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The effect of agricultural traffic and tillage on soil physical properties and crop yields

Emily Kate Smith

BSc (Hons) Geography with Environmental Management, University of Exeter, UK (2011)

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Harper Adams University, Newport, Shropshire, TF10 8NB, UK

Declaration

I declare that this thesis is a record of the work completed, analysed and reported by myself. This work has not been submitted or accepted in any previous application for a degree. Sources of information and collaboration have been specifically acknowledged.

Emily Kate Smith

Publications

Godwin, R.J., Misiewicz, P.A., **Smith, E.K.**, Millington, W.A.J., White, D.R., Dickin, E.T. and Chaney, K. 2017. Summary of the effects of three tillage and three traffic systems on cereal yields over a four-year rotation. *Aspects of Applied Biology*, 134, pp.233-242.

Godwin, R., Misiewicz, P., White, D., **Smith, E.**, Chamen, T., Galambošová, J. and Stobart, R. 2015. Results from recent traffic systems research and the implications for future work. *Acta Technologica Agriculturae*, 18 (3), pp.57-63.

Smith, E.K., Misiewicz, P.A., Girardello, V., Arslan, S., Chaney, K., White, D.R. and Godwin, R.J. 2014. Effects of traffic and tillage on crop yield (winter wheat *Triticum aestivum*) and the physical properties of a sandy loam soil. *ASABE – CSBE/ASABE Annual Meeting, Montreal, Quebec Canada, 13-16 July 2014, (Paper No: 1912652)*.

Smith, E.K., Misiewicz, P.A., Girardello, V., Arslan, S., Chaney, K., White, D.R. and Godwin, R.J. 2014. Effect of tracks and tyres on soil physical properties in a sandy loam soil. *ASABE – CSBE/ASABE Annual Meeting, Montreal, Quebec, Canada, 13-16 July 2014, (Paper No: 1912659)*.

Smith, E.K., Misiewicz, P.A., Chaney, K., White D.R. and Godwin, R.J. 2013. An investigation into the effect of traffic and tillage on soil properties and crop yields. *ASABE Annual Meeting, Kansas City, Missouri, USA, 21-24 July 2013*, *(Paper No: 131597846).*

Smith, E.K., Misiewicz, P.A., Chaney, K., White, D.R. and Godwin R.J. 2012. An investigation into the effect of traffic and tillage on soil properties, crop yields and energy requirements. *Poster and presentation at ACTFA First international Controlled Traffic Farming conference, Toowoomba, Australia, 25-27 February 2013.*

Smith, E.K., Kristof, K., Misiewicz, P.A., Chaney, K., White D.R. and Godwin, R.J. 2012. Establishment of a long-term experiment into tillage and traffic management. Part One: study background and experimental design. *Presentation at CIGR AgEng Conference, Valencia, Spain, 8-12 July 2012*.

Kristof, K., **Smith, E.K.**, Misiewicz, P.A., Chaney, K., White D.R. and Godwin, R.J. 2012. Establishment of a long-term experiment into tillage and traffic management. Part Two: Evaluation of spatial heterogeneity for the design and layout of experimental sites. *Presentation at CIGR AgEng Conference, Valencia, Spain, 8-12 July 2012.*

Abstract

The future productivity of global soils is directly threatened by soil compaction. Conventional agricultural production systems can expose up to 86% of a field to traffic-induced soil compaction, which can be minimised using low ground pressure technologies, including tracks and tyres, and traffic management systems, namely controlled traffic farming. A reduction in both traffic and tillage intensity, using shallow and zero tillage systems, not only reduces the amount of in-field traffic, and thus the cost of crop establishment, but has been shown to have a positive impact on soil properties and crop yields. The influence of traffic and tillage on soil properties has been studied worldwide, although there is a lack of replicated field study data.

An experiment, therefore, was carried out at Harper Adams University, UK to determine the effect of three traffic systems being random traffic farming at standard and low tyre inflation pressures, and controlled traffic farming, with three tillage systems being deep, shallow and zero tillage on soil physical properties and winter wheat (*Triticum aestivum*) and winter barley (*Hordeum vulgare*) yields. Soil compaction was removed, and the site was assessed for uniformity prior to the design and application of treatments. Traffic treatments were evaluated prior to their use in the field experiment.

A reduction in tyre inflation pressure reduced soil pressure and soil bulk density. Under tyres at low inflation pressure, penetration resistance and yield ranged between -7% to 13% and -2% to 4% respectively compared to standard inflation pressure. The use of low ground pressure specific tyres and tracks increased soil compaction. Tracks reduced winter barley yields by 30% compared to tyres. The removal of traffic, using a controlled traffic farming system, reduced soil bulk density and penetration resistance by 15% and 27% and increased yields between 28% to 46% compared to random traffic farming. A reduction in tillage intensity, using zero tillage, increased soil bulk density and penetration resistance, and resulted in yield differences between -9% to 1% compared to deep tillage.

This research, conducted on a uniform field site, indicates that soil compaction should be minimised in commercial agricultural operations by reducing tyre inflation pressures of standard agricultural tyres, or using controlled traffic farming, in combination with reduced tillage systems.

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List of abbreviations

ANOVA = analysis of variance

ATV = all-terrain vehicle

CT = computed tomography

CTF = controlled traffic farming

DGPS = differential global positioning systems

EC_a = apparent electrical conductivity

GNSS = global navigation satellite system

GS = growth stage

h = hours

ha = hectare(s)

IF = improved flex

Kfs = saturated hydraulic conductivity

LGP = low ground pressure

mamsl = metres above mean sea level

MBV = moisture content by volume

Mg = megagram (syn. metric tonne)

mS/m = millisiemens per metre

NDVI = normalized difference vegetation index

P_C = ground surface contact pressure

P_I = tyre inflation pressure

P_{CS} = tyre carcass stiffness

RTF = random traffic farming

RTK = real time kinematic

sCTF = seasonal controlled traffic farming

SEM = standard error of the mean

SFH = simplified falling-head

TGW = thousand grain weight

TDR = time domain reflectometry

wt = weight

1. Introduction

1.1. Agricultural soil degradation

Soils are not static in nature, but are continuously altered over time by climate, geology, topography, vegetation, organisms and management (Rowell, 1994). Anthropogenic interactions with soil, which have intensified throughout history, influence the rate at which natural processes and ecosystem services in the soil occur. Agricultural production can compromise the ability of a soil to provide crop-supporting services (Forth, 1978; Rowell, 1994).

One of the primary threats to the future of productivity of global soils can be directly linked to soil compaction (Hamza and Anderson, 2005; Badalíková, 2010), defined as a "densification and distortion of soil by which total and air filled porosity are reduced, causing a deterioration or loss of one or more soil functions" (Huber *et al*., 2008). Poor soil protection and cropping management coupled with increasing forces from off-road vehicles, cultivation, seeding and harvesting equipment (Rowell, 1994; Hamza and Anderson, 2005; Huber *et al*., 2008) produce compacted layers which deteriorate the physical, chemical and biological functions of the topsoil (from the surface to 200-350 mm) and subsoil (below 200-350 mm) (Arvidsson, 2001; Badalíková, 2010).

Whilst the total area of land in Europe affected by compaction remains to be quantified (Virto *et al*., 2015), the extent of within field compaction has been studied. Random traffic farming (RTF) with conventional tillage is the most commonly used method for tilled arable production (Virto *et al*., 2015). In this system, up to 86% of a field can be exposed to traffic and tillage forces (Kroulík *et al*., 2009) exerted by increasingly larger and heavier agricultural machinery. Farming press reports that the unit weight of agricultural vehicles has now reached in excess of 62 tonnes (Wigdahl, 2014), with tractors continuing to be released onto the UK market (Cousins *et al*., 2016) weighing 21 tonnes (Andrews, 2014). These forces alter the soils aggregation (Forth, 1978) and results in widespread compaction (Neal, 1953; Kroulík *et al*., 2009).

In order to maintain sufficient crop growth compacted soils require more intensive cultivations and as a result are exposed to more extensive in-field trafficking (Kroulík *et al*., 2009). Subsoil compaction is more difficult to remove than topsoil compaction and thus its mitigation must be achieved to avoid costly and sometimes negative remedial work (Arvidsson, 2001; Alakakku *et al*., 2003).

1.2. Low ground pressure

Low ground pressure (LGP) systems increase the area over which a load is spread thus reducing the vehicle-soil contact pressure. Methods to reduce ground pressure include an increase in tyre size, a reduction in tyre inflation pressure, and LGP tyres and tracks.

Lamandé and Schjønning (2011) studied the effect of tyre size on soil compaction and found that a larger tyre reduced both the surface contact pressure and the stresses recorded in the soil. Similarly, a reduction in tyre inflation pressure has been found to increase the contact area and reduce topsoil compaction (Raper *et al*., 1995; Arvidsson and Keller, 2007). Tyre technology itself has developed from early cross-ply tyres, prone to slip, overheating and soil damage, to radial tyres with increased durability and load distribution. Many agricultural tyre manufacturers have responded to market demands and developed new generation radial tyres for agricultural vehicles with higher load carrying capacities enabling greater efficiencies of production. By design these tyres offer greater soil protection (Bridgestone, 2014), pressure distribution, traction and road transport capabilities (Vredestein, 2016).

Michelin (2014b) have developed increased flexion (IF) tyres with greater sidewall flexibility. Increased flexion technology increases the tyre-soil contact area, soil protection, efficiency and endurance. However, limited work has been completed on the use of these tyres in the field.

Rubber tracks have been found to reduce both the contact pressure and the depth to which compaction extends vertically within the soil profile (Bashford *et al*., 1988; Ansorge and Godwin, 2007).

1.3. Controlled traffic farming

Controlled traffic farming (CTF) is a method of traffic management whereby conventional vehicles are restricted to permanent lanes known as wheelways. Tullberg *et al*. (2007) reported that the widespread adoption of CTF in Australia to minimise the impact of field traffic has improved water availability and infiltration, and increased crop performance.

There is a global resource of similar studies that report the benefits achieved using CTF including soil health (soil organic matter and biology), water regimes (porosity, infiltration) and cropping (establishment timeliness and efficiency, and yields) (Voorhees and Lindstrom, 1984; Radford *et al*., 2001; Silburn and Glanville, 2002; Chamen, 2006a; McHugh *et al*., 2009). A series of reported case studies and research from the United Kingdom (UK), Europe, Australia, Canada and Brasil, suggest farmers have experienced yield improvements reported between 7-30% (Dickson and Ritchie, 1996; Vermeulen and Mosquera, 2009). Tullberg *et al*. (2007) report that CTF is supportive in adopting reduced tillage systems, as there is a reduced need for remedial action by intensive tillage, and suggest that soil and crop improvements, coupled with time and fuel savings, can result in economic benefits by as much as 50%.

1.4. Tillage

Tillage is the mechanical loosening of soil to alleviate compaction and create a seedbed structure to promote good germination and crop establishment. Ploughing is a traditional method of inversion tillage that turns the soil over in rows or furrows, often leading to the development of compacted layers known as plough-pans which impedes water drainage at depth (Foth, 1978). Alternatively, conservation agriculture achieved through shallow or zero tillage, aims to keep soil disturbance to a minimum, retain plant or crop residue cover and to establish diverse crop rotations (Jones *et al*., 2006). When conservation tillage is used a greater amount of residue remains on the soil surface which protects the soil, improves rainfall interception and reduces loss of soil moisture by evaporation. However, agronomic and soil function management (Badalíková, 2010) are integral to the success of shallow and zero tillage systems to minimise loss of yield.

Researchers have reported the impact of a range of agricultural production systems on soil physical properties and crop yields (Negi et *al*., 1981; Botta *et al*., 2009). Kroulík *et al*. (2009) found that conventional tillage is associated with extensive trafficking and therefore both traffic and tillage cause compaction, either directly or indirectly, resulting in soil degradation, erosion, loss of organic matter and soil fertility (Tullberg *et al*., 2007; Rowell, 1994). Minimising top and subsoil compaction from increasingly larger and heavier off-road vehicles (Soane and van Ouwerkerk, 1994) that are central to modern agricultural production remains a fundamental challenge and uptake to date in both alternative traffic and tillage systems has been slow (Tullberg *et al*., 2007). Within the duration of this project, during the summer of 2012, the UK experienced variability in seasonal water availability, culminating in a twofold increase in the levels of rainfall compared to the yearly average (Benton *et al*., 2012; Wynn and Twining, 2012). Many farmers faced delayed harvests due to high soil moisture contents preventing trafficking, leading to poor or failed harvests (Wynn and Twining, 2012). Consequently establishment conditions were poor resulting in an 18% reduction in UK planted area for the 2012-2013 season (Blackburn and Harriss, 2013).

The problems encountered during 2012, coupled with a greater likelihood although unpredictability of periods of water surplus and deficit (Benton *et al*., 2012) have re-affirmed the need to understand in more detail the interactions of traffic and tillage and their impact on provisioning services to maximise the resilience of agricultural production.

The work presented in this thesis expands upon a study reported by Chamen (2011) that presented research from different field sites over a range of soil types to determine the effect of reduced trafficking on soil, yields and profitability. In the absence of replicated field experiments this work concluded that non-trafficked soils have improved structure, infiltration, nutrient and water uptake and reduced erosion and resulted in improved yields, reduced energy inputs and are practical and more profitable in UK agricultural production systems. In his work, Chamen (2011) concluded that future research should seek to establish methods of optimising conditions for crop growth and soil function. The current study was undertaken to address this requirement and provide new information to the academic and industry sectors on the ability of traffic and tillage management to optimise soil physical properties and crop performance. Figure 1.1 outlines the structure of this thesis.

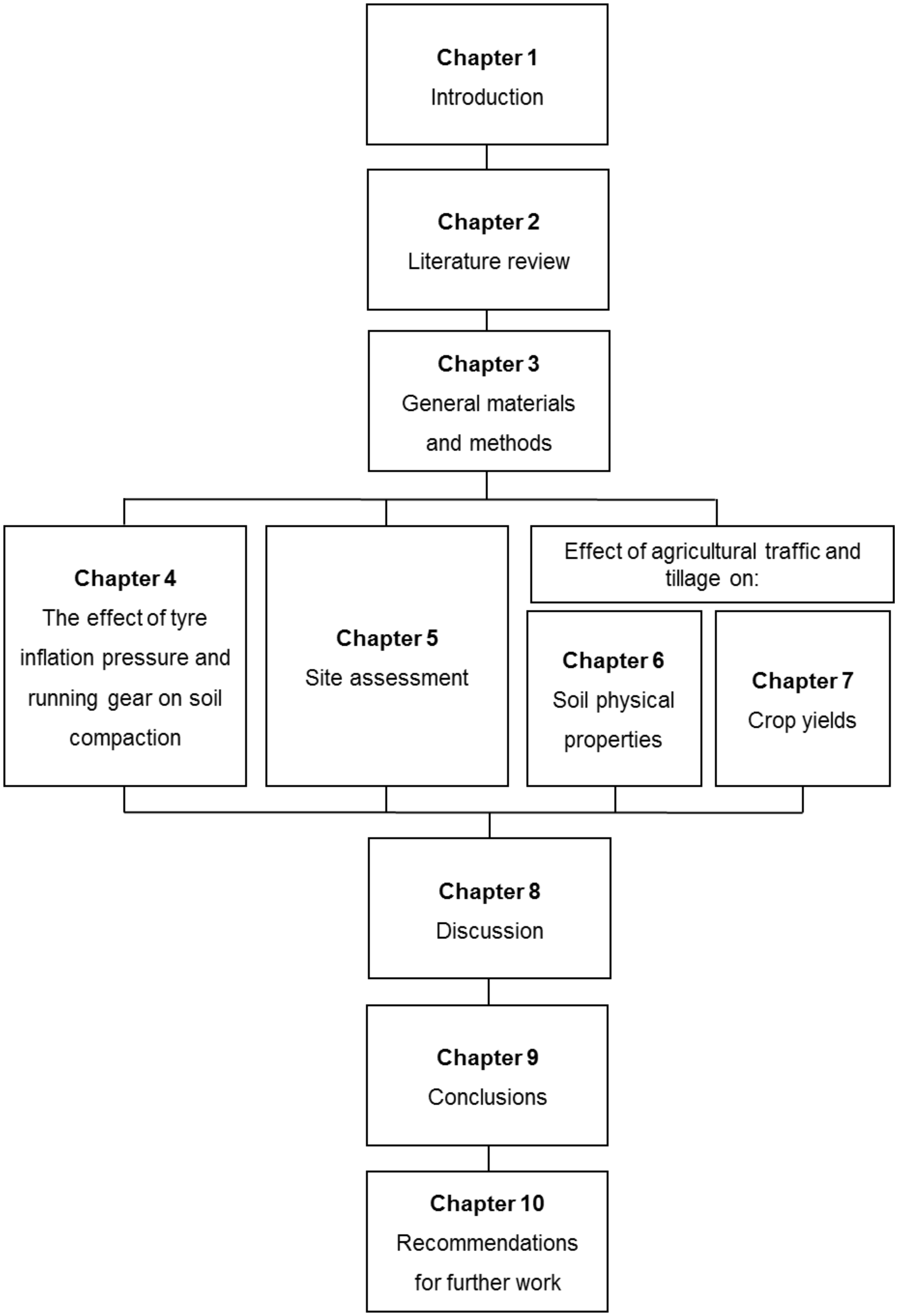


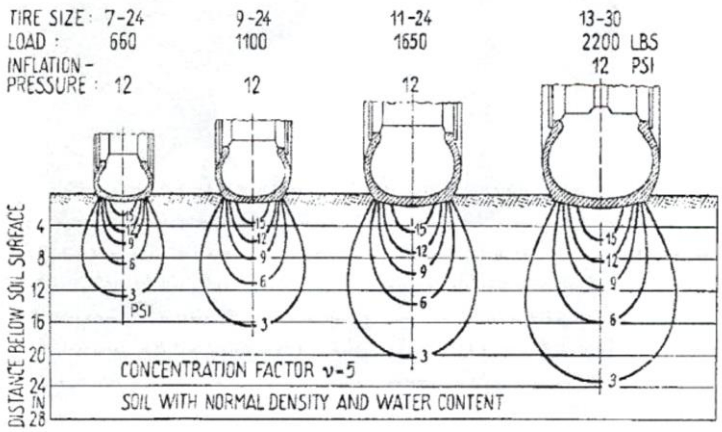
Figure 1.1. Thesis structure.

2. Literature review

2.1. Introduction to agricultural machinery

The use of off-road vehicles and mechanised establishment methods have become integral to arable crop production in the United Kingdom (UK). In 1994, Soane and van Ouwerkerk (1994) reported that agricultural production systems at the time were characterised by soil degradation. Over 20 years later, the story has not improved and Virto *et al*. (2015) confirm that agriculture production remains one of the leading contributors to physical soil degradation in Europe directly linked to compaction from machinery and soil management (Huber *et al*., 2008). The introduction of specialist agricultural machinery, and the focus on improving production efficiencies (Arvidsson, 2001; Gasso, 2013) has resulted in the significant increase in size and weight of agricultural machinery over the last 40 years. According to agricultural press, the average tractor in 1975 weighed approximately 2.5 tonnes (t) and by 2013 this had increased to 6.5 t. Tracked tractors can weigh up to 24.5 t, combine harvesters 33 t and beet harvesters 62 t (Farmers Weekly, 2014).

Work reported by Söhne (1958) proposed that under higher wheel loads stresses extend to a greater depth below the soil surface (Figure 2.1). Dickson and Ritchie (1996) found no evidence of the benefit of using wider tyres to minimise tyre-induced compaction, even when operated at low inflation pressures.



Source: Söhne (1958)

Figure 2.1. Curves of pressure under a range of tyres.

2.1.1. The effect of contact pressure on soil pressure

Equation 2.1 provides a simple calculation of contact pressure by dividing the wheel load (W) by the contact area (A) and an indication of the compactive effect of tyres within the surface layers of the soil (Spoor *et al*., 2003).

$$P_C = W / A \qquad \textbf{Equation 2.1}$$

The distribution of stress under different tyre sizes at two different wheel loads (3 Mg and 6 Mg) was modelled by Lamandé and Schjønning (2011). Modelling was based on stress measured by transducers buried at 0.3, 0.6 and 0.9 m in the soil profile. Söhne's model (1958) did not consider the depth below 0.7 m, but the findings reported by Lamandé and Schjønning (2011) showed that, although there was no significant difference in soil stress between treatments at 0.9m, the depth to which higher stresses extended in the soil profile was increased under the narrower tyre, and under the increased wheel load. At a depth of 0.3 m and a lower wheel load of 3 Mg, differences in soil stress as a result of tyre size were not significant ($P > 0.05$). Only at wheel load of 6 Mg was the soil stress significantly higher ($P = 0.02$) under the smaller tyre compared to the larger tyre.

Laboratory based research completed by Antille *et al*. (2013) reported on vertical soil displacement and increases in soil bulk density following a single pass of three sizes of combine harvester tyres at a fixed vertical load of 10.5 t. The researchers concluded that the largest tyre size, which also had the lowest tyre inflation pressure, resulted in the least amount soil displacement and increases in soil bulk density.

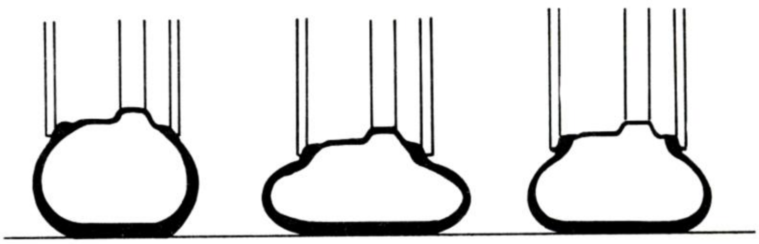
Tijink *et al*. (1995) considered that mounting additional tyres, to achieve a wider tyre-soil interface, is an economically feasible approach to reduced ground pressure under high wheel loads in the topsoil, and also its transmission through the soil profile to the subsoil.

2.1.2. The effect of tyre inflation pressure and carcass stiffness

Equation 2.1 did not consider the effect of tyre inflation pressure (P_i) or carcass stiffness (P_{CS}) on calculated contact pressure (P_C), and thus, these models often underestimate actual pressures. The contact pressure of a tyre at a given inflation pressure can be predicted using Equation 2.2 as described by Misiewicz (2010).

$$P_C = P_i + P_{CS}$$ **Equation 2.2**

Tyre inflation pressure affects the size of the tyre deflection and load distribution, as shown in Figure 2.2. Ultimately this affects the performance and wear of the tyre (Agricultural Training Board, 1989) and machinery and fuel consumption (Michelin, 2014a). If a tyre is over-inflated, the contact area is reduced which results in higher contact pressure, loss of traction and risk of wheel slip and rutting in-field (Agricultural Training Board, 1989) and accelerated wear on the roads (Michelin, 2014a). Raper *et al*. (1995) reported that with increasing tyre inflation pressure rut depth increased, suggesting that the effect of high inflation pressure traffic would have a greater vertical impact on the soil profile. In this study, pressure transducers were mounted on tyre and tyres were mounted on a frame (Raper *et al*., 1995). Under-inflation affects the longevity of the tyre by heightening the risk of failure (Agricultural Training Board, 1989). Under-inflated tyres carry more of the load near the edge of the tyre (Raper *et al*., 1995), have greater rolling resistance, and are more difficult to manoeuvre in the field and on the road.



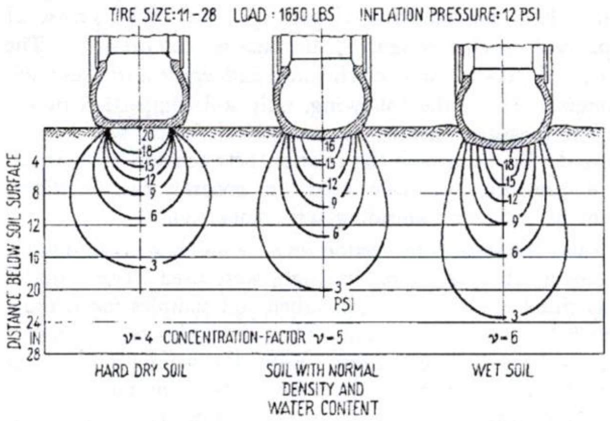
Source: Adapted from Agricultural Training Board (1989)

Figure 2.2. The effect of tyre inflation pressure on tyre deflection.

Vermeulen and Klooster (1992) observed that tyres inflated to low inflation pressures (40-80 kPa) in soil conditions that are wetter, and therefore more vulnerable to compaction, resulted in less topsoil smearing than in the high inflation pressure (80-160 kPa) treatment. There was no clear benefit of lower tyre inflation pressures on the subsoil.

Earlier work completed by Söhne (1958) considered the role of soil moisture on the vulnerability of soils to the transmission of pressure through the profile, as shown in Figure 2.3. In harder and drier soils greater pressure is concentrated in the centre of the tyre-soil contact area, in a circular pattern. Under increasing soil moisture content the pressure reaches greater depths in a narrower cylindrical pattern (Söhne, 1958).

Spoor *et al*. (2003) recommended maximum in-field tyre inflation pressures to minimise or avoid subsoil damage based on vulnerability classifications derived from soil texture, soil moisture and topsoil and subsoil condition. Where the soil is “not particularly vulnerable”, Spoor *et al*. (2003) propose a maximum tyre inflation pressure of 160 kPa. In “extremely vulnerable” conditions, the authors propose a maximum tyre inflation pressure of 40 kPa, less than half of that modelled by Söhne (1958).



Source: Söhne (1958)

Figure 2.3. The effect of soil moisture on soil pressure transmission.

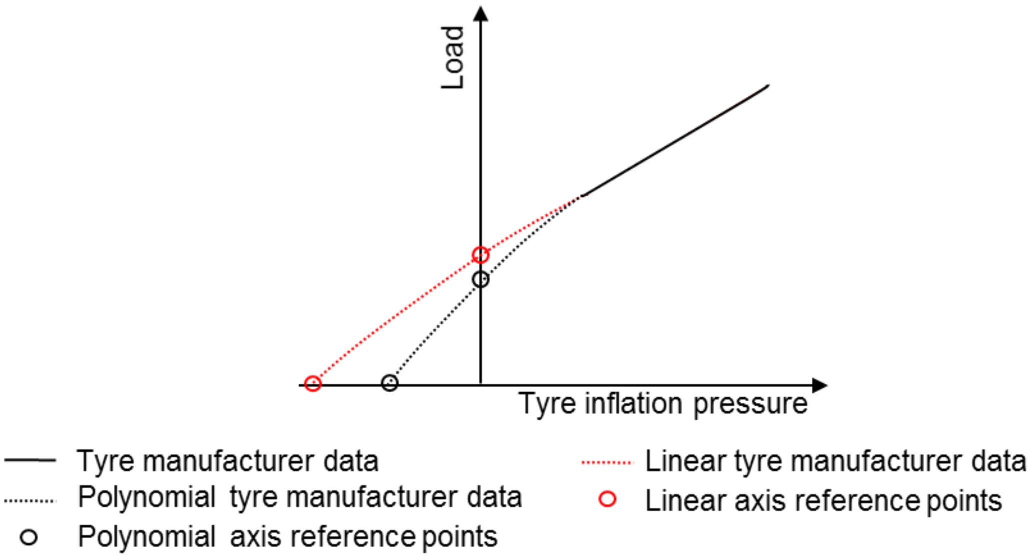
The theory of increasing soil vulnerability is supported by work reported by Antille *et al*. (2013) who reported on a linear relationship between the initial soil bulk density and the increase in bulk density following trafficking. The increased strength of the soil prior to trafficking, indicated by higher levels of soil bulk density, resulted in lower increases in soil bulk density after traffic. Seehusen *et al*. (2014) also reported that high values of soil bulk density in the subsoil minimised the effects of subsequent trafficking.

2.1.3. The effect of carcass stiffness

Researchers have concluded that a reduction in tyre inflation pressure can reduce soil pressures. When van den Akker *et al*. (1994), however, maintained a heavy wheel load (32 kN) at high (240 kPa) and low (80 kPa) tyre inflation pressures their results showed that the measured soil pressures did not reduce by the same rate that the tyre inflation pressure had been lowered; a 67% reduction in tyre inflation pressure achieved a 33% reduction in maximum stress. This suggests that the tyre construction, specifically the carcass stiffness, plays an important role in stress measured at the tyre-soil interface.

A tyre is an extremely complex structure and the technology and design of their construction has changed considerably over the last 80 years. Early tyres, known as cross ply or bias tyres, were made of a rubber moulding that houses a series of cords and wires known as plies (Michelin, 2014a) constructed from multiple overlapping plies of cotton. These tyres offered little protection against soil damage, were inflexible and thus prone to overheating, footprint deformation, increased tyre slip and loss of engine power. In 1946, Michelin developed the first commercially available radial tyres, whereby plies constructed of natural and synthetic rubbers, fabrics and chemicals are arranged in an outward direction from the centre of the tyre. Radial tyres are more durable than cross ply tyres, are able to carry heavier loads at low tyre inflation pressures, and when used at the correct inflation pressure according to the load, improve load distribution, operating performance, comfort, traction and soil protection (Michelin, 2014a) and result in less soil compaction than cross-ply tyres (Botta *et al*., 2008).

Tyre carcass stiffness is a function of tyre construction, which plays an important role in the inflated tyre profile (Evans, 2011), and influences its carrying capacity, or maximum loading weight, and the distribution of load across the tyres width (Misiewicz, 2010; Michelin, 2014a). A more flexible tyre carcass carries the load across the entire width of the tyre compared to a stiff carcass, where the load is concentrated at the edges resulting in uneven load distribution, and maximum contact pressures up to ten times greater than estimated (Alakukku *et al*., 2003). In the absence of available carcass stiffness data, Misiewicz (2010) proposed the use of prediction models for calculating the mean carcass stiffness using manufacturer specification data, as shown in Figure 2.4.



Source: Adapted from Misiewicz (2010)

Figure 2.4. Carcass stiffness prediction models based on tyre manufacturer data.

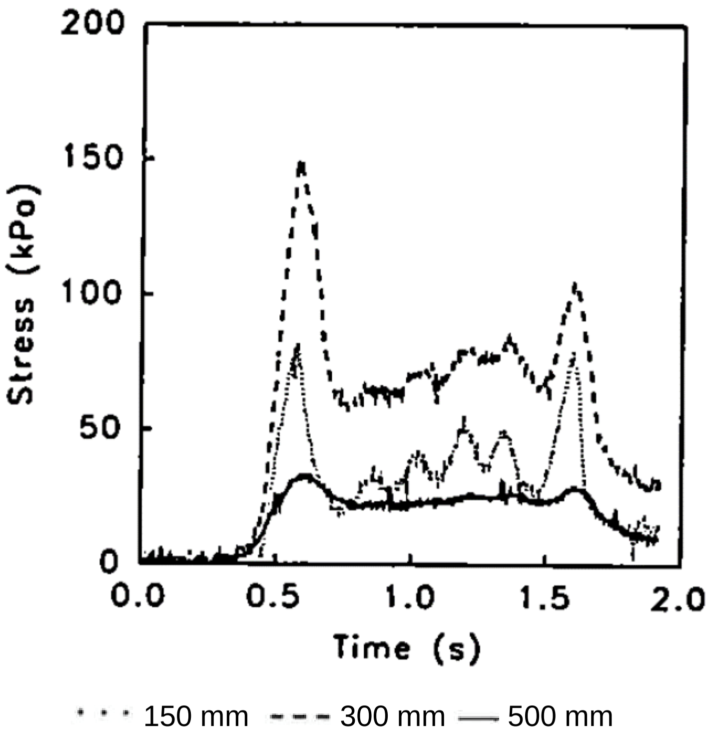
Data provided in tyre manufacturer manuals can be used to estimate the carcass stiffness (±20%). The first technique, uses the load that the un-inflated tyre can theoretically carry (y-axis intercept), which when divided by the contact area, is converted into a value of carcass stiffness, referred to as Model A hereafter. Alternatively, it is possible to estimate tyre carcass stiffness based on the inflation pressure of the tyre at zero load (x-axis intercept), referred to as Model B hereafter. The second method does not require the measurement of the tyre contact area and is therefore rapid, and provides estimates of carcass stiffness ± 20%. Misiewicz (2010) concluded that the use of a linear regression, compared to a 2nd order polynomial, produced lower coefficient of determination (R^2) values, but produced better estimations of carcass stiffness.

2.1.4. *Low ground pressure specific tyres and tracks*

The threat of topsoil and subsoil degradation has prompted the development of traffic management solutions including low ground pressure (LGP) tyres and tracks to limit exerted contact pressure (Tijink *et al*., 1995). The development of larger volume tyres that have the same external diameter as the standard equivalent avoids the problems encountered, for example highway regulations, with earlier LGP technologies achieved by fitting additional or larger tyres (Michelin, 2014b). Recent developments in tyre construction have revolutionised tyres to have even greater sideway flexibility known as Ultraflex technology (Michelin, 2014b). Manufacturers claim that these tyres are able to carry heavy loads at low inflation pressures with a greater surface contact area which improves traction, offers greater soil protection, improves efficiency, endurance, comfort, ease of use, longevity and fuel and time savings (Michelin, 2014b). Michelin have developed a range of tyres with improved flex (IF) and very high flexion (VF) for a range of agricultural machinery. No experimental work, however, has been found to support the conclusions regarding the AxioBib IF tyres although illustrative field experiments have shown that Ultraflex technology in the CereXBib range, designed for combine harvesters, results in significantly lower compaction in comparison to standard MachXBib tyres and competitor tyres over the depths investigated (0 – 250 mm) (Farming Monthly, 2011). To the authors knowledge there is no peer-reviewed experimental work to support these conclusions.

The development of rubber tracked vehicles dates back to 1987 (Cousins *et al*., 2016). Layers of rubber, fabric and steel cables form a belt surrounding a series of wheels to create a continuous track. Track design and construction has changed over time with the latest designs featuring hard wearing mid-wheels with larger casings for lasting strength, reliability and improved operating efficiency (Challenger-Ag, 2014).

Blunden *et al*. (1994) used soil strain transducers to determine the effect of a rubber tracked Cat Challenger on an earthy sand, as shown in Figure 2.5, and revealed the high stresses under the sprockets of the track construction. There was no significant difference in the maximum stress from dual tyres and the rubber-tracked vehicle at 0.3 m, although at 0.4 and 0.5 m the tyres resulted in significantly higher maximum stress, suggesting that the stresses under the tracked vehicle do not extend as deep in the soil profile. Bashford *et al*. (1998) also compared the effect of tracks and tyres on soil compaction but found no significant differences in changes in soil bulk density in the topsoil and subsoil. Their results suggested that the compactive effect of tracks did not extend as deep in the soil profile. Furthermore, Alakukku *et al*. (2003) concluded that the uneven load distribution from tracked vehicles is only evident in the soil surface layers.



Source: Blunden *et al*. (1994)

Figure 2.5. Stress (kPa) measured at 150 mm, 300 mm and 500 mm under a tracked Cat Challenger.

