481^b
STP	341	412	543	432^{ab}
Mean	357^a	432^{ab}	488^b	

c:		**TGW (g)**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	30.3	28.3	31.7	30.1
LTP	28.9	31.8	31.1	30.6
STP	30.7	29.9	29.5	30.0
Mean	30.0	30.0	30.8	

d:		**Yield (t ha^{-1})**		
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	3.07	3.46	3.03	3.19^a
LTP	3.56	3.96	4.54	4.02^b
STP	3.29	3.42	5.04	3.92^{ab}
Mean	3.31^a	3.62^{ab}	4.20^b	

(**Note**: Means not followed by the same letters are significantly different from each other)

Hand harvest mean spring wheat yield is presented by row (expressed as t ha^{-1}) for the traffic and tillage treatments at Figure 6.22. Yields were more varied across the rows in the CTF deep and shallow treatments than in the other treatments. The zero tillage treatments had smaller yield quantities than the deep and shallow tillage treatments.

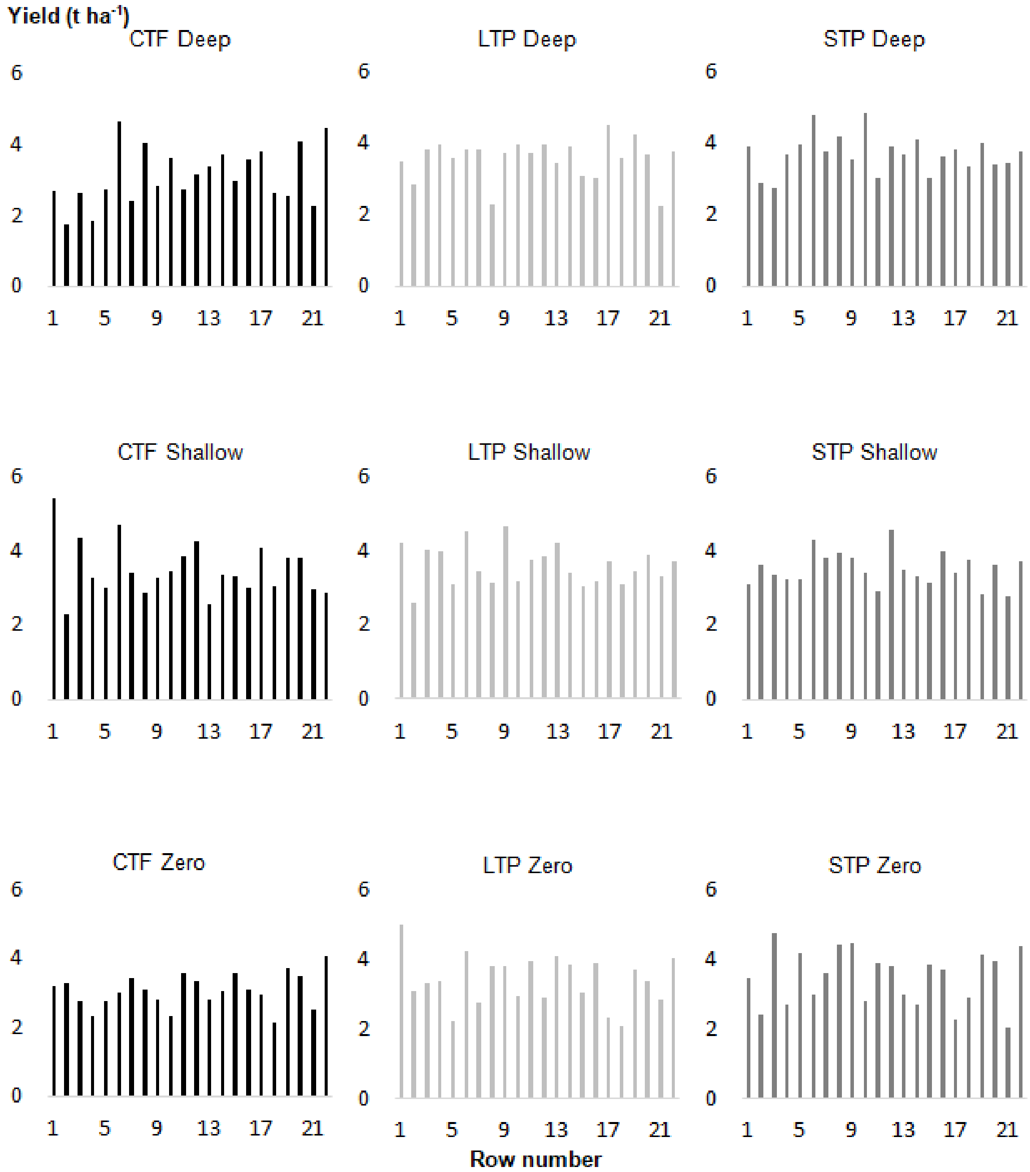

Figure 6.22 - Spring wheat yield by row (t ha^{-1}) for the traffic and tillage treatments (primary wheelways located at rows 4-7 and 16-19)

6.4.6.2 Year 3 - Spring wheat establishment and hand harvest (results for CTF plots)

Unlike the year 2 CTF establishment, tillering and hand harvest analysis (Section 6.4.4.2) there was no significant differences in traffic means from the year 3 CTF establishment and hand harvest analysis (Table 6.20). Shallow tillage treatments produced the highest plant establishment (Table 6.20 a) with a density of 327 m^{-2} which was 49% higher (*P*=0.053, SEM=30.7, %CV=33.4) than the lowest establishment mean (220 m^{-2}) in the deep tillage treatments. The shallow tillage treatments also had the highest number of heads m^{-2} (399) which was significantly (*P*=0.050, SEM=19.4, %CV=15.4) higher (21%) than the heads m^{-2} in the deep tillage treatments (330). The TGW mean (28.5 g) was 10% lower (*P*=0.084, SEM=0.915, %CV=8.6) in the shallow tillage treatments than in the zero tillage treatments (31.6 g) but yield was 19% higher (*P*=0.078, SEM=0.171, %CV=15.3) in the shallow tillage treatments (3.5 t ha^{-1}) than in the zero tillage treatments (2.93 t ha^{-1}). These results suggest that shallow tillage produced the best conditions for plant establishment and growth leading to the highest yield in the CTF plots.

Table 6.20 - Year 3 Spring wheat establishment and hand harvest means in the CTF plots for the traffic and tillage treatments
a: establishment (m^{-2}), b: heads (m^{-2}), c: TGW (g) and d: yield (t ha^{-1})

a:		Plant establishment (m^{-2})		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	221	328	252	267
Wheeled	219	326	215	253
Mean	220	327	234	

b:		Heads (m^{-2})		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	337	392	364	365
Wheeled	322	405	316	348
Mean	330^{a}	399^{b}	340^{ab}	

c:		TGW (g)		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	30.2	28.0	32.2	30.1
Wheeled	30.5	29.0	31.0	30.1
Mean	30.3	28.5	31.6	

d:		Yield (t ha^{-1})		
Traffic/Tillage	Deep	Shallow	Zero	Mean
Untrafficked	3.07	3.46	3.03	3.19
Wheeled	3.02	3.53	2.83	3.13
Mean	3.05	3.50	2.93	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.6.3 Year 3 - Spring wheat establishment and hand harvest results for 1 pass and 2 pass traffic treatments in the STP and LTP plots

Table 6.21 shows the spring wheat means in the 1 pass wheelings for the STP and LTP traffic and tillage treatments. There was no significant differences in plant establishment (Table 6.21 a) between the two traffic treatments but tillage significantly (*P*=0.002, SEM=9.32, %CV=31.6) increased (deep 80 and shallow 110%) establishment (deep 92 shallow 107 m^{-2}) compared to the zero tillage treatment (51 m^{-2}). The deep tillage and shallow tillage treatments significantly (*P*=0.001, SEM=11.9, %CV=31.6) increased (98 and 118% respectively) the number of heads m^{-2} (Table 6.21 b) compared to the zero tillage treatments. There was no significant difference in TGW for the traffic and tillage treatments (Table 6.21 c). The yields in the tillage treatments (deep 1.10 and shallow 1.12 t ha^{-1}) were significantly (*P*<0.001, SEM=0.068, %CV=20.5) higher than in the zero tillage treatments (0.58 t ha^{-1}). Reflecting establishment the yield was (*P*=0.072, SEM=0.055,

%CV=20.5) lower (15%) in the STP treatments (1.01 t ha^{-1}) compared to the LTP treatments (0.86 t ha^{-1}).

Table 6.21 - Year 3 Spring wheat means in the 1 pass wheelings for the STP and LTP traffic and tillage treatments
a: establishment (m^{-2}), b: heads (m^{-2}) and c: TGW (g) d: yield (t ha^{-1})

a:		Establishment (m^2)		
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	82	116	67	88
STP	102	98	35	78
Mean	92^b	107^b	51^a	

b:		Heads (m^2)		
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	138	150	67	118
STP	109	120	57	95
Mean	123^b	135^b	62^a	

c:		TGW (g)		
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	28.4	30.9	31.3	30.2
STP	29.6	29.7	27.2	28.9
Mean	29.0	30.3	29.3	

d:		Yield (t ha^{-1})		
Traffic/Tillage	Deep	Shallow	Zero	Mean
LTP	1.12	1.22	0.69	1.01^a
STP	1.08	1.02	0.48	0.86^b
Mean	1.10^b	1.12^b	0.58^a	

(**Note**: Means not followed by the same letters are significantly different from each other)

There was no significant differences in the mean establishment, heads m^{-2} or TGW for the 2 pass wheelings between the two traffic systems. The yield mean for the LTP 2 pass wheelings (0.98 t ha^{-1}) was lower (*P*=0.096) than the yield mean for the STP 2 pass wheelings (1.16 t ha^{-1}).

6.4.7 Year 3 Spring wheat combine harvest

Spring wheat mean combine harvest yield was significantly lower (*P*<0.001, SEM=0.047, %CV=4.6) in the zero tillage treatments (3.33 t ha^{-1}) compared to the deep and shallow tillage treatments (3.73 and 3.64 t ha^{-1} respectively). This was due to the significantly lower yields (*P*<0.001, SEM=0.237, %CV=4.6) in the CTF zero and LTP zero treatments (Figure 6.23). There was no significant difference between deep and shallow tillage treatments. The mean yields for the traffic treatments were not significantly different (CTF 3.54, LTP 3.53 and STP 3.63 t ha^{-1}).

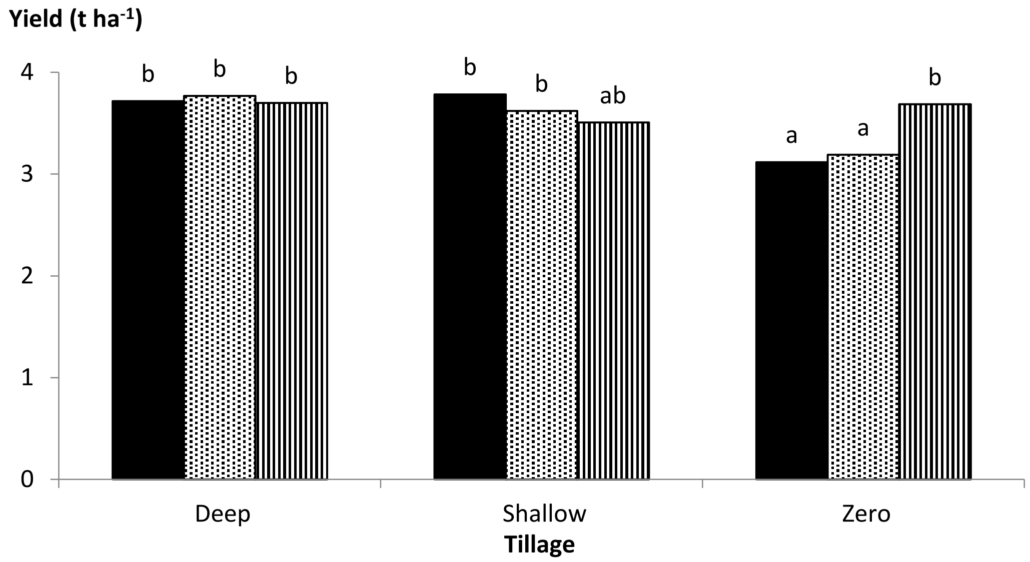

Figure 6.23 - Combine harvest traffic and tillage mean yields (t ha^{-1}) for the spring wheat (Columns: black - CTF, black dots - LTP and black stripes - STP)
(**Note**: Means not having the same letters are significantly different from each other at the 0.05 probability level)

The deep tillage grain specific weight mean (54.8 ha l) was significantly lower (P=0.012, SEM=0.447, %CV=2.8) than the shallow and zero tillage treatments means (56.6 and 56.5 ha l respectively).

The spring wheat yield was particularly poor in 2017 due to the very dry weather. The annual rainfall was 38% lower than the previous five year mean (Table 3.2). The very hot and dry conditions experienced during April, May and June (75, 31 and 38% lower rainfall than the monthly means for the previous five years respectively) would have increased the rate of development and reduced growth potential leading to low grain numbers and TGW (Smith *et al.*, 1999; Yara, not dated b).

6.4.8 Year 3 - crop residue

Table 6.22 shows the traffic and tillage means for percentage area of soil surface covered by spring wheat crop residues. There was no significant difference in soil area covered by crop residues due to the traffic treatments. As expected tillage incorporated some of the crop residues into the soil profile thereby reducing the amount of surface crop residues left on the soil surface. Tillage significantly (P<0.001, SEM=1.64, %CV=48.1) reduced the surface crop residues compared to the zero tillage treatments by 73% for deep and 66% for shallow tillage. Figure 6.22 shows sample images of spring wheat crop residue cover after application of the deep and shallow tillage treatments. There was no significant difference between the amount of soil covered by residues in the two tillage treatments indicating that tillage depth had no effect on residue incorporation into the soil profile.

Table 6.22 - Traffic and tillage means for percentage area of soil surface covered by spring wheat crop residues

	Soil covered by crop residue (%)			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	5.9	7.3	26.3	13.2
LTP	6.8	8.7	23.0	12.8
STP	5.2	6.3	16.8	9.4
Mean	5.9[a]	7.5[a]	22.0[b]	

(**Note**: Means not followed by the same letters are significantly different from each other)

Figure 6.24 - Spring wheat crop residue surface cover left: deep, centre: shallow and right: zero tillage

Freer (2006) found that the poorest wheat establishment was associated with soils that had the largest amount of loose surface residue and recommended that for disc drill no-till systems that the previous crop stubble should be left as long as possible to reduce loose surface residues. High levels of surface straw can lead to blockages in the drilling machine leading to uneven seed depth and distribution leading to poor crop establishment. Surface straw can also reduce crop emergence through phytotoxicity and reduced spring soil warming (Morris *et al.,* 2010).

6.4.9 Analysis of the three and five year mean yields from the trial crops for the traffic and tillage treatments

The mean crop combine harvest yields for the traffic and tillage treatments from the three years (2015-2017) of this research and the five years (2013-2017) of the project were combined and analysed using the REML (residual maximum likelihood) method. As the data relates to different years and crops they are considered random terms in the model (Payne, 2003). Traffic and tillage were used in the fixed model, with year and block in the random model. Note: the original combine harvest source data for 2013 and 2014 used was collected and used by Smith, E. (2016) but was not published. The two-way ANOVA analysis of combine harvest yield results together with the three year means (2015-2017) and the five year means (2013-2017) analysed using the REML are shown in Table 6.23.

Winter wheat mean yield (Table 6.23 a) was significantly (*P*<0.001, SEM=0.147, %CV=6.7) lower in the zero tillage treatments compared to the deep tillage (9%) and shallow tillage (13%) treatments. Although there was no significant difference in the traffic means (*P*=0.073) CTF treatments had the highest yield (7.78 t ha^{-1}) and STP treatments the lowest (7.28 t ha^{-1}). There was no significant differences in the mean combine harvest yields of winter barley (Table 6.23 b) for the traffic (*P*=0.682) or the tillage (*P*=0.857) treatments. The CTF shallow tillage treatments had the highest yield (9.06 t ha^{-1}) and the LTP shallow tillage treatments had the lowest yield (8.24 t ha^{-1}). Winter barley mean combine harvest yield for all treatments (2014) was 18% lower than the winter barley mean combine harvest yield (2015). This was unexpected as both crops were *Hordeum vulgare* var. Cassia. The differences in yield may have been due to the small differences in rainfall during the tillering or grain filling periods in spring and summer (Section 6.4.11). The combine harvest yields for winter barley (2015 - Table 6.25 c), spring oats (2016 - Table 6.25 d) and spring wheat (2017 - Table 6.25 e) are discussed in Sections 6.4.3, 6.4.5 and 6.4.7 respectively. In all three years zero tillage treatments had significantly (*P*<0.001) lower combine harvest yields than deep and shallow tillage treatments. The mean combine harvest yield for the spring wheat in 2017 for all the traffic and tillage treatments was 3.56 t ha^{-1}. This was 45% less than the 2017 English mean yield of 6.4 t ha^{-1} (AHDB, 2017) possibly due to the reduced TGW (Section 6.4.6.1). Combine harvest mean yields were only significantly different, due to the traffic and tillage interaction, for the spring oats (2017). Yields in the CTF zero and LTP zero treatments were significantly (*P*<0.001, SEM=0.237, %CV=4.6) lower than the yields in the other treatments (except STP shallow.

Although the traffic treatments did not show any significant difference over the three (Table 6.25 f) and five years (Table 6.25 g), STP means were lowest. LTP yields were 1% higher and CTF was 2% (three year) and 3% (five year) higher compared to the STP treatments. Over the three years 2015-2017 (Table 6.23 f) zero tillage treatments had the lowest mean yield (6.67 t ha^{-1}). Tillage significantly (*P*<0.001, SEM=0.104, %CV=8.4) increased (18%) yields (deep 7.84 and shallow 7.85 t ha^{-1}). Zero tillage treatments had the lowest mean yield (7.12 t ha^{-1}) over the five years 2013-2017 (Table 6.23 g) which was significantly (*P*<0.001, SEM=0.081, %CV=8.1) lower than the deep (11%) and shallow (13%) tillage treatments (7.93 and 8.04 t ha^{-1} respectively). These results show that tillage increased yield compared to zero tillage treatments but there was no significant difference between deep and shallow tillage treatment yields. This would indicate that for maximum yields there was no advantage in deep tillage (considering the extra draft force and fuel consumption required) and that if zero tillage was the system of choice, there was a yield penalty of 15% (three year) or 11% (five year) compared to shallow tillage treatments.

Table 6.23 - Traffic and tillage trial - five year combine harvest mean yield (t ha^{-1}) a: 2013 Winter wheat, b: 2014 Winter barley, c: 2015 Winter barley, d: 2016 Spring oats, e: 2017 Spring wheat, f: three year mean (2015-2017) and g: five year mean (2013-2017)

a:	**2013 Winter wheat yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	7.93	8.39	7.01	7.78
LTP	7.71	7.93	7.02	7.55
STP	7.29	7.67	6.87	7.28
Mean	7.64^{b}	8.00^{b}	6.97^{a}	

b:	**2014 Winter barley yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	8.48	9.06	8.37	8.64
LTP	8.54	8.24	8.62	8.47
STP	8.52	8.62	8.78	8.64
Mean	8.51	8.64	8.59	

c:	**2015 Winter barley yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	11.02	10.89	9.82	10.58
LTP	10.96	11.09	9.54	10.53
STP	10.67	11.02	9.49	10.40
Mean	10.88^{b}	11.00^{b}	9.62^{a}	

d:	**2016 Spring oats yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	9.12	9.06	7.60	8.60
LTP	8.96	8.86	6.91	8.25
STP	8.61	8.81	6.70	8.04
Mean	8.90^{b}	8.91^{b}	7.07^{a}	

e:	**2017 Spring wheat yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	3.72	3.78	3.12	3.54
LTP	3.77	3.62	3.19	3.53
STP	3.70	3.51	3.68	3.63
Mean	3.73^{b}	3.64^{b}	3.33^{a}	

f:	**Three year (2015-17) mean yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	7.95	7.91	6.85	7.57
LTP	7.89	7.86	6.55	7.43
STP	7.66	7.78	6.63	7.36
Mean	7.84^{b}	7.85^{b}	6.67^{a}	

g:	**Five year (2013-17) mean yield (t ha^{-1})**			
Traffic/Tillage	Deep	Shallow	Zero	Mean
CTF	8.05	8.24	7.19	7.83
LTP	7.99	7.95	7.06	7.66
STP	7.76	7.93	7.11	7.60
Mean	7.93^{b}	8.04^{b}	7.12^{a}	

(**Note**: Means not followed by the same letters are significantly different from each other)

6.4.10 Comparison of hand harvest and combine harvest yields

The mean yields (t ha^{-1}) for the traffic and tillage treatments for hand harvest (transect 0.3 x 4 m) and combine harvest yields were compared for each of the three years. In Year 1 the hand harvest yield mean for winter wheat exceeded the combine harvest yield by 7.1%. In Year 2 (spring oats) and Year 3 (spring wheat) the hand harvest yield was 19.3% and 4.7% lower than the combine harvest yield respectively. These differences in means only become apparent when different methods of measuring the same parameter are used. Combine harvest is considered the more precise of the two methods but hand harvest is necessary to be able to measure the components of yield of a crop (Bloom, 1985).

In plot trials, hand harvesting tends to result in higher grain yield estimations compared to combine harvesting. This is generally due to losses during combine harvesting (Bloom, 1985). The skill of the operator in making adjustments to the settings of the combine harvester can also effect the losses during harvesting (Šotnar *et al.*, 2018). The efficiency of combine harvest threshing is better when the drum is full with grain but the start/stop nature of harvesting plot trials means that the drum is only partially filled for a large portion of the plot. Losses in grain by incomplete threshing are often 5% and can be as high as 15% (Bloom, 1985). Grain can also be shed if the crop is over ripe when combined due to disturbance by the combine harvester head. Losses during hand harvest are usually less as the crop is taken several days before combining. Systematic sampling, as used in this research, can also result in biased sampling (Bloom, 1985). Grain moisture in the field was measured by a hand moisture meter but the hand harvest samples were oven dried and measured on a different moisture meter. This may have lead to differences in yield estimation.

6.4.11 The relationship between rainfall and combine harvest yields for the years 2013-2017

The effect of soil compaction on crop yield depends upon the weather conditions during the vegetation period (Kuht and Reintam, 2004). In dry years, yields in moderately compacted areas can be greater than in non-compacted areas but reduced in wetter years (Raper, 2005). Voorhees *et al.* (1985) found that wheat growth and yield in compacted soil was linked to precipitation in the growing season. They found that when rainfall was higher, wheat emergence was delayed by 10 days and grain yield was 27% lower than in untrafficked areas. In drier years yield was reduced in unwheeled soil due to excessive evaporation but yield increased by 53% in the trafficked areas. During drier years the capillary water supply to the crop is better in soil with moderate compaction compared to uncompacted soil (Kuht and Reintam, 2004). The literature identified that water availability at critical periods during crop growth affects final yield. Low nitrogen supply and water availability during the tillering period reduces tiller numbers and tiller survival rates (Smith *et al.*, 1999). Wheat yields are reduced by insufficient water at tillering and grain filling stages (Akram, 2011). Water stress at anthesis can reduce yield in barley (Aspinall, 1966).

The mean combine harvest yield of all nine traffic and tillage treatments was calculated for each of the years 2013-2017. The individual combine harvest yields for each year for each treatment were then calculated as a proportion of this mean. The proportional yields for the nine traffic and tillage treatments for the years 2013 to 2017 are shown at Figure 6.25 and compared to the total rainfall in the spring tillering (April and May) and grain filling periods (winter sown crops 21st May - 14th July; spring sown crops 21st June - 14th August (AHDB, 2015a; AHDB, 2015b; Opti-Oat, 2019)) and the period 1st March to 31st July for the crops grown in each of the seasons 2013-2017 (Harper Adams University, 2018). Note: In order to be able to compare winter and spring sown crops to identify trends, the spring tillering period of April and May was chosen. It is known that tillering in wheat can occur mainly in the autumn for crop sown in early September, slightly later sown crop can tiller in both autumn and spring and November sown crop tillers mainly in the spring (AHDB, 2015b) and that this may have a bias on results. Future analysis could compare winter and spring crops separately as more years of data become available to make results more robust.

Crop yields for CTF and LTP treatments mimicked the change in rainfall in the spring tillering period and the period 1st March to 31st July (Figure 6.25 a) i.e. comparative yields were lower when there was less rainfall and increased rainfall increased combine harvest yield. This relationship was not illustrated in all years for the rainfall during the grain filling period (yields were higher in 2013 when rainfall was higher and yields were lower in 2014 when rainfall was higher). Comparative yields increased for STP treatments from 2013 to 2017 and did not show a relationship to rainfall in any of the three test periods.
Yields from the shallow tillage treatments (for CTF, LTP and STP) where related to the amount of rainfall in the spring tillering period and the period from 1st March to 31st July (Figure 6.25 b) i.e. comparative yields were lower when there was less rainfall and increased rainfall increased combine harvest yield.

The relationship between yields for the zero tillage traffic treatments and rainfall (Figure 6.25 c) in the spring tillering period and the period 1st March to 31st July was opposite to that for the tillage treatments i.e. in years when rainfall was higher yields were lower. The yield in the CTF zero tillage plots did not follow the same pattern as for the LTP and STP zero tillage plots e.g. it was higher in 2014 when rainfall was lower but not in 2017 when the amount of rainfall was similar.

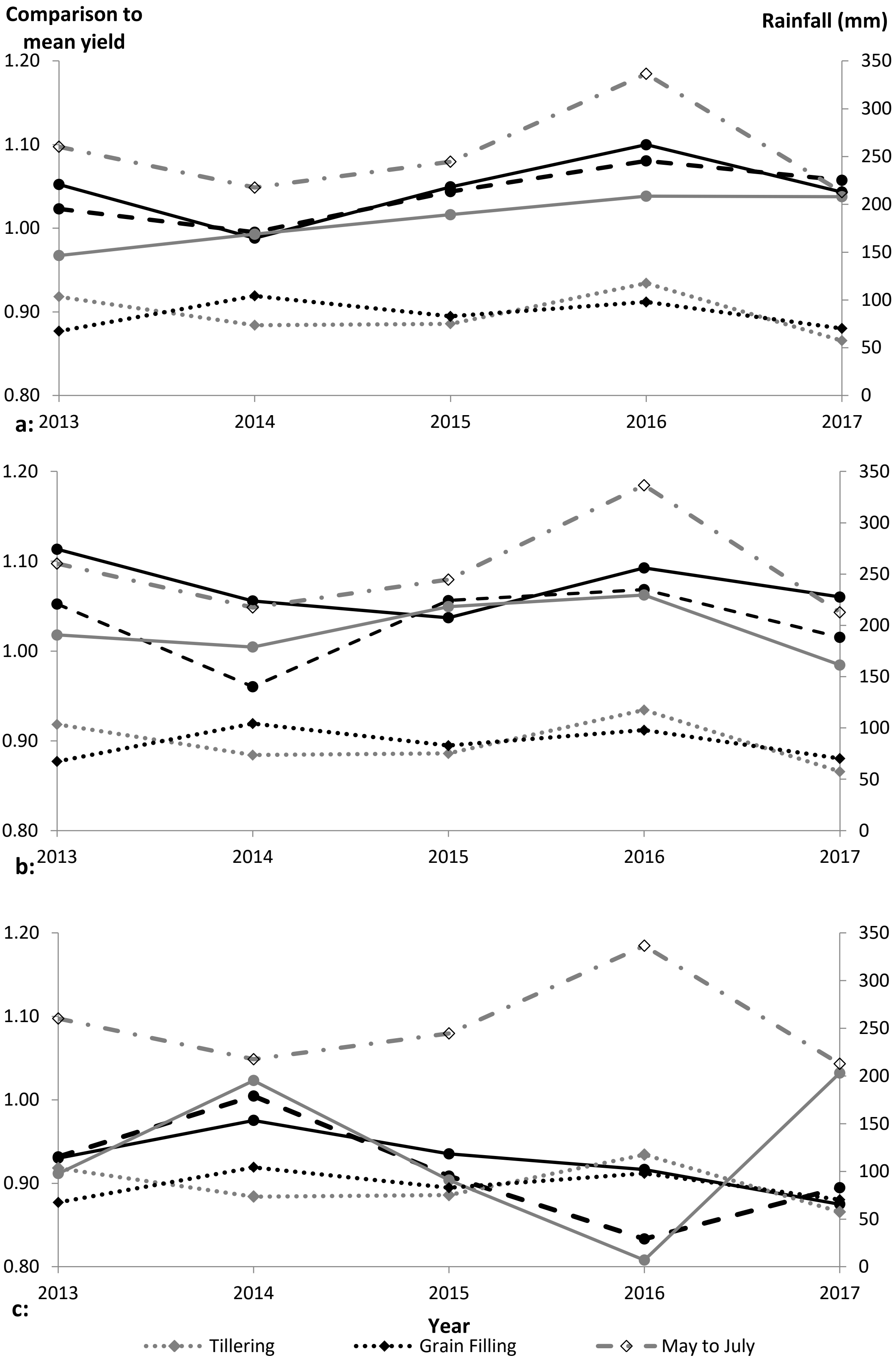

Figure 6.25 - Rainfall (mm) during spring tillering, grain filling and the period 1st March to 31st July and combine harvest yield for the years 2013-2017 (expressed as a percentage of the mean yield of all treatments) for the traffic and tillage treatments a: deep tillage, b: shallow tillage and c: zero tillage

(Lines: solid black - CTF ut, dash black - LTP w , solid grey - STP w)

Figure 6.25 indicated that there was a relationship between rainfall, traffic and tillage and crop yields as identified in the literature (Raper, 2005). The relationship between rainfall (mm), during the spring tillering and grain filling periods and the period from 1st March to 31st July (for the years 2013-2017), to the combine harvest yield in the Traffic and Tillage treatments (expressed as a percentage of the mean yield of all treatments in each of the years 2013-2017) was investigated using simple linear regression with groups (tillage, traffic and traffic x tillage).

The linear regression analysis (tillage group) of the relationship between rainfall (mm) during the spring tillering period to the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017 is shown at Figure 6.26. The model was best fitted by three separate lines accounting for 62.4% of the variance (P<0.001). The model suggested that as rainfall increased in the spring tillering period yields increased in the deep and shallow tillage treatments and that yields in the zero tillage treatments decreased. There was no significant model for the linear regression analysis for the traffic group.

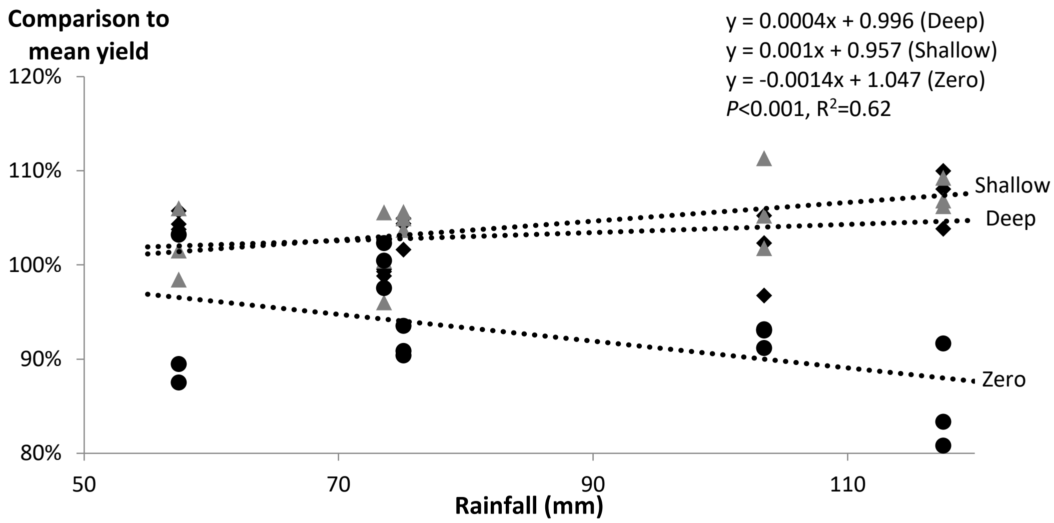

Figure 6.26 - Linear regression analysis (tillage group) of the relationship between rainfall (mm) during the spring tillering period to the yield in the Traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017
(Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

Figure 6.27 shows the linear regression analysis for the traffic x tillage group of the relationship between rainfall (mm) during the tillering period to the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017. The model was best fitted by nine separate lines accounting for 66.8% of the variance (P<0.001). The model suggested that as rainfall increased in the spring tillering period, yields increased in the shallow tillage treatments and in CTF and LTP deep tillage treatments. Yields in the STP deep tillage treatments decreased with increasing rainfall. This may have been due to recompaction of the soil following vehicular traffic as previously identified by Soane *et al.* (1986). The models suggest that yields in the LTP and STP (trafficked) zero tillage treatments reduced when rainfall increased in the spring tillering period but slightly increased in the CTF (untrafficked) treatments. This would imply that, for a no-till system, avoiding field traffic would result in no yield penalty irrespective of the rainfall during the spring tillering period and may increase yield at higher rainfall levels. The model suggests that field traffic (compaction) in no-till systems only results in higher yields than non trafficked areas when rainfall during the spring tillering period is low (<90 mm for STP and <75 mm for LTP). The model also shows the lower yields in the zero tillage plots relative to the deep and shallow tillage plots.