Spoor *et al*. (2003), however, suggests that in conditions whereby subsoil damage is of concern, the contact pressure of tracks, estimated by dividing the load (W) by the contact area (A) should be doubled as a minimum due to uneven load distribution along the track length (Equation 2.3).

$$P_C = (W / A) \times 2 \qquad \textbf{Equation 2.3}$$

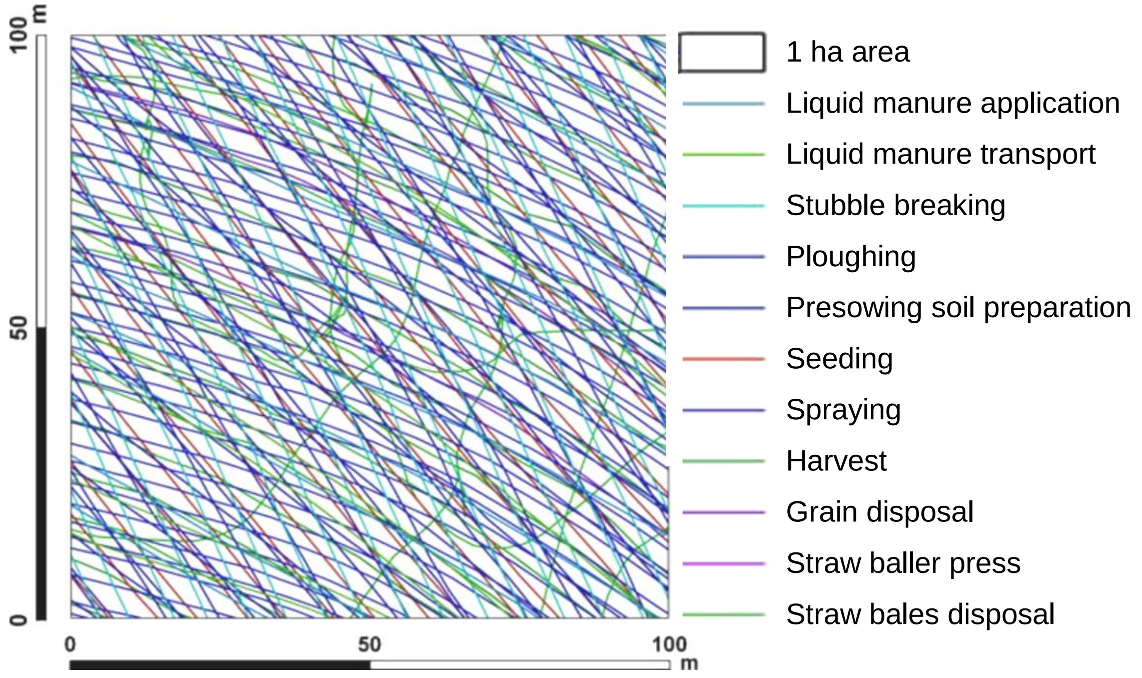
Ansorge and Godwin (2007) completed research in a soil bin in controlled laboratory conditions to compare soil deformation under wheeled and rubber tracked combine harvesters. Assessments concluded that tracks result in less soil deformation and although they have a greater compactive effect at the surface (0-120 mm) the vertical extent of the compaction, determined using a cone penetrometer, is minimal. As a result, the compaction caused by tracked vehicles is easier to remove, requiring approximately one third of the energy than tyre-induced compaction. This is not in agreement with the model proposed by Spoor *et al*. (2003), although the authors (Ansorge and Godwin, 2007) did confirm that the configuration of lugs, support wheels, track stiffness and tension in the track construction means that the distribution of the pressure is not uniform, and continues for a longer duration of time.

Similarly, Arvidsson (2014) compared the effect of dual and single wheel tyre vehicles with tracked vehicles. The results showed that whilst the highest soil stresses resulted from the single tyre treatment, the stresses along the length of the track were more variable. The influence of these peaks in soil stresses were more pronounced at 150 mm compared to 300 mm in the soil profile.

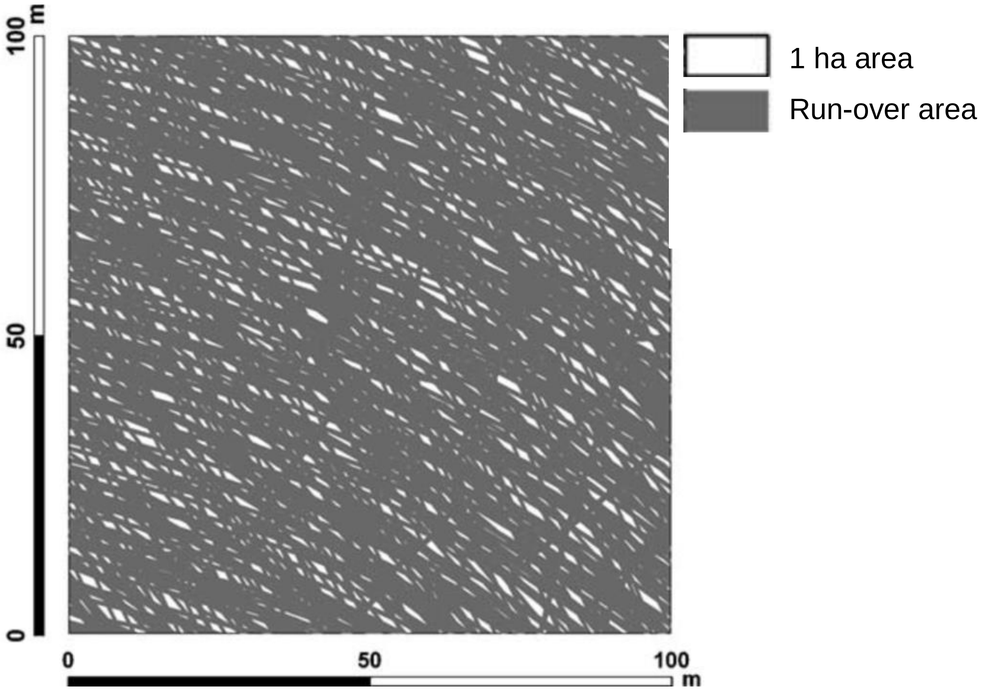
2.2. Introduction to traffic management systems

The trafficking intensity of an agricultural production system determines the area over which the stresses are applied (Kroulík *et al*., 2009). Figure 2.6a illustrates the traffic intensity in a 1-hectare area of a RTF conventional tillage system during one season of cereal production (Kroulík *et al*., 2009). At the field scale, this equates to trafficking 86% of the field in the growing year (Figure 2.6b). The use of shallow (Figure 2.7a) and zero tillage (Figure 2.8a) respectively, reduces the number of in-field operations and therefore reduces the total area exposed to a wheelings to circa. 65% (Figure 2.7b) and 43% respectively (Figure 2.8b) (Kroulík *et al*., 2009). The link between traffic and tillage intensity is self-perpetuating; as tillage intensity reduces, the amount of traffic reduces, from 11 in-field operations in a conventional system to eight, and six in-field operations in a shallow and zero tillage system respectively. This is not only due to a reduction in the compaction remedial work that is necessary, but also because additional manure applications are not required in reduced tillage systems (Figure 2.7 and figure 2.8) where straw, and therefore carbon, is not removed from the system.

a)



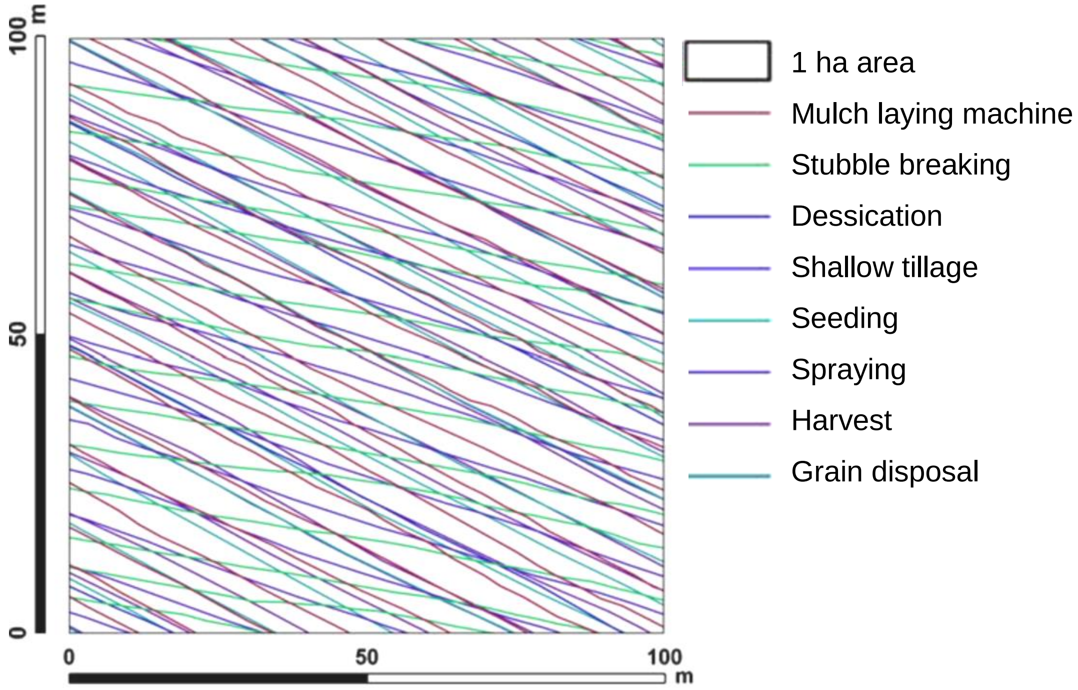
b)



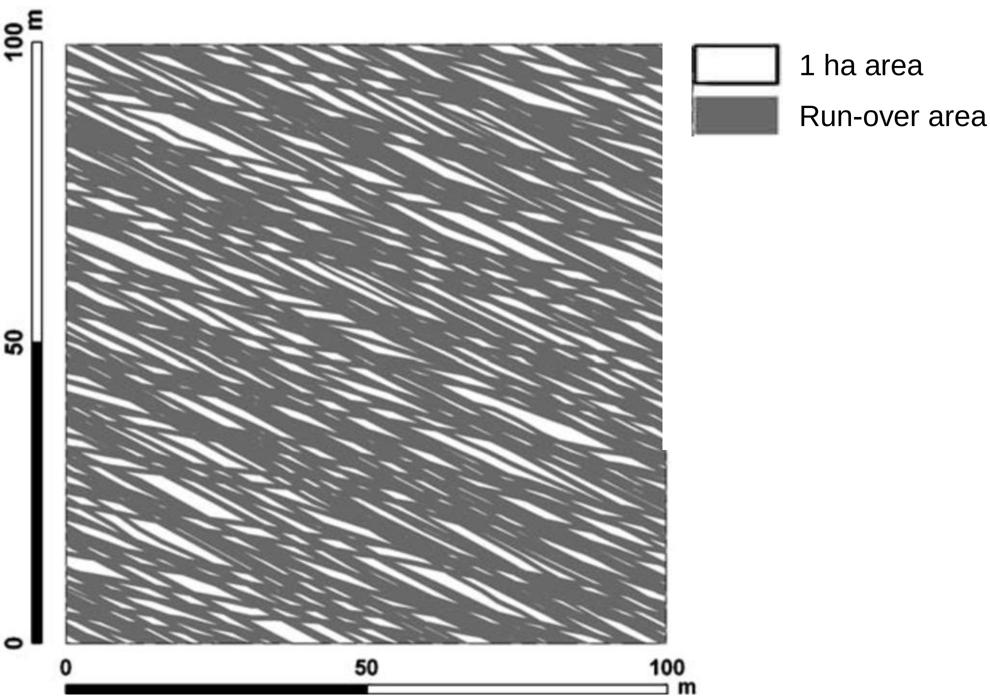
Source: Adapted from Kroulík *et al*. (2009)

Figure 2.6. Graphic representation of a) machinery trajectories, and b) total trafficked area for random traffic farming conventional tillage.

a)



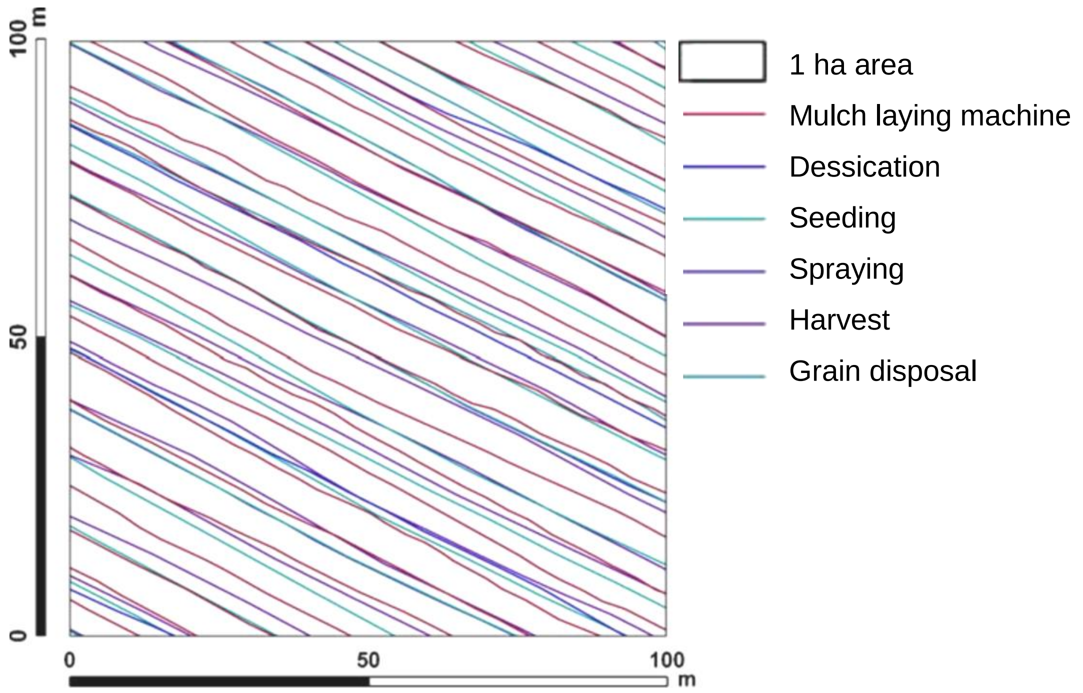
b)



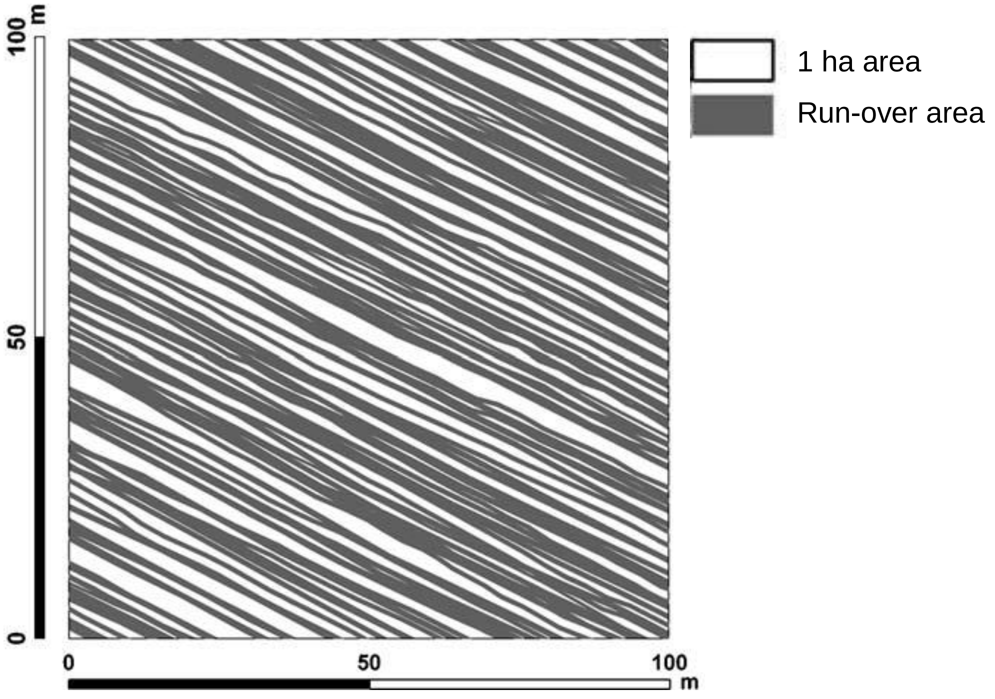
Source: Adapted from Kroulík *et al*. (2009)

Figure 2.7. Graphic representation of (a) machinery trajectories, and (b) total trafficked area, for random traffic farming shallow tillage.

a)



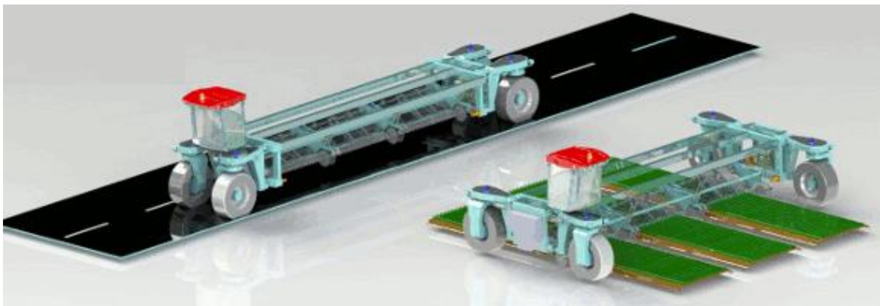
b)



Source: Adapted from Kroulík *et al*. (2009)

Figure 2.8. Graphic representation of (a) machinery trajectories, and (b) total trafficked area, for random traffic farming zero tillage.

It is possible to remove vehicle wheelings from the cropped area of a field by implementing a zero traffic system. Traffic still enters the field, but the cropped area remains untrafficked. The first examples of zero traffic systems date back over half a century to when steel rails were used (Halkett, 1858). These systems were later developed into wide-span gantry systems, an example of which is shown in Figure 2.9. A gantry system is a frame mounted on a wide track gauge, between which implements attach onto sections that are able to move independently of each other.



Source: CTF Europe (2013)

Figure 2.9. Wide span gantry system transport on the highway and working in the field.

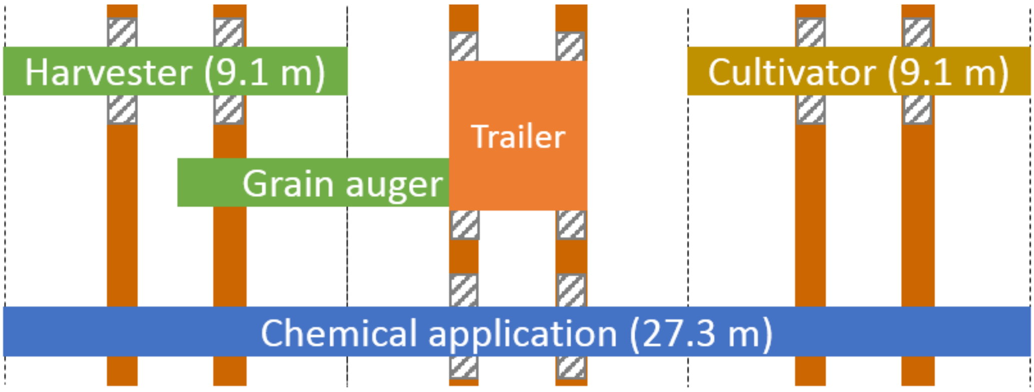
Chamen *et al*. (1992a) investigated the use of a partial 12 m-wide gantry system on energy consumption. The gantry system completed secondary cultivations and chemical applications only. Compared to conventional practice, the partial gantry system reduced fuel by up to 44% and trafficked area by 50%, and increased yield by 19% (Chamen *et al*., 1992a). There is no evidence from the authors that the work, although completed over two sites, was fully randomised and replicated. The work therefore cannot be considered wholly reliable. Furthermore, development of the gantry was required as the mechanical action of moving the plough mounted on the frame resulted in compacted and smeared conditions. During deep cultivations, the gantry experienced wheel slip and it was not possible to mount all implements, i.e. seeding equipment, on the gantry frame and alternative crop establishment methods were required (Chamen *et al*., 1992a). This method of minimising traffic-induced compaction is therefore not currently appropriate for implementation in agricultural production systems. Pedersen (2013a) continued the development of the gantry system where a 9.6 m research prototype has been implemented on a Danish vegetable farm. It has been possible to reduce trafficked area from 21% to just 6% (Pedersen, 2013a). Movement of the gantry system is not restricted by transport regulations, as it is able to travel on the highway at 2.5 m wide (Pedersen, 2013a). The benefits of this system, in addition to reducing compaction, includes flexible working widths, lighter implements, and greater efficiency in a variety of crop production systems (Pedersen, 2013a).

An alternative method of implementing a “zero traffic system” is to confine all vehicles to permanent wheelways or traffic lanes using controlled traffic farming (CTF). Controlled traffic farming is a “whole farm approach to the separation of crops and wheels” (CTF Europe, 2013). Kroulík *et al*. (2011) demonstrated that CTF minimises the areas in a field exposed to compaction to as little 31%; an average reduction in trafficking on Australian farms ranges from between 45-80% in a RTF system to 11-16% under CTF.

Researchers in Australia have stated that the system is economically viable (Tullberg *et al*., 2007) and models show that a CTF system can increase farm profits by as much as 50%. Australian farmers and researchers have concluded that CTF has improved the economics of farming (Tullberg *et al*., 2007) and has been adopted by the Australian sugar industry as a method of improving the sector’s sustainability.

Farmers have been practicing CTF for over a decade in Western Australia (Isbister *et al*., 2013) most widely in the cotton industry and increasingly so in cereal production (Silburn and Glanville, 2002). The Australian Northern Agricultural Catchments Council (NACC) published a Controlled Traffic Farming Technical Manual (Isbister *et al*., 2013) to provide key information to farmers on the benefits, challenges and mechanisation aspects of establishing a CTF system.

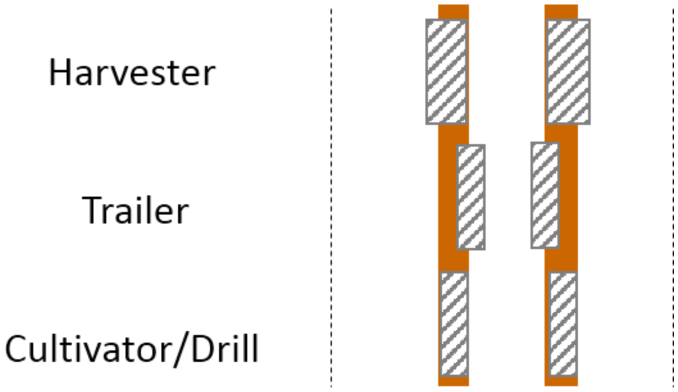
The greatest benefits of CTF systems are when the width of all track gauges match (Bell *et al*., 2003): the distance from wheel centre to wheel centre across all equipment is the same. Figure 2.10 illustrates a “3:1 ratio” layout (Australian terminology) or “ComTrac” system (European terminology). Suitable for implements less than 12 metres (Isbister *et al*., 2013), this layout uses a single wheel track and implement width and the chemical application is a direct multiple.



Source: Adapted from CTF Europe (2013)

Figure 2.10. Layout of a “3:1 ratio” or “Com Trac” controlled traffic farming system.

An “OutTrac” footprint, as shown in Figure 2.11, uses the same formula of three harvesting/implement widths to one chemical application on the same tramlines, but vehicles have slightly different wheel track widths. The header width of the combine harvester, as it is one of the heaviest machines used in farming operations, should dictate the selection of the operating width (Isbister *et al*., 2013).



Source: Adapted from CTF Europe (2013)

Figure 2.11. OutTrac controlled traffic farming vehicle footprint.

Controlled traffic farming is not a rigid system. Many configurations are possible, and the interpretation of the system when implemented into a commercial practice is dependent upon crop rotation, soil type, available machinery and investment budget (CTF Europe, 2010).

Wheelways can be cropped or uncropped: the benefit of uncropped wheelways is that they create firm compacted traffic lanes that are clearly defined and therefore useful for in-crop guidance. Wheelway maintenance can be targeted to remove isolated compaction (Rowell, 1994) and to avoid rutting under repeated wheelings (Bell *et al*., 2003).

In a seasonal CTF system (sCTF), the permanent wheelways are not used for harvesting and primary tillage operations due to the economics of these operations at smaller scales, i.e. it is more economical to cover wider working widths for primary tillage and seeding (Vermeulen and Mosquera, 2009). Seasonal controlled traffic farming was first used in organic farming in the Netherlands, where the soil structural benefits of CTF were symbiotic to those of an organic farming system (Vermeulen and Mosquera, 2009). Similar to a CTF system, the use of sCTF permits a reduction in tractor size, increased number of workable days and improved farm profit (Vermeulen, 2006). Currently there are 28 000 ha of seasonal-CTF in Europe.

The increasing use of information and communication technologies in agriculture has become a central part of CTF (Auernhammer, 2001), which relies on repeated accuracy to maintain the permanent routes of machinery passes and avoid overlaps (Kroulík *et al*., 2011). Over the last 20 years, the development of differential global positioning systems (DGPS), specifically real time kinematic (RTK), has improved the accuracy of global navigation satellite systems to allow geo-spatial positioning and navigation of agricultural vehicles and implements with an accuracy of ±20 mm (Sun *et al*., 2010).

Auto-steer equipment is becoming increasingly reliable and affordable and as the systems become more developed and accessible their uptake is increasing. A number of options are available, ranging from tractors that are manufactured “auto-steer ready” with terrain compensation to assisted steering add-ons (Trimble, 2014). Implement steering and control, where a global navigation satellite system (GNSS) antenna is mounted on the implement, maintains it in the correct position ensuring precision seeding and variable rate chemical applications.

The concept of GNSS and CTF are complementary as both encourage a whole system approach to soil, crop, field and fleet information management. For example, geographic information systems (GIS) containing information based on soil properties and crop yield monitoring from previous seasons are used to manage traffic in zones of high soil moisture content that are at higher risk of degradation (Bell *et al*., 2003). Information for both vehicle and implement guidance is available to the operator using an in-cab display which can be linked to the farm office and other vehicles to exchange data on field plans and operations, performance and productivity.

Farmers report that, once established, a CTF system requires less management. For many farmers, however, the implementation of CTF is more problematic. The Australian Grain Research Development Cooperation (GRDC) recognise the importance and difficulties when integrating large and heavy combine harvesters into a traffic management system (Webb *et al*., 2004). Similarly, it is essential, and identified as a priority that the width of seeding and spraying equipment fits into the system as both of these operations occur when soil moisture is high and at the greatest risk of compaction (Webb *et al*., 2004).

One of the primary investment costs is associated with modification, or purchasing, of machinery to fit into the system. Isbister *et al*. (2013) report that the estimated cost per farm for the establishment of a CTF system in Australia is less than $40,000 AUD (~£21,000 GBP) and modifications range from $2,000-$10,000 AUD (~£1,040-£5,200 GBP) (1.00 AUD = 0.520686 GBP).

Research completed nearly 30 years ago concluded that high investment costs compromise the whole-system benefit (Lamers *et al*., 1986). More recent work confirmed this as a perceived obstacle to the uptake of controlled traffic farming in the UK (Day, 2015). The research concluded that farmers perceive their machinery fleets to be inadequate and expensive to change, in addition to the cost of management time to implement an unfamiliar system.

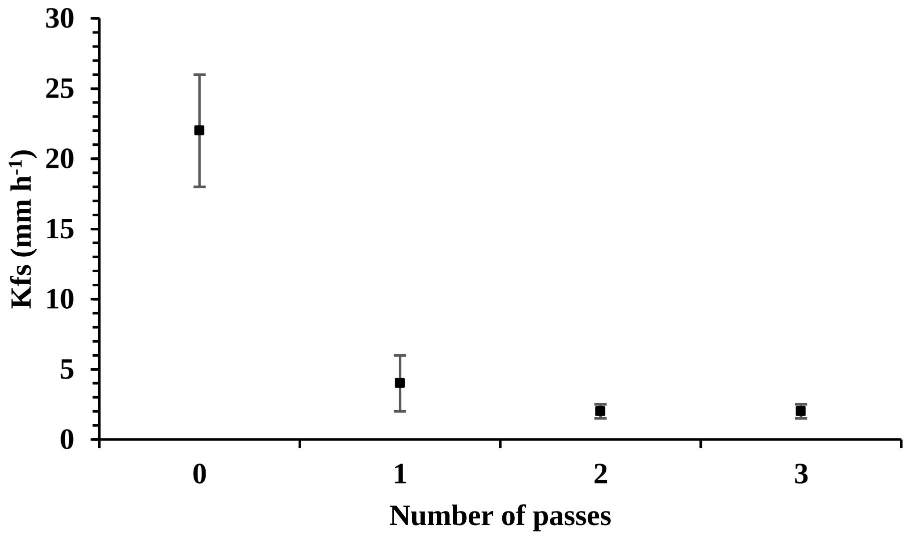
In 2013 it was reported that on a global scale there are only a few regions where CTF has been implemented. This does little to increase the availability and affordability of investment into these technologies. However, Vermeulen (2006) has shown that for a 200-hectare farm, a 2% increase in yield is needed to cover the cost of investment for a seasonal-CTF system. Increases in yield reported in the literature (section 2.2.2) are far above this level.

The availability of machinery and expertise, both engineering and agronomic, may have been a limiting factor in the uptake of CTF. However, machinery manufacturers are beginning to recognise and advocate CTF. Manufacturers of precision guidance solutions advertise their products with CTF as a marketing tool (New Holland, 2014). For the Australian market, John Deere provide “3m Controlled traffic wheel spacer kits” (Deere, 2013) to extend wheel track widths. Just over a decade ago, Case patented a hinged unloading auger to assist farmers in implementing CTF. The development of the hinged auger satisfies farmers’ demands for wider header widths but also for storage and transportation as the auger folds away (Silver, 2003). 10 years later Case released their 12.2 m combine harvester with matched auger in the UK, designed for the CTF market (Chamen, 2013). In the Czech Republic, Horsch have tested their development of an extended unloading auger on Claas combines. The extended auger allows for unloading in a chaser bin in the next wheel track of a 12 m CTF system (Pedersen, 2013b).

2.2.1. The effect of agricultural traffic on soil physical properties

Multiple traffic impacts occur in agricultural production systems, whereby areas of the field are repeatedly trafficked up to seven times throughout the year, as shown in section 2.2. Chyba (2012) concluded that the first traffic pass significantly reduces surface water infiltration rate by approximately 82%, as shown in Figure 2.12. This is in the range reported by Silburn and Glanville (2002) and Chamen (2011) who found that rates of water infiltration were 29% - 400% higher on untrafficked soils respectively.

Repeated trafficking after the second pass of a tractor did not have a significant effect on surface water infiltration rate (Chyba, 2012). Repeated wheelings can, however, result in hard compacted layers deeper in the soil profile, as reported by Arvidsson (2001). At 0.5 m depth below the soil surface an increase in wheel load from the control, zero traffic, to four traffic passes of a sugarbeet harvester (34.5 Mg) resulted in significantly ($P < 0.05$) higher soil bulk density (Mg m^{-3}). There was no significant difference in soil density under loads of 18 Mg or one pass of the 35 Mg load, suggesting that it is the effect of multiple traffic loadings that result in subsoil compaction. Similarly, Alakukku *et al*. (2003), Koch *et al*. (2008) and Botta *et al*. (2009) have also reported on the cumulative effect of repeated wheelings on increasing the risk of subsoil compaction.



Source: Adapted from Chyba (2012)

Figure 2.12. The effect of traffic passes on water infiltration rate.

The repeated trafficking of controlled traffic farming wheelways is, however, beneficial in Australia and permits increases in field input and operating efficiencies. The use of compacted permanent wheelways increases trafficability, particularly after heavy rainfall, and allows farmers to access fields for seeding operations up to eight days earlier than conventional systems (McPhee *et al*., 1995; Dickson and Ritchie, 1996).

As Australian maize, potato and cereal production has converted to CTF there has been rapid improvements in reducing the soil losses. When comparing the effects of trafficked and untrafficked soil on surface soil-water interactions, Silburn and Glanville (2002) and Li *et al*. (2007) concluded that controlled traffic farming reduced run-off by 25% and 36% respectively. A CTF system has fewer environmental impacts compared to conventional systems, which has had a positive effect on reducing soil nutrient losses and minimises herbicide leaching and pollution of groundwater (Masters *et al*., 2008).

Water in the compacted wheelways is, however, less available to plants, but this is limited to a small zone of the field surrounded by areas of improved water regime (Li *et al*., 2007). Between 0-0.5 m in the soil profile, controlled traffic farming increases plant available water by 11.5% compared to wheeled treatments (Li *et al*., 2007). Farmers are discovering that on untrafficked soil, CTF has eliminated water ponding, improved the soil water holding capacity (McHugh *et al*., 2009) and plant available water. This is proving critical in areas, or times, of limited rainfall, where water-use efficiency is essential.

Changes to the soil water regime can be attributed to changes in the soil structure as a result of trafficking. Lamers *et al*. (1986) reported that where vehicles travel on permanent wheelways in a controlled traffic farming system, the soil structure in the cropped area is improved. Chamen *et al*. (1992b) reviewed a series of European traffic and tillage experiments. Overall, zero traffic resulted in reduced soil bulk density and later work (Chamen, 2006a) agreed, concluding that soil conditions are more favourable under controlled traffic. Arvidsson (2001) showed significant differences in soil bulk density at a depth of 0.5 m below the surface between untrafficked and trafficked soil.

McHugh *et al*. (2009) determined the changes in soil structure of a clay-rich soil after a CTF permanent-bed conservation tillage system was established in two blocks on a field formerly managed with random traffic conventional tillage. After 22 months, the soil structure and soil water capacity had significantly improved. Bulk density reduced from circa. 1.40 Mg m^{-3} to 1.25 Mg m^{-3} at 100 mm. Available water capacity increased by 5.2 mm per 100 mm depth of soil. No information, however, is available for any changes to the conventionally managed soil over this time.

Vermeulen and Mosquera (2009) compared the effects of sCTF with RTF on soil structure over four years of commercial organic vegetable production in the Netherlands. Topsoil structure was improved under sCTF with a significantly lower penetration resistance ($P < 0.05$).