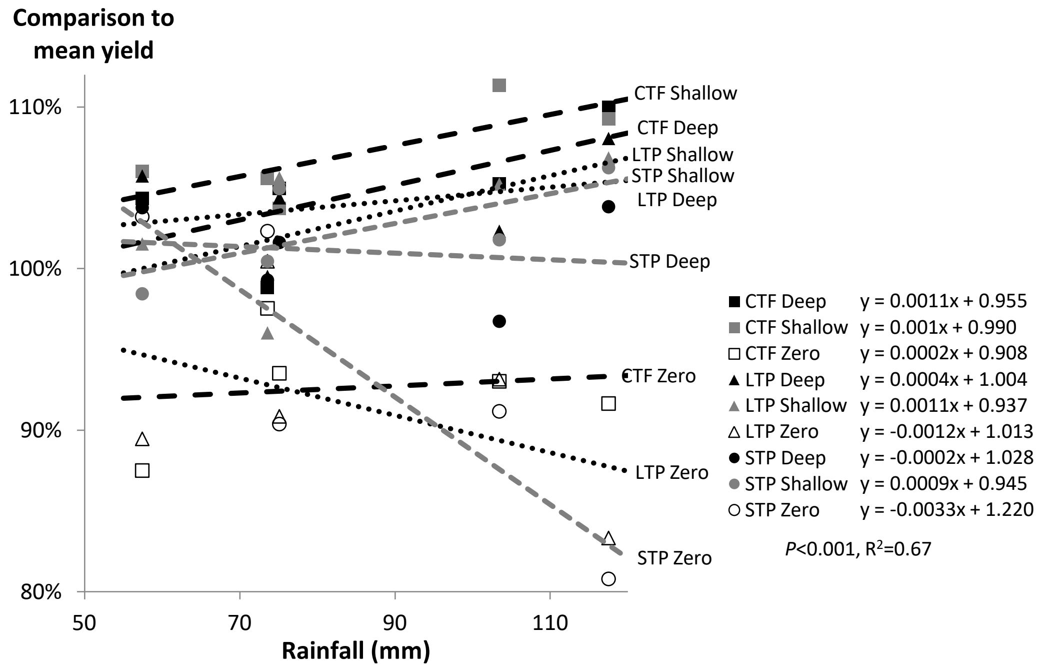

Figure 6.27 - Linear regression analysis (traffic x tillage group) of the relationship between rainfall (mm) during the spring tillering period and the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the year

The linear regression analysis for the tillage group of the relationship between rainfall (mm) during the grain filling period to the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017 is shown at Figure 6.28. The model was best fitted by three parallel lines accounting for 53.2% of the variance (*P*<0.001). The model suggested that the rainfall level during the grain filling period had no effect on combine harvest yield for any of the tillage treatments. There was no significant model for the linear regression analysis for the traffic group.

The linear regression analysis for the traffic x tillage model was best fitted by nine parallel lines accounting for 51.7% of the variance (*P*<0.001). The model (not shown) was similar to Figure 6.28 (i.e. no gradient on lines) and suggested that the rainfall level during the grain filling period had no effect on combine harvest yield for any of the traffic x tillage treatments.

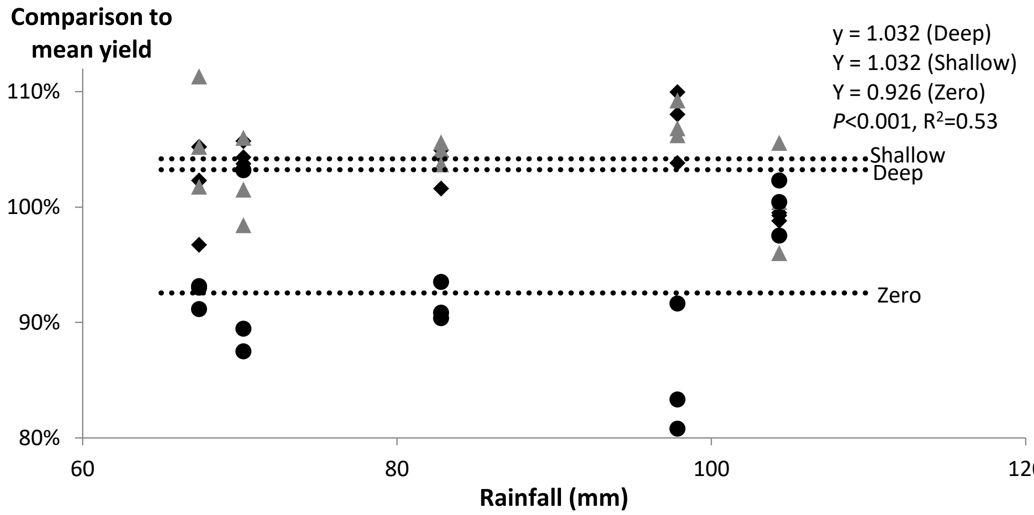

Figure 6.28 - Linear regression analysis (tillage group) of the relationship between rainfall (mm) during the grain filling period to the yield in the Traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017
(Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

The linear regression analysis (tillage group) of the relationship between rainfall (mm) during the period 1st March and 31st July to the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017 is shown at Figure 6.29. The model was best fitted by three separate lines accounting for 69.5% of the variance (*P*<0.001). The model suggested that as rainfall increased, in the period 1st March and 31st July, yields increased in the deep and shallow tillage treatments and that yields in the zero tillage treatments decreased. There was no significant model for the linear regression analysis for the traffic group.

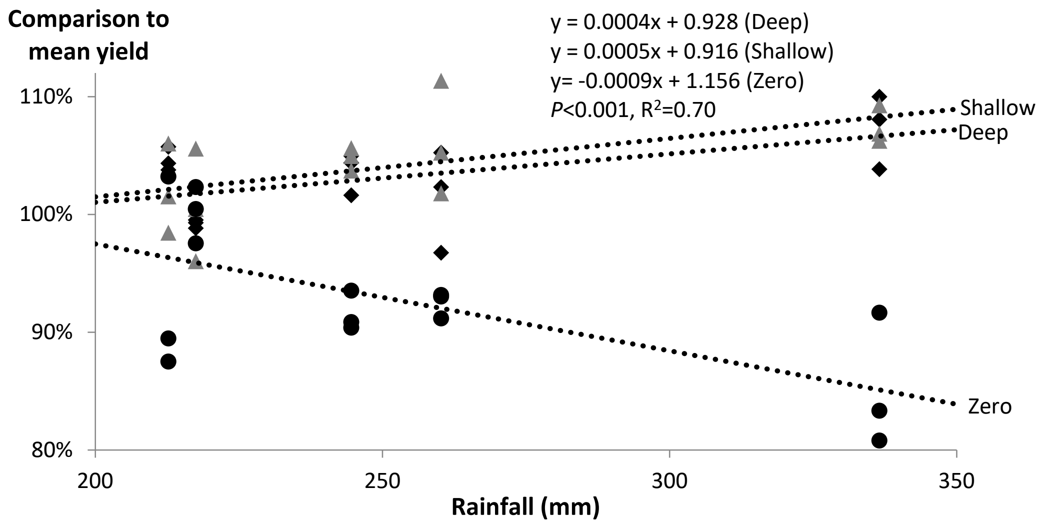

Figure 6.29 - Linear regression analysis (tillage group) of the relationship between rainfall (mm) during the period 1st March to 31st July to the yield in the Traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017 (Markers: diamond black - deep tillage, triangle grey - shallow tillage, circle black - zero tillage)

Figure 6.30 shows the linear regression analysis for the traffic x tillage group of the relationship between rainfall (mm) during the period 1st March and 31st July to the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017. The model was best fitted by nine separate lines accounting for 76.4% of the variance (*P*<0.001). The model suggested, that as rainfall increased in the period 1st March and 31st July, yields increased in the deep and shallow tillage treatments. Yields in the trafficked zero tillage treatments (LTP and STP) decreased with increasing levels of rainfall but were higher than untrafficked (CTF) zero tillage areas when rainfall was lower than 260 mm (for STP) and 245 mm (for LTP). This may have been due to reduced aeration in the compacted soils due to vehicular traffic (Fageria, 1992). Restricted soil aeration can lead to restricted root growth, reduced nutrient uptake, slower rates of leaf elongation and biomass accumulation with delayed maturation and reduced yields in cereals (Belford, 1981). Yields in the CTF zero tillage treatments were mainly unaffected by the amount of rainfall during the period 1st March and 31st July.

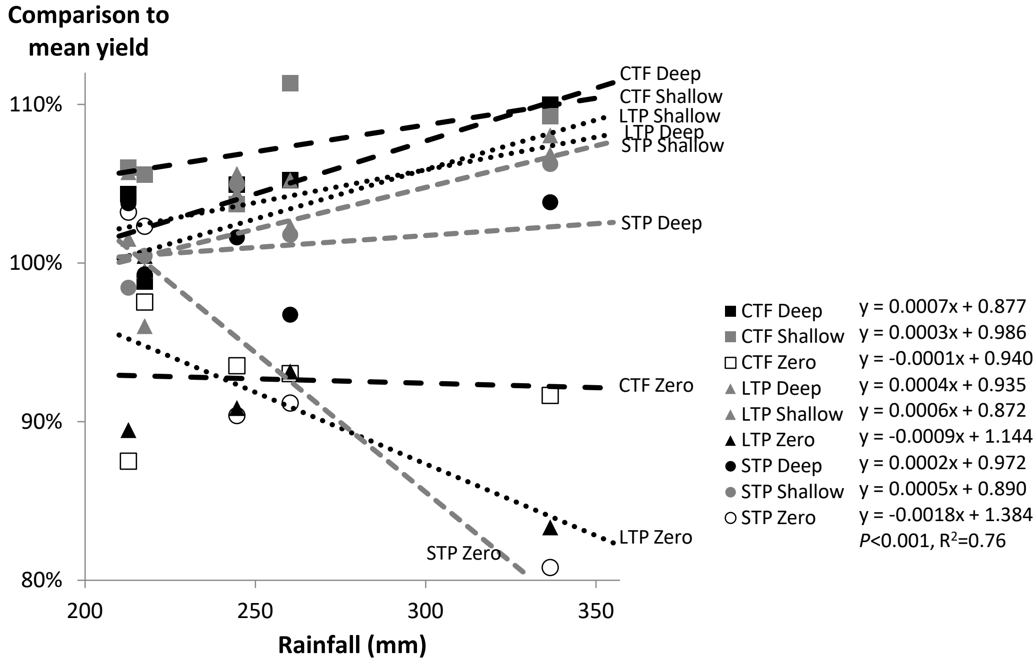

Figure 6.30 - Linear regression analysis (traffic x tillage group) of the relationship between rainfall (mm) during the period 1st March to 31st July and the yield in the traffic and tillage treatments (expressed as a percentage of the mean yield of all treatments) for the years 2013-2017

The analysis of the relationship between rainfall and combine harvest yields for the years 2013-2017 showed that rainfall during the spring tillering period had an effect on yields dependant on soil management. Tillage improved yields compared to no-till and improved yields with increasing rainfall during the spring tillering and the spring and summer (1st March to 31st July). Yields in no-till systems that had been trafficked suffered from yield reductions with increasing rainfall but were better than untrafficked no-till treatments when rainfall was low (<90 mm during spring tillering, <260 mm total rainfall for spring and summer). Smith, E. (2016) found that water infiltration was significantly (*P*=0.009) reduced by traffic. This may be related to a reduction in soil pore size distribution, associated with soil compaction, that reduced soil aeration when rainfall was higher, leading to reduced crop growth and reduced yields (Fageria, 1992). CTF zero tillage was largely unaffected by rainfall amount when not trafficked. If yields could be increased by increasing establishment in the CTF zero treatments (Section 7.3.1), then this could be a preferred option to manage yields under the range of rainfall conditions in the UK. The analysis indicated that rainfall during the grain filling period had no effect on yields suggesting that rainfall during tillering period was more important to crop yields.

6.5 Conclusion

The objectives for this part of the research were:

1. To measure the response of crops during early growth and subsequent yield from the traffic and tillage treatments.

2. To determine the effect of varying tillage depth and traffic intensity on crop growth and yield over a three year cereal crop rotation.

3. To measure the effect of the traffic and tillage treatments on the amount of combine harvest residues left on the surface of the soil prior to drilling.

Winter barley plant establishment was significantly (P=0.002) higher (34%) in the untrafficked treatments than in the wheeled treatments. The lowest establishment was in the zero tillage wheeled treatments which was significantly (P=0.004) lower than the shallow tillage wheeled treatments which had the highest plant establishment. The results indicate that vehicle traffic reduced plant establishment and that shallow tillage was better than deep tillage at producing favourable conditions for plant establishment in soils compacted by vehicular traffic. Crop root mass was significantly reduced (P<0.001) in the trafficked wheelways compared to the untrafficked treatments. The root mass in the deep and shallow treatments was significantly (P=0.001) higher than in the zero tillage treatments. This was possibly due to the significantly lower numbers of plants in the trafficked (P=0.002) and zero tillage (P=0.004) treatments. The combine harvest results showed that zero tillage treatments (9.62 t ha^{-1}) had significantly (P<0.001) lower yield than the deep and shallow tillage treatments (10.88 and 11.00 t ha^{-1} respectively).

Spring oat plant establishment was significantly (P=0.001) lower in the trafficked treatments than in the untrafficked treatments (CTF) but there was no significant difference in establishment between the LTP and STP treatments. Establishment was also significantly (P<0.001) reduced (33%) in the zero tillage treatments compared to deep and shallow tillage treatments. The combine harvest results showed that zero tillage treatments (7.07 t ha^{-1}) had significantly (P<0.001) lower yield than the deep and shallow tillage treatments (8.90 and 8.91 t ha^{-1} respectively). There was no significant difference between the combine harvest yields for the traffic treatments.

Spring wheat establishment was highest in the shallow tillage treatments which was significantly (P=0.032) higher (34%) than in the zero tillage treatments. There was no significant difference in plant establishment between the deep and zero tillage treatments. There was no significant difference in plant establishment between the traffic treatments although establishment was higher in the LTP and STP treatments. Combine harvest yields were significantly (*P*<0.001) lower in the CTF and LTP zero tillage treatments than all other treatments except STP shallow tillage. Mean yields were not significantly different between the deep and shallow tillage treatments. There was no significant differences in yield between the traffic treatments.

Tillage significantly (*P*<0.001) reduced (73%) crop residue surface cover but there was no significant difference in residue surface cover between deep and shallow tillage treatments.

Over both the three year period of this research (2015-2017) and the five year period (2013-2017) of the Traffic and Tillage trial (which adds findings from previous research) the use of tillage significantly (*P*<0.001 for three and five year periods) improved yields compared to zero tillage treatments. Compared to shallow tillage yields, the use of zero tillage resulted in a yield reduction penalty of 15% and 11% over the three and five year periods respectively. There was no significant difference in yields between deep and shallow tillage treatments and no significant difference between yields from the traffic treatments. An analysis of combine harvest yields for the traffic and tillage treatments for the five year period (2013-2017) showed a trend that as rainfall increased during the spring and summer, yields were increased in the tillage treatments compared to the zero tillage treatments. Yields in the LTP and STP zero tillage treatments reduced with increasing rainfall amounts during the spring and summer. The yield in the CTF untrafficked treatments was largely unaffected by the amount of rainfall.

Relating to the hypothesis (Section 5.2) the results showed vehicular traffic reduced establishment in all three years (significantly in years 1 and 2) but there was no significant differences in combine harvest yields. Plant establishment was significantly lower in the zero tillage treatments compared to the shallow tillage in all three years. Yields were significantly higher in the tillage treatments compared to the zero tillage treatments for the three years of this research and the five years including previous research. The use of a Controlled Traffic Farming system to prevent soil compaction would be of benefit to plant establishment but may not have a significant effect on combine harvest yields. The use of low inflation pressure tyres does not provide an advantage to increasing crop yields compared to standard inflation pressure tyres. Shallow tillage significantly increases crop yields compared to zero tillage and there is no significant difference in crop yields between deep and shallow tillage. This would suggest that shallow should be the preferred tillage option.

Chapter 7 Discussion

7.1 Soil properties

7.1.1 Tillage

Deep tillage significantly (*P*=0.030) reduced the soil shear strength compared to that of the zero tillage treatments. Although not significant, penetration resistance was higher (*P*=0.089) when vehicular traffic followed deep tillage than when it followed shallow tillage. This is in agreement with Soane *et al.* (1986) and Yavuzcan *et al.* (2002) who found that deep tillage reduces the bearing capacity of soils which leaves soils prone to further compaction damage by subsequent field traffic. This was seen in the X-ray CT results where deep tillage had the highest soil macro porosity (19.5%) but subsequent traffic reduced macro porosity to 11.5% for low inflation pressure tyre and 8.9% standard inflation pressure tyre treatments due to recompaction. This suggests that deep tillage should be avoided when possible and if deep loosening is required, then careful management of subsequent field operations is required to reduce the risk of recompaction and to preserve the properties of the loosened soil (Soane *et al.,* 1986; Batey, 2009).