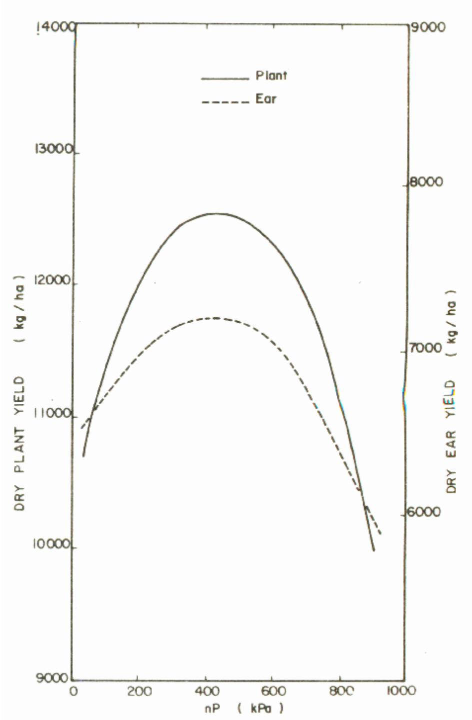
Dickson and Ritchie (1996) concluded that CTF saves both time and money with a significant reduction in energy requirements. Similarly, Chamen *et al*. (1992a) reported findings from European traffic research concluding that reduced ground pressure and zero traffic systems minimise cultivation input. This research quantified the effect of traffic on energy consumption using a gantry system to remove trafficking from plots, and concluded that 50% of the draught and energy was required on untrafficked soil to create a good seedbed. Farmers have also reported that CTF reduces energy requirements, and saves time and costs from having to perform fewer operations at shallower depths, thus reducing equipment and labour costs. Concerns surrounding rising fuel prices are abated by a 39% reduction in tractor hours (h) and 40% fuel savings are reported in the literature (Bowman, 2008) and range on-farm between 5%-58%.

Tullberg (2000) completed a study to determine the effect of wheel traffic on the power requirement of tillage operations only. Tillage draught forces, the horizontal soil force on tillage tools and therefore the effort required to cultivate the soil, were determined following the pass of a tractor wheel across soils cultivated to different intensities. The draught required to cultivate wheelways was significantly greater throughout the soil profile than untrafficked soil. This is in agreement with work reported by Auernhammer (2001) who concluded that CTF lessens the need for remedial action with intensive tillage.

2.2.2. The effect of agricultural traffic on crop yields

The first indicator of soil quality index is "the ability of soil to enhance crop production" (Arshad and Martin, 2002). Surface applied loads from agricultural traffic can expose the soil to conditions whereby crop-supporting thresholds are reached or exceeded whereby plant root extension is inhibited, and thus crop establishment, growth and yields can be negatively affected due to limited access to air, water and nutrients. The monitoring of soil indicators and thresholds is often used to assess management practices (Arshad and Martin, 2002), yet reliance on them can be misleading as a well-structured soil permitting good root extension could register high values of penetration resistance (Huber *et al*., 2008). Critical limits, or thresholds, of key soil indicators and their comparison is dependent on crop type as some crops are more compaction tolerant, and thus visual assessments, albeit subjective, can compliment quantitative measurements of the soil profile (Huber *et al*., 2008).

Raghavan *et al*. (1979) reported on the effect of soil pressure in a clay soil on corn plant and ear yield, as shown in Figure 2.13. In a dry year, a moderate amount of trafficking of a clay soil, and consequently soil compaction, is advantageous for increasing water availability and corn crop yield. An increase in compaction, from moderate (1.05 Mg m^{-3}) to heavy, resulted in inhibited root extension and crop growth (Raghavan *et al*., 1979). Logsdon and Karlen (2004) concluded that for silt and silt loam soils, a bulk density of 1.55 Mg m^{-3} is often the minimum value at which root restriction may be observed, for sandy and sandy loam soils this critical threshold is increased to 1.6 Mg m^{-3} (Huber *et al*., 2008).



Source: Raghavan *et al*. (1979)

Figure 2.13. The effect of soil pressure on plant and ear yield.

To investigate the effect of traffic-induced compaction on crop yields, Arvidsson and Håkansson (2014) applied four differential levels of traffic-induced compaction, in an experiment across 13 sites in Sweden. Traffic treatments were realised by zero traffic, one pass at low load (1590-2099 kg) and low tyre inflation pressure (55-95 kPa), one pass at moderate load (2650-3010 kg) and moderate tyre inflation pressure (90-105 kPa), and three passes at high load (3130-3900 kg) and high tyre inflation pressure (155-195 kPa). With moderate compaction, wheat and barley showed relative yield increases of up to 12% compared to zero traffic. Under increased trafficking crop yields decreased, although both wheat and barley were less sensitive to soil compaction in comparison to the other crops in the research which included peas, potato and sugarbeet. As this study was completed across multiple sites, and not all sites were cropped consistently, actual yield differences were not presented and therefore percentage yield increases cannot be presented here. The highest degree of compactness was identified at bulk densities of 1.40-1.45 Mg m^{-3}.

In their investigation into the effects of wheeling intensities of two different tractor and slurry tanker combinations at a total load of 16 Mg and 36 Mg, Seehusen *et al*. (2014) concluded that a single wheeling at 16 Mg and 36 Mg resulted in a 23% and 28% yield reduction respectively. In this study, 10 traffic passes at 36 Mg resulted in total crop loss. This study focused on the effect of load and did not compare the role of tyre inflation pressure to minimise traffic-induced compaction.

Yield increases under controlled traffic farming are reported widely in the literature. Li *et al*. (2007) considered the effect of intensive and controlled traffic on soil water and crop production in Australia. This study concluded that zero traffic increased winter wheat grain yields by 9% compared to plots that were exposed to one pass of a tractor. Similarly, Gamace (2013) found increases in wheat and barley yields of 30% and 9% respectively under controlled traffic farming on commercial farm-scale trials. In European studies, Chamen *et al*. (1992b) reported that yields of sugar beet, potatoes, onions and ryegrass increased under controlled traffic farming between 4-14%. Yield improvements of cereal crops, wheat and barley, are more variable in the range of -9-21%. The variation in data in this research could be because a number of different projects formed the study that all used different methodologies during different time-periods and across a range of soil types and climatic conditions. Later work by Chamen (2011) reported a 16% decrease in winter wheat yield under trafficking. These results are similar to those of Dickson and Ritchie (1996) who reported that where traffic was completely removed, winter wheat, winter barley and oilseed rape yields increased by 19% compared to low ground pressure and random traffic.

McPhee *et al*. (2015) have reported on two field experiments and one farm demonstration performed in Tasmania to compare controlled and random traffic in vegetable production systems. Overall the research demonstrated that the use of controlled traffic is beneficial to soil physical properties, but results were variable. Yield results were also variable, ranging from -14 to 24%, perhaps due to the design of the experiment over a range of sites that varied in topography, soil type, cropping and management.

Between 1982-1986, Chamen *et al*. (1990) investigated the effects of random traffic at standard and low tyre inflation pressures, and zero traffic on winter wheat yields established with shallow and zero tillage. To achieve a low ground pressure system dual tyres were used, thus exposing a greater area to trafficking. No significant differences between treatments were found.

Experiments were performed in Scotland, UK (Ball and Ritchie, 1999) to determine the effect of soil compaction on crop performance and soil conditions. Differential treatments were achieved by zero traffic, light compaction by roller and heavy compaction by tractor. The researchers concluded in dry soil conditions, even the increased surface applied loads did not result in any changes to crop growth. In wet conditions, however, yields were reduced by 24% compared to untrafficked soil.

Researchers in Slovakia have imposed compacted strips to simulate RTF onto a field managed in CTF system (Galambošová *et al*., 2014). Controlled traffic farming proved beneficial in terms of overall yield improvements in the range of 10-50% (Godwin *et al*., 2015), but crop yield from the permanent wheelways was 13-17% lower than untrafficked parts of the field (Galambošová *et al*., 2014). The influence of traffic passes on tillage quality was also determined, measured by soil roughness and residue distribution (Galambošová *et al*., 2010). The study compared an out-trac controlled traffic farming system with a random traffic farming concluded that, after two years of the study, there were no significant differences in tillage quality, and permanent zones of wheelway compaction did not interfere with residue management (Galambošová *et al*., 2010; Macák *et al*., 2015).

There has been concerns over yield loss on and next to wheelways in controlled traffic farming systems, due to the compaction extending beyond the width of the wheels themselves (Lamers *et al*., 1986). However, yield compensation from edge rows that border the traffic lanes is reported (Bell *et al*., 2003).

Further European studies have been reported by Demmel *et al*. (2015), across three field experiments in Germany, which demonstrated generally higher wheat and rye yields from untrafficked zones.

Vermeulen and Mosquera (2009) concluded that there were significant ($P < 0.05$) improvements in yields using a sCTF system in organic vegetable farming in the Netherlands; yield benefits were recorded for 70% of the crop varieties, which included green pea, spinach, onions and carrots (Vermeulen, 2006) but this was inconsistent between different crops and years. This study did not consider the effect of sCTF in an arable farming system.

2.3. Introduction to tillage

Tillage is the primary tool for creating appropriate soil structures to support crop production and is the greatest consumer of energy in the entire farming system (Koga *et al*., 2003) including operational time and machinery wear (Hamza and Anderson, 2005). It predominantly alters the physical properties of the soil and processes that support good crop establishment, growth, development and yield (Badalíková, 2010). Tillage is essential in removing compaction from previous crop growth (Rowell, 1994), yet plays a key role in determining the risk, or resilience, of soil to compaction (Huber *et al*., 2008). There is a direct link between excessive tillage and traffic intensity. Where more intensive tillage systems are used (i.e. ploughing) additional traffic passes, fuel and time is required (Kroulík *et al*., 2011).

For over 6,000 years, conventional UK agricultural production systems have used a plough for primary cultivations (Rowell, 1994). Originally made from a series of wooden and now metal plates, or mouldboards, arranged along its length, the plough turns the soil over in lines known as furrows to a depth of approximately 250 mm. Alternative designs of ploughs, namely the chisel plough, loosen soil at depth but do not remove crop residues from the surface or invert the soil as with a mouldboard (Regnier and Janke, 1990).

The aim of alternative tillage systems, known broadly as conservation tillage, is to improve the sustainability of agricultural production (Rusu, 2005). Conservation tillage is a broad term, which encompasses non-inversion reduced tillage and zero tillage systems. The definition of the system varies but conclusions from the literature suggest that the main aims are: 1) to protect the soil surface from rainfall erosion and runoff by maintenance of crop surface residues (Rowell, 1994); 2) cultivate to a shallower depth; and 3) perform fewer operations (Foth, 1978).

Non-inversion tillage techniques often combine conventional operations in a single pass to reduce traffic, minimise soil disturbance and degradation, time, and cost. Sometimes referred to as “ploughless tillage” or “deep reduced tillage”, a combination implement, differs from a chisel plough in that it cultivates the shallow and deeper soil in one single pass using a series of independently depth adjustable discs, tines and a roller. Crop stubbles are incorporated into the soil but not inverted and buried at depth, as in ploughing.

It has been shown that reduced tillage systems are more profitable due to decreased energy consumption by the removal of intensive ploughing cultivations (Foth, 1978; Koga *et al*., 2003; Rusu, 2005). There has been a transition towards conservation tillage in Europe, primarily as a way of reducing production costs, in addition to protecting soil (Holland, 2004). A summary of costing for conventional and reduced tillage systems is provided in Table 2.1.

Table 2.1. Tillage and drilling costs of agricultural systems

Deep tillage		Shallow tillage		Zero tillage	
Operation	**Cost (£/ha)**	**Operation**	**Cost (£/ha)**	**Operation**	**Cost (£/ha)**
Ploughing	85	Shallow tillage	53	Direct drilling	52
Seedbed preparation	43	Drilling	46		
Drilling	29				
Press	25				
Total	**182**		**99**		**52**

(Source: adapted from Redman, 2016)

There are no soil cultivations before seeding in zero tillage, also known as direct drilling. Seed is drilled directly into the stubble of the previous crop and as little as 5% of the soil surface is cultivated (Morris *et al*., 2010; Väderstad, 2014). Establishment costs are closely linked to the working depth and number of operations, and thus, direct drilling has the lowest establishment costs in the UK (Redman, 2016). Increased weed and pest pressures in these systems can, however, result in increased use and cost of chemical applications (Morris *et al*., 2010).

2.3.1. The effect of tillage on soil physical properties

Between 1975-1977, Clutterbuck and Hodgson (1984) investigated the effect of ploughing, shallow tillage and zero tillage of a clay loam soil. Zero tillage resulted in significant increases in penetration resistance and soil bulk density to a depth of 190 mm and 180 mm respectively. Mühlbachová *et al*. (2015) also reported that zero tillage resulted in the significantly higher soil bulk densities from 0-200 mm compared to mouldboard ploughing. After three years of the study (Clutterbuck and Hodgson, 1984), however, differences in soil bulk density throughout the profile were not significant. Similarly, Rusu (2005) reported that differences in the soil bulk density between ploughing and minimum tillage were small.

Li *et al*. (2007) compared chisel ploughing and zero tillage to determine their effect on the soil moisture regime. The authors concluded that zero tillage reduced runoff by 16%. This is lower than reported by Keeble (2007), who reported that ploughing increased runoff, on a clay loam soil in Essex, UK, by 29% and 63% compared to reduced and zero tillage systems respectively.

The studies reviewed thus far have been completed over time-scales of 2-6 years. Longer-term studies, conducted over 4-22 years (Voorhees and Lindstrom, 1984; Kahlon *et al*. (2013) reported that the benefits of conservation tillage, including improvement in soil porosity and water infiltration, are realised after a longer period of time. These benefits, however, were only seen in the absence of traffic.

Tillage induced improvements to soil and crop properties in the absence of trafficking were also observed by Chan *et al*. (2006). The use of deep ripping to remove a layer of pre-existing soil compaction initially increased yields by 20%, although this was only seen in the absence of trafficking, whereby bulk density values were measured at 1.27 Mg m^{-3}. Subsequent trafficking caused this layer to reform, with bulk density values of 1.54 Mg m^{-3}.

Over a ten-year period, Botta *et al*. (2009) compared mouldboard ploughing and harrowing, with zero tillage regimes. This study, completed in Argentina on clay soil, focused on the vulnerability of soils under different tillage systems to the effect of traffic-induced soil compaction. It was reported that conventionally tilled soil was more susceptible to traffic-induced compaction as a result of multiple traffic incidences, indicated by increased rut depth. Ankeny *et al*. (1995) also investigated the effect of wheelings across five field locations and compared the effect of chisel ploughing and zero tillage. The effect of traffic was dominant over the effect of tillage and was also more profound in ploughed soil compared to zero tillage. Results reported by Reichert et al. (2016) suggest that this could be due to increases in the soil organic matter in the surface layers following coversion to zero tillage, and thus the soil is more resilient to the impact of traffic.

2.3.2. The effect of tillage on crop yields

Clutterbuck and Hodgson (1984) reported that the greatest yield depreciation from direct drilling was realised in the first growing year, whereby it resulted in 16% lower yields compared to ploughing. Over the three years of the study, the mean difference in yield between ploughing and zero tillage was 4%, with yields from zero tillage lower in two out of the three years.

Between 1998 and 2002, Knight (2003) investigated the effect of ploughing, minimum tillage and direct drilling on continuous winter wheat yields across three field sites in the UK. Over the four-year period of the study, the mean winter wheat yield from across the three sites ranged from 6.90-7.19 t ha^{-1}, 6.64-7.94 t ha^{-1}, and 5.54-7.18 t ha^{-1} for the plough, minimum tillage and zero tillage systems respectively. Within this study Knight (2003) also investigated the effect of reduced traffic passes (3 and 4 passes) compared to the standard (7 traffic passes). These passes, however, refer to traffic related to chemical applications only and therefore differences in yields were attributed to crop husbandry and not as a consequence of traffic induced soil compaction.

Rusu (2005) concluded that ploughing resulted in increased yields of 3.99-3.73 t ha^{-1} compared to 3.49-3.68 t ha^{-1} for minimum tillage, a maximum difference of 14%. Alvares and Steinbach (2009) performed meta-analysis of 39 experiments to compare mouldboard ploughing, chisel ploughing, and zero tillage on Argentinian yields of soybean, wheat and maize. Wheat and maize yields were 10% lower under chisel plough and zero tillage. The duration of use of establishment systems ranged across the experiments used in this research, from 0.5-20 years, and data on all treatments were not available for every site. Much smaller differences in yields were reported by Rieger *et al*. (2008), who compared the use of a mouldboard plough, a chisel plough and zero tillage on two sites in Switzerland between 1995-1999. Grain yield of winter wheat under conventional tillage was 0.9% and 2.9% higher than minimum and zero tillage respectively. These results represent a mean across the four-year period of the experiment, and the authors do not provide any data on the change in yields over time, a factor that is reported to play a key role in the success of zero tillage systems (Voorhees and Lindstrom, 1984; Kahlon *et al*., 2013; Monsefi *et al*., 2016; Reichert *et al*., 2016).

Seehusen *et al*. (2014), from an experiment performed in Norway, concluded that winter wheat yields are strongly dependent on tillage, and direct drilling reduced yields by 24% compared to ploughing. Where ploughing was used on alternating years with harrowing, yields increased 5% compared to ploughing alone. This study also considered the effect of trafficking intensities at two different vehicle loads (16 Mg and 36 Mg), and concluded that ploughed soil was more resilient against yield loss due to traffic than direct drilling. In ploughed soils, trafficking resulted in a yield loss of 21%, whereas in direct drilled soils, the impact of traffic was much greater with a yield reduction of 84%.

Researchers have, however, reported increase in crop yields in zero tillage systems, even within the first few years following its adoption. Logsdon and Karlen (2004) showed that switching to no-till did not negatively impact crop yields. These results could be, however, distorted as the researchers also changed the cropping rotation from continuous corn to a two or six-year rotation. This change in itself would promote better crop yields, and could have mitigated negative effects of adopting a zero-tillage system.

Li *et al*. (2007) concluded that over the five-year period of a study in Queensland, Australia, zero tillage increased winter wheat grain yield by 3.4% compared to chisel ploughing. The authors noted that the effect of traffic and tillage appears to be cumulative, whereby controlled traffic zero tillage represented best practice and increase grain yields by 15%. This split-plot designed study, however, completely removed trafficking from one plot, and exposed the other plot to total coverage of one pass of a tractor tyre at a constant tyre inflation pressure of 100 kPa. It is not clear in the literature if grain yields were taken from untrafficked soil, or if the analysis included the permanent wheelways.

Similarly, De Vita *et al*. (2007) reported increased winter wheat yields using zero tillage by as much as 80%. In this study, two field sites were used, and each responded differently to the implementation of zero tillage systems. Differences in yields at the site with higher sand content were greater than the site with a higher silt content, indicating that different soil types are either more, or less suitable for the adoption of zero tillage to increase crop yields. The response of this study reported by De Vita *et al*. (2007), however, differs to the classification of soil suitability for zero tillage reported by Butterworth *et al*. (1980). The authors outlined three categories of soils whereby the adoption of zero tillage would be favourable (chalk, limestone, well drained loams, calcareous clays), equal (well drained loams, calcareous clays, other clays) and risky (sandy, silty and wet alluvial) on crop yields.

Keeble (2008) published findings on the impact of tillage system on crop growth and yield, in a three-year wheat, barley and oilseed rape rotation in the UK. Across the whole rotation, yields in the minimum and zero tillage systems were in the range of 89-123% and 79-110% of those of the ploughed system respectively.

The rotation used in the study reported by Mühlbachová *et al*. (2015) was peas, winter wheat, oilseed rape, winter wheat. Between 2007-2010, pea and winter wheat crop yields were significantly lower than mouldboard ploughing. Only in winter wheat were yields significantly lower under zero tillage compared to chisel ploughing. In the second experimental cycle, between 2011-2014, only pea yields were significantly lower under zero tillage compared to mouldboard ploughing.

Monsefi *et al*. (2016) considered the role of conventional and zero tillage on wheat yields on a sandy loam soil in New Delhi. This study also considered the use of raised and flat beds, but for the purposes of this review only the yields from the flat beds have been considered. In the first experimental year, conventional tillage, completed by ploughing and disc harrowing, produced winter wheat yields of 4.44 t ha^{-1} compared to 4.46 t ha^{-1} in zero tillage. In the second experimental year, the reduction in yield in zero tillage was 0.06 t ha^{-1} and differences were not found to be statistically significant.

2.4. Critical review of missing aspects

The review of literature presented in this chapter demonstrates that a variety of studies have been completed on the effect of agricultural traffic and tillage systems on the effect of soil pressures on soil compaction and crop yields. It reveals, however, that the majority of work on traffic and tillage management systems has been completed outside of Europe, and have neglected the use of either low ground pressures systems by focusing solely on the use of controlled traffic farming, or *vice versa*. Where controlled traffic farming has been included in the research, it has often been implemented by the complete removal of traffic from a plot, and thus the influence of permanent wheelways on the overall system performance has not be considered (Dickson and Ritchie, 1996).

Chamen *et al*. (1992b) provided a synthesis of four European studies which investigated the effects of traffic and tillage. Studies which considered three traffic systems, for example in the Netherlands, between 1985-1989 investigated random conventional, low ground pressure and zero traffic, but only intensive tillage was included. Furthermore, the cropping in this study was not a cereal rotation. Only one study, performed in Germany between 1984-1990, considered three tillage systems. These three tillage systems, however, consisted of conventional tillage, and two approaches to conservation tillage, with and without topsoil loosening. The traffic systems included in this study were conventional and low ground pressure, and thus omitted the use of controlled traffic farming. The design of previous research, therefore, has been limited in scope.

The work completed by Chamen (2011) represents the key piece of work, following which this current project was instigated. Chamen (2011) states that the field scale studies he completed, to compare controlled traffic zero tillage, random traffic with plough, non-inversion and zero tillage, were completed without appropriate replication and utilised comparisons made with conventionally managed fields. In a separate study, again across several sites, the Chamen (2011) investigated the use of low ground pressure, achieved using tracks, although treatments changed within the duration of the project. At each site, soils received consistent tillage, although variations in cultivations existed between sites (Chamen, 2011).

Ansorge and Godwin (2007) and Arvidsson (2014) considered the use of low ground pressure systems, namely low inflation pressure tyres, dual tyres and tracks, to minimise soil compaction. Additional axles and tyres, or wider tyres are unlikely to be a practical solution for farmers to increase the contact area whilst maintaining load as they expose a wider area of soil and crops to compaction and damage during field operations (Dickson and Ritchie, 1996). In addition, UK regulations limit the movement of wide vehicles on the highway to <2.55 metres (Gov, 2013). To the authors knowledge there is no peer-reviewed experimental work to support conclusions of the ability of Ultraflex technology to minimise soil compaction in commercial agricultural production systems.

As demonstrated in this literature review, current European knowledge is based on experiments completed across multiple sites and soil types using different crop rotations and vehicle management regimes. Research has often been designed whereby one field, or zone within a field, is compared to a neighbouring area and treatments have been applied to fields or zones over different time scales without appropriate site preparation. These studies are therefore not fully randomised and replicated. To the authors knowledge there is no evidence in the literature of the effect of the range of traffic and tillage systems that are currently available in commercial practice in cereal production systems. The effect of different traffic and tillage management systems on soil is still not fully understood. Therefore, there was a need for research to review the previous studies reported, investigate the soil pressures using modern tyres and tracks, and to develop and implement a field study to determine their effects.

2.5. Research hypothesis and objectives

This thesis documents a three-year study with a primary aim to determine the effect of three traffic systems: random traffic farming standard, random traffic farming low, and controlled traffic farming using three tillage systems: deep, shallow and zero tillage on soil structural properties and function, crop growth and yield.

The hypothesis for this research was that changes to soil structure and function, measurable by penetration resistance, bulk density, soil moisture and hydraulic conductivity, and crop establishment, growth and harvestable yield will be affected by the intensity of traffic and tillage, such that a reduction in traffic and tillage intensity, using controlled traffic farming and reduced tillage, will result in lower values of penetration resistance, bulk density, and increased hydraulic conductivity, crop establishment growth and harvestable yield compared to conventional traffic and tillage.

The objectives of this study were:

1. To establish a fully randomised and replicated single-site field experiment to determine the effect of random traffic farming with standard and low tyre inflation pressures and of controlled traffic farming under deep, shallow and zero tillage.

2. To determine the effect of agricultural traffic and tillage practices on soil physical properties and function, crop growth and yield.

3. General materials and methods

3.1. Introduction

This chapter provides an overview of the experimental facilities, instrumentation and methodology used for the experimental work within this study. Where modifications to methods were used, specific details are included within experimental chapters.

Traffic systems were evaluated, and the proposed site was investigated for uniformity, prior to the design and implementation of a field experiment. The research was completed in three experimental phases:

Phase 1. The effect of tyre inflation pressure and running gear on soil physical properties;

Phase 2. Site assessment;

Phase 3. The effect of agricultural traffic and tillage on soil physical properties and crop yields.

3.2. Outline methodology

Phase 1 involved measuring soil pressures and penetration resistance under multiple traffic passes of tyres and tracks in a sandy loam soil in a covered soil hall experimental facility at Harper Adams University. The tyre and track contact area and contact pressure on the soil surface were determined. A simple method, described by Saarilahti (2002) and Arvidsson and Keller (2007) was used to measure the tyre and track contact area. Two methods for determining tyre contact pressure were evaluated. Firstly, the contact pressure was determined by dividing the load by the measured contact area. Secondly, the influence of tyre carcass stiffness, determined by models described by Misiewicz (2010), was also used to calculate contact pressures for tyre treatments only. The use of these models is only relevant to tyre carcass stiffness, and therefore the contact pressure of the tracked vehicle was determined using the first method. Strain gauge pressure transducers were used to measure vertical pressure at depth within the soil profile. A penetrometer was used to indicate soil compaction. The analysis of tyre and track treatments was necessary to provide treatments that would provide differential soil conditions in the field experimental phase of this research.

Phase 2 was an assessment of the uniformity of a proposed field site and experimental design of the subsequent traffic and tillage study. In-field and remote sensing techniques were employed to examine the variations in elevation, soil type, shallow and deep electrical conductivity, penetration resistance, soil moisture, plant establishment, crop growth and yield.

Phase 3 determined the effect of agricultural traffic and tillage systems in a 3 x 3 factorial experiment on soil physical properties and crop yield of winter wheat (*Triticum aestivum* var*. Duxford*) and winter barley (*Hordeum vulgare* var. *Cassia*). The effects of treatments on soil properties were determined by measurements of bulk density, penetration resistance, soil water content, infiltration and water holding capacity. The effect of treatments on crop yields were determined by measurements of crop establishment, crop growth, harvestable yield, harvest index and grain quality.

3.3. Field site

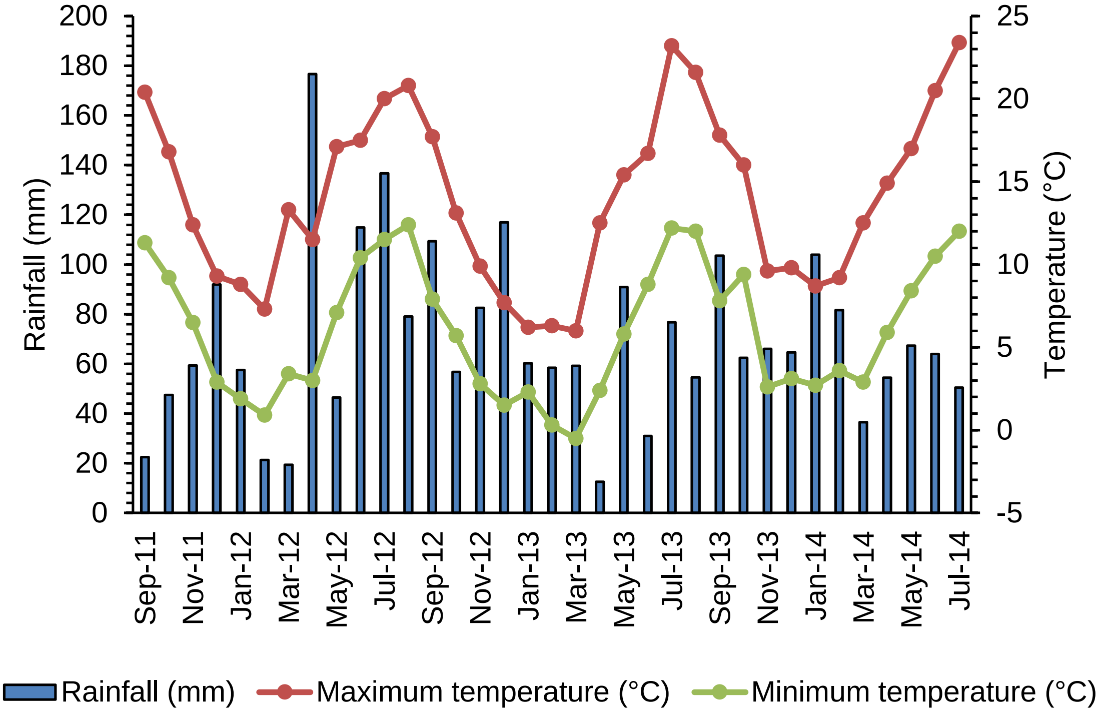
The field site, shown in Figure 3.1, was chosen by the project supervisory team in the summer of 2011 at Harper Adams University, Newport, Shropshire, United Kingdom (UK) (52°46.7899'N, 002°25.5236'W, SJ 71097 20701).

Source: Adapted from Google (2015)

Figure 3.1. Location of the field experiment site at Harper Adams University.

The 8.5-hectare (ha) site used for Phase 2 and 3 of this study, named Large Marsh, lies at 63 metres above mean sea level (mamsl). The predominant soil type was identified according to Beard (1988) as Claverley (Cvy), a very slightly stony sandy loam. The site had a topsoil pH 6.6 and subsoil pH 6.1 (Appendix C). Rosselló and Fernández de Gorostiza (1993) advise avoiding sites that have previously been used for experiments. The experimental site in this current research had previously been managed with conventional soil and agronomic practices, with a cropping history of grassland in 2010, and barley in 2009 and 2008 (Harper Adams, 2014a). Hawkins Drainage Systems contactors designed and installed a sub-surface gravel back-fill land drainage system at 13 m intervals in September 2011.

The mean annual rainfall is 712 mm and mean annual air temperature ranges between 14.3°C (maximum) and 6.1°C (minimum) (2000-2010 average) (Harper Adams, 2014b). Figure 3.2 shows monthly minimum and maximum temperatures and total monthly precipitation during the experiment.



Source: Adapted from Harper Adams (2014b)

Figure 3.2. Monthly rainfall (mm) and mean maximum and minimum air temperatures (°C) from September 2011 to July 2014 at the experimental site in Shropshire, UK.

3.4. Agricultural vehicles

Figure 3.3 shows the two tractors used in this research. Vehicle loads are provided in Table 3.1.

Figure 3.3. Running gear used throughout this research.

Table 3.1. Vehicle loads and load distribution.

Vehicle	Weight (kg)		
	Front	Rear	Total
MF8480	2370	3830	12180
MT765	4460	3315	15945

3.5. Traffic

Existing soil compaction had been removed prior to drilling (section 3.6) as a process of site normalisation, and the field site was subsequently drilled in October 2011 with a 4 m power harrow drill combination in a controlled traffic farming (CTF) system (Figure 3.4). CTF system was used to establish the field to avoid random and extensive soil re-compaction. The 4 m wide CTF system consisted of untrafficked (UT) areas totalling 2.8 m wide, and the wheelways (WW) totalling 1.2 m. These traffic wheelways were mapped using a Leica GPS1200+ (Hexagon, Nasdaq Stockholm) and, with the operating width of the cultivator drill, formed the traffic wheelways and plot widths for the subsequent experiment. They are defined in the experiment as the primary wheelways, and remained the cultivation, seeding and harvesting wheelways for the duration of the project.

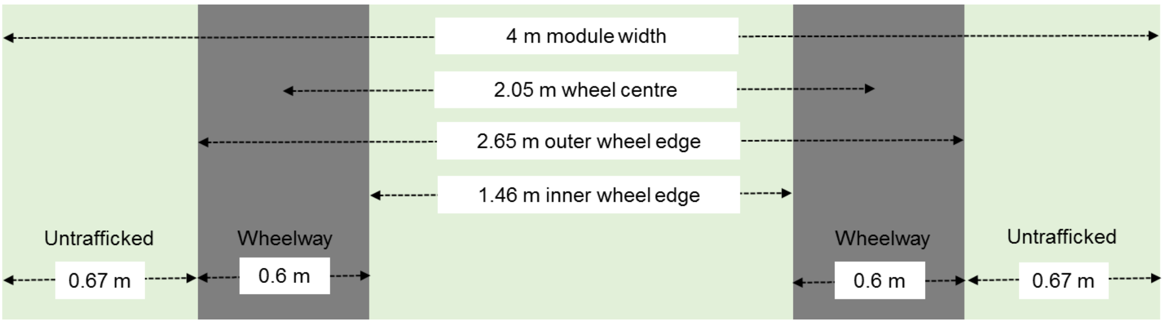


Figure 3.4. Controlled traffic farming system established in autumn 2011.

The experimental plots were established in autumn 2012, to determine the effect of traffic and tillage management systems on soil physical properties and winter wheat (*Triticum aestivum* var*. Duxford*) and winter barley (*Hordeum vulgare* var. *Cassia*) yields. The experiment comprised four replicated blocks of nine 4 x 80 m strips, with each block separated by 4 m border zones for navigation and access. The experimental site was bordered by 12 m headlands. The layout of the experiment was designed to allow long plots (measuring 80 m) as this has been shown to increase accuracy (Day, 1920). Zhang *et al*. (1994) state that optimum plot dimensions balance precision and economics. It can be reasoned that machinery operation and navigation logistics should be considered in addition. Therefore, the turning circle of the vehicle and implements was investigated and the headland widths set at 12 m to enable this.

The effect of traffic and tillage consisted of nine treatments. Three tillage and three traffic regimes were compared within each block (Appendix A). Three traffic treatments of random traffic farming at standard and low tyre inflation pressures, and controlled traffic farming, and three tillage treatments of deep, shallow and zero tillage were selected as appropriate. Using a factorial skeleton ANOVA (Mead *et al*., 1993), four replicates were found appropriate to exceed the minimal residual degrees of freedom (RDF) of 12 (EPPO, 2012), achieving 24 RDF (Appendix B).

3.5.1. Traffic intensities

Additional traffic intensities were designed based on previous traffic management research reported by Kroulík *et al*. (2009). The author determined the intensity of in-field machinery passes, percentage of total wheeled area. Later work (Kroulík *et al*., 2011) reported on the number of repeated passes that occur during one growing season dependent on the traffic and tillage system adopted. For conventional random traffic farming with deep cultivation Kroulík *et al*. (2011) concluded that 85.4% of a field is exposed to tractor tyre within one cropping season. For shallow and zero tillage this is reduced to 64.6% and 42.3% respectively (Figures 2.6 to 2.8, Chapter 2).

Within these systems, Kroulík *et al*. (2011) reported on the percentage of repeated agricultural machinery passes across a field. In conventional random traffic farming with deep tillage, 33.26% was trafficked once, 31.06% wass trafficked twice and 15.6% was trafficked three times. The area of the field exposed to between four and seven passes was 6.22%, and thus the effects of these passes were combined into the three pass zones for the present study. For shallow tillage systems, 39.26% and 19.56% of a field was exposed to one and two traffic passes respectively (Kroulík *et al*., 2011). The area of the field exposed to between three and five passes is 4.93% and therefore these were combined into the two pass zones for the present study. For zero tillage systems, Kroulík *et al*. (2011) did not state the percentage areas repeatedly run-over. Based on their data presented, however, it was possible to calculate the percentage area covered by each operation. Therefore, 20.2% of the field was exposed to traffic at seeding, and crop protection, harvest and grain disposal result in a further 28.91%.