The macro porosity in untrafficked shallow tillage treatments (16.5%) was of similar value to untrafficked zero tillage (15.4%) and wheeled shallow tillage (16.5% with low inflation pressure tyres and 15.4% with standard inflation pressure tyres) treatments. This would suggest that shallow tillage was the most appropriate tillage for wheeled soils and that if soils were untrafficked then no tillage is required. Although deep tillage produces a larger macro pore size distribution than shallow tillage in untrafficked soils, traffic reduced the pore size distribution to values similar to that of shallow tillage. This would suggest that deep tillage is no better than shallow tillage at increasing soil pore size distribution in wheeled soils and again therefore it is unnecessary. It is clear that decisions on tillage need to focus on what the objectives of the tillage are, especially as tillage can have a disruptive effect on complex ecosystems present in soil (Whalley *et al.*, 1995). Field operations especially during harvest influence the structure of the soil and distribution of crop residues which, together with the needs of the next crop, will determine the tillage requirement. This will differ dependent upon climate, soil type and cropping system (Boone, 1988).

7.1.2 Traffic

As identified in the literature review field traffic significantly (P<0.001) increased the soil bulk density and there were corresponding significant increases in soil strength (P<0.001) and penetration resistance (P<0.001). The effect of this increased soil bulk density could be changes to the pore size distribution and a reduction in soil aeration (Fageria, 1992). Increases in soil strength can reduce root penetration in the soil, limiting the number and length of roots, leading to a decrease in leaf thickness and an increase in the dry mass shoot:root ratio (Grzesiak *et al.*, 2013). This was confirmed by the root analysis (Section 6.4.1), which identified that vehicular traffic significantly reduced root mass by 30% and root to stem ratio was increased by 13%, possibly due to a decrease in nutrient availability (Brain *et al*., 1992). This reduced root growth, reduces shoot growth and function that ultimately reduces crop yield (Lipiec *et al.*, 2003b). Increasing water content reduces mechanical resistance but also decreases soil aeration. The increase in soil bulk density and associated change is soil pore size distribution due to soil compaction reduces the non-limiting water range (NLWR) by increasing mechanical resistance and restricting oxygen availability that restricts root growth (Kirkham, 2005). Smith, E. (2016) found that water infiltration was significantly (P=0.009) reduced by traffic. This may be related to a reduction in soil pore size distribution, associated with soil compaction, that reduced soil aeration when rainfall was higher, leading to reduced crop growth and reduced yields (Fageria, 1992). This may explain why yields in no-till systems that had been trafficked suffered from yield reductions with increasing rainfall (Section 6.4.11). There was no significant difference in soil bulk density, strength or penetration resistance between LTP w and STP w traffic treatments therefore the use of low tyre inflation pressure tyres did not reduce compaction of the soil between the depths of 0-250 mm compared to standard tyre inflation pressure tyres. This was as expected as Smith, E. (2016) also found no significant differences in soil bulk density and penetration resistance between the LTP and STP wheelways. Smith, E. (2016) measured gravimetric soil moisture content and found no significant differences is soil moisture content suggesting that the moisture content in all treatments would be the same during traffic treatments. Wetter soils can increase the compaction effect from a vehicle load (Håkansson and Petelkau, 1994) and Negi *et al.* (1981) found that the optimum soil moisture for maximum compaction of a sandy loam in experimental plots was 23% (field capacity for a sandy loam soil). This would suggest that any traffic treatments applied at lower than field capacity (as estimated for this research for 2015) may not have compacted the soil to their maximum. However it could be argued that this would reflect good agricultural practice for cereal farming as agricultural traffic on wet soil would not be the norm. This would not necessarily be the case for cropping systems that require later harvests or drill spring crops when soils can be wetter (Soane *et* *al.*, 2012). The mean soil bulk density for all treatments was within the 1.3 to 1.45 Mg m^{-3} optimum mean bulk density range (for 0-300 mm soil depth) for maximum corn yields identified by Negi *et al.* (1981). This would suggest that irrespective of the tyre pressures, the load applied (12.5 tonne) during compaction treatments may not have been sufficient to cause excessive soil compaction. Vehicular traffic significantly (P=0.006) reduced the soil macro porosity by 32% compared to the untrafficked treatments. This was as expected as soil compaction mainly affects the larger pores (macro) reducing soil porosity for a given mass (increase in bulk density) and increasing the number of smaller pores (Berisso *et al.*, 2012: Whalley *et al.*, 1995). Controlled traffic farming should be the preferred method of reducing soil compaction as it removes vehicular traffic from the cropping areas between dedicated wheelways. Compacted soils that are subsequently loosened by tillage are less stable compared to untrafficked soil which is naturally well structured and therefore stronger and less prone to erosion (Horn *et al.*, 1995).

Chamen *et al.* (2015) identified the use of low inflation pressure tyres as a method to reduce soil compaction. Low inflation pressure tyres can reduce soil compaction and increase crop yields compared to higher (standard) tyre inflation tyres (Hamza and Anderson, 2005) because they change the distribution of stresses at the tyre-soil interface. There was no significant difference in the mean soil bulk densities or penetration resistance between the LTP w and STP w treatments (0-250 mm depth) but the effect of lower inflation pressure tyre on soil compaction in the plot wheelways resulted in a higher penetration resistance in the STP w treatments compared to LTP w treatments from 0-170 mm but between 250-350 mm depth LTP w treatments had a higher penetration resistance. This may be due to variations in soil moisture and/or soil structure due to previous compaction treatments at succeeding vehicular traffic events. Wheeled traffic in agricultural soils has been found to produce heterogeneous vertical soil compaction (Pfeifer *et al.*, 2014). However Raper *et al.* (1995) found that low inflation pressures increased the footprint of the tyre and concentrated more of the load towards the outside of the tyre whilst higher inflation pressures concentrated more of the load in the centre of the tyre. This could cause differences in the relative action of soil volumetric strain and shear deformation under the two differing tyre inflation pressures as identified in the literature (Berisso *et al.*, 2013). The potential for the maximum soil stress to occur at different positions relative to the centre of the wheelway may have caused some of the differences seen in the penetrometer readings and in the soil pore distributions for the STP and LTP treatments. This suggests that an X-ray CT study of the effects of tyre pressure on soil, using a series of samples collected across a wheel track transect, could be useful to explore the differences in soil properties due to the changes in tyre inflation pressures. It is suggested that a complimentary study could also be the use of Tekscan sensors as used by Misiewicz (2010) to measure the relative soil pressure distribution for the different tyre inflation pressures. This research used Michelin Axiobib tyres, a low inflation tyre using this concept, known as 'Ultraflex Technology' (Michelin, 2014). In 2017, Michelin introduced the Evobib tyre which has new adaptive technology that uses central tyre inflation technology to change the shape of the tyre depending upon whether it is to be used on the road or in the field. At low pressures it produces a more even distribution giving a 20% larger soil contact area compared to the Axiobib (Michelin, 2017). As there is no data as yet available measuring the effect of the Michelin Evobib in relation to soil compaction, it is recommended that it should included as part of future studies.

7.1.3 Soil moisture

As the harvesting, application of the compaction treatments, cultivations and drilling operations for this trial were, of practical necessity, conducted over a typical period of 14 days and therefore possibly at slightly different moisture contents, it is not possible to say whether the critical stress value, identified by Larson and Gupta (1980), was reached in some or all parts of the soil profile during these operations. Soil compaction in the main wheelways was dependent upon traffic applied during late summer harvest and when the compaction and tillage treatments were carried out. The compaction effect would be dependent upon the soil moisture at the time of trafficking. Wet soils are less able to resist vehicular compaction (Chamen *et al.,* 2015). Soils with moisture content near to field capacity have reduced soil strength (Raper, 2005). Stresses in the soil under a load become more concentrated downwards as the soil becomes wetter and therefore they penetrate deeper into the soil profile (Håkansson and Petelkau, 1994). The compaction and tillage treatments were carried out previously in autumn, when soils are drier after the summer but changed to spring in 2016. Soils in spring are comparatively wetter than autumn soils after the wet winters and the often wet springs of northern and western Europe (Soane *et al.*, 2012). The estimated soil moisture at the time of the traffic and tillage treatments was 13% (2015), 21% (2016) and 21% (2017). The 2015 compaction treatment was carried out in autumn and was below the optimum soil moisture content of 23% (+/- 3%) for a sandy loam soil suggested by Negi *et al.* (1981) for maximum soil compaction in experimental plots. The spring compaction treatments (2016 and 2017) were carried out at this optimum soil moisture level. As wheeled traffic in agricultural soils have been found to produce heterogeneous vertical soil compaction (Pfeifer *et al.*, 2014) and compaction treatments are applied repeatedly from season to season, it is likely that moisture content will be different at different parts of the profile (due to hysteresis). Therefore the compaction effect from soil stress may vary at different depths due to the interaction between soil moisture and tyre inflation pressure.

7.2 X-ray Computed Tomography

The use of X-ray Computed Tomography (CT) on this long term Traffic and Tillage trial provided a non destructive assessment of soil porosity, with both visual and quantified differences in spatial arrangement of soil components and porosity throughout the depth of the soil profile, at a far greater resolution than can be measured indirectly by using bulk density measurements or water retention functions (Keller *et al.*, 2013).

Measures such as pore connectivity and pore circularity were easily obtained during the image analysis of X-ray CT scans. Pore circularity was significantly (P=0.009) higher in untrafficked areas of the Controlled Traffic Farming plots compared to the wheelways possibly due to better soil aggregation, as identified by Rachman *et al.* (2005). The wheelways also had lower pore connectivity than for the untrafficked areas. A significant difference in crop biomass, due to circularity or connectivity, was not observed. This might be due to the soil type being sandy loam (coarse textured). Gebhardt *et al.* (2006) found that although soil porosity in coarse textured soils reduced under vehicle load, proportionately macro porosity reduction was relatively low. Macro pores control the flow of water during infiltration and affect soil aeration (Kay and VandenBygaart, 2002). A reduction in soil aeration can reduce crop yields (Czyz, 2004). The relatively small difference in macro pore connectivity would have a correspondingly small effect on water flow and soil aeration which could explain no significant differences in biomass or yield. Gebhardt *et al.* (2006) also found that on fine textured soils under similar loadings that most macro pores were lost. This would suggest that the analysis of pore connectivity using X-ray CT would be particularly useful on fine textured soils.

Whilst X-ray CT measured parameters such as macro pore size, numbers and circularity are useful in identifying differences between soils from the different treatments they have limited capacity to describe soil volume behaviour (Gantzer and Anderson, 2002). Yield response to compaction is dependent on the interaction of the plant, soil and weather. This has been illustrated by this research. As could be predicted from the literature, this research found that soil bulk density and penetration resistance were significantly increased by vehicle traffic and this was associated with the measured reduction in soil macro porosity. However, despite crop establishment being significantly lower in trafficked soil this did not result in significantly lower crop yield. This may have been due to the crop being able to compensate for reduced plant numbers by producing more tillers as suggested by AHDB (2015a). The presence of cracks and biopores, associated with earthworms and roots, provide opportunities for roots to bypass areas of compaction to access nutrients and water (Lipiec *et al.*, 2006; Glab and Kopec, 2008). If the roots are able to access sufficient water and nutrients needed by the plant shoots then yields may not be decreased (Taylor and Brar, 1991). The high pore connectivity measured using the X-ray CT was largely unaffected by vehicular traffic and therefore the crop roots were possibly able to access sufficient water and nutrients to support good growth leading to better than expected yields in the traffic treatments. This research has concentrated on responses of crop and soil properties to the applied traffic and tillage treatments. The trend analysis of crop yield in response to rainfall suggested that crop yields in the zero tillage trafficked soils were lower when rainfall during spring and summer was higher and higher when the rainfall was lower as found by Voorhees *et al.* (1985) and stated by Raper (2005). Further work is required to explore the effect of weather conditions on soil moisture and aeration in the soil profile, as affected by the traffic and tillage treatments and the consequences for crop growth and yield.

Although some investigators have been able to correlate X-ray CT derived soil porosity to macro porosity such as Kim *et al.* (2010) the author is unaware of an X-ray CT study that has directly linked X-ray CT measured porosity to field measured soil porosities. Using a novel technique for determining the total porosity, based on traffic treatment means, and linear regression analysis has allowed a comparison of soil porosities derived from bulk density measurements and X-ray CT measured porosities and found that a constant of 31% could be added to the X-ray CT porosities, to give the total soil porosity for a sandy loam soil. This constant (31%) related to water filled porosity identified by Hall *et al.* (1977), equivalent to the percentage of pores below 30 µm diameter as indicated by (Russell, 1977). This confirmed that the X-ray CT resolution (72 µm) used was able to capture all porosity above the size boundary between macro and meso pores and that the X-ray CT porosity measured was macro porosity (air filled porosity at field capacity) which is important for soil water, air and nutrient distribution to the crop.

The X-ray CT used made comparisons between the different traffic and tillage treatment effects on soil physical properties within the confines of achievable X-ray resolution in relationship to the 50 mm diameter sample size. For larger soil samples (e.g. 20-40 mm diameter) a resolution of 30 µm is sufficient to easily capture macro pores but in order to visualise intra and inter-aggregate pore space requires higher resolutions and the sample can only be a few millimetres in diameter (Vaz *et al.*, 2011). Soil compaction changes macro pores structure (Berisso *et al.*, 2012) which can affect thermal conductivity (Lipiec *et al.*, 2003b), alter soil pore size distribution and reduce soil aeration. The associated increase in bulk density affects root growth that reduces nutrient use efficiency (Fageria, 1992) leading to reduced yields (Lipiec *et al.*, 2003b). As this research investigated the effects of soil compaction (and tillage) on crop yields, it was important that the X-ray CT used in this research was of sufficient resolution to capture porosity in the macro pore range. This was confirmed to be the case in Section 5.5. Although this research compared X-ray CT derived porosity to bulk density derived porosity and found a difference of a constant 31%, it is not necessary to use empirically determined data to prove X-ray CT derived pore size. Pore size can be determined from X-ray CT image analysis as used by Udawatta and Anderson (2008) who used X-ray CT pore size to explain changes in saturated hydraulic conductivity.

7.3 Crop yield

7.3.1 Tillage

Although crop yields were slightly higher in shallow tillage than deep tillage treatments (three year means) the statistical analysis indicated that there was no significant difference in crop yield between deep and shallow tillage over the three years of this research. This would suggest that deep tillage was unnecessary on this sandy loam soil. Adopting a shallow tillage depth of 100 mm could reduce the draft force requirement for tillage and lead to corresponding reductions in fuel costs of up to 42.5% as found by Arslan *et al.* (2014). Winter barley establishment was significantly (P=0.004) lower in the CTF treatments using zero tillage compared to CTF shallow tillage treatments in 2015 (establishment was measured at GS 30). In 2016 spring oat establishment was significantly (P<0.001) reduced compared to deep and shallow tillage treatments and spring wheat establishment in 2017 was significantly reduced (P=0.032) in the zero tillage treatments compared to the shallow treatments. A possible explanation for this is the presence of previous crop residues on the surface of the soil affecting plant establishment due to reduced germination in response to toxic substances produced during straw decomposition (Russell, 1977). Comparisons of soil surface crop residues in year 3 found that the zero tillage treatments had significantly more surface crop residue (22%) than deep (5.9%) and shallow (7.5%) tillage treatments. These results suggest that a reduction in soil surface trash on the zero tillage treatments could increase germination success. However, there was no significant difference in surface residue cover between deep and shallow treatments but there was a significant difference between crop establishment between zero tillage and shallow tillage but not deep tillage treatments for winter barley (Table 6.5) and spring wheat (Table 6.18 a). In years 1 and 2 the reduction in establishment in the zero tillage establishment was mainly due to a large reduction in establishment due to traffic (Tables 6.5 and 6.13 a). In year 3 establishment in the zero tillage untrafficked (CTF) treatments was lower than the LTP and STP zero tillage treatments (Table 6.18 a). These establishment results suggest that the amount of residue on the soil surface in the zero plots had not affected crop establishment or that if it had, then traffic or traffic and season/crop may be a contributing factor. Clearly the effect of management of crop residues in trafficked zero tillage treatments requires further investigation.

The crop establishment was 33% lower in the zero tillage treatments compared to in the deep and shallow treatments. The corresponding combine yields in the zero tillage treatments were significantly (P<0.001) lower (21% year 2 and ~10% year 2) than in the deep and shallow tillage treatments. This would suggest that that, although the crop had been able to compensate for some of the reduction in plant numbers by an increase in tiller numbers per plant (Section 6.4.1.1.2), reduced establishment of the crop was a large contributing factor to the lower crop yields associated with zero tillage plots. Over the three years of this research (2015-17) and the five years including previous research findings (2013-17) zero tillage significantly (P<0.001) reduced crop yields compared to shallow tillage by 15% and 11% respectively. This is higher than the findings of a global meta-analysis of side by side comparisons of no-till and conventional tillage farming by Pittelkow *et al.* (2015) who found that the use of no-till agriculture reduced cereal yields by 5% with the impact on wheat being a reduction of 2.6%. Martínez *et al*. (2016) found that winter wheat and winter barley yields were significantly (P<0.050) higher (5.9%) over two decades of no-till farming compared to mouldboard ploughing on a sandy loam soil in Switzerland. Pittelkow *et al.* (2015) also found that no-till was better in rain fed dry climates and yields were lower in the early years after adoption in wetter climates. As discussed in the literature, Cannell *et al.* (1978) showed that in the UK direct drilling of combinable crops was better suited to the east of the country. Harper Adams is located on the border of an area assessed as at risk of producing lower yields under no-till when compared to conventional tillage practice (Figure 2.13). The results from this research suggest the assessment is correct.

7.3.2 Traffic

Vehicular traffic significantly reduced the establishment of the winter barley crop in year 1 (P=0.002) and spring oats in year 2 (P=0.001) by approximately 25%. The reduced establishment in the STP and LTP treatments was possibly due to increased moisture content, as a result of increased bulk density near the surface (keeping soils colder for longer due to higher thermal capacity thus delaying germination (Cannell and Finney, 1973)) or as suggested by Reintam *et al.* (2009), the mechanical resistance of compacted soils prevented seedling emergence. This latter explanation fits with the results of the regression analysis of soil penetration resistance and biomass (Table 4.18 a) which identified that increases in soil strength in the top 50 mm of soil reduced biomass by 3.17 t ha^{-1} for every increase in 0.5 MPa of penetration resistance and this was likely to be due to poor crop establishment (Section 4.5). As weather conditions are generally cooler for winter than for spring sown crops, establishment may be different because soil compaction can affect plant survival due to increased risk of waterlogging (Arvidsson and Håkansson, 2014). It is not possible to confirm that the winter barley plant establishment measured in year 1 at GS 30 is a true representation of plant establishment at GS 13-15 because the crop was established in the autumn prior to this research beginning (research started January 2015) and the establishment data had not been collected. Some losses would be expected as unlike winter wheat, winter barley and oats are susceptible to overwinter losses in the UK (Blake *et al.*, 2003). Combine harvest yields were not significantly different between controlled traffic farming (CTF) treatments and random traffic farming treatments (STP and LTP) in the three years except for between CTF and STP for the spring oats in year 2. This may have been due to oats being more affected by compaction than wheat or barley as found by Arvidsson and Håkansson (2014).

The statistical analysis did not show a significant difference in combine harvest yields, for each of the three years, between the low inflation pressure tyre (LTP) and standard inflation pressure tyre (STP), the use of low inflation pressure tyres and CTF systems showed an increase in crop yields compared to conventional UK soil cultivation (standard inflation pressure tyres deep tillage). A comparison of the five years of combine harvester yield found that by utilising low tyre inflation pressure tyres gave a yield improvement of 2.9% but this was not significant.

Chapter 8 Conclusion

The use of low inflation pressure tyres in this research did not result in any significant differences in soil bulk density or penetration resistance compared to the use of standard inflation pressure tyres. This was as expected as Smith, E. (2016) also found no significant differences in soil bulk density or penetration resistance. The benefits reported from the use of low inflation pressure tyres are mixed. Arvidsson and Keller (2007) found that a reduction in tyre inflation pressure reduced stresses in the soil at 100 mm depth which can lead to significantly reduced soil compaction and increased crop yield as found by Boguzas and Håkansson (2001) and Ridge (2002) cited by Hamza *et al*. (2005). However, Chamen *et al*. (1990) cited by Chamen e*t al*. (2015) compared low inflation pressure tyres to standard inflation pressure tyres in a four year trial and found no significant increase in crop yields or reductions in tillage inputs. The use of low inflation pressure tyres in this research did not result in any significant differences in combine harvest yields compared to the use of standard inflation pressure tyres.

Field traffic significantly (P<0.001) increased the soil bulk density, strength and penetration resistance. Vehicular traffic significantly reduced crop establishment of winter barley in year 1 (P=0.002) and spring oats in year 2 (P=0.001) by approximately 25%. Vehicular traffic significantly (P=0.006) reduced (32%) soil macro porosity compared to untrafficked treatments. Controlled traffic farming should therefore be the preferred method of reducing soil compaction as it removes vehicular traffic from the cropping areas between dedicated wheelways.

Although not statistically significant, low inflation pressure tyres and the CTF system in this research did show an increase in crop yields compared to conventional UK soil cultivation (standard inflation pressure tyres with deep tillage). A comparison of the five year combine harvest yields found, that utilising low tyre inflation pressure tyres, gave a yield improvement of 2.9% and that adopting controlled traffic farming (with low inflation pressure tyres) increased yields by 3.9% compared to standard inflation pressure tyres deep tillage treatments. These yield improvements would suggest that there is still an advantage for UK farmers from utilising low inflation pressure tyre technology and adopting Controlled Traffic Farming systems. Godwin *et al.* (2017) calculated that using a 15% CTF system gave a 0.61 t ha^{-1} increase in yields compared to a conventional random traffic system and that for a farmed area over 168 ha this yield increase would cover the annual costs of the necessary RTK systems.

Over the three years of this research (2015-17) and the five years including previous research findings (2013-17), zero tillage significantly (*P*<0.001) reduced crop yields compared to shallow tillage by 15% and 11% respectively. The literature suggested that crop residues can affect crop establishment. An analysis of the soil surface area covered by crop residues, for the traffic and tillage treatments, concluded that this was unlikely to be the cause of the reduced establishment during this research. However, regression analysis of penetration resistance and biomass identified that an increase in soil strength in the top 50 mm of the soil is more likely to cause the reduced establishment in the zero tillage treatments. For farmers wishing to reduce the costs of tillage and its negative impacts on soils by reducing tillage intensity, the management of the seedbed is clearly important.

There was no significant difference in crop yield between deep and shallow tillage treatments. Employing shallow rather than deep tillage provides an opportunity to reduce fuel costs associated with the reduction in draft force required for the tillage operations. If possible deep tillage should be avoided as it leaves soils prone to further compaction damage by subsequent field traffic. Deep tillage significantly (*P*=0.030) reduced the soil shear strength compared to the zero tillage treatments and penetration resistance was higher (*P*=0.089) when vehicular traffic followed deep tillage than when it followed shallow tillage. Deep tillage produced the highest soil macro porosity (19.5% measured using X-ray CT) but subsequent traffic reduced macro porosity to 11.5% for low inflation pressure tyre and 8.9% standard inflation pressure tyre treatments due to recompaction. The macro porosity in untrafficked shallow tillage treatments (16.5%) was of similar value to untrafficked zero tillage (15.4%) and wheeled shallow tillage (16.5% low inflation pressure tyres and 15.4% standard inflation pressure tyres) treatments. For better soil structure, recommendations for farmers with similar soils should be, that shallow tillage is the most appropriate tillage for wheeled soils but no tillage is required for untrafficked soils. If deeper loosening of soils is required then subsequent vehicular traffic should be avoided.

The use of X-ray Computed Tomography (CT) on this long term Traffic and Tillage trial provided a non destructive assessment of soil porosity with both visual and quantified differences in porosity through the depth of the soil profile at a far greater resolution than can be calculated using bulk density measurements. The X-ray CT porosity measured was macro porosity which is important for soil water, air and nutrient distribution to the crop. As part of this study a novel technique was used, based on traffic treatment means, that allowed a comparison of soil porosities derived from bulk density measurements and X-ray CT measured porosities. It was found that a constant of 31% could be added to the X-ray CT porosities to give the total physical soil porosity. This constant (31%) related to water filled porosity which confirmed that the X-ray CT resolution (72 µm) used was able to capture all porosity above the size boundary between macro and meso pores. The research identified that although the soil sample size restricted the X-ray CT resolution due to the field of view, it was sufficient to capture the soil macro porosity that is important to soil water movement, nutrient availability and soil aeration important for crop growth. Future research using of X-ray CT to access soil properties will need to consider soil heterogeneity, sample size, resolution and scanning time in relation to the desired outcome. In this research, the use of the X-ray CT identified the reduction is percentage soil porosity and pore size distribution associated with vehicular traffic. It also identified that soil pore connectivity was high and largely unaffected by increases in soil bulk density due to vehicular traffic. It is suggested that the high pore connectivity allowed the crops in compacted soil to access sufficient water and nutrients for growth which may explain why no significant differences in crop yield for the traffic treatments were found. The research suggested that the analysis of pore connectivity and circularity using X-ray CT would be particularly useful on fine textured soils. Analysis showed that the use of X-ray CT derived mean pore size to determine the effect of the traffic and tillage treatments on crop growth was limited.

Chapter 9 Recommendations for further work

Recommendations for further work are listed below. The literature identifies that no-till can make beneficial improvements to soil properties and therefore priority should be given to investigating how establishment (and crop yields) can be improved in the no-till treatments (Recommendation 1).

1. Crop establishment was reduced in zero tillage treatments compared to deep and shallow tillage treatments (significantly lower than shallow tillage in Year 1 P=0.004 and Year 3 P=0.032). A possible explanation for this is the presence of crop residues from the previous crop on the surface of the soil during drilling causing hairpinning in the seed slots. The results suggest that a reduction in soil surface trash could reduce the occurrence of hairpinning and therefore increase germination success. The management of crop residues in the zero traffic treatments requires further investigation.

2. The potential for the maximum soil stress to occur at different positions relative to the centre of the wheelway may have caused some of the differences seen in the penetrometer readings and in the soil pore distributions for the STP and LTP treatments. This suggests that an X-ray CT study of the effects of tyre pressure on soil, using a series of samples collected across a wheel track transect, could be useful to explore the differences in soil properties due to the changes in tyre inflation pressures. This would require a protocol for an experiment to study the effects of tyre pressure on soil using a series of core samples along a transect (both vertically and horizontally) under a wheel track similar to that used by Berisso *et al.* (2013) who took stress measurements with Bolling probes (Figure 9.1 shows the arrangement of soil sampling locations used). It was not possible to use a similar protocol in this research due to the constraints on the availability of the X-ray CT equipment and required scan time described in Section 4.3.1. Such a study will have a significant advantage over previous soil stress research (such as that by carried out by Arvidsson and Keller (2007) who removed the top 10 cm of topsoil to install stress sensors and then backfilled soil over the sensors) as it uses undisturbed soil samples taken directly from the field and does not rely on soil disturbance to place measuring equipment in the soil prior to the application of compaction treatments. A complimentary study could also be the use of Tekscan sensors as used by Misiewicz (2010) to measure the relative soil pressure distribution for the different tyre inflation pressures. These studies should include the use of the new Michelin Evobib tyre (Michelin, 2017) and vehicles with tracks as they could provide valuable data that could be used to evaluate their potential to reduce agricultural soil compaction.

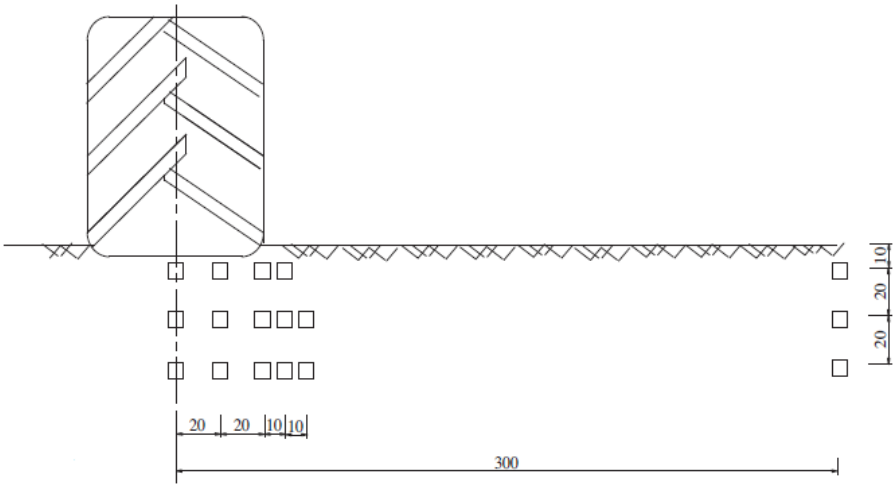

Figure 9.1 - Soil core sample locations used by Berisso *et al.* (2013) Dimensions are in cm.

(Source: Adapted from Berisso *et al.*, 2013)

3. This research has concentrated on responses of crop and soil properties to the applied traffic and tillage treatments but further work is required to explore the effect of weather conditions on soil moisture and aeration in the soil profile as affected by the traffic and tillage treatments and the consequences for crop growth and yield. Future work needs to establish whether compaction, already applied, affects the moisture profile within the wheelway and therefore changes the soil compaction effect (both intensity and depth) of subsequent wheelings and whether this is different for STP and LTP tyres. It is recommended that future research could include the continuous monitoring of soil water content to identify any differences in water content between the treatments and any moisture variation due to heterogeneous vertical soil compaction. In addition, soil moisture content measurements should be taken during any field operations and any relevant soil sampling in order to provide a background to the work.

4. This research, and the earlier research, identified that there can be large differences in crop yield between wheelways and untrafficked soils. The Väderstad Spirit used in this research had wheel track eradicators that were mounted on the front of the drill and positioned behind the rear driving wheels of the pulling tractor (Figure 9.2). These were used during drilling of the deep and shallow tillage treatment plots but lifted out of the soil during drilling of the zero tillage (no-till) plots to preserve their no-till status. Väderstad (2015) state that these tines are effective by ensuring that the soil structure is the same across the whole width of the drilling machine. The mean porosity for the deep tillage treatments shown at Table 5.1 suggests that this is not necessarily the case for deeper tillage. As the eradicators were used after tillage it is not known how effective they would

be in no-till soils. It is suggested that wheel track eradicators may be able to reduce the negative impacts of tyres on soils and therefore their use warrants further investigation.

Figure 9.2 - Wheel track eradicator tines fitted to Väderstad Spirit pneumatic seed drill

5. This research found correlations between soil properties which varied with tillage intensity suggesting that soil macro porosity was important to plant growth. X-ray CT could be used to investigate the relationship between root structure and soil macro pore distribution and connectivity.

6. Using a novel technique, developed during this study, it was possible to find a relationship between X-ray CT derived soil porosities and actual soil porosities for a sandy loam soil. It is recommended that this method is used on other soil types to prove that the method can evaluate total porosity and field capacity using X-ray CT.

7. This work has evaluated the different traffic and tillage treatment effects on crop yield. Further work should be done to evaluate the economic consequences of the differing treatments by including costs of all operations and agricultural inputs as well as final yield values to give an overall cost analysis of adopting Controlled Traffic Farming and low inflation pressure tyres and reduced tillage.

8. The traffic and tillage research carried out was for a sandy loam soil. It is recommended that this research is extended to different soils, to evaluate the effect that traffic and tillage has on soil properties and crop yield.