For the present study, traffic treatments were designed, within the constraints of the operating widths of machinery, to represent the traffic intensities defined by Kroulík *et al*. (2009). For random traffic farming standard inflation and low inflation, deep tillage treatments the areas exposed to one and three passes were lower and higher respectively, than reported by Kroulík *et al*. (2011). This was due to presence of the existing permanent wheelways within each plot that were required for tillage and seeding operations. Furthermore, due to the relatively fixed wheel widths and wheel track width of the tractor, there were limitations to the distance by which it could be driven offset from the centre line without trafficking on the neighbouring plot. Minor deviation, therefore, from the work of Kroulík *et al*. (2011) on percentage areas repeatedly trafficked was unavoidable. Differences in total percentage area trafficked between tillage treatments were maintained according to Kroulík *et al*. (2011). Table 3.2 shows the annual traffic intensities applied to each treatment including the number of repeated passes and total percentage area of each treatment trafficked.

Table 3.2. Traffic applied to treatments, including the number of repeated passes and total percentage area of each plot covered, to represent traffic intensities in commercial practice observed by Kroulík *et al*. (2011).

Traffic		Random traffic farming (standard/ low)				Controlled traffic farming			
		Number of passes							
		1	2	3		1	2	3	
		Percentage area trafficked (%)							
					Total				Total
Tillage	Deep	15	30	30	75	0	30	0	30
	Shallow	30	30	0	65	0	30	0	30
	Zero	15	30	0	45	0	30	0	30

Traffic intensities were applied to each plots using a tractor mounted Trimble RTK satellite navigation system and FmX display. The coordinates of each plot were mapped prior to the application of traffic, and used to offset the vehicle from the centre of each plot to apply the additional traffic passes (Figure 3.5).

Figure 3.5 shows the annual traffic compaction intensities applied to each plot across the four blocks, whereby the colour relates to the number of additional passes completed, and the number indicates the total number of traffic passes in each zone including the tillage, seeding and mechanical harvesting operations completed using the primary wheelways. Treatments were coded according to their traffic and tillage system, where the subscript letter refers to the tyre inflation pressure (S = standard; L = low) and the bracketed subscript letter refers to the tillage treatment ((D) = deep; (S) = shallow; (Z) = zero) (Table 3.3).

Table 3.3. Traffic and tillage treatment coding.

Treatment coding	Traffic system	Tyre inflation pressure	Tillage
$RTF_{S(D)}$	Random traffic farming	Standard	Deep
$RTF_{S(S)}$	Random traffic farming	Standard	Shallow
$RTF_{S(Z)}$	Random traffic farming	Standard	Zero
$RTF_{L(D)}$	Random traffic farming	Low	Deep
$RTF_{L(S)}$	Random traffic farming	Low	Shallow
$RTF_{L(Z)}$	Random traffic farming	Low	Zero
$CTF_{(D)}$	Controlled traffic farming	-	Deep
$CTF_{(S)}$	Controlled traffic farming	-	Shallow
$CTF_{(Z)}$	Controlled traffic farming	-	Zero

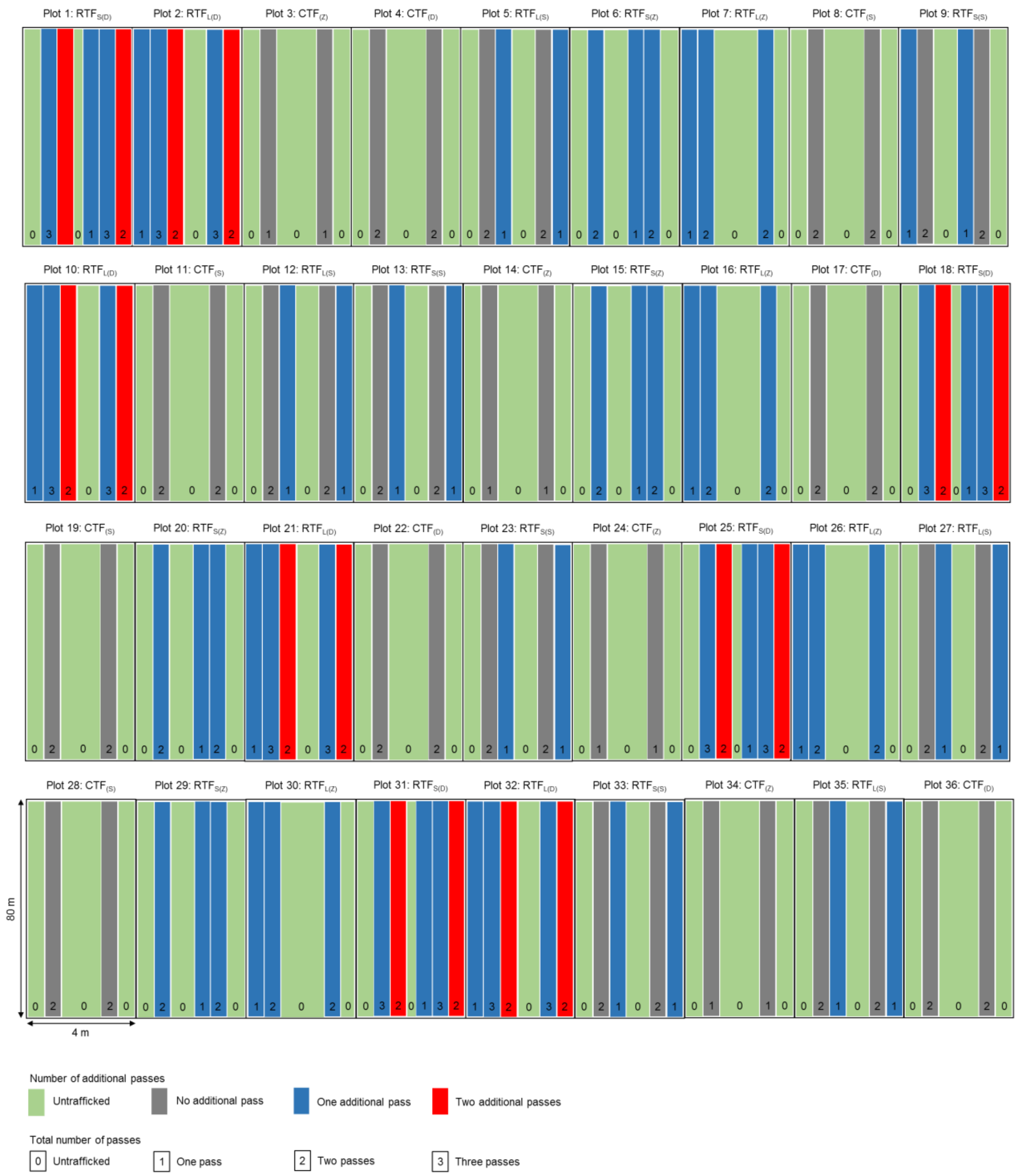


Figure 3.5. Annual traffic compaction intensities.

3.5.2. Tyre inflation pressures

Differential traffic intensities were applied to the plots before the tillage operation preceding planting (18 October 2012 and 7 September 2013) using a compaction protocol designed for this experiment (Appendix C). Traffic intensities were applied at the end of the growing season to simulate the total within field traffic that would be experienced within a field in a year, in accordance with the work presented by Kroulík *et al*. (2009). All high inflation pressure traffic treatments were completed, followed by all low tyre inflation pressure treatments. Where neighbouring plots required differential inflation pressure treatments, the tyres on one side of the tractor were reduced to the appropriate inflation pressure.

Single (1x) and multiple (2x and 3x) wheelings were completed with a 12 tonne 290 HP Massey Ferguson (MF) 8480, fitted with real time kinematic (RTK) satellite navigation system and FmX Trimble® EZ-Steer steering system (±20 mm). Tyre inflation pressures and forward speed (7 km h^{-1}) were in accordance to the results of Phase 1, which determined the effect of tyre inflation pressure and running gear on soil physical properties (Chapter 4). Random traffic farming standard (RTF_S) and controlled traffic farming treatments were applied with MachXBib 600/70 R28 (front) and 650/85 R38 (rear) tyres inflated to 0.12 and 0.15 MPa respectively. Random traffic farming low (RTF_L) treatments were applied with MachXBib 600/70 R28 (front) and 650/85 R38 (rear) tyres inflated to 0.07 MPa

3.6. Cultivation and seeding

Initial soil conditions were restored during Phase 1 of the experiment to alleviate existing compaction by subsoiling to 600 mm using a Flatlift, followed by ploughing to 250 mm. In November 2011, the field was cultivated and sown into winter wheat (*Triticum aestivum* var. *Duxford*) with a 4 m Kverneland Accord power harrow drill combination.

Phase 3 of this experiment compared three different tillage treatments: 1) deep tillage (D), 2) shallow tillage (S) and, 3) zero tillage (Z). Tillage systems were chosen to represent the range of cultivation methods that are used in commercial cereal production whereby 56% of farmers operate a deep tillage system, 30-40% implement reduced tillage and 4% zero tillage (DEFRA, 2010a; Townsend *et al*., 2016). Straw residues from the preceding crop were chopped and retained. In the years 2012 to 2014, tillage and seeding was performed in the autumn (6 November 2012 and 10 September 2013) using a Challenger MT765.

Tilled plots were cultivated at a forward speed of 8 km h^{-1}. Tillage and seeding operations were applied according to a protocol designed by the researcher (Appendix D).

Deep and shallow tillage was performed using a 4 m Väderstand TopDown (Figure 3.6a) to a depth of 250 mm and 100 mm respectively (Morris *et al*., 2010). Väderstad's TopDown single pass non-inversion cultivator is depth adjustable and consists of a series of discs, tines, levelling discs and a reconsolidation packer. Rigid tines are spaced at 270 mm behind two rows of discs and behind the TopDown's wheels (Väderstad, 2015a).

All treatments were sown using a 4 m Väderstand Rapid (Figure 3.6b) in 2012 (9 November 2012) and a 4 m Väderstad Spirit (Figure 3.6c) in 2013 (26 September 2013). The Väderstad Rapid (Figure 3.6b) disc drill has front cultivation tools that were raised out of work for zero tillage plots. In autumn 2013 a Väderstad Spirit disc drill was used to establish the crop, with front tools again raised for zero tillage plots. Both the Rapid and the Spirit drilled at 125 mm row widths. The timings of cultivation and seeding were determined according to field conditions.

a)

b)

c)

Source: Väderstad (2014; 2015b)

Figure 3.6. a) Väderstad TopDown, b) Väderstad Rapid, c) Väderstad Spirit.

3.7. Agronomy and crop husbandry

In November 2011, group 4 winter wheat (*Triticum aestivum* var. *Duxford*) seed was drilled with a seed dressing of fluquinconazole prochloraz applied as Jockey®, to prevent bunt, seedling blight, take-all, yellow rust, *Septoria tritici* and brown rust (BASF, 2016a).

On 9 November 2012, group 4 winter wheat (*Triticum aestivum* var. *Duxford*) seed was drilled with a seed dressing of fludioxonil, applied as Beret Gold®, and silthiofam, applied as Latitude®, to prevent fungal diseases including *Microdochium nivale* (snow mould), *Fusarium culmorum* (seedling blight, ear blight), *Septoria nodorum* (shrivelled grains) and *Gaeumannomyces graminis* (take all), all of which are common risks in second wheat

(Syngenta, 2016; Monsanto, 2016). On 26 September 2013, winter barley (*Hordeum vulgare* var. *Cassia*) was drilled with a fungicidal seed dressing of prochloraz and triticonazole, applied as Kinto®, to protect against *Ustilago nuda* (loose smut), *Ustilago hordei* (covered smut) *Pyrenophora graminea* (leaf stripe), *Microdochium nivale* (seedling blight) and *Fusarium* spp. (foot rot) (BASF, 2016b).

Application tramlines at 24 m intervals were perpendicular to the direction of seeding to avoid unequal additional trafficking and applications. Agronomic and application recommendations were provided by Hodges and Moss (H.L. Hutchinson Ltd). All plots received the same input levels of phosphorus (P), potassium (K) and magnesium (Mg) and nitrogen (N) fertiliser applications based on soil sample indexes (Table 3.4) (Eurofins, 2012).

Table 3.4. Soil indices of phosphorus, potassium, magnesium and total nitrogen.

	Topsoil	Subsoil
Phosphorus (P)	2	3
Potassium (K)	1	2-
Magnesium (Mg)	3	3
Total Nitrogen (N) (g/100 g DM)	0.09	0.26

Source: Eurofins (2012)

Primary and trace elements were applied as necessary according to RB209 recommendations (DEFRA, 2010b). Comprehensive pest management strategies were employed including post-emergence herbicide and spring herbicide applications, T0 to T3 fungicide applications, insecticide and molluscicide applications where necessary, plant growth regulators and dessicant prior to harvest. Further information on crop protection products and fertiliser applications for 2011 to 2014 are provided in Appendix E.

3.8. Instrumentation

3.8.1. Tyre inflation pressure

Tyres were inflated using a Sealey © compressor (SA812) and checked using a calibrated Newbow Ltd © tyre pressure gauge (NB604).

3.8.2. Tyre and track contact pressure

The static tyre-soil contact area (A) for each treatment was determined by driving the tractor onto the soil surface. The contact area was marked with flour, and after the vehicle had been removed the uncovered area was measured (Saarilahti, 2002; Arvidsson and Keller, 2007). Contact pressure (Pc) was calculated for all treatments, using Equation 3.1, based on the wheel load (W) and contact area (A).

$$P_C = W / A$$ **Equation 3.1.**

Agricultural tyre contact pressures and the resulting ground pressure have been attributed to the sum of inflation pressure and the tyre carcass stiffness, as reported by Misiewicz (2010). Therefore, estimated contact pressure (P_C) of tyre treatments were also calculated (Equation 3.2), from tyre inflation pressure (P_i) and estimated carcass stiffness (P_{CS}).

$$P_C = P_i + P_{CS}$$ **Equation 3.2.**

Tyre carcass stiffness was estimated using the prediction models described by Misiewicz (2010) whereby manufacturer specifications of tyre load and inflation pressure (Michelin, 2013 and 2014b) are evaluated using linear and 2nd order polynomial regression. The loads at zero inflation pressure were converted into carcass stiffness pressure (MPa) using the load at zero tyre inflation pressure divided by the measured contact area (Model A). Estimations of tyre carcass stiffness were also calculated using Model B, whereby the tyre inflation pressure at zero load is calculated from the x-axis intercept of the linear and 2nd order polynomial regression.

3.9. Measurements of soil physical properties

For laboratory weighing of soil and crop samples, a PC 4400 (Delta Range (R) calibrated balance was used. Soil samples were dried in a 105˚C oven.

3.9.1. Soil pressure

Vertical soil pressures were measured during Phase 1 of this research using Roxspur© strain gauge transducers (Appendix F) calibrated using an air pressure calibrator every 0.05 MPa over a range of 0.0-0.5 MPa. Soil was excavated using a rear tractor-mounted auger reversed over the experimental site to avoid trafficking. Eight transducers, mounted in protective cylindrical units (Figure 3.7), were buried in the centre of the wheeltrack at 150 mm (n=4) and 300 mm (n=4) below the surface.

Figure 3.7. Pressure strain gauge transducer in protective cylinder.

Once the sensors had been placed in the soil profile, the excavated soil was backfilled in layers, using a circular ended rod, to represent the surrounding undisturbed soil conditions. Ansorge and Godwin (2007) proposed this methodology to ensure the removal of compacted layers that would otherwise inhibit the propagation of pressure within the profile. The methodology for re-filling soil above the pressure sensors was verified by measuring the penetration resistance of the backfilled and undisturbed soil. Data from the transducers were collected using a National Instruments CompactRio© system and logged with virtual instrument software on a laptop PC at 0.1s intervals. Resulting traffic induced soil pressures were calculated according to transducer calibrations (Appendix G).

3.9.2. Penetration resistance

During Phase 1 and Phase 2 of this study, an Eijkelkamp penetrologger (Eijkelkamp Soil and Water, Netherlands) fitted with a 100 mm^2 60° top angle cone was used to measure soil penetration resistance at 10 mm intervals from the soil surface to a depth of 300 mm, with data averaged every 100 mm. During Phase 3, penetration resistance was used to determine the compactive effect of treatments on soil collected using a hydraulic penetrometer (Figure 3.8) in collaboration with SOYL (Newbury, UK). This allowed for data to be collected more accurately by the elimination of operator error as the speed of penetration is consistent. Data were collected using the application tramlines which ran perpendicular to the direction of cultivating and seeding.

Figure 3.8. SubSOYL ATV mounted penetrometer.

3.9.3. Soil bulk density

A direct method of determining soil bulk density was used, as described by Campbell and Henshall (2000), whereby intact wet soil cores were weighed before they were dried in an oven at 105°C for 24 h and reweighed to determine dry bulk density, using Equation 3.3.

Dry bulk density (Mg m^{-3}) = dry soil weight (Mg) / soil volume (m^{-3}) **Equation 3.3.**

Soil bulk density was measured using the core method, whereby a cylinder measuring 72 mm diameter, 70 mm height and 20 mm thickness, was driven into the soil to 100, 200 and 300 mm. This methodology was later developed whereby an Eijkelkamp liner sampler set (Eijkelkamp Soil and Water, Netherlands) (Figure 3.9) was used to extract intact soil cores measuring 50 mm in width and 350 mm in length.

Source: Eijkelkamp Soil and Water, Netherlands (2015)

Figure 3.9. Liner sampler set used for soil bulk density measurements in 2014.

3.9.4. Measurement of surface and sub-surface soil water properties

At the time of penetration resistance measurements, the soil water status was determined using a FieldScout soil moisture meter fitted with a 160 mm probe.

The gravimetric moisture content of the soil (W_d) was calculated using Equation 3.4 (Reynolds, 1970). The water weight (grams water) was determined from the wet bulk density samples (moist soil wt) after they had been dried in an oven at 105°C for 24 h (dry soil wt).

W_d = grams water / dry soil wt **Equation 3.4.**

The simplified falling head method was used to determine hydraulic conductivity, whereby a cylinder of 152 mm diameter, 150 mm height and 2 mm thickness was hammered into the soil to 70 mm depth. A known quantity of water, 0.3 litres, was poured into the cylinder and the time at which all water had moved into the soil was recorded. A FieldScout soil moisture meter was used to measure the moisture within and near to the infiltration ring and the difference calculated. The saturated hydraulic conductivity (K_{fs}) was calculated according to Equation 3.5 (Bagarello *et al*., 2004). Equation 3.5 requires t_a (time) and $\Delta\theta$ (the difference between the saturated water content and the initial water content). The estimation of $\propto^*$ (the ratio between the soils saturated hydraulic conductivity and the ability of a soil to take up water) of 12 m^{-1} was determined according to Elrick *et al*. (1989).

$$K_{fs} = \frac{(\Delta\theta)}{(1 - \Delta\theta)t_a}\left[\frac{D}{(\Delta\theta)} - \frac{\left(D + \frac{1}{\alpha^*}\right)}{(1 - \Delta\theta)} ln\left(1 + \frac{(1 - \Delta\theta)D}{(\Delta\theta)\left(D + \frac{1}{\alpha^*}\right)}\right)\right]$$

Equation 3.5.

Soil water measurements were taken with a neutron probe (Wallingford Soil Moisture Probe (Type IH II)) (Figure 3.10) using semi-permanent access tubes with a rubber stopper in each tube. Prior to the installation of the access tubes, the soil was augered. Neutron probe counts per second measurements were converted into volumetric moisture content from the surface to a depth of 800 mm. Due to the radiation hazard (Gardner *et al*., 2000) and thus legal restrictions on the use of the neutron probe, it was necessary for authorised users, whom the author acknowledges with thanks for their assistance, to conduct measurements.

Figure 3.10. Neutron probe device.

3.9.5. Measurement of crop properties: Phase 2 and Phase 3

3.9.5.1. Crop establishment

Crop establishment was measured by non-destructive plant counts at emergence using the methodology described by Bell and Fischer (1994), whereby quadrats (2011-2013) or rows (2013-2014) were sampled at random.

3.9.5.2. Crop growth

The normalised difference vegetation index (NDVI) was calculated from measurements of near infrared and visible red NDVI (Equation 3.6) recorded using a using a Crop Circle handheld system and a hand-held CS-45 RapidSCAN (Holland Scientific, Nebraska). Photographs of the plots were taken at key stages within the experiment using a compact digital camera: compaction, during crop construction phase at GS37/39 (construction phase is a two month period from first node to flowering when yield forming leaves form) and pre-harvest. Photographs are provided in Appendix H.

$$\text{NDVI} = (\text{near infrared} - \text{visible}) / (\text{near infrared} + \text{visible})$$ **Equation 3.6.**

3.9.5.3. Harvestable yield

During Phase 3, hand samples were obtained from each plot using a 0.4 m by 4 m transect Crops were removed at the base of the straw stem, and processed in the laboratory. The heads of the crops were removed from the straw by hand, and threshed to separate the grain and chaff using an F. Walter & H. Wintersteiger KG laboratory thresher (Figure 3.11a). Grains were passed through a sample cleaner manufactured by Pfeuffer (Figure 3.11b), counted using a Henry Simon KL8 Count Master and analysed to determine yield and yield quality based on total weight, thousand grain weight and specific weight (Figure 3.11c).

Grain, chaff and straw yields were calculated for each treatment based on the area from which they were obtained. Samples were collected using a 0.1 m^{-2} quadrat. Random traffic farming standard and low area (ha) was calculated using total plot width (Appendix A) multiplied by the quadrat width (0.3 m). Controlled traffic farming untrafficked and wheelway yields were calculated by multiplying the untrafficked yield (plot width – 1.2 m) and the area trafficked (1.2 m) by the quadrat width (0.3m). Controlled traffic farming whole plot yields were calculated taking into account the ratio between untrafficked and wheelway areas.

The harvest index (%), the ratio between grain yield on a dry basis and the total crop dry weight at harvest, was calculated using Equation 3.7.

$$\text{Harvest index (\%)} = (\text{weight of grain} / \text{total crop dry mass}) \times 100 \qquad \textbf{Equation 3.7.}$$

Figure 3.11. Processing of hand samples, a) threshing, b) grain sample cleaning, and c) grain counting.

Whole plot yields were obtained during Phase 2 and Phase 3 by mechanical (combine) harvesting of each 4 m operating width using a Claas Dominator 85 combine (Figure 3.12a) with 4 m cutter bar. Individual total plot yields (Mg ha^{-1}) were calculated from the weight of the grain removed from each plot by the combine harvester (Figure 3.12b). The grain specific weight (kg hl^{-1}) was measured in-field and a sample of grain was obtained. Grain moisture, thousand grain weight and specific grain weights were measured from samples obtained in the field. Plots were harvested at grain moisture content 14-16.5 %, measured using a Sinar AP6060-001AG Moisture Analyser (Sinar, 2014). Yields are presented at 15% grain moisture content (MC).

Figure 3.12. a) Combine harvester, and b) grain weighed in-field.

3.9.6. Statistical analyses

Statistical analyses were completed using GenStat (2014) Seventeenth Edition. For independent data, such as yield, general analysis of variance (ANOVA) with Tukey test at 5% probability for multiple comparisons were performed. For related data, such as soil penetration resistance, where incremental depths influence each other, repeated measures ANOVA were performed to account for the relatedness of data. Multiple comparisons were completed using least significant difference (LSD) at 5% probability.

4. The effect of tyre inflation pressure and running gear on soil physical properties

4.1. Introduction

The operation of agricultural machinery for crop production can involve infield traffic that covers up to 86% of a field in one year (Kroulík *et al*., 2009). The physical structure and functional properties of trafficked soil can be significantly different from untrafficked soil with increased soil compaction inhibiting root development, water availability, nutrient uptake and yields (Raghavan *et al*., 1979; Chamen, 2011). In response to the intensification of agricultural production systems, farm machinery is increasing in weight and size (Gasso *et al*., 2013; Wigdahl, 2014; Andrews, 2014; Cousins *et al*., 2016). Consequently, and coupled with a lack of appropriate soil management, the risk of soil compaction is ever present, and increasing (Trautner and Arvidsson, 2003; Virto *et al*., 2015). Spoor *et al*. (2003) concluded that once compaction has been caused, reversing the damage is costly and can sometimes exacerbate the poor soil characteristics if poorly performed.

Tyre inflation pressure is critical to tyre deflection, load distribution (Agricultural Training Board, 1989) and thus tyre-soil interaction (Michelin, 2014a). Topsoil compaction can be minimised by reducing tyre inflation pressure (Raper *et al*., 1995; Arvidsson and Keller 2007), but the benefits of this are regulated by the ability of the tyre to deflect (van den Akker *et al*., 1994) known as the tyre carcass stiffness (Evans, 2011; Misiewicz, 2010). Modern low ground pressure (LGP) tyres have been designed to minimise compaction by distributing the load over a larger contact area, through increased flexion (IF) in the sidewall. They allow higher load capacities to be carried at lower inflation pressures whilst reducing compaction, maintaining traction and improving efficiency (Michelin, 2014b).

Alternatively, the use of tracked vehicles distributes the load over a much larger area than tyres. Research has demonstrated that tracks have low slippage and thus are superior to tyres in providing traction and minimising rutting (Vermeulen, 2007). The vertical extent of compaction from tracked vehicles is less than from tyres (Ansorge and Godwin, 2007), yet their design and construction can lead to non-uniform distribution of pressure in the topsoil (Blunden *et al*., 1994).

Previous studies have documented methods to reduce the effect of traffic compaction using LGP technologies to increase vehicle-soil contact area by a reduction in tyre inflation pressure (Raper *et al*., 1995), the fitting of specialist tyres or the use of rubber-tracked vehicles (Ansorge and Godwin, 2007). Whilst the use of radial or cross-ply tyres, and the fitting of additional tyres including dual tyres and flotation tyres has been studied, to date no published research has been reported that investigates the use of increased flexion LGP tyres to mitigate soil compaction.

This chapter details a study investigating the effect of a reduction in tyre inflation pressure, the use of modern low ground pressure specific tyres, and rubber tracks to minimise soil pressure under repeated traffic passes.

4.2. Research hypothesis and objectives

The aim of this research was to test the hypothesis that low ground pressure technologies (a reduction in tyre inflation pressure, increased flexion (IF) tyres and rubber tracks) minimise soil compaction, measurable by changes in soil pressure and penetration resistance, under repeated passes compared to standard tyre inflation pressure treatments.

The objectives of this experiment were:

1. To develop an experimental methodology to determine soil pressure under traffic;
2. To calculate the tyre carcass stiffness and contact pressure of a range of tyres and a tracked vehicle;
3. To determine the effect of tyre type, tyre inflation pressure and running gear on soil pressure and penetration resistance;
4. To recommended the optimum tyre/track selection to implement differential traffic pressure treatments in a field experiment. Criteria for selection were that the same tyre type could be used at two inflation pressures to produce differential soil conditions under standard and low tyre inflation pressure.

4.3. Materials and methods

The soil, a sandy loam soil (65% sand, 19% clay, 15% silt) (Chyba, 2012), within the experimental soil hall facility was uniformly prepared by loosening with subsoiler tines at 150, 300 and 450 mm followed by a power harrow to a depth of 150 mm. The site had an average bulk density of 1.50 Mg m^{-3} and moisture content of 7% MBV (20% of FC). A soil hall experimental facility was divided into four blocks, each containing two soil pressure transducers (Figure 4.1) at a depth of 150 mm and 300 mm below the soil surface. Tyres and inflation pressures for each treatment (Table 4.1) were determined according to manufacturer's recommendations based on load per tyre (kg) and operational forward speed (Michelin, 2008). Each treatment configuration was applied to the tractor separately, and repeated traffic was applied to all four blocks whilst sensors remained in the soil profile. Between each treatment test, sensors were removed, checked, and re-buried following the methodology provided in Chapter 3 (section 3.6.3.1).

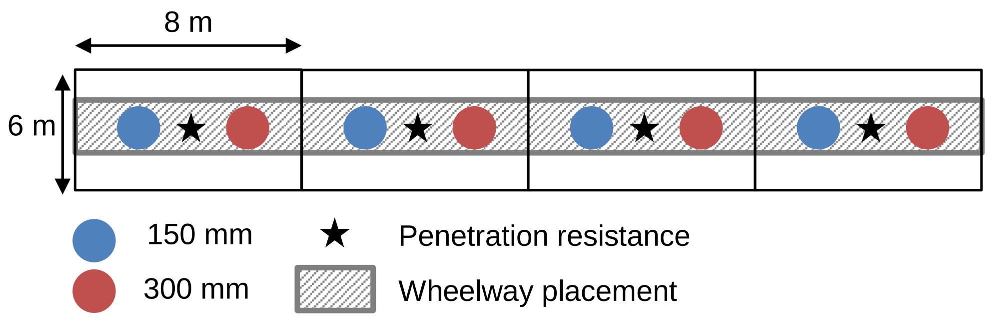


Figure 4.1. Experimental layout (not to scale) with wheeling placement and location of measurements. Pressure transducers were buried at 150 mm and 300 mm. Penetration resistance (4 per run) was measured after the passage of individual treatment configurations.

A Massey Ferguson MF8480 wheeled tractor was fitted with two tyre types: 1) standard MachXBib tyres (front 600/70 R28, and rear 650/85 R38), and 2) increased flexion AxioBib tyres (front IF600/70 R30, and rear IF650/85 R38). Standard inflation pressure (S) treatments were based on those commonly used in commercial agricultural practice (Mozziconacci, 2012. Pers. Comm. Mr. L. Mozziconacci is the Michelin Agricultural Division Product Category Manager and Technical Manager for the UK and Republic of Ireland). Low inflation pressure (L) treatments were designed according to Mozziconacci (2012) to be the lowest tyre inflation pressure possible whilst maintaining traction, performance and protecting tyre longevity. A Cat Challenger MT765 was used to determine the effect of rubber tracks on soil physical properties.

Table 4.1. Treatment configurations.

Treatment	Vehicle	Front tyre Inflation pressure (MPa)	Rear tyre Inflation pressure (MPa)
MachXBib standard	MF8480	600/70 R28 0.12	650/85 R38 0.15
MachXBib low	MF8480	600/70 R28 0.07	650/85 R38 0.07
AxioBib standard	MF8480	IF600/70 R30 0.12	IF650/85 R38 0.15
AxioBib low	MF8480	IF600/70 R30 0.07	IF650/85 R38 0.07
Challenger	MT765	-	

Treatments effects were determined by measuring the change in soil pressure and penetrometer resistance following the passage of both the front and rear tyres, and the entire vehicle pass of the tracked Challenger. Baseline differences in starting pressures were removed, by subtracting the starting soil pressure from the maximum value, to determine change in soil pressures under traffic. Replicated penetrometer measurements (n=4) were taken between the first and second soil pressure transducers. Measurements were taken in the centre of the wheel track before any traffic, and after each traffic pass (n=4) to calculate the change in penetration resistance under trafficking.

4.4. Statistical analyses

The results of contact area, carcass stiffness and contact pressure were based on calculations that were not replicated, and thus have not been statistically analysed. For mean values of maximum soil pressure and penetration resistance were calculated for all treatments, passes and depths and combined. These are presented with the standard error of the mean (SEM).

Two analyses were carried out for the penetrometer data:

1. For the burying of sensors, a paired t-test was used to determine the equality of means between undisturbed and disturbed soil;
2. Repeated measures ANOVA was used to determine the effect of treatments and repeated passes.

For the soil pressure measured using the transducers, repeated measures ANOVA was used to analyse the effect of traffic treatment and passes on soil pressure at the depths measured.

4.5. Results and discussion

4.5.1. Contact area and contact pressure

The effect of tyre inflation pressure on contact area, whereby an increase in tyre inflation pressure resulted in a decrease in the contact area, is shown on the primary vertical axis of Figure 4.2. A decrease in tyre inflation pressure resulted in an increase in contact area for all tyres. A decrease in AxioBib tyre inflation pressures in the front (0.12 MPa to 0.07 MPa) and rear tyres (0.15 MPa to 0.07 MPa) increased the contact area by 17% and 11% respectively. A decrease in the MachXBib front (0.12 MPa to 0.07 MPa) and rear (0.15 MPa to 0.07 MPa) tyre inflation pressures increased the contact area by 5% and 23% respectively. The contact area of the tracks is shown on the secondary vertical axis of Figure 4.2.

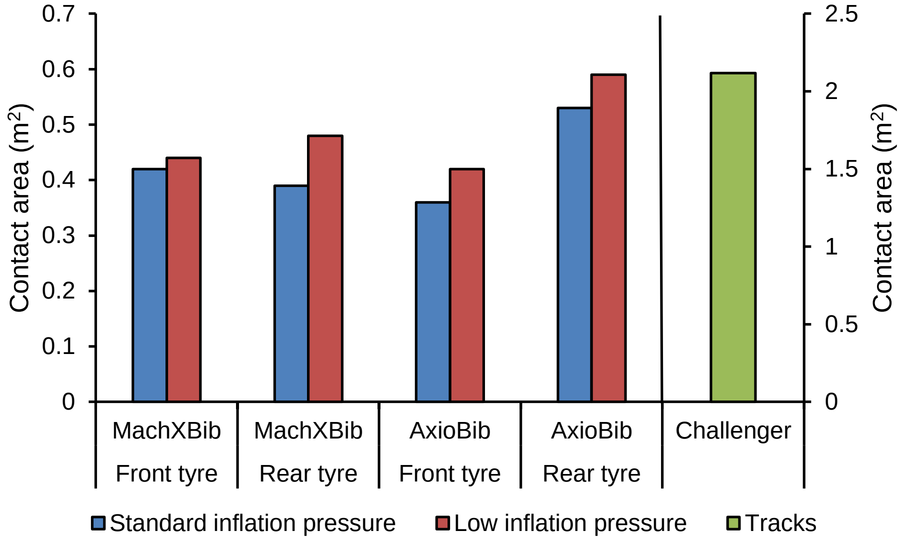


Figure 4.2. Static contact area (m^2) of individual tyres and tracks.

The total vehicle-soil contact area for each treatment was calculated based on the measurements obtained. The total vehicle-soil contact area of the MF8480 fitted with AxioBib tyres at standard inflation pressure was calculated as 1.78 m^2, a 9.87% increase in the contact area of tractor fitted with MachXBib tyres (1.62 m^2) at the same inflation pressures. At low inflation pressures, the total vehicle-soil contact area of the tractor fitted with AxioBib tyres was calculated as 2.02 m^2, 9.78% increase in contact area of the tractor when fitted with MachXBib tyres (1.84 m^2). The total vehicle-soil contact area of the Cat Challenger MT765 measured 4.23 m^2, a 109% and 130% increase compared to the low tyre inflation pressure AxioBib and MachXBib tyres respectively.