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Appendix A Traffic, tillage and drilling protocols

Table 1 - Traffic treatment (compaction) protocol

	Sequence 1	☐		Sequence 2	☐		Sequence 3	☐
1	Set High Pressures		34	Set LH to low pressure		53	Set pressures to low	
2	**Go to plot 1**		35	**Go to plot 1**		54	**Go to plot 2**	
3	Drive AB line		36	Drive Offset (1200)		55	Drive AB line	
4	Return		37	**Go to plot 6**		56	Return	
5	Drive Offset (600)		38	Drive Offset (1200)		57	Drive Offset (600)	
6	Return		39	**Go to spare 1**		58	Return	
7	Drive Offset (600)		40	Drive Offset (1200)		59	Drive Offset (600)	
8	**Go to plot 18**		41	**Go to plot 15**		60	**Go to plot 10**	
9	Drive AB line		42	Drive Offset (1200)		61	Drive AB line	
10	Return		43	**Go to plot 18**		62	Return	
11	Drive Offset (600)		44	Drive Offset (1200)		63	Drive Offset (600)	
12	Return		45	**Go to plot 20**		64	Return	
13	Drive Offset (600)		46	Drive Offset (1200)		65	Drive Offset (600)	
14	**Go to plot 25**		47	**Go to plot 25**		66	**Go to plot 21**	
15	Drive AB line		48	Drive Offset (1200)		67	Drive AB line	
16	Return		49	**Go to plot 29**		68	Return	
17	Drive Offset (600)		50	Drive Offset (1200)		69	Drive Offset (600)	
18	Return		51	**Go to plot 31**		70	Return	
19	Drive Offset (600)		52	Drive Offset (1200)		71	Drive Offset (600)	
20	**Go to plot 31**					72	**Go to plot 32**	
21	Drive AB line					73	Drive AB line	
22	Return					74	Return	
23	Drive Offset (600)					75	Drive Offset (600)	
24	Return					76	Return	
25	Drive Offset (600)					77	Drive Offset (600)	
26	**Go to plot 9**					78	**Go to plot 5**	
27	Drive Offset (600)					79	Drive Offset (600)	
28	**Go to plot 13**					80	**Go to plot 12**	
29	Drive Offset (600)					81	Drive Offset (600)	
30	**Go to plot 23**					82	**Go to plot 27**	
31	Drive Offset (600)					83	Drive Offset (600)	
32	**Go to plot 33**					84	**Go to plot 35**	
33	Drive Offset (600)					85	Drive Offset (600)	

Table 2 - Traffic treatment (compaction) protocol (additional for Spring 2016)

	Sequence	Check
1	**Set High Pressures**	
2	**Go to Plot 1**	
3	Drive Offset (600)	
4	Return	
5	Drive Offset (600)	
6	**Go to Plot 9**	
7	Drive Offset (600)	
8	**Go to Plot 13**	
9	Drive Offset (600)	
10	**Go to Plot 18**	
11	Drive Offset (600)	
12	Return	
13	Drive Offset (600)	
14	**Go to Plot 23**	
15	Drive Offset (600)	
16	**Go to Plot 25**	
17	Drive Offset (600)	
18	Return	
19	Drive Offset (600)	
20	**Go to Plot 31**	
21	Drive Offset (600)	
22	Return	
23	Drive Offset (600)	
24	**Go to Plot 33**	
25	Drive Offset (600)	
28	**Set pressures to low**	
29	**Go to Plot 2**	
30	Drive Offset (600)	
31	Return	
32	Drive Offset (600)	
33	**Go to Plot 5**	
34	Drive Offset (600)	
35	**Go to Plot 10**	
36	Drive Offset (600)	
37	Return	
38	Drive Offset (600)	
39	**Go to Plot 12**	
40	Drive Offset (600)	
41	**Go to Plot 21**	
42	Drive Offset (600)	
43	Return	
44	Drive Offset (600)	
45	**Go to Plot 27**	
46	Drive Offset (600)	
47	**Go to Plot 32**	
48	Drive Offset (600)	
49	Return	
50	Drive Offset (600)	
51	**Go to Plot 35**	
52	Drive Offset (600)	

Table 3 - Tillage (cultivation) protocol

1	**Set Pressures High**	
2	**Set Topdown for Deep Tillage**	
3	**Go to Spare 1**	SPARE 1
4	Drive	
5	**Go to Plot 1**	STP DEEP
6	Drive	
7	**Go to Plot 18**	STP DEEP
8	Drive	
9	**Go to Plot 25**	STP DEEP
10	Drive	
11	**Go to Plot 31**	STP DEEP
12	Drive	
13	**Set Topdown for Shallow Tillage**	
14	**Go to Spare 2**	SPARE 2
15	Drive	
16	**Go to Plot 9**	STP SHALLOW
17	Drive	
18	**Go to Plot 13**	STP SHALLOW
19	Drive	
20	**Go to Plot 23**	STP SHALLOW
21	Drive	
22	**Go to Plot 33**	STP SHALLOW
23	Drive	

24	**Set Pressures Low**	
25	**Keep Topdown for Shallow Tillage**	
26	**Go to Plot 5**	LTP SHALLOW
27	Drive	
28	**Go to Plot 8**	CTF SHALLOW
29	Drive	
30	**Go to Plot 11**	CTF SHALLOW
31	Drive	
32	**Go to Plot 12**	LTP SHALLOW
33	Drive	
34	**Go to Plot 19**	CTF SHALLOW
35	Drive	
36	**Go to Plot 27**	LTP SHALLOW
37	Drive	
38	**Go to Plot 28**	CTF SHALLOW
39	Drive	
40	**Go to Plot 35**	LTP SHALLOW
41	Drive	
42	**Set Topdown for Deep Tillage**	
43	**Go to Plot 2**	LTP DEEP
44	Drive	
45	**Go to Plot 4**	CTF DEEP
46	Drive	
47	**Go to Plot 10**	LTP DEEP
48	Drive	
49	**Go to Plot 17**	CTF DEEP
50	Drive	
51	**Go to Plot 21**	LTP DEEP
52	Drive	
53	**Go to Plot 22**	CTF DEEP
54	Drive	
55	**Go to Plot 32**	LTP DEEP
56	Drive	
57	**Go to Plot 36**	CTF DEEP
58	Drive	

Table 4 - Drilling protocol

1	**Set Pressures High**	
2	**Set Spirit for Direct Drill**	
3	**Go to Spare 3**	SPARE 3 - Zero
4	Drill	
5	**Go to Plot 6**	STP ZERO
6	Drill	
7	**Go to Plot 15**	STP ZERO
8	Drill	
9	**Go to Plot 20**	STP ZERO
10	Drill	
11	**Go to Plot 29**	STP ZERO
12	Drill	
13	**Set Spirit for Shallow Drill**	
14	**Go to Spare 2**	SPARE 2 - Shallow
15	Drill	
16	**Go to Plot 9**	STP SHALLOW
17	Drill	
18	**Go to Plot 13**	STP SHALLOW
19	Drill	
20	**Go to Plot 23**	STP SHALLOW
21	Drill	
22	**Go to Plot 33**	STP SHALLOW
23	Drill	
24	**Set Spirit for Deep Drill**	
25	**Go to Spare 1**	SPARE 1 - Deep
26	Drill	
27	**Go to Plot 1**	STP DEEP
28	Drill	
29	**Go to Plot 18**	STP DEEP
30	Drill	
31	**Go to Plot 25**	STP DEEP
32	Drill	
33	**Go to Plot 31**	STP DEEP
34	Drill	

35	**Set Pressures Low**	
36	**Keep Spirit for Deep Drill**	
37	**Go to Plot 2**	LTP DEEP
38	Drill	
39	**Go to Plot 4**	CTF DEEP
40	Drill	
41	**Go to Plot 10**	LTP DEEP
42	Drill	
43	**Go to Plot 17**	CTF DEEP
44	Drill	
45	**Go to Plot 21**	LTP DEEP
46	Drill	
47	**Go to Plot 22**	CTF DEEP
48	Drill	
49	**Go to Plot 32**	LTP DEEP
50	Drill	
51	**Go to Plot 36**	CTF DEEP
52	Drill	
53	**Set Spirit for Shallow Drill**	
54	**Go to Plot 5**	LTP SHALLOW
55	Drill	
56	**Go to Plot 8**	CTF SHALLOW
57	Drill	
58	**Go to Plot 11**	CTF SHALLOW
59	Drill	
60	**Go to Plot 12**	LTP SHALLOW
61	Drill	
62	**Go to Plot 19**	CTF SHALLOW
63	Drill	
64	**Go to Plot 27**	LTP SHALLOW
65	Drill	
66	**Go to Plot 28**	CTF SHALLOW
67	Drill	
68	**Go to Plot 35**	LTP SHALLOW
69	Drill	
70	**Set Spirit for Direct Drill**	
71	**Go to Plot 3**	CTF ZERO
72	Drill	
73	**Go to Plot 7**	LTP ZERO
74	Drill	
75	**Go to Plot 14**	CTF ZERO
76	Drill	
77	**Go to Plot 16**	LTP ZERO
78	Drill	
79	**Go to Plot 24**	CTF ZERO
80	Drill	
81	**Go to Plot 26**	LTP ZERO
82	Drill	
83	**Go to Plot 30**	LTP ZERO
84	Drill	
85	**Go to Plot 34**	CTF ZERO
86	Drill	

Appendix B Fertiliser, herbicide and fungicide applications

Table 1 - Fertiliser, herbicide and fungicide applications for the traffic and tillage trial on Large Marsh, Harper Adams University, UK years a: 2014/15, b: 2015/16 and c: 2016/17

a:	**2014/2015 Winter barley (Cassia)**			
Chemical	**Name**	**Qty ha^{-1}**	**Units**	**Date**
Herbicide	Roundup Flex glyphosate	2.000	Litre	23/09/14
Compounds	Origin Sulphur N 26N-0P-0K-35SO3	180.000	Kg	06/03/15
Herbicide	Pico Pro	3.000	Litre	30/03/15
Nitrogen	Yara Prilled 34.5%N	202.000	Kg	16/04/15
Herbicide	Starane XL fluroxypyr + florasul	1.000	Litre	20/04/15
Fungicide	Justice proquinazid	0.125	Litre	20/04/15
Fungicide	Proline 275	0.408	Litre	20/04/15
Fungicide	Imtrex fluxapyroxad	0.600	Litre	20/04/15
Chemical	Headland Manganese Super 80	2.000	Litre	13/05/15
Fungicide	Bravo 500 Chlorothanonil	1.000	Litre	13/05/15
Fungicide	Siltra Xpro Prothioconazole + Bixafen	0.400	Litre	13/05/15
Herbicide	Azural glyphosate	2.500	Litre	15/07/15
Wetter & Stickers	Spryte Aqua	1.000	Litre	15/07/15

b:	**2015/2016 Spring Oat (Aspen)**			
Chemical	**Name**	**Qty ha^{-1}**	**Units**	**Date**
Nitrogen	Yara Prilled 34.5%N	192.308	Kg	19/05/16
Chemical	Manganese 15% Headland	3.205	Litre	02/06/16
Fungicide	Justice proquinazid	0.125	Litre	02/06/16
Herbicide	Hurler fluroxypyr	0.750	Litre	02/06/16
Chemical	Thor tribenuron-methyl	25.000	Gram	02/06/16
Fungicide	Siltra Xpro Prothioconazole + Bixafen	0.600	Litre	09/06/16
Growth regulator	Belcocel 700 chlormequat	2.000	Litre	09/06/16

c:	**2016/2017 Spring wheat (Mulika)**			
Chemical	**Name**	**Qty ha^{-1}**	**Units**	**Date**
Herbicide	Azural glyphosate	4.000	Litre	14/12/16
Nitrogen	Yara Prilled 34.5%N	260.000	Kg	04/05/17
Growth regulator	Stabilan 750 chlormequat	0.481	Litre	18/05/17
Growth regulator	Belcocel 700 chlormequat	0.321	Litre	18/05/17
Fungicide	Justice proquinazid	0.125	Litre	18/05/17
Herbicide	Hurler fluroxypyr	0.500	Litre	18/05/17
Herbicide	Jubilee Sx metsulfuron-methyl	30.000	Gram	18/05/17
Adjuvant	Adigor	1.000	Litre	18/05/17
Herbicide	Axial pinoxaden	0.300	Litre	18/05/17
Nitrogen	Yara Prilled 34.5%N	260.000	Kg	30/05/17

Appendix C Additional statistical analysis

Shear vane

Shear vane analysis was discussed in Section 4.4.2. Tables 1 to 3 show additional shear vane analysis of variance (ANOVA) output for 100, 200 and 300 mm soil depth.

Table 1 - Shear vane analysis of variance 100 mm depth

Variate: 100 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.161181	0.053727	10.26	
Block.*Units* stratum					
Traffic	2	0.181224	0.090612	17.30	<0.001
Tillage	2	0.226764	0.113382	21.65	<0.001
Traffic.Tillage	4	0.009481	0.002370	0.45	0.770
Residual	24	0.125705	0.005238		
Total	35	0.704355			

Means

Traffic	CTF	LTP	STP
	0.164	0.271	0.336

Tillage	Deep	Shallow	Zero
	0.173	0.235	0.363

Traffic/ Tillage	Deep	Shallow	Zero
CTF	0.086	0.155	0.252
LTP	0.197	0.253	0.364
STP	0.236	0.298	0.475

Tukey's 95% confidence intervals

Traffic	Mean	
CTF	0.164	a
LTP	0.271	b
STP	0.336	b

Tillage	Mean	
Deep	0.173	a
Shallow	0.235	a
Zero	0.364	b

%CV=28.1

Table 2 - Shear vane analysis of variance 200 mm depth

Variate: 200 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.106438	0.035479	10.79	
Block.*Units* stratum					
Traffic	2	0.228741	0.114371	34.78	<0.001
Tillage	2	0.010122	0.005061	1.54	0.235
Traffic.Tillage	4	0.023679	0.005920	1.80	0.162
Residual	24	0.078921	0.003288		
Total	35	0.447902			

Means

Traffic	CTF	LTP	STP
	0.225	0.369	0.412

Tillage	Deep	Shallow	Zero
	0.312	0.349	0.345

Traffic/ Tillage	Deep	Shallow	Zero
CTF	0.160	0.240	0.276
LTP	0.355	0.377	0.375
STP	0.420	0.431	0.385

Tukey's 95% confidence intervals

Traffic	Mean	
CTF	0.225	a
LTP	0.369	b
STP	0.412	b

%CV=17.1

Table 3 - Shear vane analysis of variance 300 mm depth

Variate: 300 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.160986	0.053662	12.28	
Block.*Units* stratum					
Traffic	2	0.113556	0.056778	12.99	<0.001
Tillage	2	0.024444	0.012222	2.80	0.081
Traffic.Tillage	4	0.051566	0.012891	2.95	0.041
Residual	24	0.104861	0.004369		
Total	35	0.455412			

Means

Traffic	CTF	LTP	STP
	0.283	0.39	0.411

Tillage	Deep	Shallow	Zero
	0.395	0.358	0.331

Traffic/ Tillage	Deep	Shallow	Zero
CTF	0.28	0.262	0.307
LTP	0.428	0.439	0.303
STP	0.477	0.373	0.384

Tukey's 95% confidence intervals

Traffic	Mean	
CTF	0.283	a
LTP	0.390	b
STP	0.411	b

Tillage	Mean	
Zero	0.331	a
Shallow	0.358	ab
Deep	0.395	b

Bonferroni test 0.05

Traffic x tillage	Mean	
CTF Shallow	0.262	a
CTF Deep	0.280	ab
LTP Zero	0.303	ab
CTF Zero	0.307	ab
STP Shallow	0.373	abc
STP Zero	0.384	abc
LTP Deep	0.428	abc
LTP Shallow	0.439	bc
STP Deep	0.477	c

%CV=18.3

X-ray CT percentage porosity

X-ray CT percentage porosity analysis was discussed in Section 5.4.2. Tables 4 to 8 show additional X-ray CT percentage porosity analysis of variance (ANOVA) output for 0-250 mm soil depth in 50 mm increments.

Table 4 - X-ray CT porosity (%) analysis of variance 0-50 mm depth

Variate: 0-50 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	14.82	4.94	0.08	
Block.*Units* stratum					
Traffic	2	122.98	61.49	0.97	0.394
Tillage	2	788.69	394.35	6.21	0.007
Traffic.Tillage	4	240.09	60.02	0.94	0.455
Residual	24	1525.20	63.55		
Total	35	2691.79			

Means

Traffic	CTF	LTP	STP
	22.1	20.3	17.6

Tillage	Deep	Shallow	Zero
	20.7	25.3	13.9

Traffic/Tillage	Deep	Shallow	Zero
CTF	22.4	23.2	20.6
LTP	21.9	27.6	11.3
STP	17.8	25.1	9.9

Tukey's 95% confidence intervals

Tillage	Mean	
Zero	13.91	a
Deep	20.69	ab
Shallow	25.31	b

%CV=39.9

Table 5 - X-ray CT porosity (%) analysis of variance 50-100 mm depth

Variate: 50-100 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	114.88	38.29	2.15	
Block.*Units* stratum					
Traffic	2	357.39	178.7	10.03	<0.001
Tillage	2	245.73	122.86	6.90	0.004
Traffic.Tillage	4	337.00	84.25	4.73	0.006
Residual	24	427.42	17.81		
Total	35	1482.41			

Means

Traffic	CTF	LTP	STP
	16.72	10.7	9.53

Tillage	Deep	Shallow	Zero
	15.8	11.64	9.51

Traffic/Tillage	Deep	Shallow	Zero
CTF	24.0	13.0	13.2
LTP	13.8	14.0	4.3
STP	9.6	7.9	11.0

Tukey's 95% confidence intervals

Traffic	Mean	
STP	9.53	a
LTP	10.7	a
CTF	16.72	b

Tillage	Mean	
Zero	9.51	a
Shallow	11.64	ab
Deep	15.8	b

Bonferroni test

Traffic x Tillage	Mean	
LTP Zero	4.26	a
STP Shallow	7.9	a
STP Deep	9.64	a
STP Zero	11.04	a
CTF Shallow	12.98	a
CTF Zero	13.22	ab
LTP Deep	13.81	ab
LTP Shallow	14.03	ab
CTF Deep	23.95	b

%CV=34.3

Table 6 - X-ray CT porosity (%) analysis of variance 100-150 mm depth

Variate: 100-150 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	131.58	43.86	1.17	
Block.*Units* stratum					
Traffic	2	572.1	286.05	7.62	0.003
Tillage	2	47.07	23.53	0.63	0.543
Traffic.Tillage	4	410.86	102.72	2.74	0.052
Residual	24	901.31	37.55		
Total	35	2062.91			