Figure 4.3 shows the contact pressure of each individual tyre calculated from the weight of the load divided by the measured contact area. For all tyres investigated, a reduction in the tyre inflation pressure resulted in an increase in the contact area, thus resulting in a decrease in tyre-soil contact pressure. A decrease in AxioBib tyre inflation pressures in the front (0.12 MPa to 0.07 MPa) and rear tyres (0.15 MPa to 0.07 MPa), reduced the contact pressure by 16.67% and 14.29% respectively. A decrease in the MachXBib front (0.12 MPa to 0.07 MPa) and rear (0.15 MPa to 0.07 MPa) tyre inflation pressures reduced the contact pressure by 16.67% and 20% respectively.

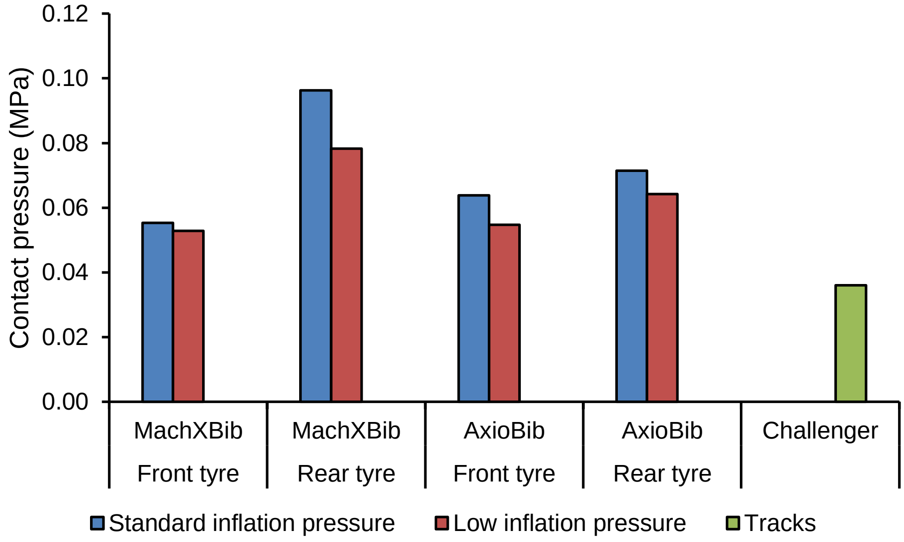


Figure 4.3. Calculated contact pressure (MPa) of tyres and tracks based on the static contact area.

The total vehicle-soil contact pressure for each treatment was calculated based on the measurements obtained. The vehicle-soil contact pressure of the MF8480 fitted with AxioBib tyres at standard inflation pressure was calculated as 0.26 MPa, a 15.38% increase in the contact pressure of tractor fitted with MachXBib tyres (0.22 MPa) at the same inflation pressures. Similarly, the percentage difference in contact pressure of the total vehicle fitted with AxioBib and MachXBib tyres at low inflation pressure was 15.38%, but at low inflation pressures the contact pressure of the MF8480 fitted with AxioBib tyres (0.22 MPa) was lower than that of the tractor fitted with MachXBib tyres (0.26 MPa). The total vehicle-soil contact pressure of the Cat Challenger MT765 was calculated as 0.07 MPa, a 68.12% and 73.08% decrease compared to the low tyre inflation pressure AxioBib and MachXBib tyres respectively.

4.5.2. Tyre manufacturer data

To determine tyre carcass stiffness for each tyre, load and inflation pressure data from the manufacturers manual (Michelin, 2013 and 2014b) were plotted and extrapolated by fitting a linear and 2nd order polynomial regression (Figure 4.4 to Figure 4.7), as described by Misiewicz (2010).

Linear regression between inflation pressure and load provided a lower coefficient of determination (range from R^2 = 0.9345 to R^2 = 0.9985) compared to the 2nd order polynomial regression (coefficient of determination ranged from R^2 = 0.9876 to R^2 = 0.9999). Misiewicz (2010) reported similar findings and concluded that although carcass stiffness values generated by linear regression had a lower coefficient of determination, they were closer to those measured in contact pressure experiments.

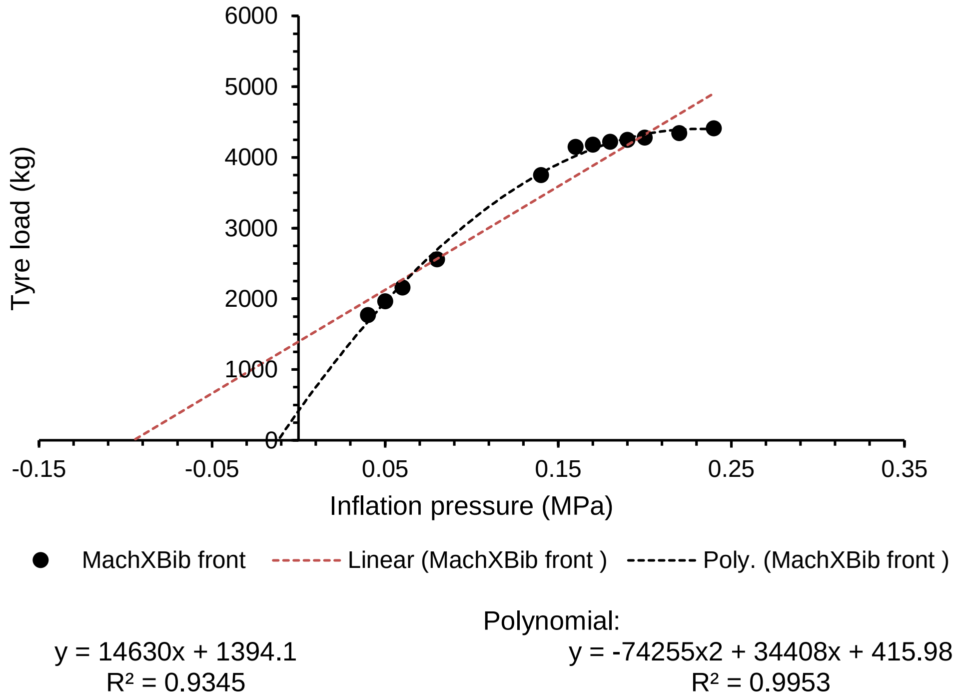
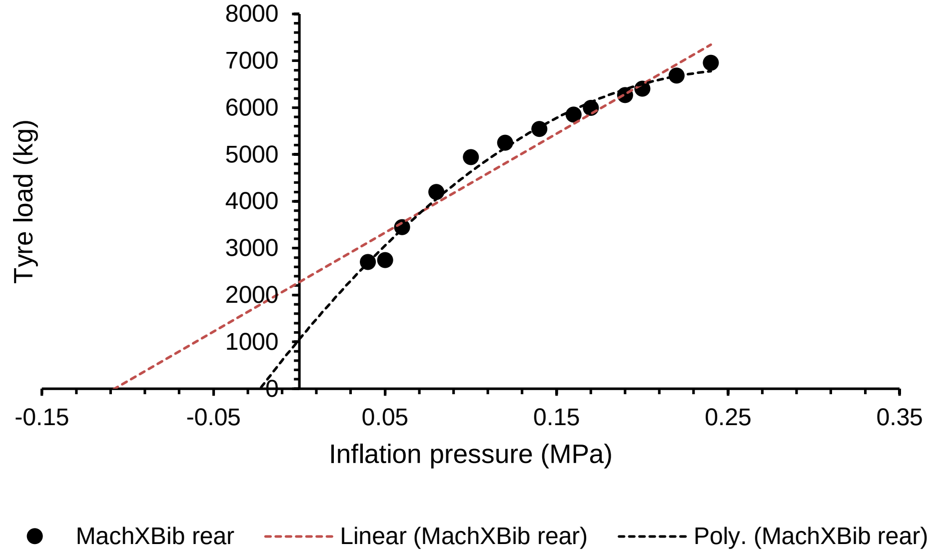


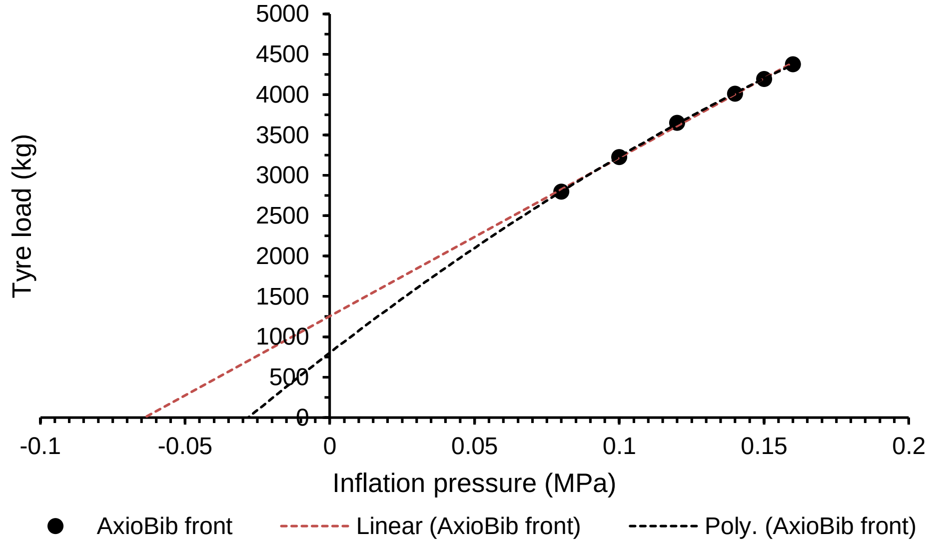
Figure 4.4. Manufacturer data of MachXBib front tyre load (kg) and inflation pressure (MPa) fitted with linear and 2nd order polynomial regression.



Linear:
$y = 21124x + 2274.3$
$R^2 = 0.943$

Polynomial:
$y = -85176x^2 + 44286x + 1051.6$
$R^2 = 0.9876$

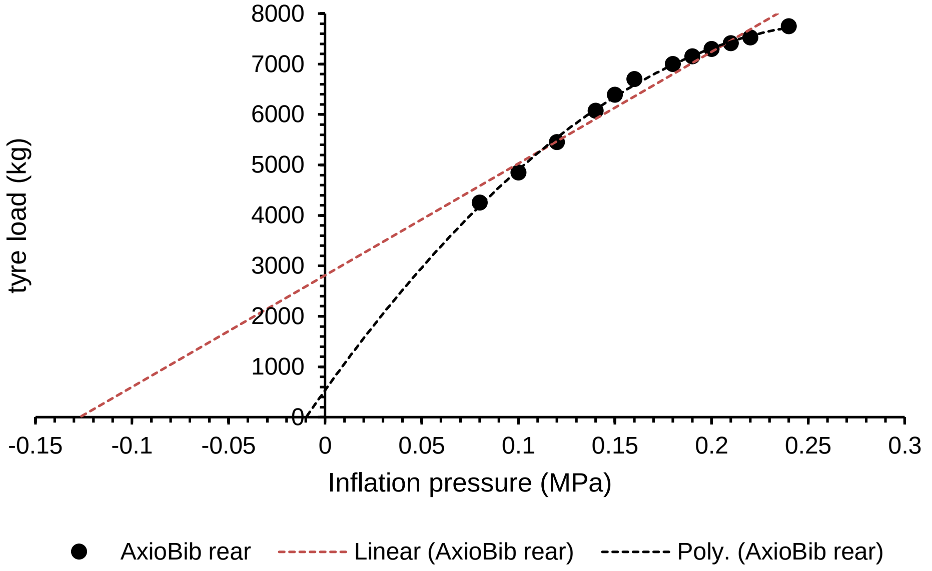
Figure 4.5. Manufacturer data of MachXBib rear tyre load (kg) and inflation pressure (MPa) fitted with linear and 2nd order polynomial regression.



Linear:
$y = 19637x + 1254.6$
$R^2 = 0.9985$

Polynomial:
$y = -33159x^2 + 27612x + 801.97$
$R^2 = 0.9999$

Figure 4.6. Manufacturer data of AxioBib front tyre load (kg) and inflation pressure (MPa) fitted with linear and 2nd order polynomial regression.



Linear:

$y = 22146x + 2814.9$

$R^2 = 0.9578$

Polynomial:

$y = -98013x^2 + 53476x + 536.06$

$R^2 = 0.9975$

Figure 4.7. Manufacturer data of AxioBib rear tyre load (kg) and inflation pressure (MPa) fitted with linear and 2nd order polynomial regression.

Estimations of tyre carcass stiffness were calculated using Model A (Figure 4.8a) and Model B (Figure 4.8b) and the results obtained using both linear and 2nd order polynomial regression were plotted for all four tyres at low and standard inflation pressure. For both models, estimations of carcass stiffness using linear regression provided larger values than 2nd order polynomial regression.

Using Model A, as inflation pressure increased and the contact patch decreased, the estimated carcass stiffness increased. The work presented here agrees with Misiewicz (2010) who showed that increasing tyre inflation pressure and load resulted in an increase of carcass stiffness. Using the linear regression of Model A, as suggested by Misiewicz (2010), at a standard tyre inflation pressure the carcass stiffness of the AxioBib front and rear tyres was calculated as 0.35 MPa and 0.53 MPa respectively. For the MachXBib tyres at the same inflation pressure, the front and rear carcass stiffness was calculated as 0.33 MPa and 0.56 MPa respectively. A reduction in tyre inflation pressure reduced the carcass stiffness of the front and rear AxioBib tyres by 14.23% and 10.17% respectively. For the

MachXBib tyres, a reduction in tyre inflation pressure of the front and rear tyres resulted in a reduction in tyre carcass stiffness of 3.58% and 18.74% respectively.

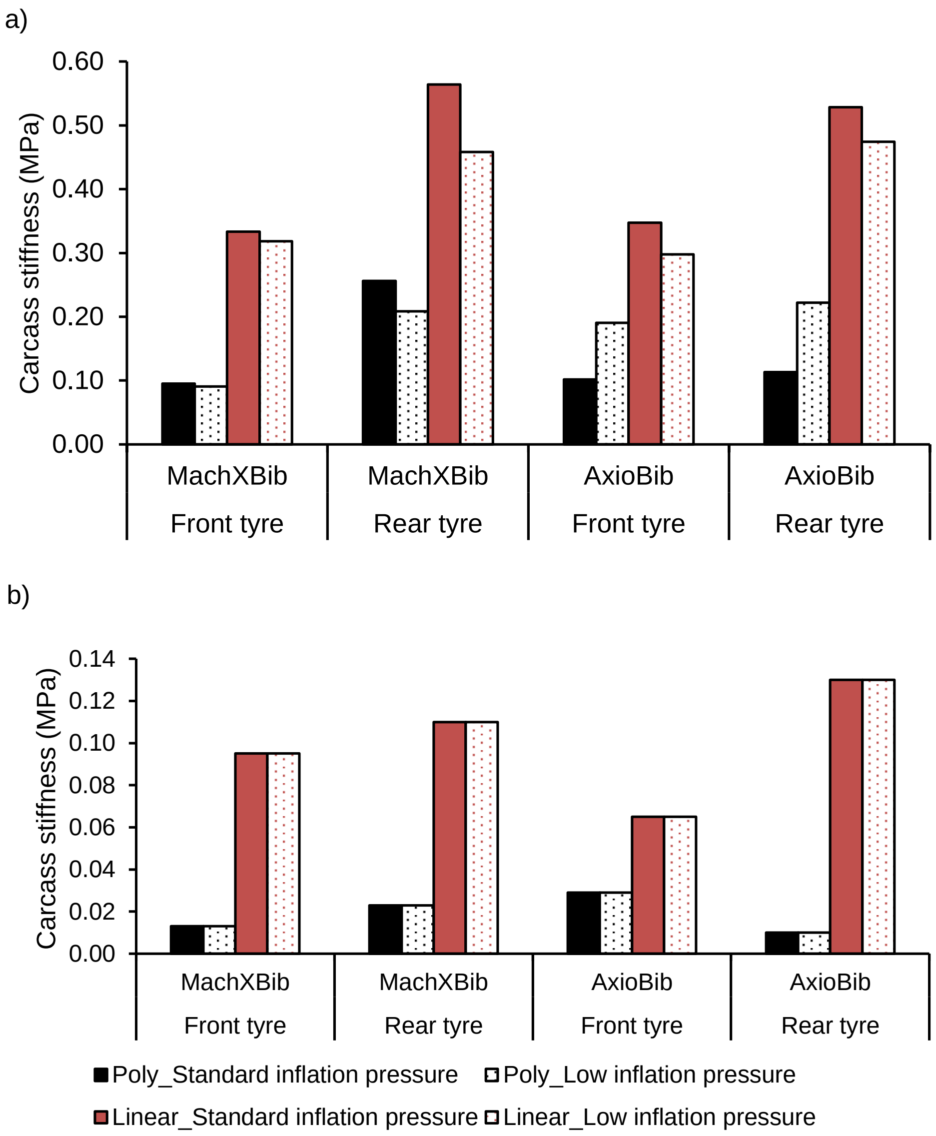


Figure 4.8. Predicted values of tyre carcass stiffness according to a) load at zero tyre inflation pressure, and b) tyre inflation pressure at zero load. Different scales have been used on the Y axis due to the large differences between the models in calculated carcass stiffness (MPa).

Similarly, Lines and Murphy (1991) studied the factors influencing changes in dynamic stiffness of rolling agricultural tractor tyres, concluding that the greatest contributing factors include tyre inflation pressure, tyre size and tyre age. They concluded that tyre stiffness is attributable to both the carcass stiffness and the inflation pressure. The study also considered the role of tyre age in carcass stiffness, and studied tyres ranging from new to 16 years of use. The researchers concluded that differences in carcass stiffness are not simply a result of age, and thus use, but more likely due to the different design and manufacturing materials used on old and new tyres.

Model B whereby the tyre inflation pressure at zero load was used to calculate carcass stiffness, provided lower estimations of carcass stiffness (Figure 4.8b). This method does not require the measurement of the tyre contact patch and therefore changes in inflation pressure are not reflected in the calculated values of carcass stiffness. This method is therefore only useful when comparing tyre of different ply ratings and design. However, Misiewicz (2011) recommends using this model, with a linear fit, in instances when the measurement of the tyre contact area is impossible. Using the linear regression of Model B, the carcass stiffness of the AxioBib front and rear tyres was calculated as 0.065 MPa and 0.13 MPa respectively. For the MachXBib tyres the front and rear carcass stiffness was calculated as 0.095 MPa and 0.11 MPa respectively.

Misiewicz (2010) concluded that the conversion of load at zero inflation pressure obtained by the linear extrapolation of tyre manufacturer data, method a in the present study, provided the closest results to measured values obtained using a pressure mapping system.

In the absence of a surface pressure mapping system for the present study, the calculated values of carcass stiffness for each of the tyres tested will be discussed in relation to observed measurements of soil pressure using strain gauge pressure transducers and soil physical structure using a penetrometer.

4.5.3. The influence of carcass stiffness on contact pressure

Figure 4.9 illustrates the contact pressure of each tyre calculated from the weight of the load divided by the measured contact area (Equation 3.1) and those calculated by the combination of tyre inflation pressure and carcass stiffness using 2nd order polynomial and linear extrapolations (Equation 3.2). Figure 4.9a shows the predicted values whereby carcass stiffness was calculated using load at zero inflation pressure (Model A). Figure 4.9b) shows the predicted values whereby carcass stiffness was calculated using the inflation pressure at zero load (Model B).

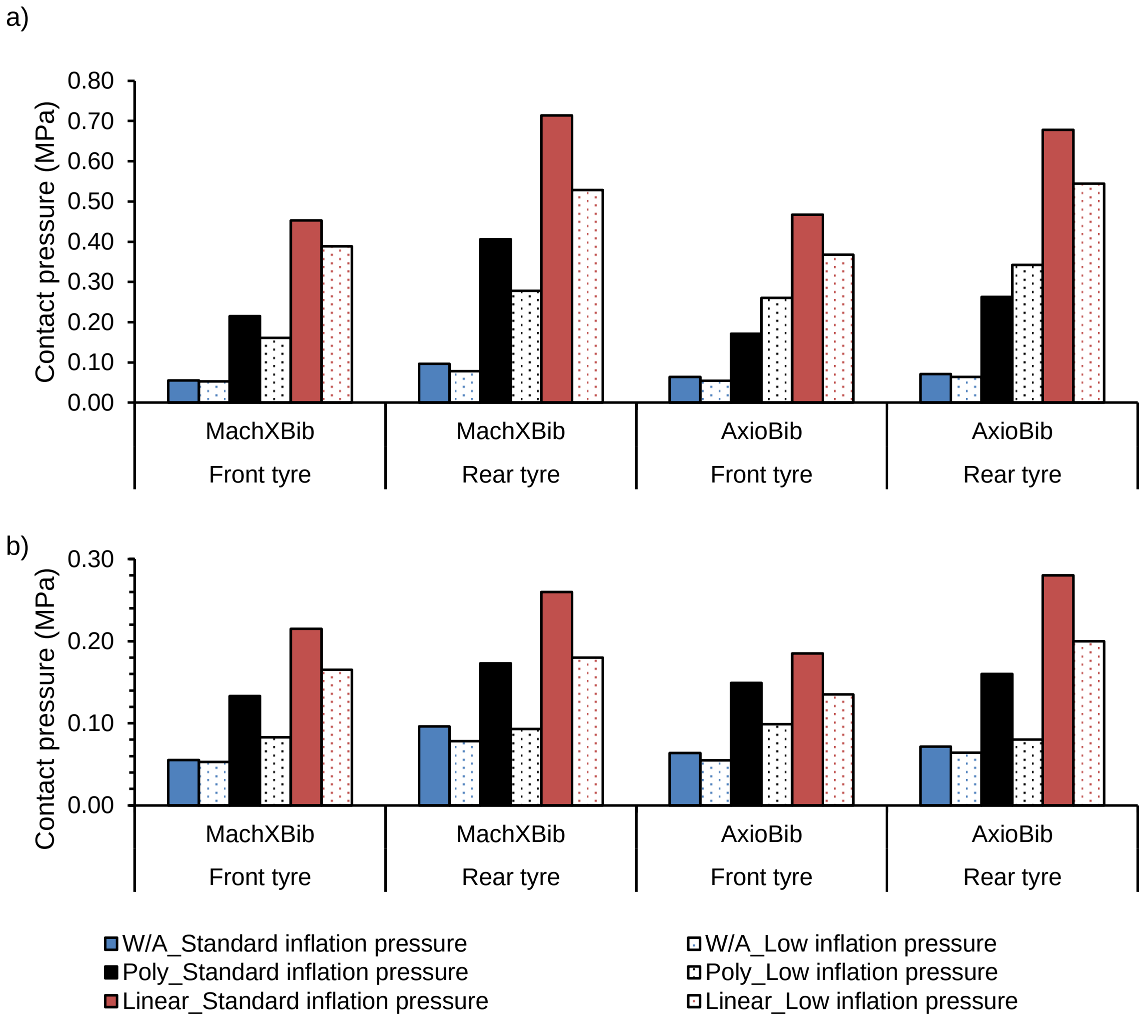


Figure 4.9. Contact pressure for each tyre according to measured contact area and load, tyre inflation pressure and carcass stiffness using 2nd order polynomial regression of a) load at zero inflation pressure and, b) tyre inflation pressure at zero load.

A reduction in tyre inflation pressure for all tyres resulted in a reduction in the predicted contact pressure. The greatest total reduction in predicted contact pressure calculated by dividing the load by the contact area was under the AxioBib front (-14%) and rear (-10%) tyres. A reduction in tyre inflation pressure of the front and rear MachXBib tyres reduced the predicted contact pressures by -5% and -19% respectively.

However, when tyre carcass stiffness, calculated from 2nd order polynomial regression, and tyre inflation pressure are included in estimations of contact pressure (Model A), a reduction in tyre inflation pressure of the AxbioBib resulted in a 52% and 30% increase in the predicted contact pressures of the front and rear tyres respectively. The predicted contact pressures of the MachXBib front and rear tyres were -25% and -32% lower as a result of a reduction in tyre inflation pressure.

Calculated tyre carcass stiffness using linear and 2nd order polynomial regression in Model A and Model B showed that a reduction in tyre inflation pressure of the front and rear AxioBib and MachXBib tyres reduced the predicted contact pressures.

Both Model A and Model B produced estimations of contact pressure greater than those calculated using the load divided by the measured contact area. Contact pressures predicted using Model A with 2nd order polynomial and linear regression were 290% and 671% greater than those calculated by the load divided by the contact area. Contact pressures predicted using Model B with 2nd order polynomial and linear regression were 82% and 205% greater than those calculated by the load divided by the contact area. Previous research has also commented on the fact that models of contact pressure, whereby the tyre load and the contact area are the only factors, predict the ground pressure to be much lower than in reality (Vermeulen and Klooster, 1992; Blunden *et al*., 1994; Spoor *et al*., 2003), chiefly due to carcass stiffness, tyre inflation pressure (Misiewicz, 2010) and uneven distribution of pressure.

Predicted values of carcass stiffness using 2nd order polynomial regression were lower than linear regression, and thus the predicted contact pressures were also lower. Similarly the contact pressure of tyres using Model B were lower than those predicted using Model A. The contact pressures predicted using linear regression were 106% and 74% greater than those predicted using 2nd order polynomial regression for Model A and Model B respectively.

The use of Model A, whereby the load at zero inflation pressure is used to estimate carcass stiffness, and the inclusion of carcass stiffness in estimations of contact pressure, recorded closer values to the soil pressure at 50 mm when measured using the penetrometer (section 4.3.6).

4.5.4. The effect of running gear on change in soil pressure under multiple traffic passes

The burying of sensors within a soil profile is disruptive to the soil structural conditions created by mechanical operations. Therefore, following the excavation of the soil to place the sensors at depth, the soil was backfilled in layers to a uniform condition, as shown in Figure 4.10, as proposed by Ansorge and Godwin (2007). This methodology ensures a uniform soil profile, by removing layers of compaction that would otherwise inhibit the propagation of pressure within the profile. Figure 4.10 shows the penetration resistance (±SEM) before (undisturbed) and after (disturbed) burying the pressure sensors.

A paired t-test for all depths showed that there were no differences in penetration resistance between undisturbed and disturbed soil (P = 0.136) and thus the burying of sensors did not affect the soil conditions; the soil above the buried sensors represented the surrounding structural conditions.

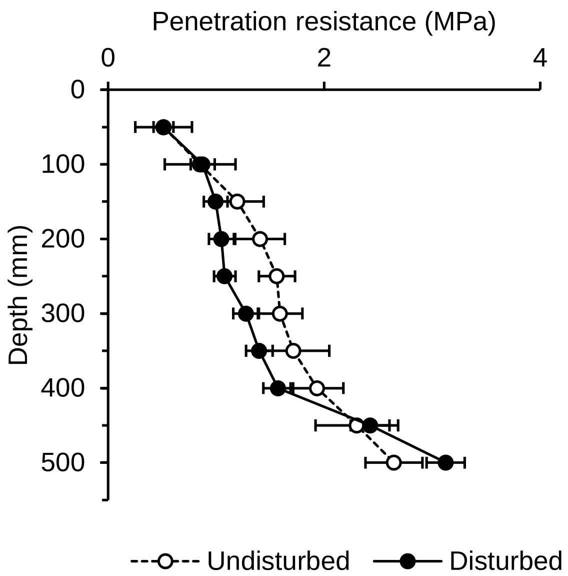


Figure 4.10. Measurements of penetration resistance (±SEM) to verify the methodology for burying sensors within the soil profile.

The effect of passes on soil structure were analysed by treatment, determined by the change in soil pressure (±SEM) under multiple traffic passes measured at a) 150 mm and b) 300 mm (Figure 4.11) below the soil surface. The change in soil pressure was calculated for each traffic incidence by subtracting the pressure recorded before trafficking from the measured maximum soil pressure as the tractor passed over the sensor.

Significantly greater changes in soil pressure were recorded at 150 mm compared to 300 mm (*P* < 0.001, LSD 5% = 0.00364). Similarly, Erbach *et al*. (1991) measured compaction beneath agricultural traffic using strain gauges and concluded that pressure decreased at depth. At a depth of 300 mm below the soil surface, the first traffic pass resulted in the greatest changes in soil pressure, and subsequent traffic passes resulted in smaller changes in recorded soil pressures. Overall, soil pressure was significantly (*P* = 0.026, LSD 5% = 0.0052) greater under the first traffic pass. There was no significant difference in measure soil pressure between the second and third traffic pass. These findings are consistent to those reported by Wiermann *et al*. (1999) and Chyba (2012).

Significant differences (*P* < 0.001, LSD 5% = 0.00364) were found between the changes in soil pressure recorded at 150 mm and 300 mm. At a depth of 150 mm and 300mm, the greatest change in soil pressure as an average across all three passes was recorded under the AxioBib tyres at standard tyre inflation pressure (0.0391 and 0.02 MPa). The lowest recorded change in soil pressure at both depths was recorded under the Challenger (0.0121 and 0.0119 MPa). This supports the work reported by Ansorge and Godwin (2007) who concluded that the soil displacement under tracked vehicles was smaller compared to tyre treatments. The authors also reported significant differences between low inflation pressure tyres and tracks. In this study, use of AxioBib and MachXBib tyres at low inflation pressure resulted in significantly (*P* < 0.001, LSD 5% = 0.00282 MPa) greater recorded soil pressures than the Challenger tracks. Significant differences were also found between the AxioBib and MachXBib tyres at low inflation pressure. The MachXBib low inflation pressure tyres resulted in 21% lower soil pressures than the AxioBibs.

In this present study the interaction between treatment and depth was found to be significant (*P* = 0.007, LSD 5% = 0.00813). A reduction in tyre inflation pressure reduced the recorded soil pressures at both depths. For the MachXBib tyres a reduction in tyre inflation pressure reduced soil pressures by 35% and 27% at 150 mm and 300 mm. For the AxioBib tyres, the reduction in soil pressure was lower at 150 mm (27%) but greater at 300 mm (57%), indicating that a reduction in tyre inflation pressure of IF tyres minimises soil pressure beyond the surface layers. Although greater reductions in measured soil pressure were achieved using AxioBib tyres at low inflation pressure compared to standard inflation pressure, the use of MachXBib tyres resulted in lower recorded soil pressures at both depths.

The increased soil pressures recorded under the IF tyres suggests that these tyres should not be operated at increased inflation pressures. The total contact patch of the AxioBib tyres at standard inflation pressure was larger than that of their MachXBib equivalent, yet still they contributed greater soil pressure. This result was unexpected. It is possible that the carcass stiffness could be contributing to increased soil pressures, yet the carcass stiffness of the AxioBib tyre was estimated to be lower than the MachXBib tyre. The calculation of the mean carcass stiffness proposed by Misiewicz (2010) is recommended in the absence of surface pressure mapping system and was therefore suitable for use in the current study. However, the model (Misiewicz, 2010) does not calculate the maximum carcass stiffness, reported to be in the range of 2.5-4 times greater than the mean.

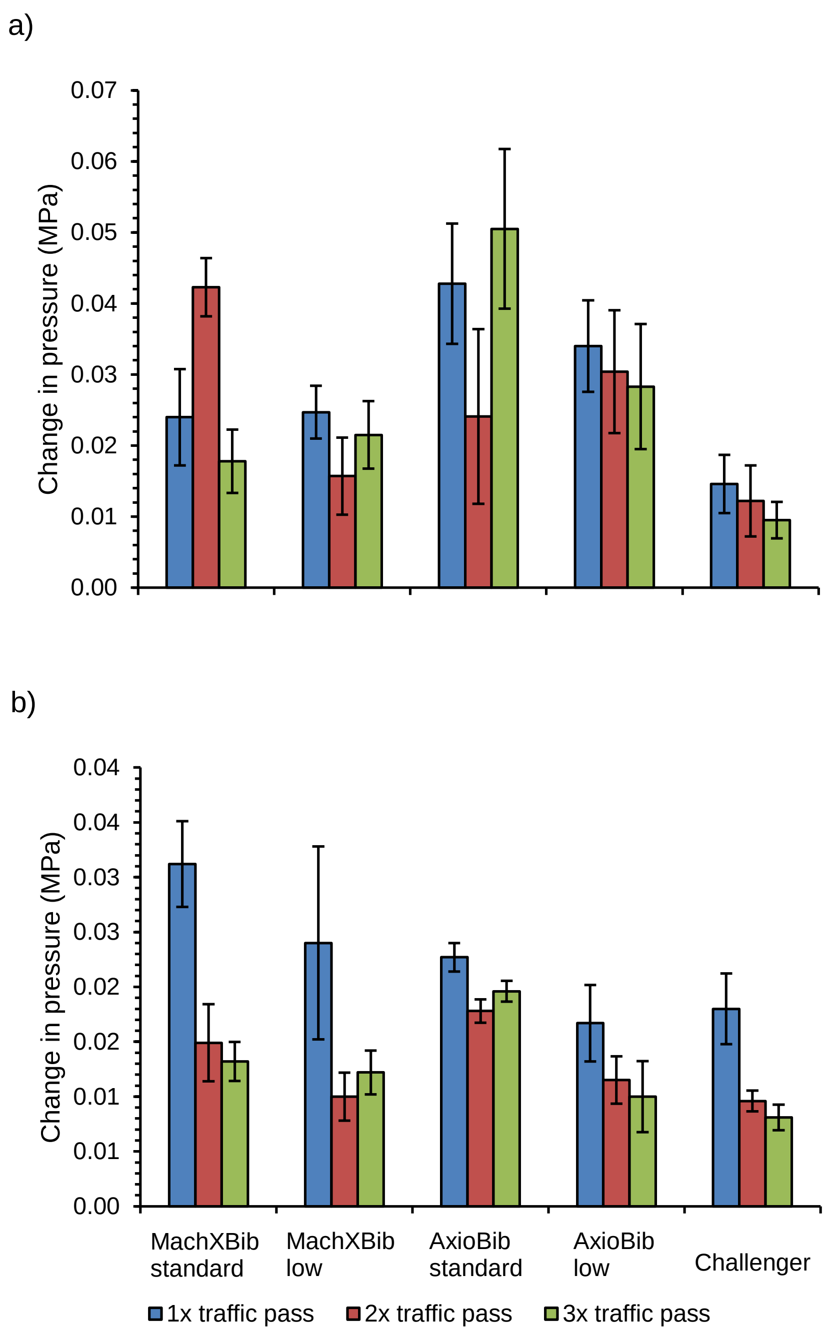


Figure 4.11. Average maximum soil pressures (± SEM) recorded under multiple passes of MachXBib tyres at standard and low inflation pressures, AxioBib tyres at standard and low inflation pressures and a rubber tracked Challenger, at a) 150 mm and, b) 300 mm below the soil surface.

4.5.5. The effect of running gear on soil pressure distribution

The means of the first traffic pass was found to be significantly greater than the mean values of subsequent passes. Therefore, the distribution of pressure at a) 150 mm and, b) 300 mm under the first traffic pass was determined, as shown in Figure 4.12. Stresses under the Challenger were also applied over a greater contact area than tyres, and thus greater soil areas would be compacted with the tracked vehicle during in-field operations.