Means

Traffic	CTF	LTP	STP
	17.1	8.4	8.9

Tillage	Deep	Shallow	Zero
	11.9	12.6	9.9

Traffic/Tillage	Deep	Shallow	Zero
CTF	23.1	13	15.3
LTP	8.1	11.7	5.4
STP	4.4	13.2	9.1

Tukey's 95% confidence intervals

Traffic	Mean	
LTP	8.42	a
STP	8.9	a
CTF	17.1	b

Bonferroni test 0.05

	Mean	
STP Deep	4.45	a
LTP Zero	5.43	a
LTP Deep	8.07	ab
STP Zero	9.07	ab
LTP Shallow	11.74	ab
CTF Shallow	12.98	ab
STP Shallow	13.18	ab
CTF Zero	15.25	ab
CTF Deep	23.08	b

%CV=53.4

Table 7 - X-ray CT porosity (%) analysis of variance 150-200 mm depth

Variate: 150-200 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	145.27	48.42	2.08	
Block.*Units* stratum					
Traffic	2	313.52	156.76	6.73	0.005
Tillage	2	139.65	69.83	3.00	0.069
Traffic.Tillage	4	188.97	47.24	2.03	0.122
Residual	24	558.84	23.28		
Total	35	1346.26			

Means

Traffic	CTF	LTP	STP
	15.91	9.35	10

Tillage	Deep	Shallow	Zero
	9.48	14.28	11.5

Traffic/Tillage	Deep	Shallow	Zero
CTF	16.31	15.12	16.29
LTP	7.85	13.69	6.5
STP	4.27	14.03	11.7

Tukey's 95% confidence intervals

Traffic	Mean	
LTP	9.35	a
STP	10	a
CTF	15.91	b

Tillage	Mean	
Deep	9.48	a
Zero	11.5	ab
Shallow	14.28	b

%CV=41.1

Table 8 - X-ray CT porosity (%) analysis of variance 200-250 mm depth

Variate: 200-250 mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	273.56	91.19	2.02	
Block.*Units* stratum					
Traffic	2	116.58	58.29	1.29	0.294
Tillage	2	454.83	227.41	5.03	0.015
Traffic.Tillage	4	32.11	8.03	0.18	0.948
Residual	24	1085.2	45.22		
Total	35	1962.3			

Means

Traffic	CTF	LTP	STP
	13.9	9.6	12.5

Tillage	Deep	Shallow	Zero
	8.6	16.9	10.5

Traffic/Tillage	Deep	Shallow	Zero
CTF	11.9	18.3	11.4
LTP	5.6	15.4	7.7
STP	8.1	17	12.5

Tukey's 95% confidence intervals

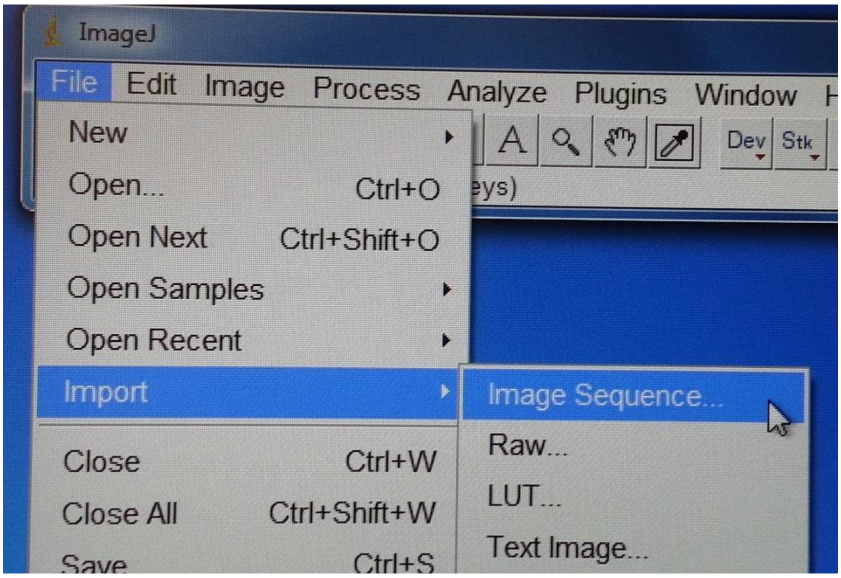
Tillage	Mean	
Deep	8.56	a
Zero	10.51	ab
Shallow	16.88	b

%CV=56.1

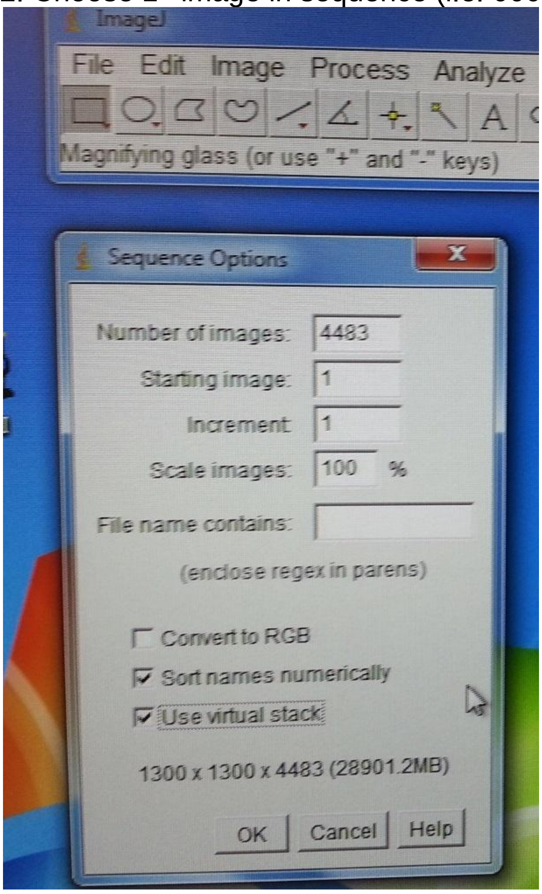
Appendix D Image analysis protocols

ImageJ – Pore Space Analysis Procedure

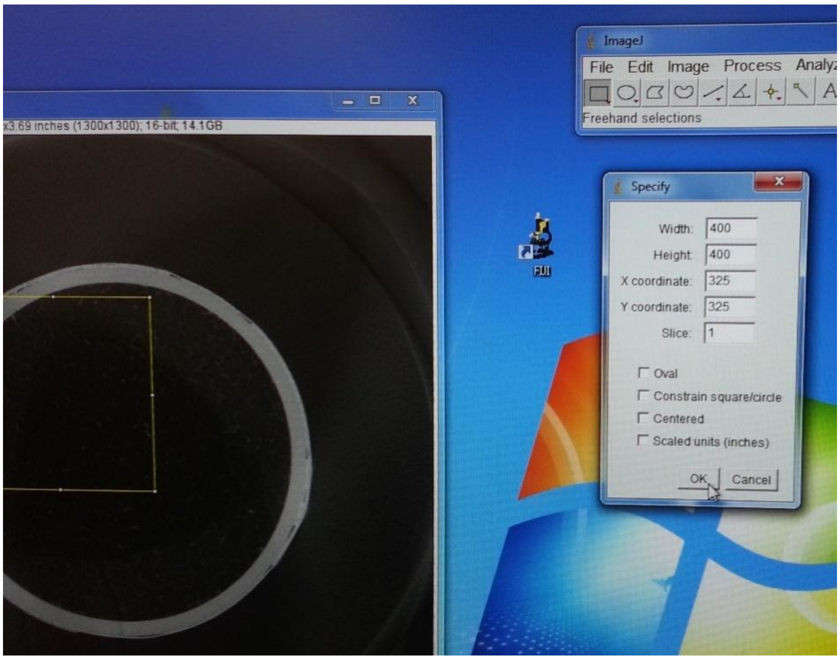
1. File → Import → Image Sequence (Folder: Top View).

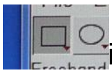


2. Choose 1st image in sequence (i.e. 0000) ☑ Virtual stack → okay

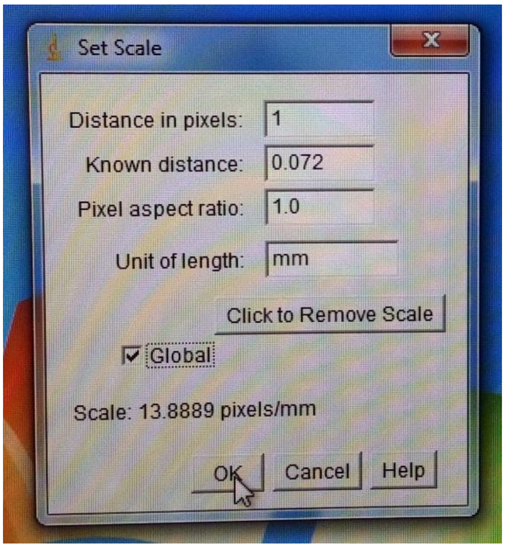


3. Edit → Selection → Specify. Set Width to 400 pixel and height to 400 pixel (28.8mm x 28.8mm) → okay



4. Move yellow box with left mouse click. Make sure  is selected. Move through stack to check position of box.

5. Analyse → Set Scale. Pixel = 1. Known Distance = 0.072 (µm). Pixel Aspect Ratio = 1.0. Unit = mm. ☑ Global → Okay.



6. When scrolling through images error message comes up. ☐ Disable Global Calibration. Disable These Messages.

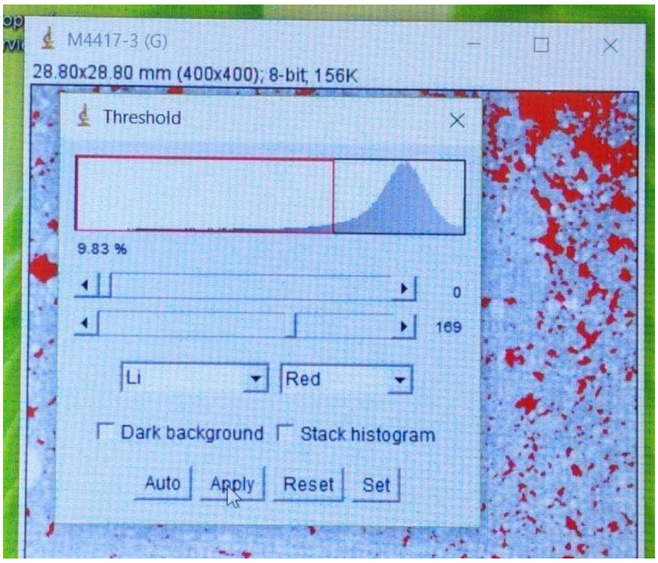
7. Range. Click through images to find start and finish of images e.g. 226/4478 (0225) to 4258/4478 (4257).

8. Image → Duplicate ☑ Duplicate Stack (Rename e.g. M4417_Core1_cropped_. Change range e.g. 226-4258. File →Save As → Image Sequence (Folder: Cropped) This is 16bit.

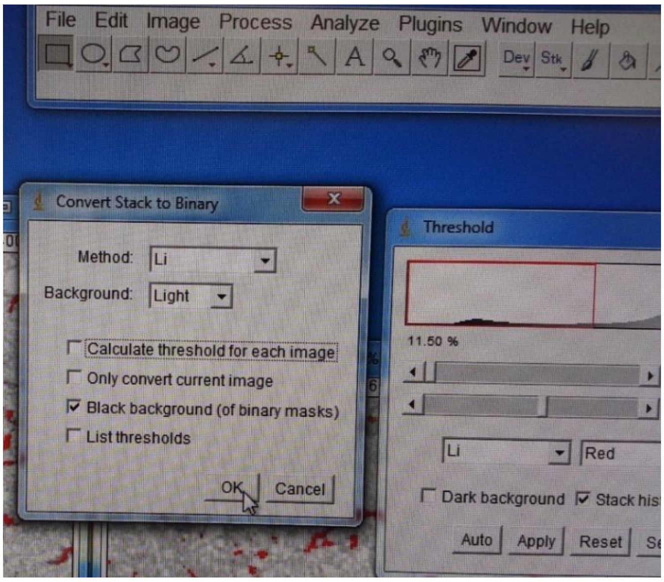
9. Select a good slice i.e. stone soil and pores (a large pore space gives an 'air' peak in the histogram. Image → Duplicate ☐ Duplicate Stack →okay. Change to 8bit (8bit = 0-255). Image → Type → ✓ 8bit. Image → Adjust → Threshold. Set to Li. → Auto. Check if

covers all you want? Record Values for Minimum, Li and Otsu algorithms e.g. M = 0-48, L= 0-120 and O = 0-145.

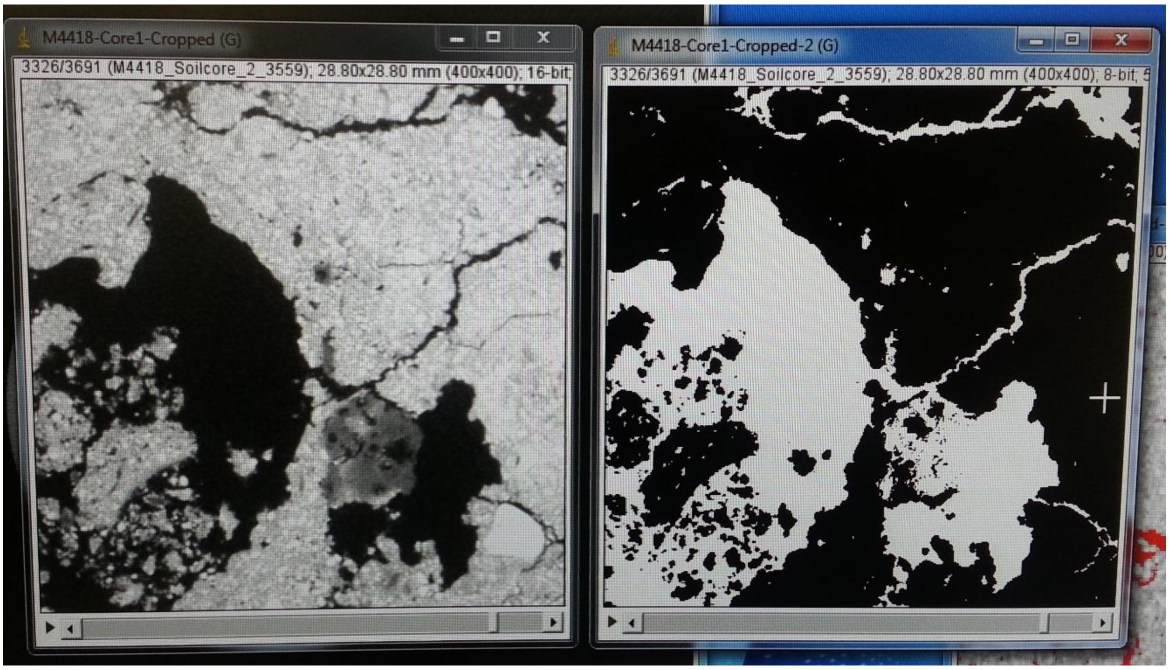
10. Duplicate cropped data then Image → Type ✓ 8bit. Image → Adjust → Threshold. ☐ Stack Histogram. Select same image as in paragraph 9. → Auto (Applies to all slices)→ Apply (sets mask) (no longer stack histogram)



11. Convert Stack to Binary box ☐ Calculate Threshold For Each Image ☑ Black Background (of binary masks) → okay.

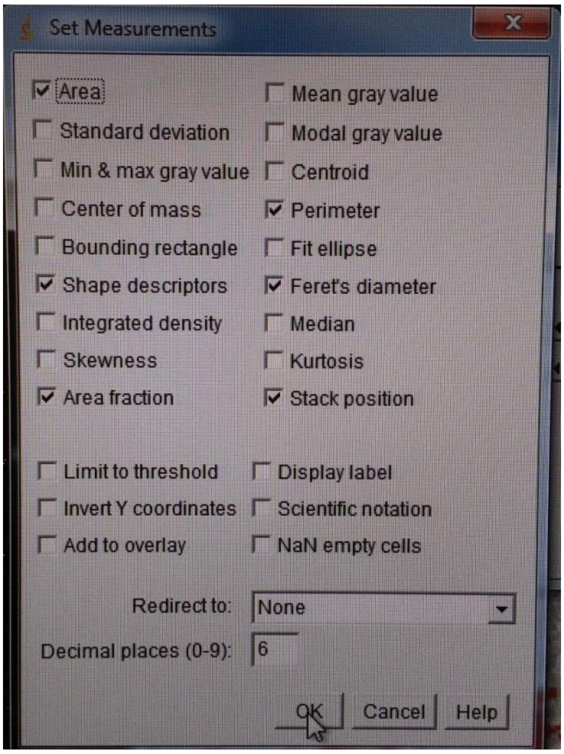


12. Check through images and compare binary (8bit) to greyscale (16bit) i.e. pick the same slice number.

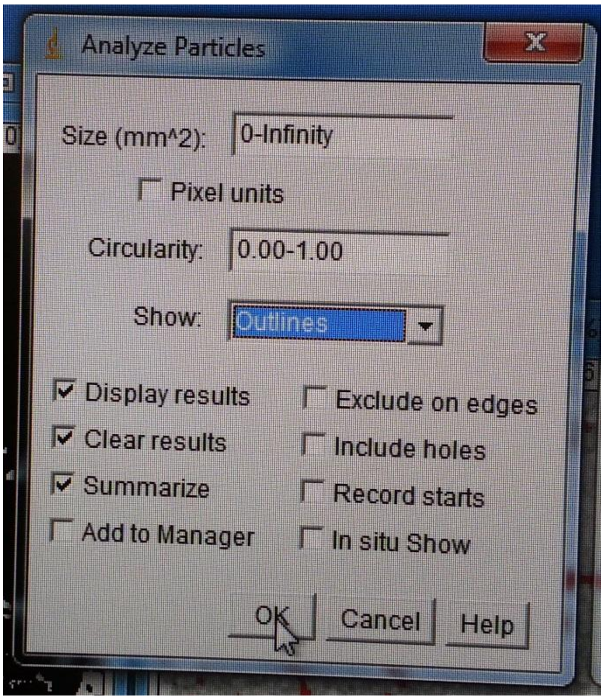


13. Edit →Invert →Yes

14. Analyse → Set Measurements. ☑ Area Shape ☑ Descriptions ☑ Area Fraction ☑ Perimeter ☑ Feret's Diameter ☑ Stack Position. Decimal places = 6 →okay



15. Click on stack →Analyse →Analyse Particles. 0-Infinity, 0.00-1.00, Outlines ☑ Display Results ☑ Clear Results ☑ Summarise

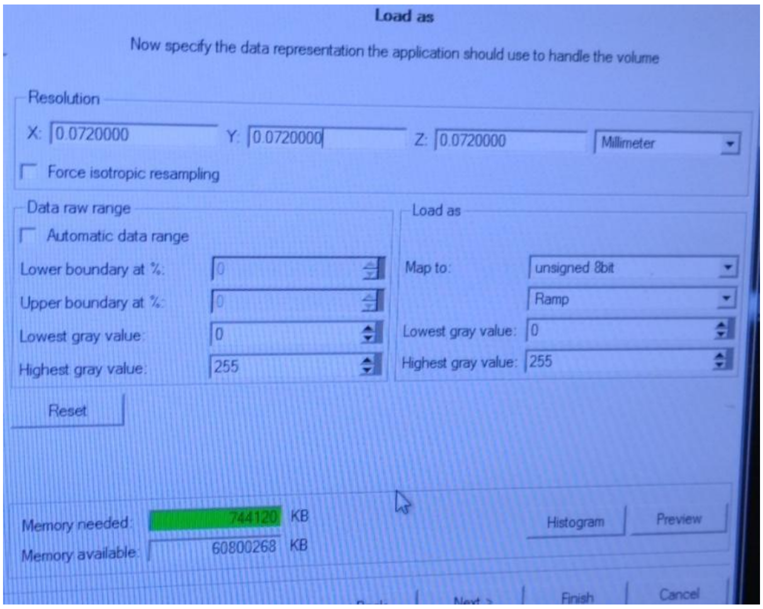


16. Box Process all 3691 images → yes

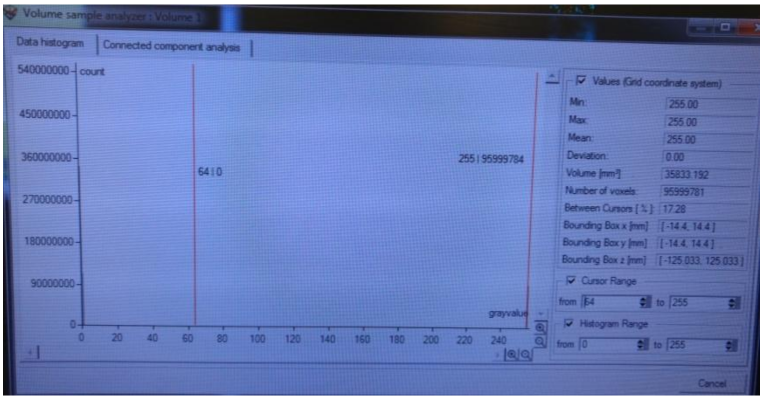
17. Two xls files created. Results and Summary. File → Save As (Folder: ImageJ Results). Click on Binary Stack File → Save As → Image Sequence (8bit) (Folder: Threshold Li)
18. Remember: Images are upside down

Studio Max 2.0 – Pore Connectivity Analysis Procedure (Volume Graphics Quick Method)

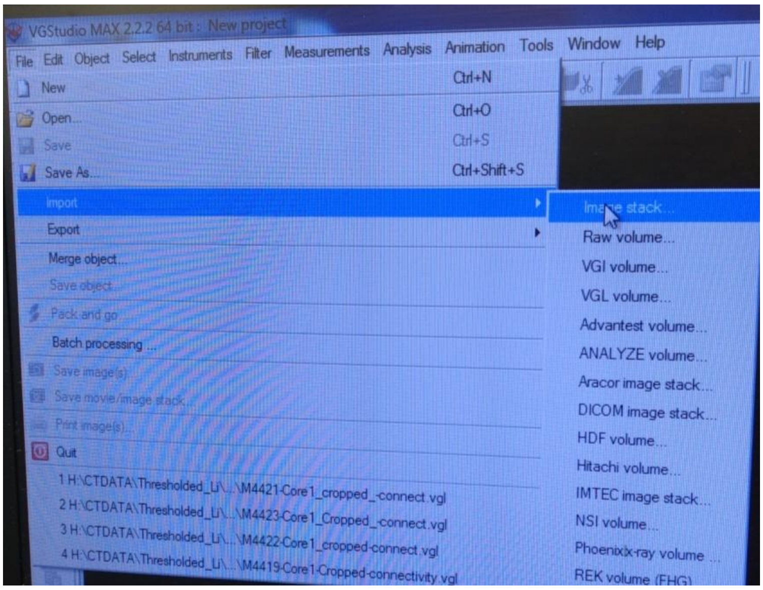
1. Set resolution for X, Y and Z to 0.072 mm



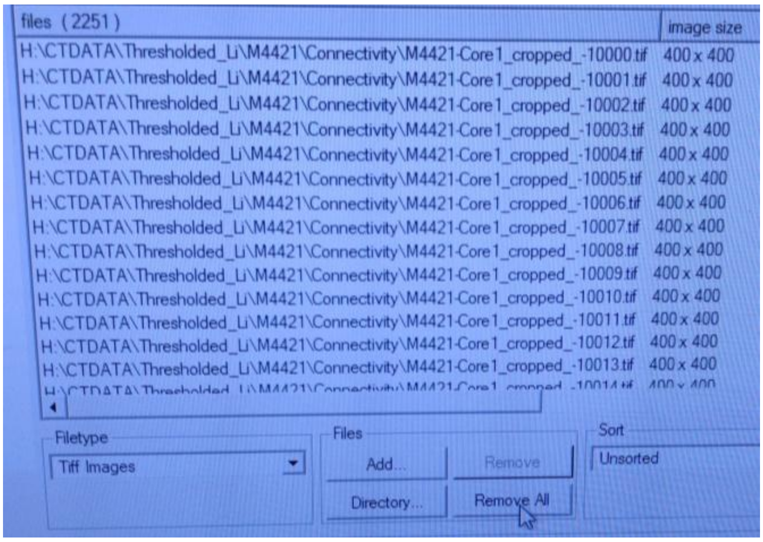
2. Copy blank slice and add to slices. Copy last name + 1. Start at slice no. - 3472 e.g. = 384. New folder = connectivity. Click new



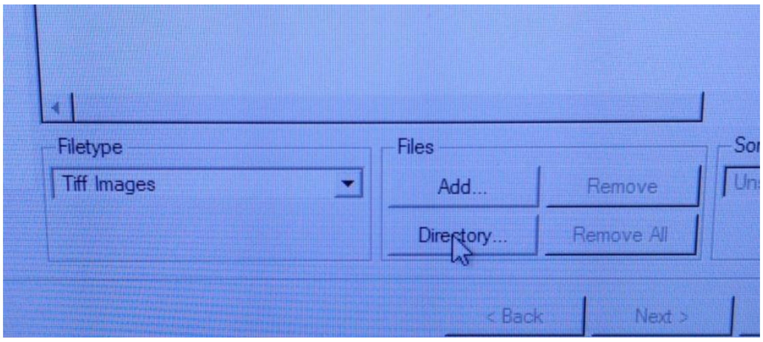
3. File → Import → Image stack



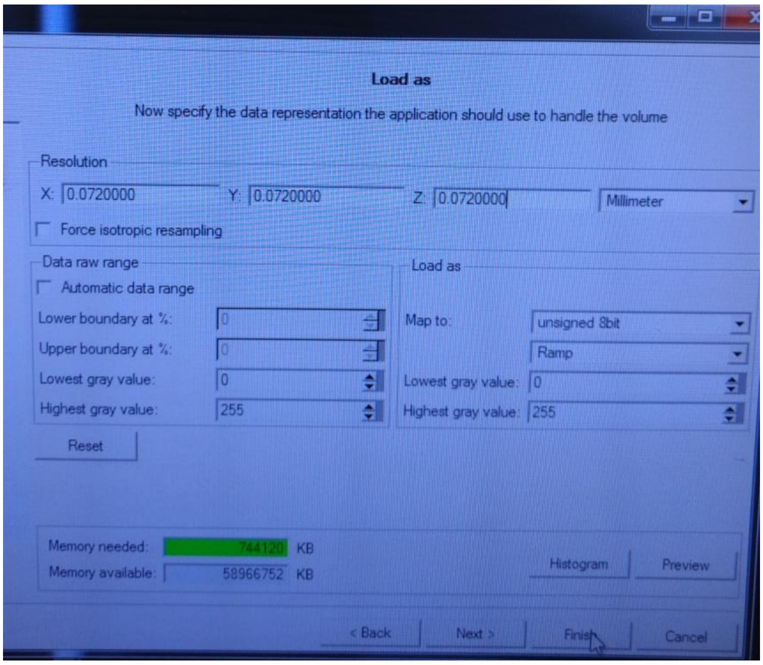
4. Remove all



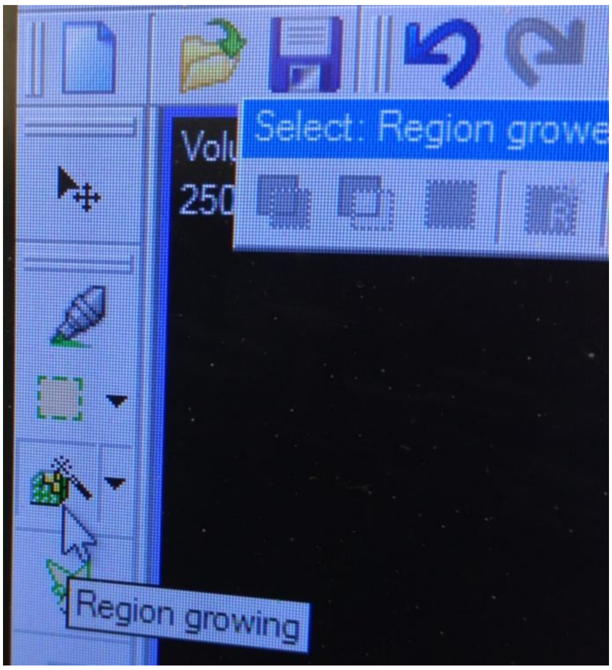
5. Directory → Next



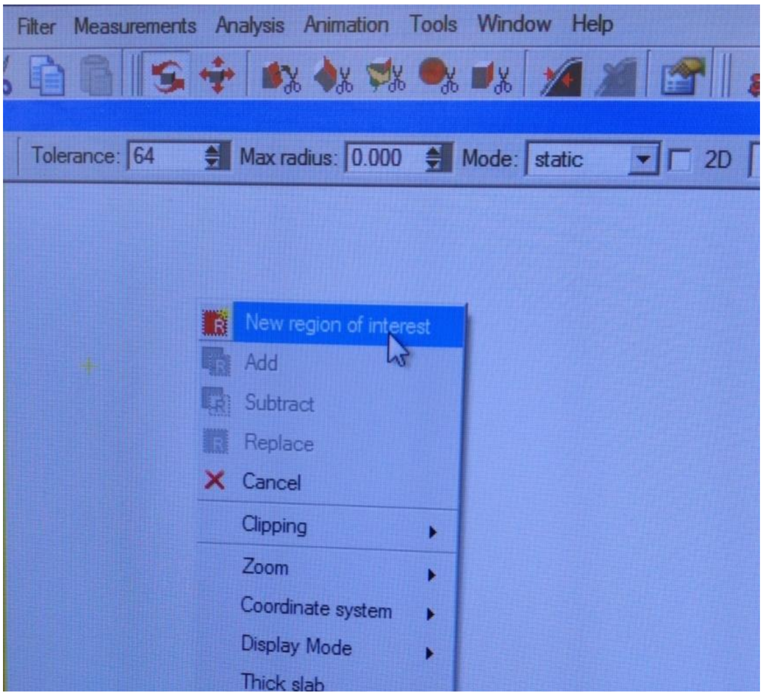
6. → Finish



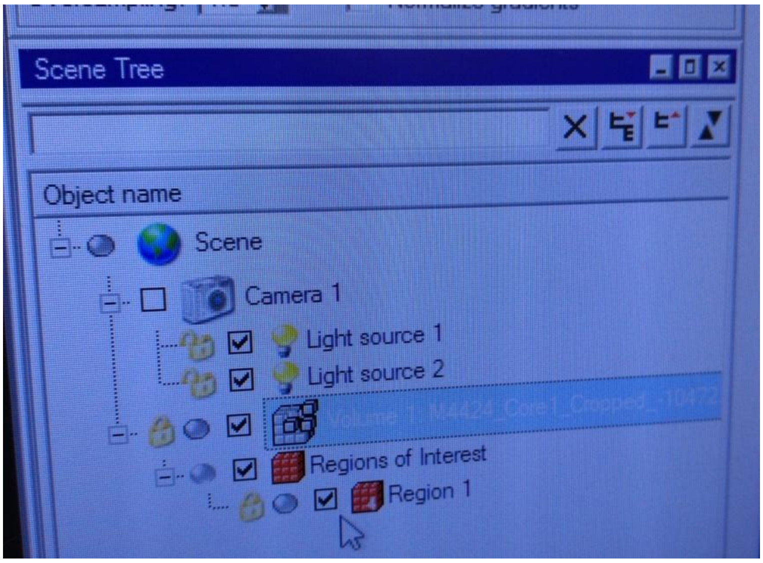
7. Top image → Region grower



8. New region of interest

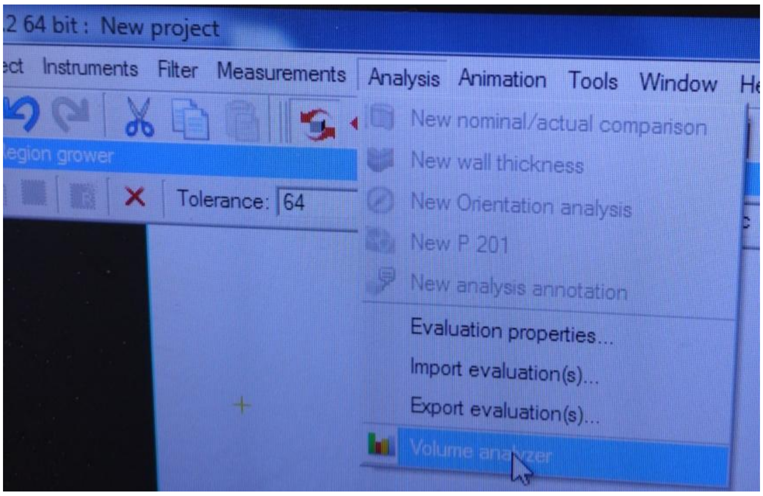


9. Select region 1



10. . One slice down. Using ☐ selection tool, draw over slide. Drag red line. Right click → New region of interest.

11. Analysis → Volume analyser



12. Record Total volume, Total pores and connected pores

Appendix E Trial photographs

Figure 1 shows year 3 spring wheat plant establishment in the nine treatment plots in block 1

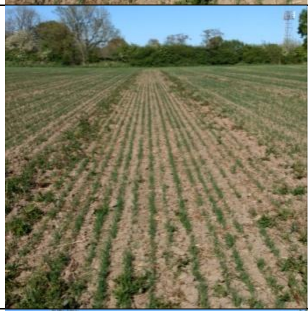
	Deep Tillage	Shallow Tillage	Zero tillage
CTF			
LTP			
STP			

Figure 1 - Spring wheat plant establishment in the nine treatment plots in Block 1 (taken 5th May 2017)