The pressure distribution along the length of the Challenger tracks was not uniform, and resulted in higher pressures being applied over a longer period of time compared to the tyre treatments. Non-uniformity of pressure under tracked vehicles has been reported by other researchers (Keller and Arvidsson, 2006; Arvidsson, 2014). Maximum stresses have been recorded under tracks, with the load carried more at the front of the tracks (Arvidsson, 2014) In the present study, although maximum stresses were identified, no forward or rear loading effect was observed at 150 mm. At a depth of 300 mm marginal front-loading can be observed from the pressure distribution graph (Figure 4.12b), which supports work by Alakukku *et al*. (2003), who concluded that the uneven load distribution from tracked vehicles is evident in the soil surface layers to a depth of 0.5 m.

A limitation of the current research was that no ground-engaging implement was used, which in previous studies has been found to improve the uniformity of pressure distribution under tracks (Blunden *et al*., 1994).

The maximum pressures measured in the current experiment were 50% lower than reported by Blunden *et al*. (1994), suggesting that changes to the soil structure resulting in soil compaction would also be reduced. The weights of the tracked vehicles used in both experiments were similar, however, the calculated track contact pressure was much lower in the current study, which could be linked to the reduced soil pressures measured within in the soil profile.

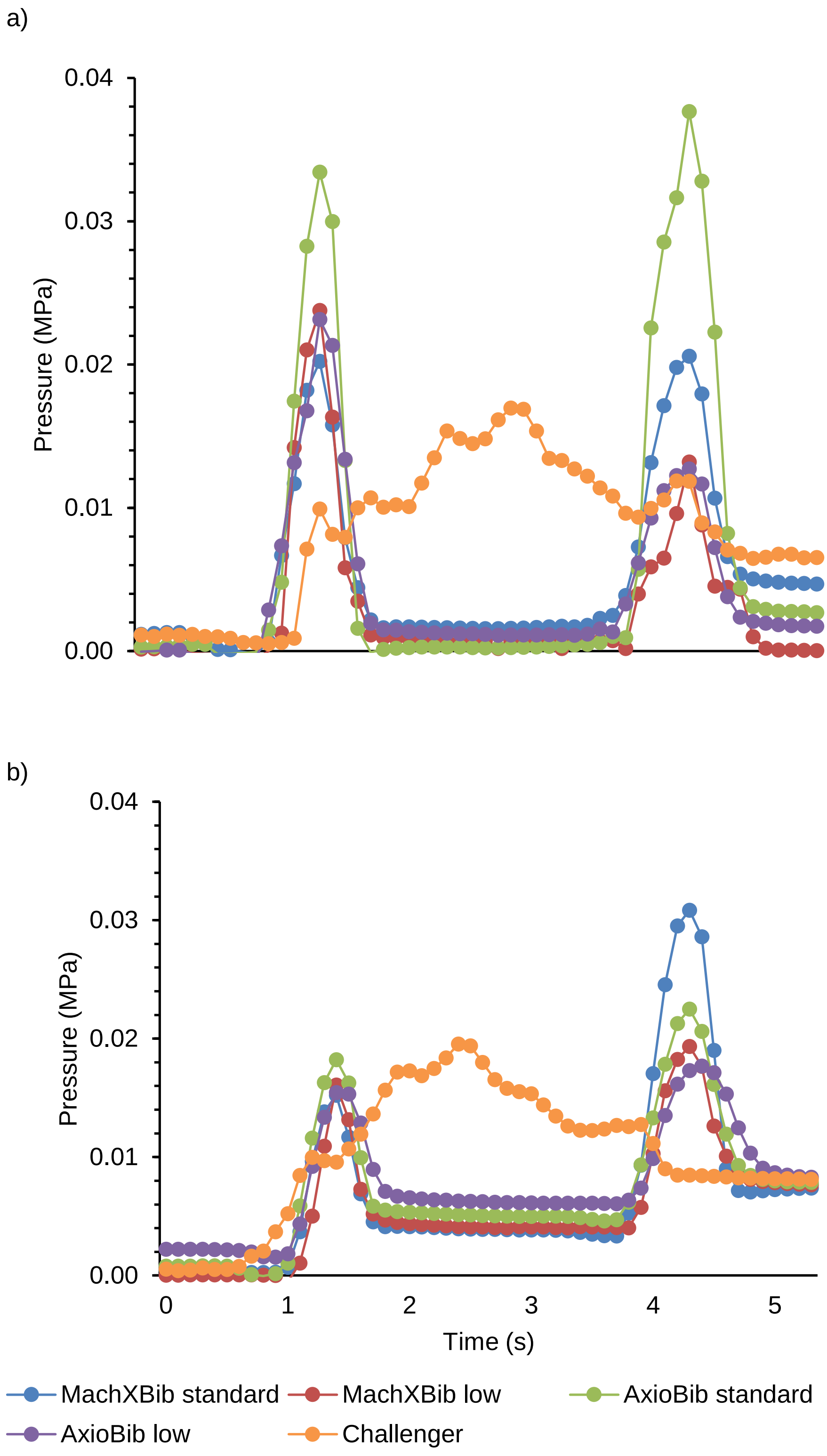


Figure 4.12. Distribution of pressure under the first traffic pass of MachXBib tyres at standard and low inflation pressures, AxioBib tyres at standard and low inflation pressures and a rubber tracked Challenger, at a) 150 mm and b) 300 mm.

4.5.6. Penetration resistance

Figure 4.13 shows the calculated change in penetration resistance. Over a depth of 0 – 300 mm, the highest recorded change in penetration resistance as an average across three passes occurred under the AxioBib standard treatment (1.10 MPa). This is consistent with the findings of soil pressure measured by the transducers. The MachXBib low treatment resulted in the lowest change in penetration resistance (0.869 MPa). There was no evidence of statistical difference between treatments (P = 0.779).

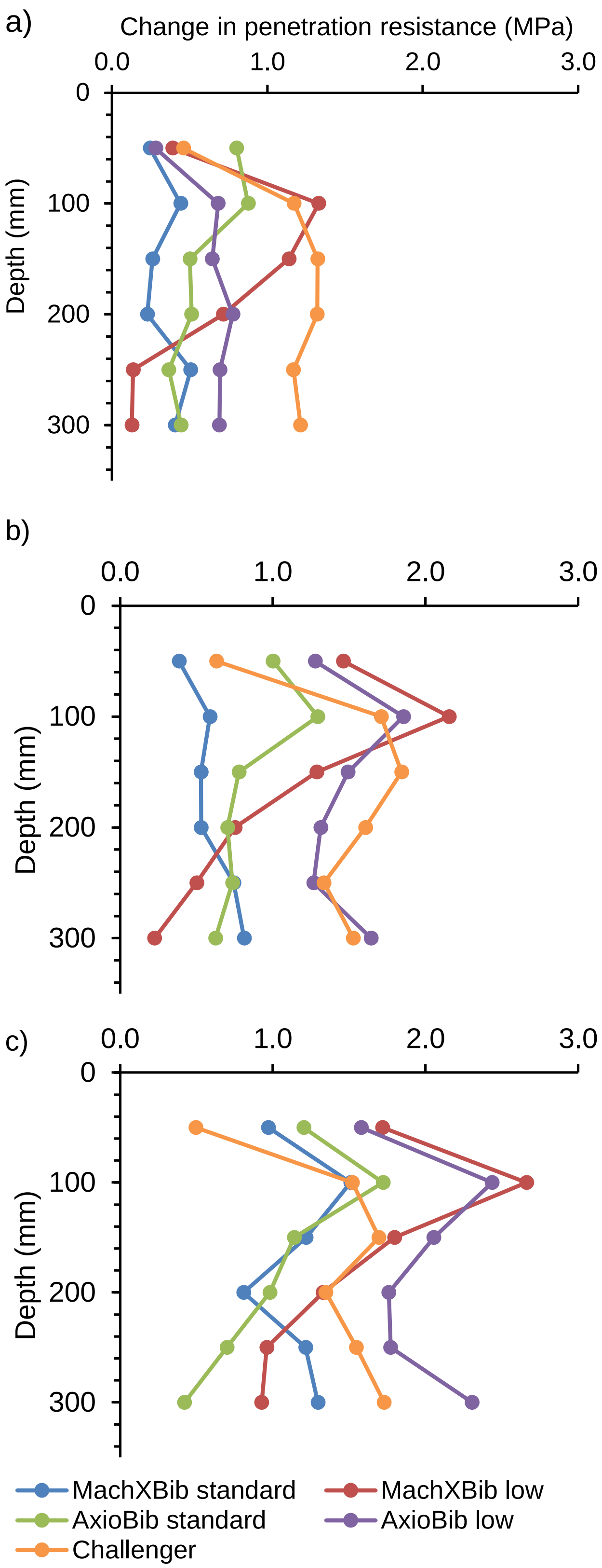


Figure 4.13. Change in penetration resistance (MPa) (± SEM of depth and treatment = 0.6148) under a) 1x, b) 2x, and c) 3x traffic passes.

Overall, the first traffic pass resulted in an increase in penetration resistance of 0.66 MPa, the second pass an increase of 1.09 MPa and the third pass an increase of 1.23 MPa. There was a significant increase of 0.43 MPa between the first and second pass ($P < 0.002$). Subsequent traffic passes did not have a significant effect on increase in penetration resistance. This finding is consistent with the soil pressures recorded using the strain gauge transducers in the present study, and those reported by Chyba (2012) on the effect of repeated wheelings on surface water infiltration.

These results suggest that repeated in-field trafficking of the same wheelways where soil moisture remains constant, do not lead to continually increasing soil pressures. Potentially, if the first pass is performed when the soil is in a low soil moisture status, this will further improve the resilience of soil to the impact of subsequent passes later in the season. The role of changes in soil moisture, however, were not studied. As the first pass results in the greatest change in soil pressure, its timing and application in-field are critical to minimise potential soil compaction. Cumulative effects of wheelings, however, were reported by Arvidsson (2001), although these were observed at greater depths in the soil profile (500 mm), due to the deeper propogation of stress under increased wheeloads (Söhne, 1958). The total weight of the vehicle used in the study reported by Arvidsson (2011) was circa. 6 times greater than the vehicle used in the current study, suggesting that in order to reduce soil pressure it is necessary to reduce tyre load. The MachXBib tyres recorded lower changes in penetration resistance under the first traffic pass compared to the AxioBib tyres. Overall, low inflation pressure tyres, both MachXBib and AxioBib, did not result in the lowest changes to the soil penetration resistance under the first pass; this was only apparent by the third pass. These results suggest that to minimise the effect of repeated wheelings on soil pressure it is necessary to reduce tyre inflation pressure.

It is important to note the depth at which soil pressures increase under repeated wheelings. There was a significant interaction between treatment, pass and depth ($P < 0.001$). The MachXBib low treatment recorded greater changes in penetration resistance under the second pass, but only to a depth of 150 mm. The third pass contributed the greatest change in penetration resistance below a depth of 150 mm. The AxioBib low treatment also recorded greater increase in penetration resistance under the second pass, until a depth of 250 mm whereby the third pass again began to contribute the greatest change in penetration resistance. These results suggest that repeated wheelings of AxioBib tyres results in greater increases in soil penetration resistance deeper in the soil profile than was found under the MachXBib tyres. Subsequent passes of high inflation pressure treatments

(MachXBib standard and AxioBib standard) increased the penetration resistance throughout the soil profile.

In this present study, the inflation pressure of the MachXBib tyre low pressure treatment was 60% that of the standard inflation pressure. The greatest difference in stress measured using the cone penetrometer, was found at a depth of 300 mm, whereby the high inflation pressure recorded a pressure of 1.08 MPa and the low inflation pressure recorded 0.55 MPa, approximately 50% of the pressure. The differences in pressure between the two IF treatments were a lot lower than those observed between the standard tyres. The maximum difference in soil pressure of the IF tyre at low inflation pressure, measured at a depth of 100 mm, was 88% that of the high inflation pressure tyre. Similarly, van den Akker *et al*. (1994) reported that although the inflation pressure of the low pressure tyre is 33% that of the normal inflation pressure, the maximum stress, measured using a cone penetrometer, at a depth of 0.35 m was approximately 60% of the normal trailer tyres. They concluded that the effect of the carcass stiffness of the tyre at low inflation pressures is increasingly important. Furthermore, treatments with similar calculated contact pressures resulted in different pressures in the soil profile, indicated by measurements of soil pressure and penetration resistance. Lamandé and Schjønning (2011) similarly reported differences in stresses within the soil profile than those predicted using contact pressure calculations. This was attributed to the differential transmission of stress through layers present within the soil. In the current study however, soil preparation was consistent between all treatments to prevent the interaction of soil layers and the transmission of pressure.

The penetrometer results support the earlier findings reported on soil pressures measured using transducers (section 4.3.4). The standard tyres at low inflation pressure resulted in lower soil pressures below 100 mm depth. In comparison, the soil pressure resulting from the same tyres at high inflation pressure affected the whole of the soil profile measured.

4.5.7. Methodology for determining soil compaction

The mean soil pressure, averaged for three traffic passes, for the front and rear tyres at (a) 150 mm and (b) 300 mm were calculated and compared with the penetration resistances from the same depths (Figure 4.14).

At 150 mm the strain gauge transducers sensors recorded higher values of pressure than the penetrometer. At a depth of 300 mm the values of pressure measured using the two techniques are more similar. The point of contact between the tyre and the soil (i.e. lugs and rubber track) and the deformation of the soil surface as a result of trafficking, is likely to have resulted in higher readings by the transducers at a depth of 150 mm than the penetrometer. The use of a penetrometer for field experiment allows the collection of spatial and temporal replicated data. The burial of sensors, although appropriate in a proof of concept, is destructive to the surrounding site, which in a cropped field experiment, will impact on yield. Furthermore, a penetrometer can be used to characterise the soil profile after traffic, rather than observing the stresses resulting from the tyre at distinct depths within it that are measured with transducers. Rowell (1984) stated that cone penetrometers are potentially capable of a higher degree of spatial resolution than is possible with methods that involve the removal of a soil sample.

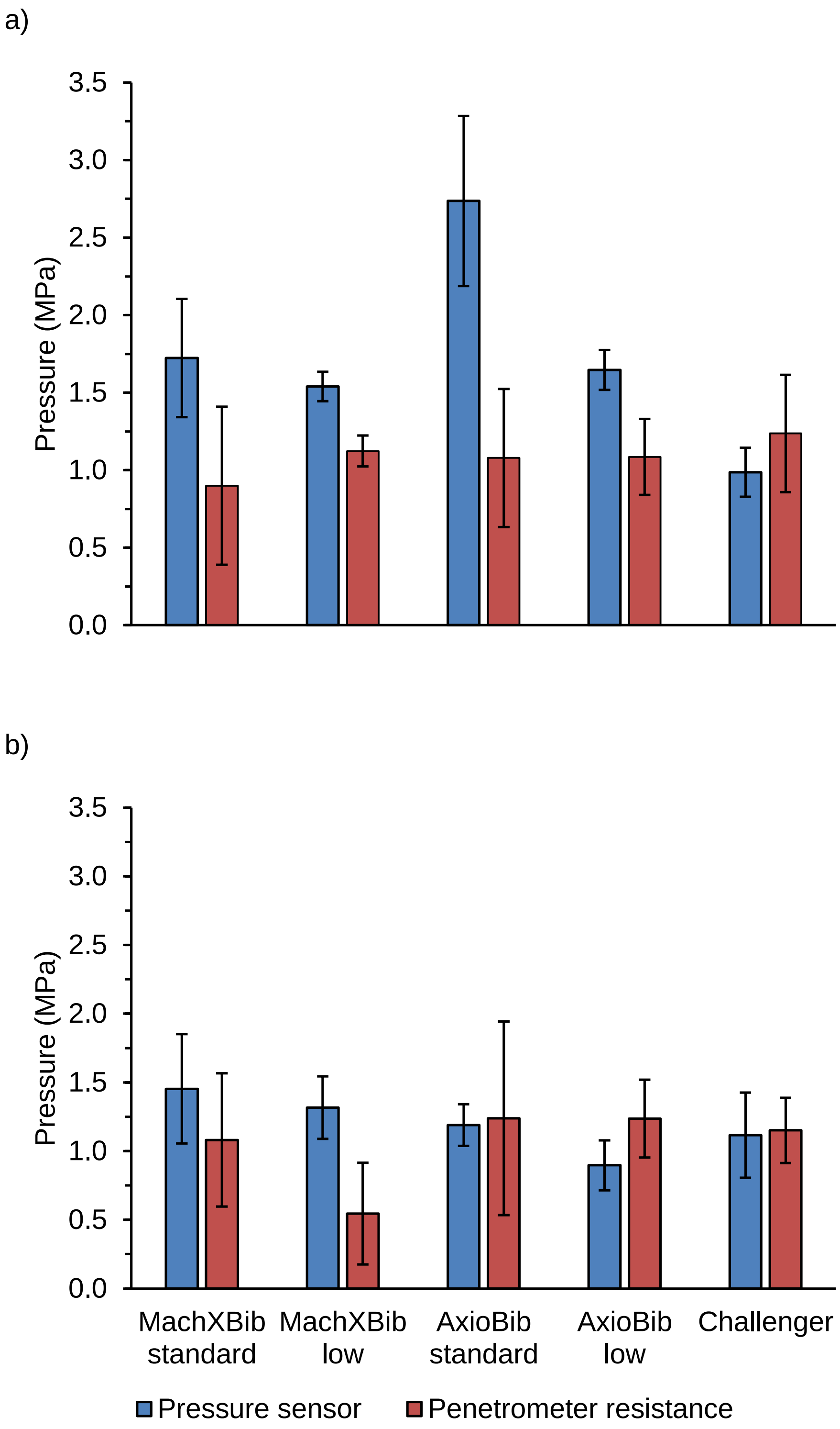


Figure 4.14. Comparison of soil pressures (±SEM) measured using pressure sensors and penetration resistance at (a) 150 mm and (b) 300 mm.

4.6. Conclusions

The results presented and discussed in Chapter 4 confirm that a reduction in tyre inflation pressure of MachXBib tyres can be used to minimise changes in soil pressure under repeated passes. These results, however, result to dry soil conditions and so must be transposed to soils of higher soil moisture content with care, as the impact of traffic would be greater due to reduced soil strength (Figure 2.3; Söhne, 1958). The use of increased flexion tyres within the conditions of this experiment did not minimise changes in soil pressure. Differential inflation pressures of MachXBib tyres produced greater differences in soil pressure than AxioBib tyres. The results presented in this chapter, of the differential soil pressures and penetration resistance measurements recorded under MachXBib tyresinflated to standard and low inflation pressures, supports the selection criteria that the same tyre type could be used in a field experiment to create differential soil conditions. Tracks consistently resulted in lower soil pressure than tyre treatments. Therefore, MachXBib tyres at standard and low inflation pressures could be implemented into a field experiment to achieve differential standard and low traffic pressure treatments, measurable by penetration resistance. The use of a tracked vehicle would complement low inflation pressure tyres.

Future field based research in this project, therefore, will implement the following differential ground pressure traffic treatments using MachXBib 600/70 R28 (front) and 650/85 R38 (rear) tyres:

- Standard pressure treatment: 0.12 MPa (front) and 0.15 MPa (rear)
- Low pressure treatment: 0.07 MPa (front and rear)

5. Field site assessment

Some of the information presented in this chapter is based on the work completed in collaboration with, and reported by, Kristof *et al*. (2012). The author acknowledges this work by direct reference throughout the chapter.

5.1. Field site assessment

Traffic and tillage induced compaction is considered to be a key driver in agricultural soil structural degradation affecting crop-supporting processes (Huber *et al*., 2008; Virto *et al*., 2015). Research discussed in the earlier literature review (Chapter 2) identified that much of the evidence base for the effect of traffic and tillage management systems has been outside of the United Kingdom. Few studies have been performed in Europe, and where there have been studies they have been implemented across different soil types, spatial and temporal scales (Chamen, 2011), whereby neighbouring fields, or zones within fields have been compared. Researchers have not always considered the range of traffic and tillage management systems available for arable production systems (Chamen *et al*., 1992b) in their research, leading to a need for a more comprehensive study into the effects of the latest commercially available traffic and tillage management systems. The effect of a reduction in tyre inflation pressure on soil pressure and compaction, indicated by penetration resistance, was investigated and discussed in Chapter 4. This phase of the study was completed in a controlled soil hall environment, without the presence of ground engaging implements, and without the influence of external factors including weather and crop growth. Soils are variable at any spatial scale due to their formation, but also because of management strategies imposed upon them for crop production (Odlare *et al*., 2005). The mapping and management of this variability in cereal and grassland agricultural fields (Serrano *et al*., 2010) is becoming more accessible using precision farming techniques for the management of inputs (Atherton *et al*., 1999) including seeding, fertiliser and irrigation. Furthermore, it allows site-specific management of processes and real-time monitoring of outputs including yield mapping and yield improvements (Atherton *et al*., 1999; Serrano *et al*., 2010).

Quantification of the natural spatial variability of soil properties is essential when establishing agricultural field experiments. Soil variability is the key contributor to experimental error (Rosselló and Fernández de Gorostiza, 1993) and as it increases it becomes increasingly difficult to distinguish treatment effects (Gezan *et al*., 2010). Spatial variability is not only found at the same location, but between locations (Zhang *et al*., 1994). It is important to therefore choose a single-site area with low levels of variation to minimise effects on the interpretation of results and outcome of the experiment (Odlare *et al*., 2005). Methods of monitoring soil physical and structural properties, including bulk density, penetration resistance, and soil water content, can be used to study the spatial variability of a field (Pramanik and Aggarwal, 2013). The measurements of soil properties themselves are associated with a level of variability, the threshold of which must be relevant to the scale at which the research question is posed (Cambardella *et al*., 1994). The randomisation of treatments, and replication of sampling, seeks to better identify treatment effects (Gezan *et al*., 2010). Sample size and plot dimensions should be considered in the design of an experiment to overcome the limitations imposed by soil spatial variability (Zhang *et al*., 1994). Work reported by Day (1920) showed an increase in accuracy when long and narrow plots were used. Nevertheless, optimum plot size must balance precision and economics (Zhang *et al*., 1994), in addition to delivering a realistic comparison with commercial practice. A uniformity assessment can help determine underlying variation independent of treatment effects (Selwyn, 1996). Rosselló and Fernández de Gorostiza (1993) describe a “blank tests” process whereby a single variety of crop is sown across the site and managed with consistent soil management and agronomic practices.

The review of published literature presented in Chapter 2, identified the need for a statistically robust experiment on a single field site to determine the effect of traffic and tillage systems using the most current commercially available tyre technology in cereal production. Traffic and tillage experiments reported in the literature to date are characterised by the use of agricultural land where soil degradation is unresolved, or where knowledge on soil spatial variations and crop performance is limited. This study plays a central role in resolving inconsistencies in the current knowledge base due to spatial variability of previous experiments, and the contributes to the development of evidence and knowledge for European farming systems.

5.2. Research hypothesis and objectives

The hypothesis for this phase of the research was that soil properties, measurable by penetration resistance, apparent electrical conductivity, soil moisture, and crop establishment, growth and harvestable yield will be affected by variations in elevation and soil type, such that field areas of more uniform elevation and soil type will have less variation in measurable soil and crop properties.

The objectives of this research were:

1. To design an experimental methodology to determine the site uniformity;
2. To determine the most uniform area by measurement of soil and crop properties including elevation, soil type, electrical conductivity, soil moisture, penetration resistance and crop establishment, growth and yield.
3. To recommend the most appropriate location for a field experiment based on the uniformity assessment.

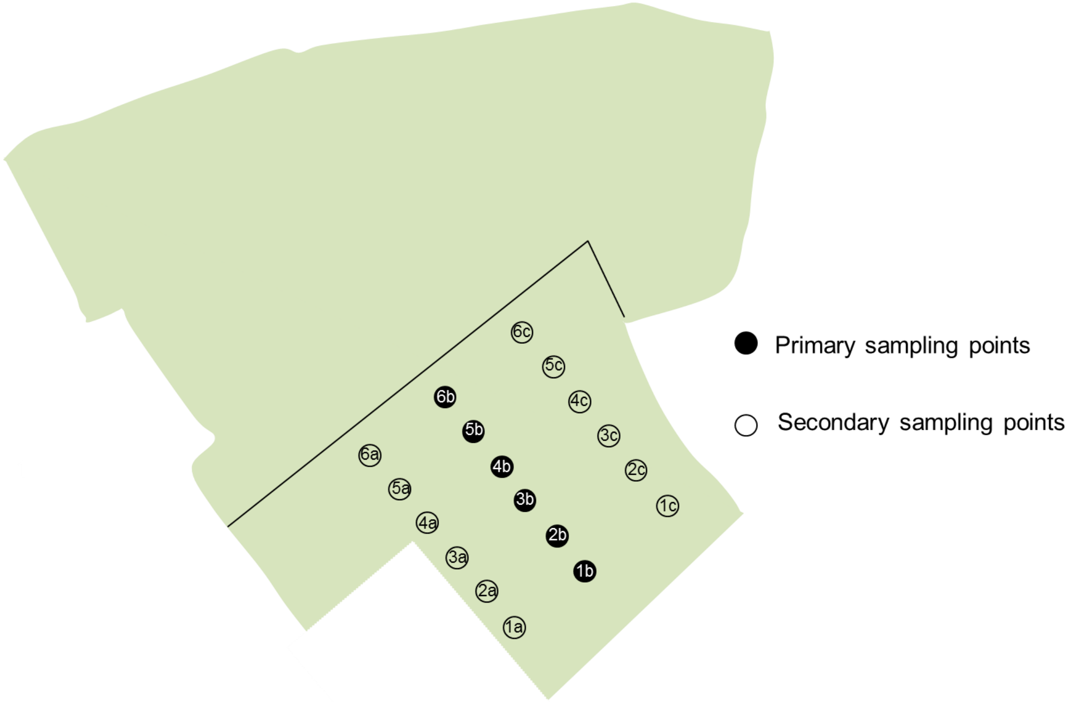
5.3. Materials and methods

In September 2011 the field site was assessed to facilitate the design of a long-term replicated experiment. Historical maps and farm records were reviewed to provide a history of the management of Large Marsh. These revealed that the site formerly consisted of three fields separated by boundaries until 2006, and thus the site was considered as three zones. As zones B and C were identified to be non-uniform they were removed from any further sampling and analysis.

5.3.1. Soil physical properties

Soil series maps (Beard, 1988) were verified by in-field sampling and hand texture analysis in the laboratory. In collaboration with Precision Decisions© (2011), a non-invasive Dualem sensor collected shallow (0-500 mm) and deep (0-1200 mm) electrical conductivity measurements across the entire site in October 2011. Soil electrical conductivity (EC_a) is a sensor measurement of the soils ability to transfer an electric current, and is indicative of soil physical and chemical properties (Sudduth *et al*., 2005).

Figure 5.1 shows the primary sampling points used for penetration resistance and soil moisture measurements. Soil penetration resistance was measured in untrafficked and wheelway zones at the primary sampling points (Figure 4.5) using an Eijkelkamp penetrologger (Eijkelkamp Soil and Water, Netherlands), fitted with a 100 mm^2 60° top angle cone. Data were collected at 10 mm intervals from the soil surface to a depth of 400 mm and averaged every 50 mm. Penetrometer measurements were taken after seeding operations on 22 November 2011.



Source: Adapted from Kristof *et al*. (2012)

Figure 5.1. Soil sampling points where the number at each sampling location identifies the sampling column, and the letter identifies each sampling row.

Soil moisture measurements were taken using a time domain reflectometer (TDR) FieldScout soil moisture meter in November 2011 after seeding, at the same time and in the same locations as the penetrometer samples (primary sampling locations). After the field had been sprayed (March 2012) and fertiliser had been applied (April 2012), secondary sampling points (Figure 5.1) were used to assess spatial variation in soil moisture in the direction of seeding, and across the field.

5.3.2. Crop properties

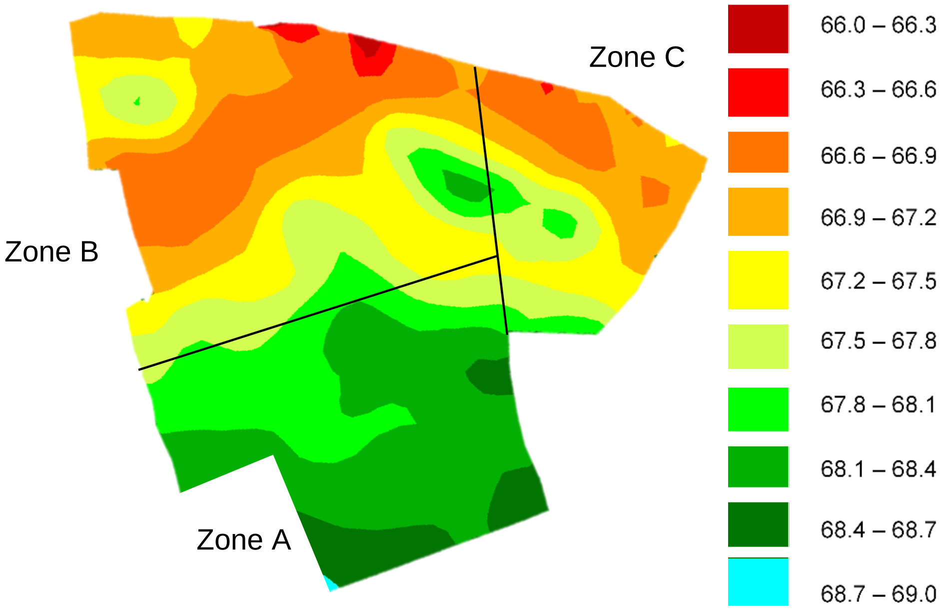
Rosselló and Fernández de Gorostiza (1993) stated that although quantitative measurements of soil variations can be used to study the uniformity of an experimental site, the conclusions of uniformity are more routinely based on yield obtained by division of the field into zones that are analysed separately. Therefore, the crop establishment was measured on 8 December 2011 by plant count at emergence. Normalised difference vegetation index (NDVI) was calculated from measurements of near infrared and visible red of the crop biomass, recorded on 22 June 2012 (Kristof *et al*., 2012). Harvestable yield was collected on 6 September 2012.

5.4. Results and discussion

5.4.1. Field site

The field site was divided into three zones, corresponding to former field boundaries. The area of each zone was determined. Zone A: 3.67 ha, B: 3.74 ha and C: 1.5 ha. The limited size of Zone C resulted in it being discounted from any further sampling and analysis.

The field elevation, shown in Figure 5.2, of Zone A varied from 67.5-68.7 mamsl, a difference of 1.2 m. The small area above 69.0 m contour was not included in this range due to its location at the boundary of the field, and the likelihood that this would become experimental area was extremely low. Zone B varied by 2.4 m from 66.0-68.4 mamsl and thus had double the difference in elevation compared to Zone A. Furthermore, variations in the elevation of Zone B were more frequent and dispersed.

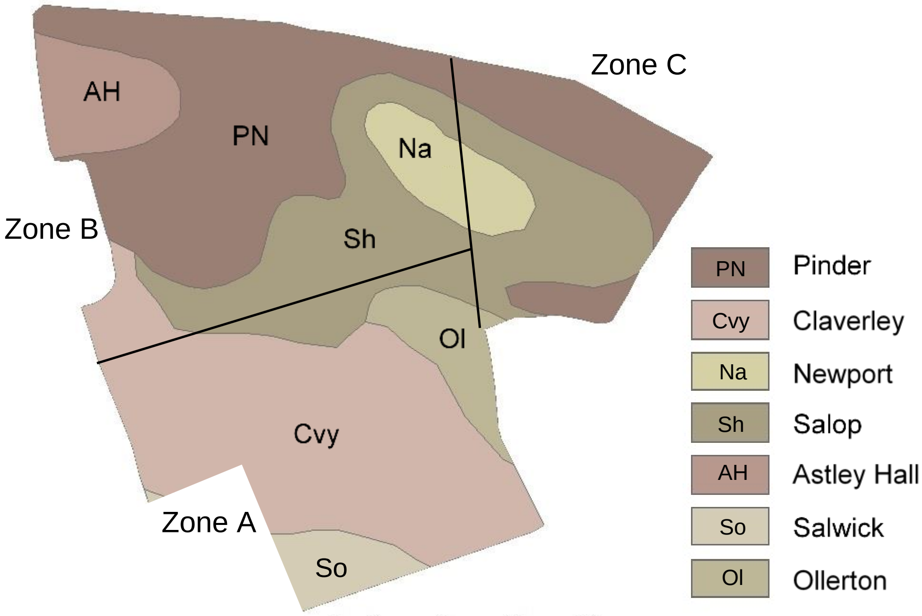


Source: Adapted from Precision Decisions (2011)

Figure 5.2. Elevation (mamsl).

5.4.2. Soil physical properties

Data obtained from records of the Soil Survey and Land Research Centre (Beard, 1988) were verified using in-field hand sampling and soil texture analysis (Appendix I). Four soil types were identified in Zone A (Figure 5.3) (Kristof *et al*. 2012). The area is, however, predominantly Claverley (Cvy), a very slightly stony sandy loam, with smaller areas on the perimeter of the field of Salop (Sh) and Ollerton (Ol) and Salwick (So). Four soil types, Astley Hall (AH), Newport (Na), and “seasonally waterlogged slowly permeable soils” Salop (Sh) and Pinder (PN) (Beard, 1988), were identified in Zone B. The increased frequency and dispersion of variations in Zone B, which were seen previously in changes in elevation, were also identified in changes in soil type.

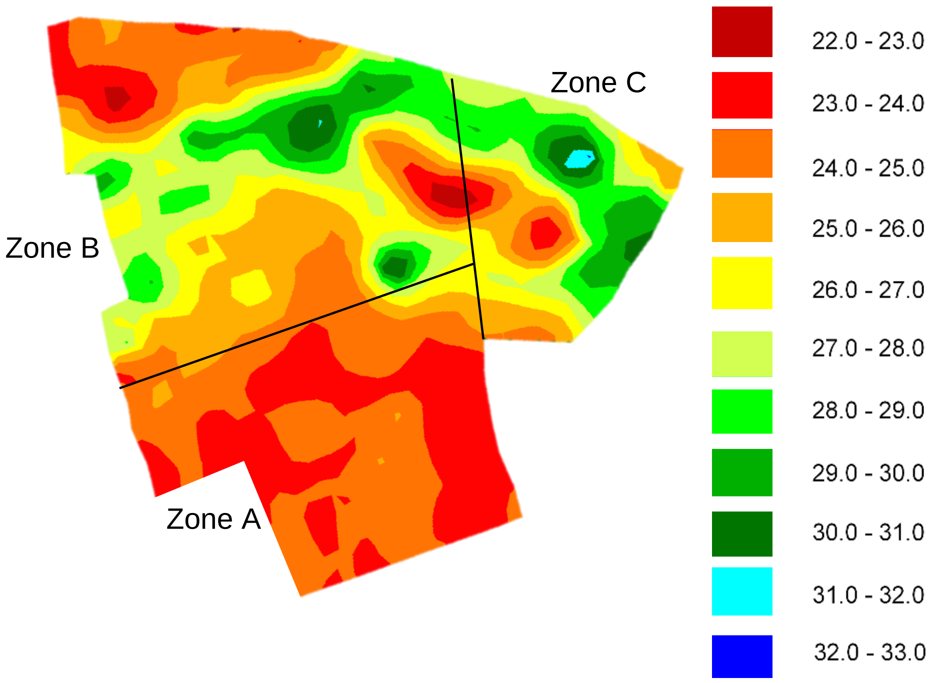


Source: Adapted from Kristof *et al*. (2012)

Figure 5.3. Soil series map.

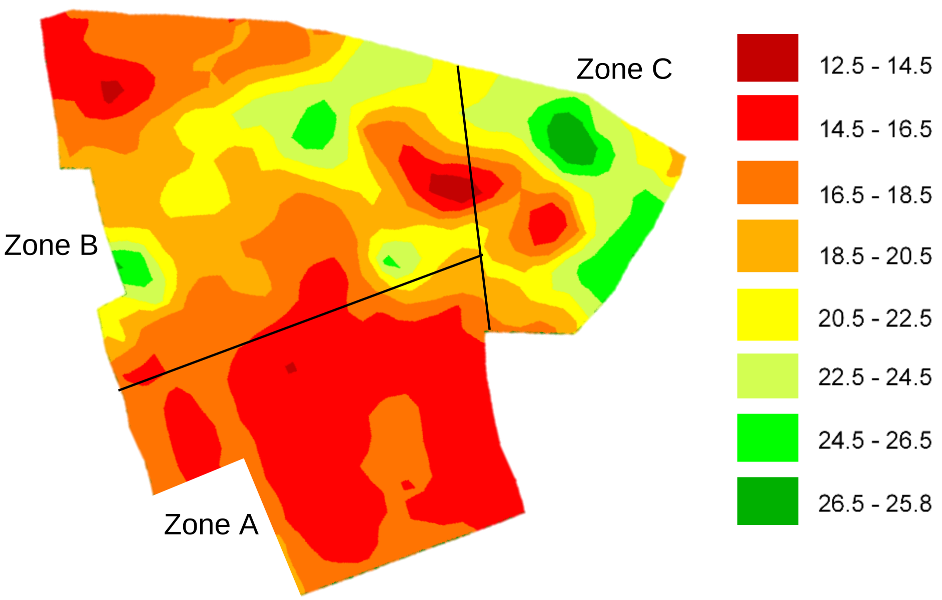
Apparent electrical conductivity (ECa) of the soil was measured from the surface to a depth of 0.5 m (Figure 5.4), and 1.2 m (Figure 5.5). Zone A was lighter textured soil, indicated by lower values of ECa and more uniform compared to Zone B. Apparent electrical conductivity is correlated with clay content; as clay content increases, the ECa increases (Sudduth *et al*., 2005).

In Zone A, the soil conductivity from the surface to 0.5 m ranged from 24.0-25.0 mS/m. There was greater variation in Zone B, from 24.0-31.0 mS/m. The soil electrical conductivity from the surface to 1.2 m ranged from 16.5-18.5 mS/m in Zone A, whereas in Zone B the variation was greater, from 14.5-26.5 mS/m.



Source: Adapted from Precision Decisions (2011)

Figure 5.4. Shallow electrical conductivity (mS/m) to 0.5m depth.



Source: Adapted from Precision Decisions (2011)

Figure 5.5. Deep electrical conductivity (mS/m) to 1.2m depth.

Based on the assessments of soil series, deep and shallow electrical conductivity, the author concluded that Zone A was the most uniform area. Therefore, a detailed analysis of the soil structure and crop properties within Zone A was completed.

The average penetration resistance (data not shown) at sampling point 1 was recorded as 1.73 MPa. This was significantly greater than points 5 and 6 ($P = 0.043$, LSD 5% = 0.4464).

Data were collected from untrafficked and wheelway areas, as shown in Figure 5.6. Overall, untrafficked soil (1.17 MPa) had significantly lower penetration resistance than trafficked soil in the wheelways (1.53 MPa) ($P < 0.001$, LSD 5% = 0.1736). At two of the sampling points however, points 1 and 4, the penetration resistance of the wheelways was significantly lower than the untrafficked soil ($P = 0.005$, LSD 5% = 0.4252). The interaction between depth, sampling point and traffic was found to be significant ($P < 0.001$, LSD 5% = 0.7338) and thus the effect of traffic on soil penetration resistance across the site was not uniform.

Differences in the effect of surface applied loads on soil structure could be due to variations in soil properties, including soil organic matter and moisture. The resilience of soil to compaction from surface applied loads such as agricultural traffic has been attributed to the application of organic matter in the form of farmyard and green manures (Mudjeci *et al*., 2017). Soils with a higher organic matter content have greater soil water holding capacities, and thus dry out more slowly than soil with a lower soil organic matter, due to increased pore size from biological activity. As soils dry out, readings of penetration resistance increase (Gliński *et al*., 2011). It is possible that in the current experiment variations in soil type, including organic matter and therefore water holding capacities, as shown in Figure 5.7, could have resulted in variations in readings of penetration resistance.

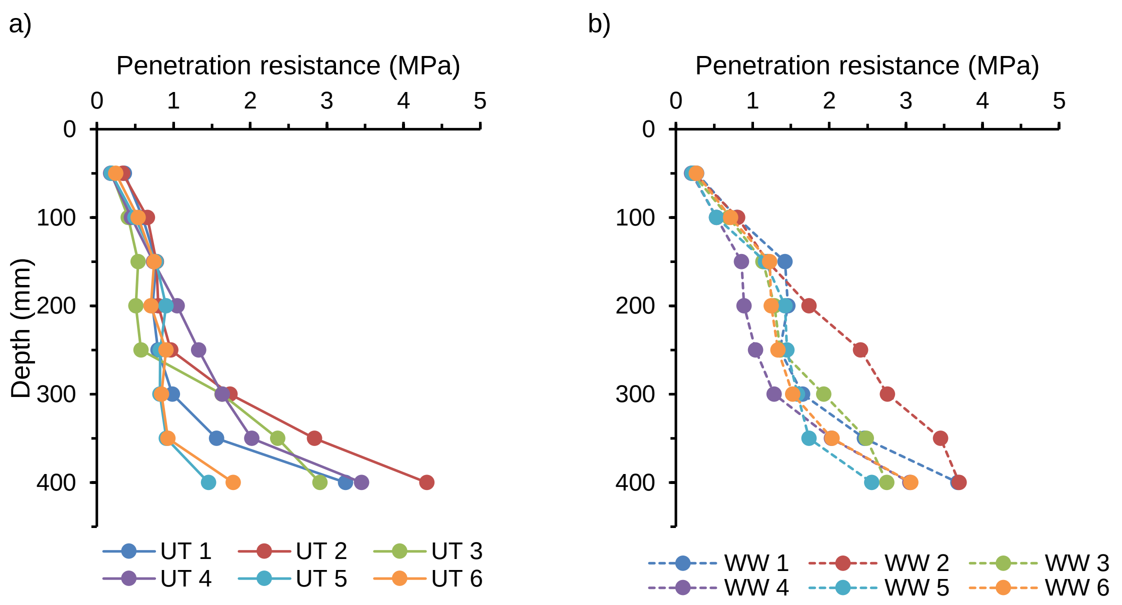
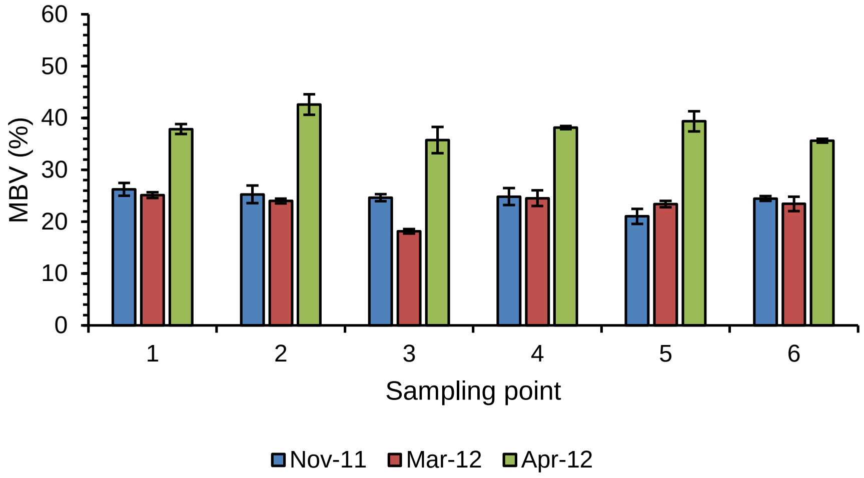


Figure 5.6. Soil penetration resistance in a) untrafficked (UT) and b) wheelways (WW).

Penetration resistance increased significantly with depth (P < 0.001, LSD 5% = 0.1915). In untrafficked soil, the lowest value was recorded at 50 mm (0.26 MPa) and the highest value recorded at 400 mm (2.99 MPa). In trafficked soil, the lowest value was again recorded at 50 mm (0.24 MPa) and the highest value recorded at 400 mm (3.13 MPa). In trafficked soils the penetrometer values increased more rapidly with depth resulting in higher values being recorded nearer the soil surface compared to untrafficked conditions.

Figure 5.7 shows the average moisture content of the soil collected at the primary sampling locations (1-6b) in November 2011, March 2012 and April 2012 in a) untrafficked and, b) wheelways.

a)



b)

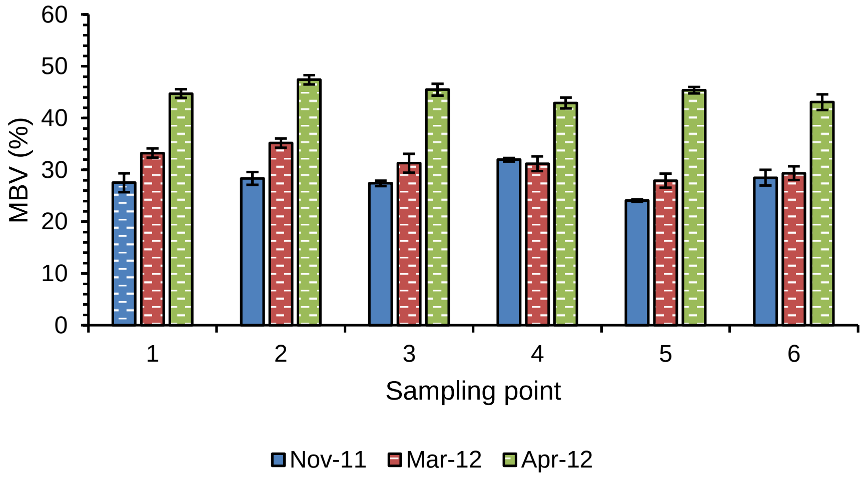


Figure 5.7. Soil moisture content (± SEM) collected at the six primary sampling points in November 2011, March 2012 and April 2012 in a) untrafficked (UT) and, b) wheelways (WW).

Untrafficked soil recorded significantly lower soil moisture contents on average (28.6%) compared to the trafficked soil in the wheelways (34.7%) ($P < 0.001$, LSD 5% = 0.676). There were significant differences in the soil moisture recorded at the sampling columns ($P < 0.001$, LSD 5% = 1.171), and thus the soil moisture characteristics of the site were not consistent.

Figure 5.8 shows the variations with sampling points measured in March and April 2012 using the additional sampling locations.

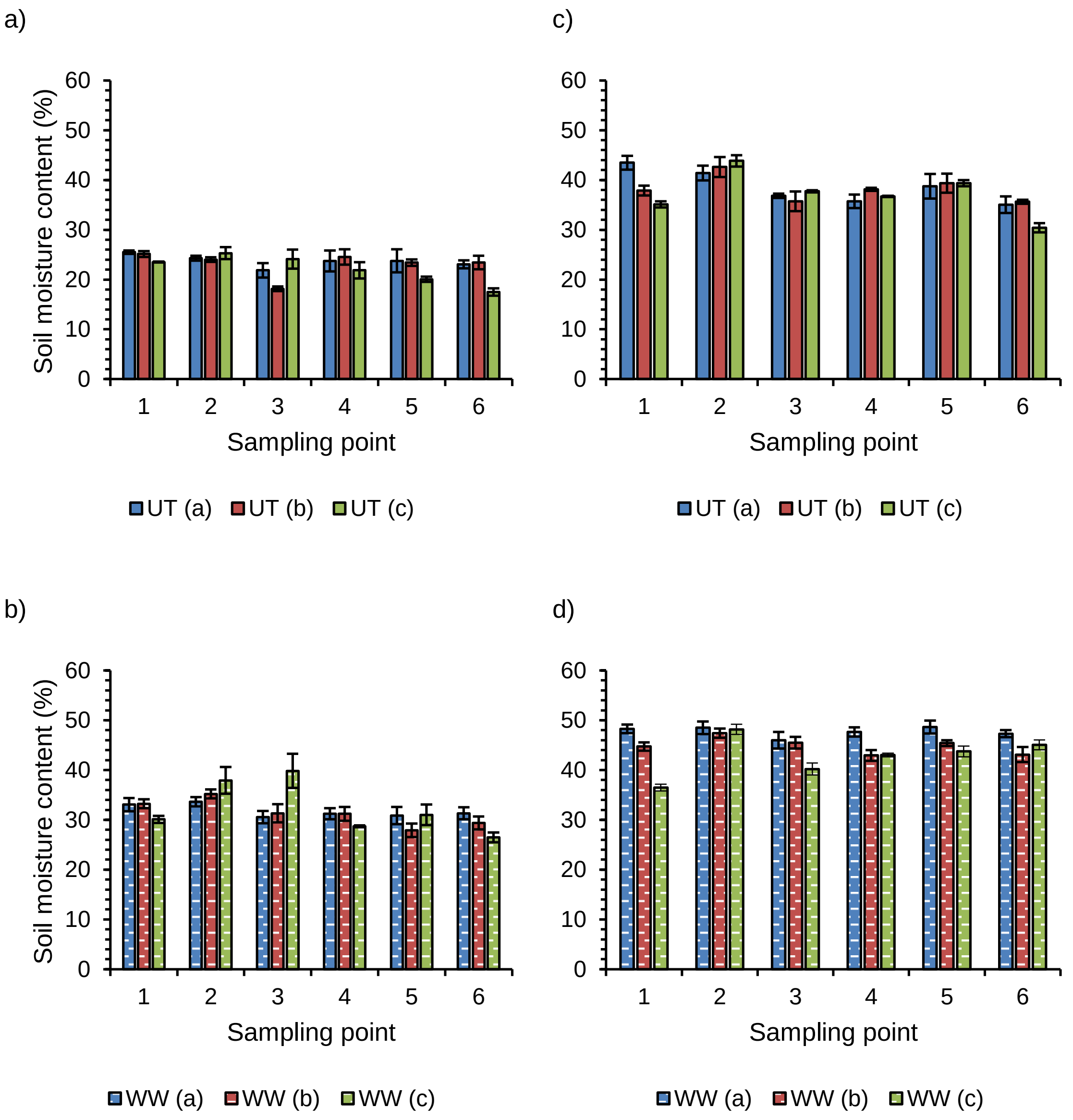


Figure 5.8. Soil moisture content (± SEM) in March 2012 in (a) untrafficked (UT) and (b) wheelways (WW), and April 2012 in (c) untrafficked (UT) and (d) wheelways (WW).

In March, the untrafficked soil recorded significantly lower soil moisture (23.0%) compared to the wheelways (31.8%) ($P < 0.001$, LSD 5% = 0.947). The sampling point (1-6) was again significant ($P < 0.001$, LSD 5% = 1.640), whereby column 2 was significantly higher than the other points. Most importantly however, there was no significant difference in the soil moisture measured within sampling point ($P = 0.583$). In April, untrafficked soil recorded significantly lower soil moisture (38.0%) compared to the wheelways (45.11%) ($P < 0.001$, LSD 5% = 0.810). There were significant differences in the soil moisture measured at different sampling points, and as found before, point 2 recorded significantly higher soil moisture than the other sampling points ($P < 0.001$, LSD 5% = 1.404). There were, however, significant differences in soil moisture recorded within the sampling columns ($P < 0.001$, LSD 5% = 0.993). The soil moisture recorded at sampling row a) was significantly higher at b) and c).

5.4.3. Yield analyses

Figure 5.9 shows the results of plant establishment counts (number of plants per m^2). Plant data was not replicated and has therefore has not been analysed statistically. Sampling points 2 and 4 had greater within plot plant establishment variation. Overall, the range of plant establishment between all sampling points was 41 plants/m^2.

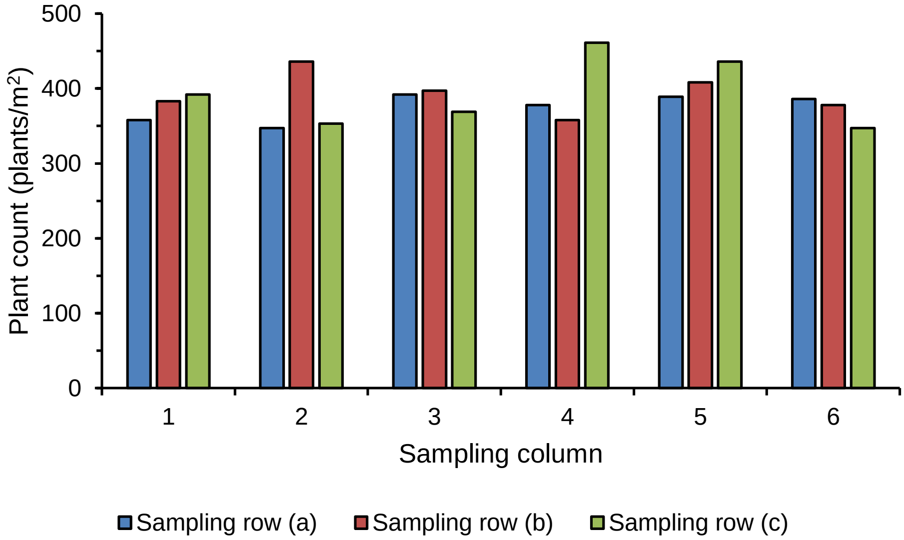
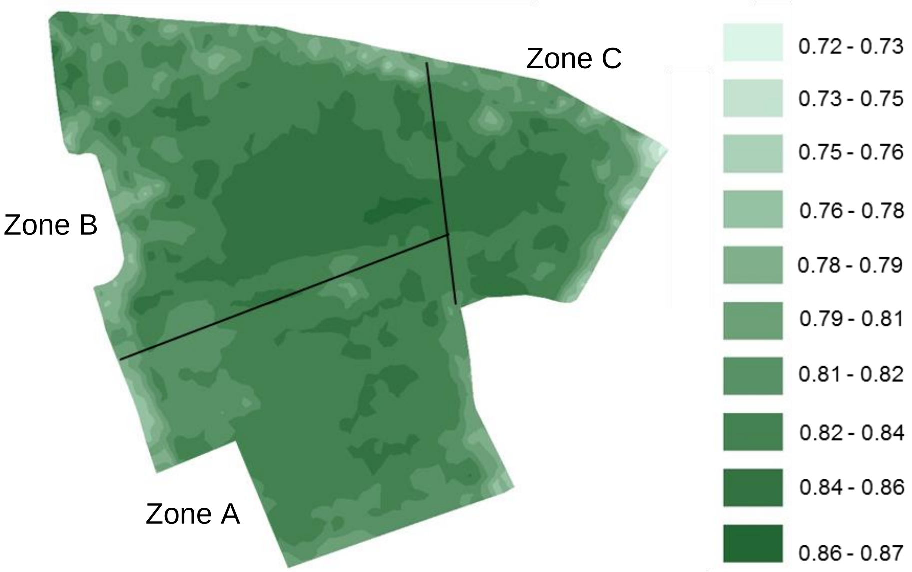


Figure 5.9. Plant establishment (plants/m^2).

Measurements of crop biomass derived from normalised vegetation difference index (NDVI) are shown in Figure 5.10. The maximum and minimum NDVI values recorded in Zone A were 0.88 and 0.74 respectively, a range of 0.14.



Source: Adapted from Kristof *et al*. (2012)

Figure 5.10. Normalised difference vegetation index.

Grain samples were taken from the combine harvested grain and the yield adjusted to standard moisture content of 15%. Whole plots yields were determined, as shown in Figure 5.11. The average yield (± SEM) in Zone A was 4.2 ± 0.01 Mg ha^{-1}. The Home Grown Cereals Authority (HGCA) (Wynn and Twining, 2012) reported national wheat yields were 10-15% below the 5-year UK average at approximately 6.8 Mg ha^{-1}, due to low insolation levels during the crops production phase, from approximately the end of May to early August (HGCA, 2008). In June 2012, the average daily solar energy recorded at Harper Adams University was 13.58 MJ m^{-2} compared to a ten-year average of 19.03 MJ m^{-2} (2001-2011).

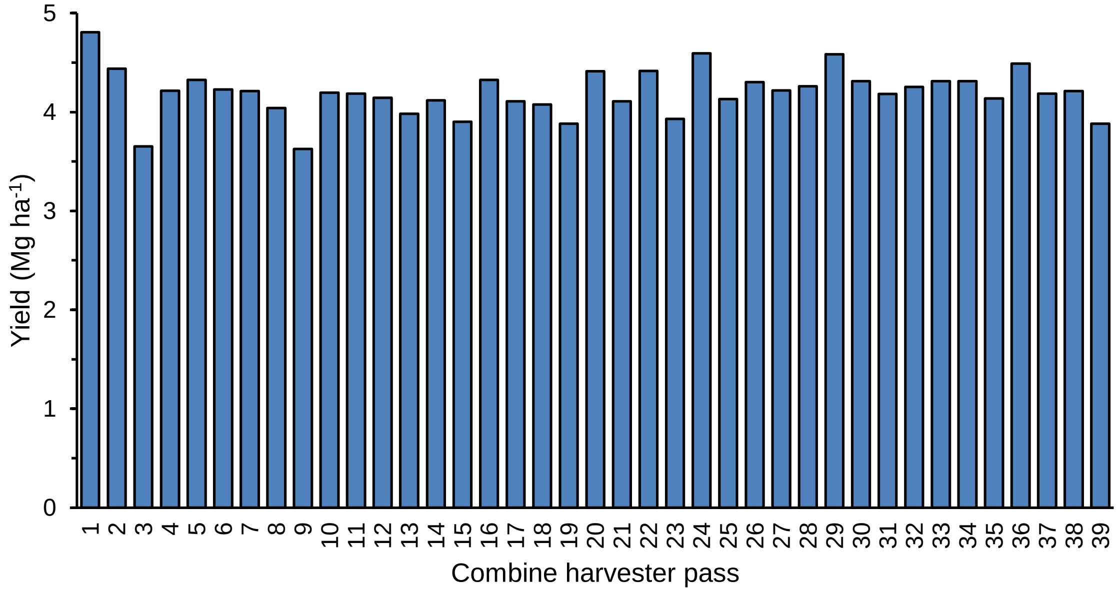


Figure 5.11. Winter wheat crop yield (Mg ha^{-1}). Plot 1 was located 12 m from the field boundary within Zone A.

5.5. Conclusions

This study provided a thorough understanding of the soil and crop performance parameters in Large Marsh. This knowledge will support the results of the experimental plots, and that the information collected in the subsequent field experiment will show effects of treatments imposed and not of underlying soil variations.

Zone A had the lowest variations of elevation change (1.2 mamsl), shallow (1.0) and deep (2.0) electrical conductivity and thus was the most uniform zone within the field upon which to locate the experiment. Therefore, the subsequent field experiment was located within Zone A. Measurement of the soil penetration resistance showed that both untrafficked and trafficked soil in the wheelways were significantly different across the site. The measurement of untrafficked soils within each plot in subsequent experimental work will overcome this and allow for the change in penetration resistance to be calculated and analysed. Winter wheat crop yields were uniform across the site, with an average yield of 4.2 ± 0.01 Mg ha^{-1}.

The site normalisation and assessment of uniformity prior to the implementation of a traffic and tillage experiment that has been presented in this chapter represents the first of its kind in traffic and tillage research.

6. The effect of agricultural traffic and tillage on field soil physical properties

6.1. Introduction

Soil compaction is the alteration of the arrangement of particles to a more packed condition associated with an increase in soil bulk density and penetration resistance and a reduction in water infiltration. These properties of soil are fundamental to promoting good crop growth and yields, yet they are increasingly characterising European agricultural production systems (Virto *et al*., 2015). In-field trafficking by off-road vehicles is necessary in cereal crop production, the consequence of which is often extensive compaction (Kroulík *et al*., 2009).

Methods of reducing the extent of traffic-induced compaction can include low ground pressure (LGP) or controlled traffic farming (CTF) systems. Low ground pressure systems seek to reduce the contact pressure between running gear and soil by distributing it over a wider area. The research presented in Chapter 4 concluded that this could be achieved through a reduction in tyre inflation pressure or the use of a rubber tracked vehicle.

A reduction in traffic intensity is associated with a reduction in tillage; as less traffic enters a field, less tillage work is required to remove the compaction resulting from trafficking (Kroulík *et al*., 2009). Researchers state that ploughing is necessary to remove compaction under extensive trafficking (Kroulík *et al*., 2009). When experiments have compared ploughing with zero tillage, the latter has often resulted in increases in soil bulk density and penetration resistance (Clutterbuck and Hodgson, 1984; Mühlbachová *et al*., 2015). However, research completed over longer times scales, in a range of 2-22 years, has shown that a reduction in tillage results in improvements to soil water movement (Voorhees and Lindstrom, 1984; Kahlon *et al*., 2013). Furthermore, it has been shown that the vulnerability of soils to traffic induced compaction increases as a result of the soil management imposed by intensive tillage systems (Ankeny *et al*., 1995; Chan *et al*., 2006; Botta *et al*., 2009), and a reduction in tillage intensity creates a soil structure that is more resilient to applied forces.

6.2. Research hypothesis and objectives

The hypothesis for this phase of research was that soil compaction will be affected by traffic intensity and tillage intensity, such that a reduction in traffic and tillage intensity using controlled traffic farming and reduced tillage will reduce soil compaction measured by lower values of bulk density and penetration resistance, and increased hydraulic conductivity.

The objectives of this research were:

1. To measure changes in soil bulk density, penetration resistance, soil moisture content, and hydraulic conductivity resulting from three agricultural traffic systems being random traffic farming at standard and low tyre inflation pressures, and controlled traffic farming, and three tillage systems being deep, shallow and zero tillage;
2. To measure soil properties of permanent wheelways and untrafficked soils in controlled traffic farming.

6.3. Materials and methods

This research was completed in a randomised and replicated field experiment, as described in Chapter 3. In 2012 to 2013, bulk density samples were collected on 14 August 2013 from an excavated soil profile pit in an area adjacent to, but treated as a continuum of, the plots. Samples were taken from the 2x passes for RTF_S and RTF_L, and untrafficked and wheelway areas for CTF for all tillage treatments. Samples were taken from these traffic zones as they are most representative of each of the traffic systems at all intensities of tillage (Figure 3.5). Samples were not replicated and disturbance to the area was high. In 2013 to 2014, therefore, the methodology for bulk density measurements was developed to cover all plots. On 30 July 2014, forty-eight intact undisturbed soil cores measuring 50 mm in width and 350 mm in length were extracted from the site. From RTF_S and RTF_L plots, cores were taken from 2x passes (n = 24). From CTF plots cores were taken from untrafficked (n = 12) and wheelway (n = 12) zones. Cores were extracted using an Eijkelkamp soil corer (Eijkelkamp Soil and Water, Netherlands). In the laboratory, these samples were divided into three sections from 0-100 mm, 100-200 mm and 200-300 mm, before weighing and drying to calculate dry bulk density.

Penetration resistance was used to determine the compactive effect of treatments on soil. Data were collected using a hydraulic penetrometer in collaboration with SOYL (Newbury, UK). This allowed for data to be collected more accurately by the elimination of operator error as the speed of penetration is consistent. In 2012 to 2013, the site was sampled on 24 April 2013. In RTF_S and RTF_L plots, replicated measurements (n = 3) were collected from all traffic intensities (untrafficked, 1x, 2x and 3x passes, where present). In CTF plots, data were collected from untrafficked and wheelway zones. In 2013 to 2014, on 11 August 2014, the sampling method was developed whereby replications of data (n = 10) were collected from 2x passes in RTF_S and RTF_L. Two traffic passes represents the greatest percentage area covered within these treatments, and therefore characterises the traffic and tillage management systems in commercial production systems. In CTF plots, data were again collected from untrafficked and wheelway zones. Soil moisture at the time of measuring penetration resistance was determined using a TDR. The experimental site was found to be of uniform soil texture and thus differences identified in soil moisture using the TDR are independent of changes in soil texture.

In 2012 to 2013, neutron probe access tubes were located in the centre of each plot (n = 36). Seven repeat measurements were obtained on 04 April, 07 May, 29 May, 11 June, 25 June, 11 July and 19 July. In 2013 to 2014 data were collected on 18 June 2014 from access tubes (n = 36) located in 2x passes in RTF_S and RTF_L plots. In CTF plots, data were collected from untrafficked zones.

The saturated hydraulic conductivity ($L\ T^{-1}$) was measured on 2 August 2013 by simplified falling-head (SFH) using a single-ring water infiltrometer. Replicated measurements (n = 4) were taken in the 2x passes for random traffic farming standard and random traffic farming low, and untrafficked and wheelway areas for controlled traffic farming for all tillage treatments.

6.4. Statistical analyses

Replicated measurements of bulk density, penetration resistance and soil moisture content data from traffic passes in random traffic standard and low inflation pressure treatments, and the wheelways of controlled traffic farming plots, were analysed using repeated measured ANOVA to determine the effect of traffic and tillage. Deep and shallow tillage traffic was measured under 2x traffic passes; zero tillage only received one traffic incidence.

The effect of permanent wheelways and untrafficked soil on bulk density, penetration resistance and soil water content, were analysed using repeated measures ANOVA.

Hydraulic conductivity was analysed using two-way ANOVA.

6.5. Results and discussion

Data are presented graphically within this chapter, data tables are provided in Appendix J.

6.5.1. Bulk density

Figure 6.1 shows the dry bulk density for the first experimental year (2012-2013). In most cases, the bulk density of soil at 300 mm depth was greater than at 100 mm. The bulk density recorded under RTF_S on soil cultivated with deep tillage resulted in the highest overall soil bulk density. The mean for the soil profile, from a depth of 100 – 300 mm, was 1.67 Mg m^{-3}, exceeding the maximum optimum of 1.6 Mg m^{-3}, beyond which crop rooting structure becomes impeded (Huber *et al*., 2008). Sandy loams soils have an optimum range of bulk density between 1.30 and 1.45 Mg m^{-3} (Negi *et al*., 1981). Under RTF_S and RTF_L tyre inflation pressure treatments cultivated with deep tillage, the representative traffic intensity of 2x passes exceeds the optimum maximum limit. Under zero tillage, all measurements obtained exceeded the maximum optimum. Previous tillage research has demonstrated that in the years immediately following the implementation of zero tillage, soil bulk density increased to a depth of 180 mm (Clutterbuck and Hodgson, 1984) and 200 mm compared to deep tillage (Mühlbachová *et al*., 2015). A reduction in tyre inflation pressure reduced soil bulk density for deep and shallow tillage systems, but led to an increase for zero tillage system at 200 and 300 mm depth. In controlled traffic farming treatments, wheelways recorded an increase in bulk density compared to untrafficked soil, from 1.50 – 1.52 Mg m^{-3}. Under shallow tillage, wheelways recorded an 11% increase in bulk density compared to untrafficked soil. However, under deep and zero tillage the reverse was found, whereby soil in the wheelways was 1% and 5% lower in soil bulk density compared to untrafficked soil.

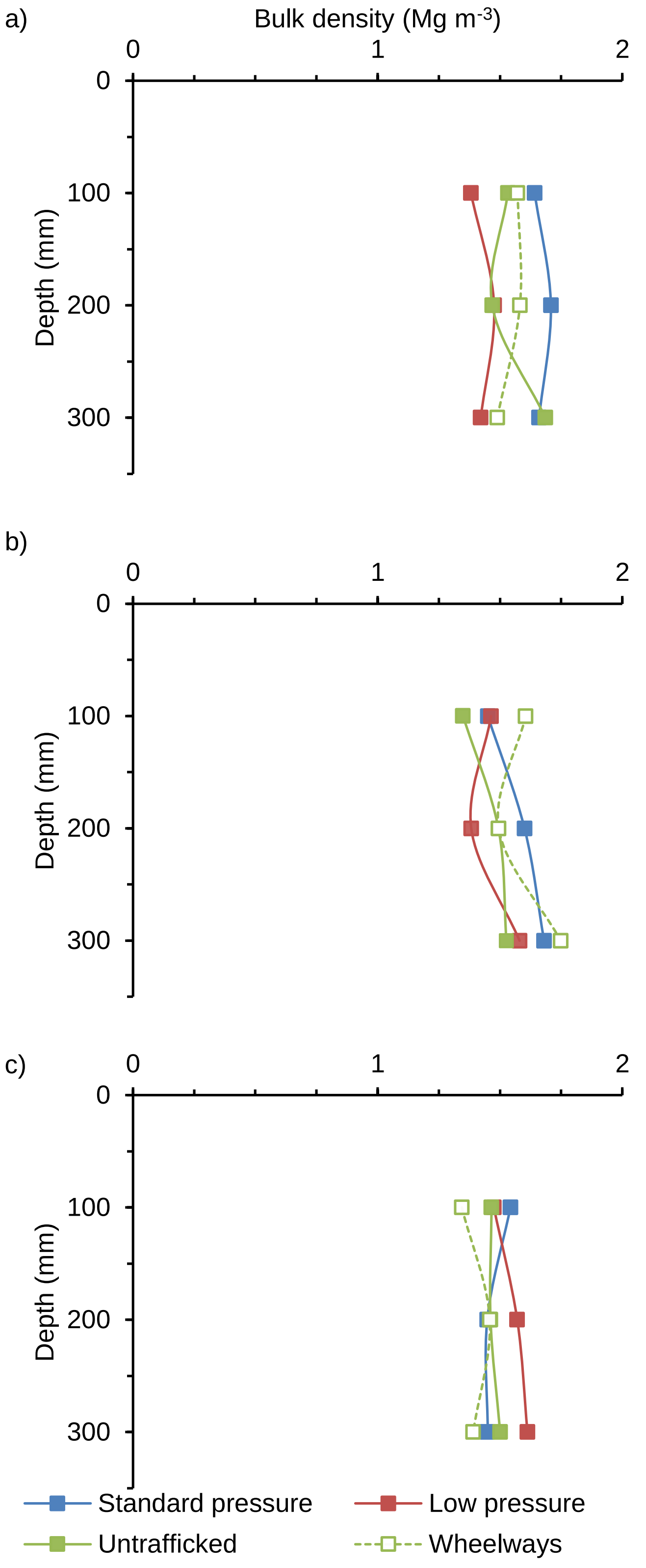


Figure 6.1. Soil bulk density (Mg m^{-3}) 2012-2013 under random traffic farming with standard and low tyre inflation pressures and controlled traffic farming at three tillage intensities: deep (a), shallow (b), and zero (c).

Figure 6.2 shows the bulk density of soil in the second experimental year (2013-2014). Soil bulk density increased significantly ($P < 0.001$, LSD 5% = 0.03773) with depth. Overall, bulk density recorded at 300 mm depth was significantly greater than measured at 100 mm and 200 mm depth. After 2 years of traffic and tillage treatments, standard tyre pressure (1.62 Mg m^{-3}) resulted in increased soil bulk densities compared to low pressure treatments (1.59 Mg m^{-3}), which could be attributed to the increased contact pressure and 13.5% smaller contact area of the MachXBib tyres at standard inflation pressure compared to the tyres at low inflation pressure. Similarly, Antille *et al*. (2013) reported less soil compaction, indicated by lower values of soil bulk density, under lower inflation pressure tyres with a larger contact area. Standard tyre inflation pressure treatments exceeded the maximum optimum threshold for crop growth (1.6 Mg m^{-3}) (Huber *et al*., 2008) whereas low ground pressure treatments did not. Differences in means between traffic treatments were not significant (P = 0.075, LSD 5% = 0.07783).

Overall, shallow (1.66 Mg m^{-3}) and zero (1.65 Mg m^{-3}) tillage treatments recorded significantly (P = 0.042, LSD 5% = 0.07783) higher bulk densities than deep tillage (1.57 Mg m^{-3}). Jabro *et al*. (2016) reported that tillage did not significantly influence soil bulk density, and attributed this to the role of soil texture governing total porosity, rather than changes as a result of tillage practice. The study, however, rotated tillage treatments across plots, which could have led to the influence of soil conditions as a result of tillage practice between years. Similarly, Martínez *et al*. (2008) concluded that tillage did not have a significant effect on soil bulk density, and suggested that opposing conclusions of the effect of tillage on soil bulk density between studies is due to machinery configurations, soil conditions and traffic intensities.

Zero tillage had a significantly (P = 0.007, LSD 5% = 0.09414) higher soil bulk density compared to shallow and deep tillage, but only at 100 mm depth. At a depth of 200 mm and 300 mm, shallow tillage recorded the highest value of soil bulk density but differences in means were not found to be significant. Previous research has reported on the vulnerability of soils to traffic compaction dependent on the soil tillage systems imposed (Ankeny *et al*., 1995; Botta *et al*., 2009). This current study however did not find a significant interaction between traffic and tillage (P = 0.505).

Differences in means between soil bulk density measured in CTF untrafficked and wheelway zones were significant (P = 0.001, LSD 5% = 0.1067). In untrafficked soil the bulk density was recorded as 1.48 Mg m^{-3}, 13.6% lower than recorded in the wheelways (1.68

Mg m^{-3}). A 7% change in bulk density below the critical threshold has been shown to increase root growth by 15% (McHugh *et al*. 2009 cited Cook, 1988). The soil bulk density of wheelways in zero tillage (1.64 Mg m^{-3}) was greater than deep (1.53 Mg m^{-3}) and shallow (1.56 Mg m^{-3}) tillage. Differences in means, however, were not significant (P = 0.209).

McHugh *et al*. (2009) reported on the use of controlled traffic farming to restore soil structure at the same time as the implementation of a zero tillage system. Over 22 months, soil bulk density declined. During the 2 years of the current study, mean bulk density values measured in untrafficked and wheelway zones of zero tillage treatments increased by 3% and 19% respectively. Changes in bulk density that were observed in previous research (McHugh *et al*., 2009) could be attributed to the re-structuring capabilities of the clay soil upon which the study was performed. In the present study, in the absence of re-structuring characteristics, the greatest reduction in soil bulk density over the period of the study using CTF was found in the deep tillage treatment. The bulk density of untrafficked soil measured in the second experimental year was 6% lower than measured in the first experimental year. The bulk density of the wheelways increased, however, by 5%, and thus a smaller percentage increase than observed in the zero tillage treatments. The results, therefore, indicate that after two years of the implementation of tillage systems, deep tillage resulted in lower soil bulk densities than zero tillage.

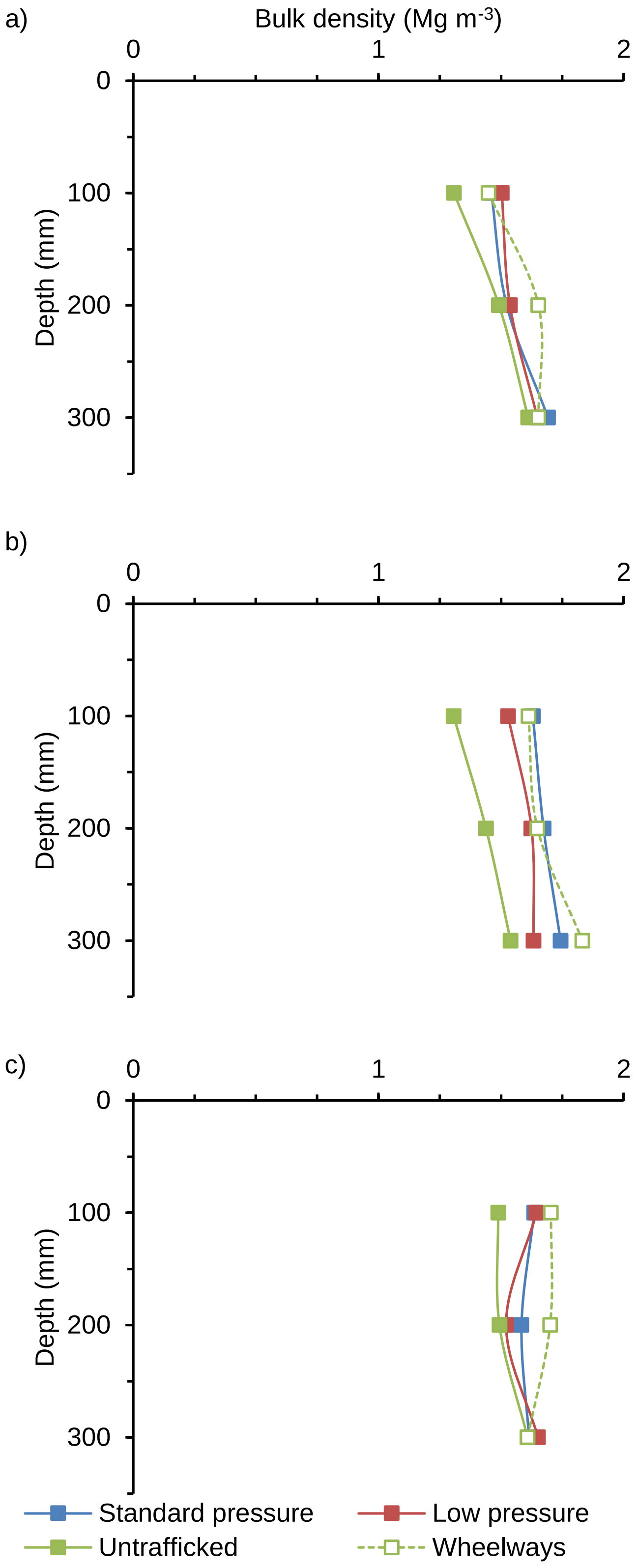


Figure 6.2. Soil bulk density (Mg m^{-3}) 2013-2014 under random traffic farming with standard and low tyre inflation pressures and controlled traffic farming at three tillage intensities: deep (a), shallow (b), and zero (c).

6.5.2. Penetration resistance

Figure 6.3 shows the values of penetration resistance measured in the first experimental year 2012-2013. Penetration resistance increased with depth and differences in penetration resistance between each depth measured were significant (*P* < 0.001, LSD 5% = 0.1316). Standard tyre inflation pressure (1.175 MPa) tyre treatments resulted in lower penetration resistance than low tyre inflation pressure (1.256 MPa) treatments, although differences in means were not significant (*P* = 0.476, LSD 5% = 0.1369). Dickson and Ritchie (1996) also reported greater penetration resistance under reduced ground pressure treatments, compared to conventional traffic, at a depth of 60 – 150 mm. In the present study the greatest differences between standard and low tyre inflation pressures were observed in shallow tillage to a depth of 250 mm. Results of penetration resistance in the first experimental year differed from bulk density measurements, and greater differences were observed in the former measurements.

Across all traffic treatments, the mean penetration resistance measured in deep tillage soils was greater (1.266 MPa) compared to shallow (1.179 MPa) and zero (1.213 MPa), although differences in means were not significant (*P* = 0.431, LSD 5% = 0.1369).

Differences in penetration resistance measured in CTF untrafficked and wheelway zones were significant (*P* = 0.028, LSD 5% = 0.1352). In untrafficked soil the penetration resistance was recorded as 1.073 MPa, compared to 1.227 MPa in the wheelways. In the first experimental year, lower penetration resistance values were recorded under the tracked Challenger (1.227 MPa) compared to the low inflation pressure tyre treatment (1.256 MPa), although differences in traffic treatments were not found to be significant.

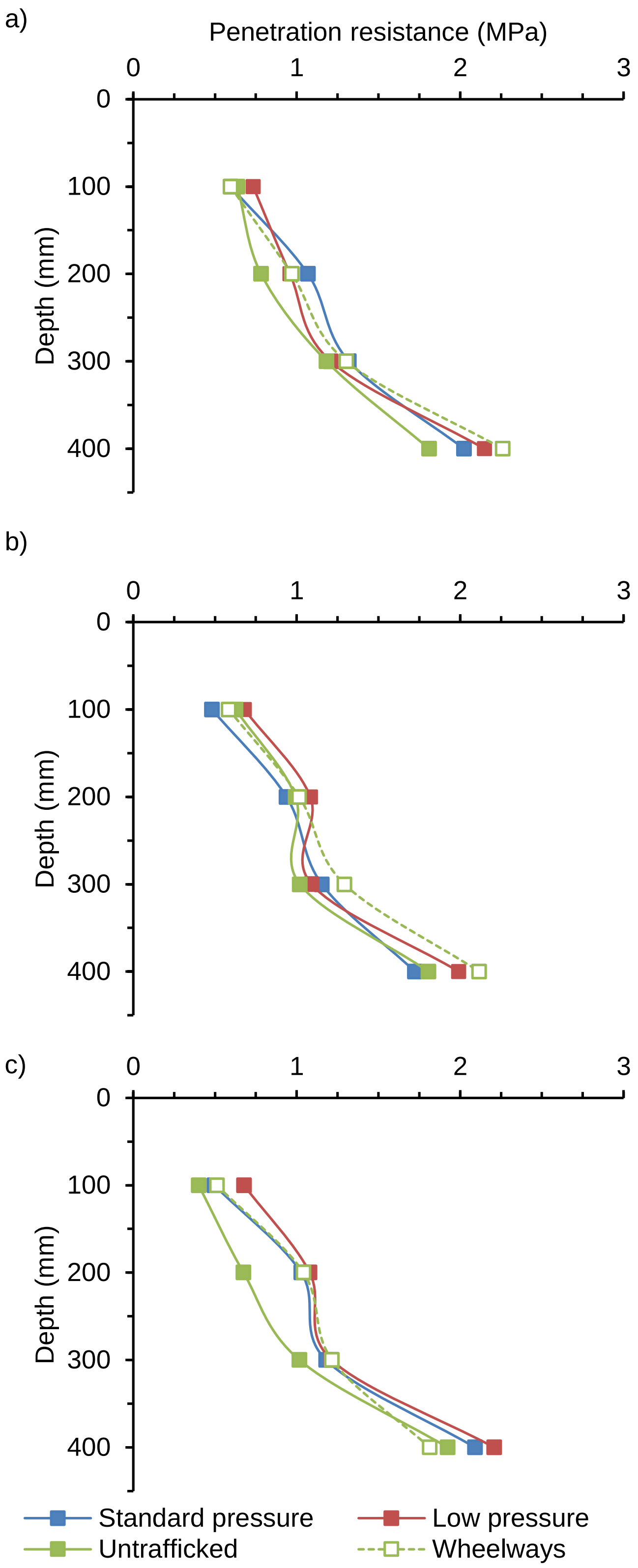


Figure 6.3. Soil penetration resistance (MPa) 2012-2013 under random traffic farming with standard and low tyre inflation pressures and controlled traffic farming at three tillage intensities: deep (a), shallow (b), and zero (c).

Figure 6.4 shows the values of penetration resistance measured in the second experimental year 2013-2014. Penetration resistance increased significantly with depth ($P < 0.001$, LSD 5% = 0.696). The results of the first and second experimental years differed, whereby in the second year standard tyre inflation pressure (0.727 MPa) resulted in increased levels of penetration resistance compared to low tyre inflation pressure treatments (0.646 MPa). These differences were only observed in deep and shallow tillage treatments, and below a depth of 200 mm. Greater differences between standard and low tyre inflation pressure treatments were identified in deep tillage treatments. Differences in means between traffic treatments were not found to be significant ($P = 0.176$, LSD 5% = 0.943). The results presented in the current research are after two years of the application of traffic and tillage systems. Similarly, Arvidsson (2001) did not observe significant differences in traffic induced compaction treatments until between 2 and 4 years of treatments. The results of penetration resistance for the current study support the results of bulk density from the same year, although greater differences were observed in penetration resistance.

Zero tillage resulted in the highest overall penetration resistance (0.777 MPa), indicating increased levels of compaction, compared to deep (0.619 MPa) and shallow (0.694 MPa). Differences in means between zero and deep tillage treatments were significant ($P = 0.008$, LSD 5% = 0.0943). This result is consistent with those presented by other researchers (Clutterbuck and Hodgson, 1984; Alvarez and Steinbach, 2009; Mühlbachová *et al*., 2015). The results presented in this current study are representative of the early years of adoption of a zero tillage system, whereby soil structure becomes more compact in the short-term, and the benefits of the system are only realised after 3-4 years, and in the absence of traffic (Voorhees and Lindstrom, 1984).

Differences in penetration resistance measured in CTF untrafficked and wheelway zones were significant ($P = 0.006$, LSD 5% = 0.1021). In untrafficked soil the penetration resistance was recorded as 0.564 MPa, compared to 0.717 MPa in wheelway zones. Over the two years, lower values of soil bulk density and penetrometer resistance were recorded in untrafficked soil, indicating improved soil structure. Researchers have studied the implications of increased soil compaction as a result of wheel traffic on doubling tillage draught force (Tullberg, 2000). After two years of the experiment, low ground pressure tyres (0.646 MPa) recorded lower values of penetration resistance compared to the tracked Challenger (0.717 MPa), although differences in traffic treatments were not significant.

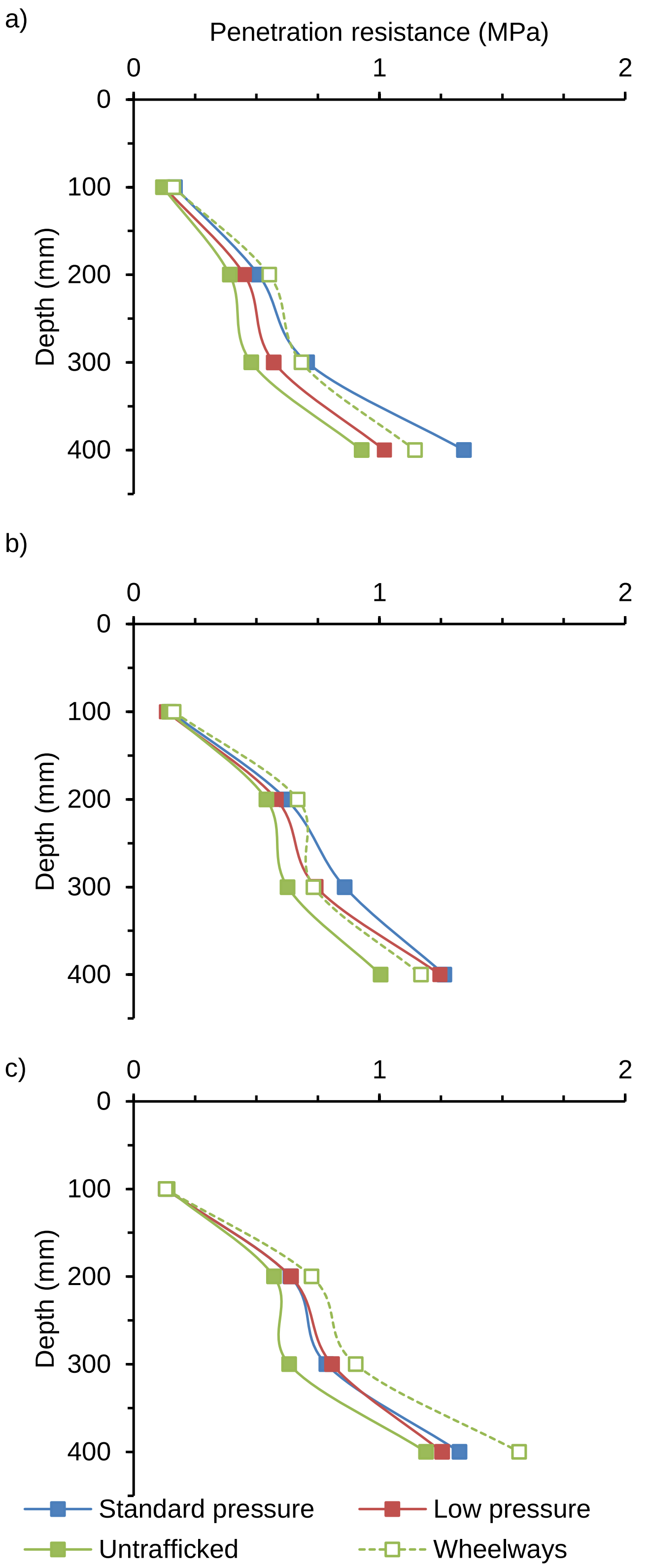


Figure 6.4. Soil penetration resistance (MPa) 2013-2014 under random traffic farming with standard and low tyre inflation pressures and controlled traffic farming at three tillage intensities: deep (a), shallow (b), and zero (c).

6.5.3. Soil moisture content

Figure 6.5 shows the gravimetric soil moisture content measured at 100 mm intervals from the soil surface to a depth of 300 mm. In the first experimental year 2012-2013 samples were unreplicated. In the second experimental year (2013-2014), shown in Figure 6.6, each measurement was replicated (n=4), and thus statistical analysis has been completed on these measurements only.

Differences in means between standard tyre inflation pressure (19.97 g g^{-1}), low tyre inflation pressure (19.98 g g^{-1}) and controlled traffic farming (19.81 g g^{-1}) treatments were not found to be significant (P = 0.985). The soil water content was higher under deep (20.12 g g^{-1}) and shallow (20.58 g g^{-1}) tillage compared to zero tillage (19.07 g g^{-1}). Differences in means were not significant (P = 0.367). Zero tillage also recorded the highest bulk density and penetration resistance compared to deep and shallow tillage systems. As differences in soil water content were not found to be significant, these results suggest that soil structural differences did not significantly affect soil moisture content in zero tillage soils. The values of penetration resistance did not exceed the maximum threshold whereby crop growth and water movement becomes inhibited, indicating a compacted state. Bulk density in zero tillage treatments only slightly exceeded the reported threshold, but did not appear to impact on the soil water.

Differences in means between untrafficked and wheelway zones of controlled traffic farming plots were not significant (P = 0.257). The differences in soil moisture in zero tillage plots between trafficked and untrafficked zones were greater than those observed in deep and shallow tillage treatments. Richard *et al*. (1999) reported that multiple traffic incidences could have a greater impact on reducing soil porosity than the same traffic over a cultivated soil.

Samples for gravimetric moisture content were taken on 30 July 2014, therefore towards the end of the crops growing season where differences between tillage treatments have been shown to decline (De Vita *et al*., 2007), indicating the reduced water uptake by the crop following senescence.

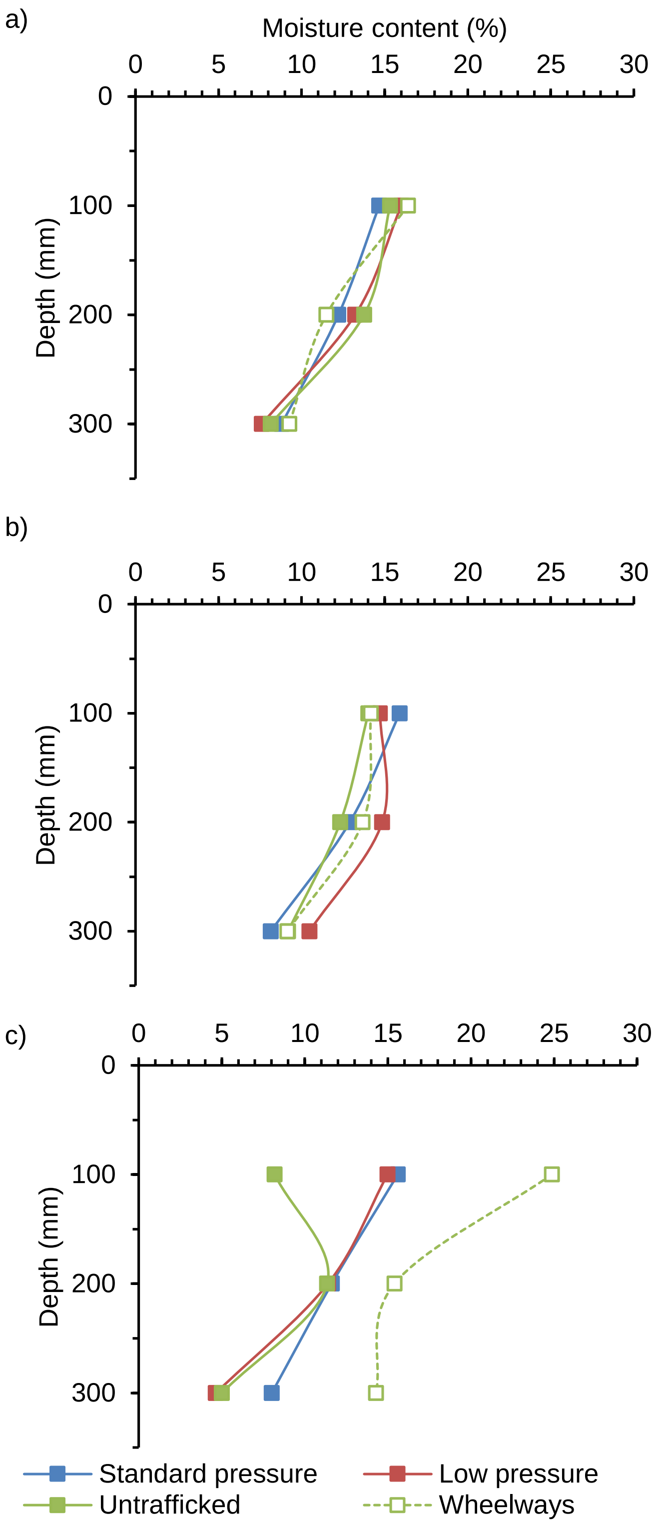


Figure 6.5. Soil moisture content 2012-2013 under random traffic farming with standard and low tyre inflation pressures and controlled traffic farming at three tillage intensities: deep (a), shallow (b), and zero (c).

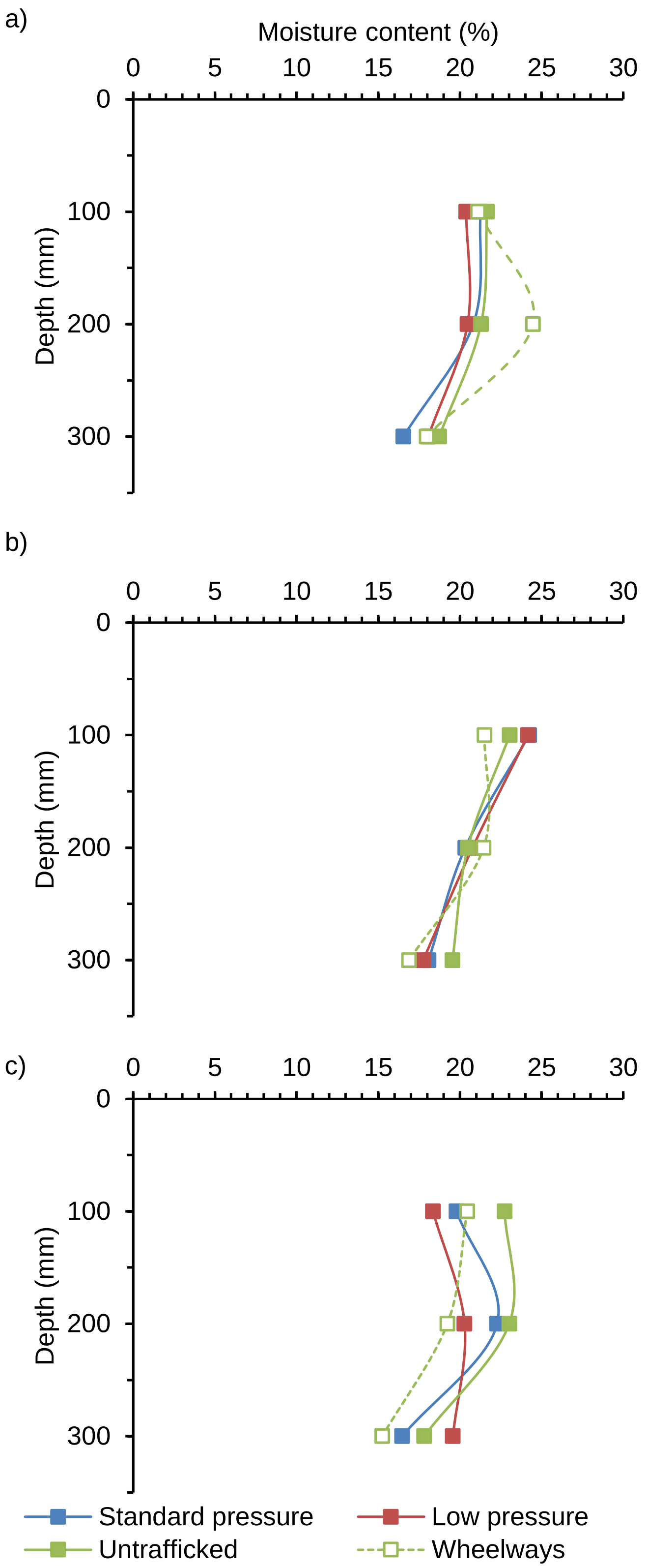


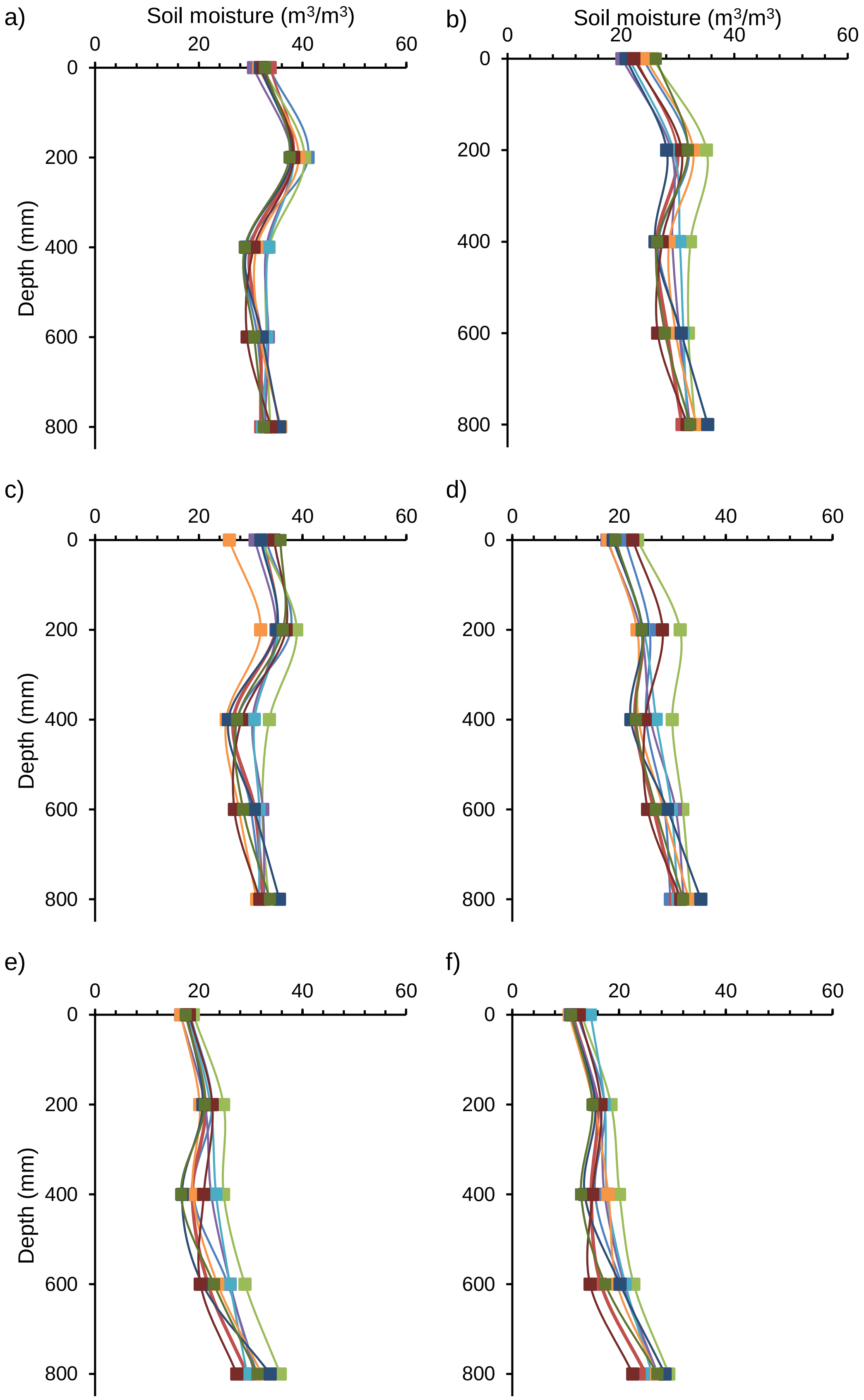
Figure 6.6. Soil moisture content 2013-2014 under random traffic farming with standard and low tyre inflation pressures and controlled traffic farming at three tillage intensities: deep (a), shallow (b), and zero (c).

Figure 6.7 shows the variation in volumetric moisture measured using the neutron probe during the crops growing season. Over the period of the growing season, soil moisture decreased significantly ($P < 0.001$, LSD 5% = 1.0538). Differences in means between each depth were found to be significant ($P < 0.001$, LSD 5% = 0.5173). Overall, as depth increased, soil moisture increased. It is worth noting, however, that a depth of 200 mm, soil moisture was higher than at 400 mm and 600 mm.

Controlled traffic farming (24.672 m^3/m^3) resulted in significantly lower soil moisture than standard (25.906 m^3/m^3) and low (25.366 m^3/m^3) tyre inflation pressure treatments (P = 0.002, LSD 5% = 0.6899). Raghavan and McKeyes (1978) reported that traffic-induced compaction resulted in higher soil moisture contents. Barik *et al*. (2014) reported similar findings also, whereby the soil water content increased after trafficking as a result of the applied load leading to a reduction in porosity, which itself is dependent on the field operation, for example harvesting, tillage and seeding (Richard *et al*., 1999).

Differences in means between zero (25.749 m^3/m^3) and shallow (24.823 m^3/m^3) tillage were significant (P = 0.031, LSD 5% = 0.6899). Deep tillage (25.372 m^3/m^3) resulted in lower soil moisture than zero tillage. Differences in means between deep and zero tillage, however, were not significant. This supports the work reported by De Vita *et al*. (2007) who attributed these differences to reduced water evaporation from zero tillage.

The interaction between traffic and tillage was also found to be significant ($P < 0.001$, LSD 5% = 1.1949). Under standard tyre inflation pressure and controlled traffic farming, the soil moisture was lower in shallow tillage compared to deep. For both traffic treatments, the soil moisture increased with zero tillage compared to shallow tillage. For low inflation pressure tyres, however, shallow tillage resulted in the highest soil moisture, compared to deep and zero. The interaction between traffic, tillage and depth within the soil profile was significant ($P < 0.001$, LSD 5% = 1.8803). For standard tyre inflation pressure treatments, higher soil moisture was recorded under zero tillage compared to deep and shallow at all depths observed. The use of low inflation pressure tyres with shallow tillage resulted in the highest soil moisture contents from 0 mm – 600 mm. At 800 mm within the profile, however, higher soil moisture was recorded in zero tillage. For controlled traffic farming plots, a similar trend was identified, whereby increased soil moisture was recorded in shallow tillage from 0 mm to 400 mm. Below this depth, the highest soil moisture values were recorded under deep tillage.


a)
Soil moisture (m3/m3)
0
20
40
60
0
200
400
600
800
Depth (mm)
b)
Soil moisture (m3/m3)
c)
d)
e)
f)

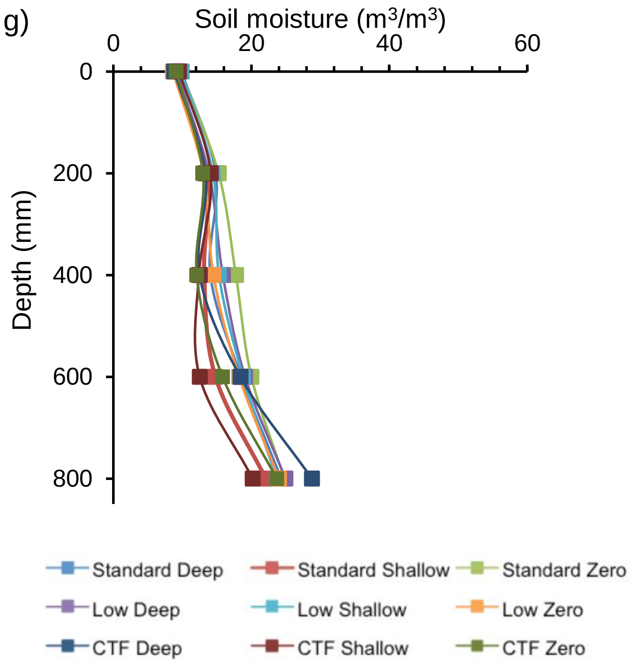


Figure 6.7. Mean values of soil moisture profiles in 2013 from a) 4 April, b) 7 May, c) 29 May, d) 11 June, e) 25 June, f) 11 July, and g) 19 July (SEM = 1.6795).

The percentage changes in soil moisture for each water profile were calculated by reference to the soil moisture status at field capacity on 04 April 2013, considered equivalent to 100%, at each depth observed. Subsequent values throughout the growing season were referenced to this to calculate the change in soil moisture under standard tyre inflation pressure (Figure 6.8), low tyre inflation pressure (Figure 6.9), and controlled traffic farming (Figure 6.10) with deep, shallow and zero tillage systems.

The greatest percentage change in soil moisture in July 2013, measured across the whole soil profile, was observed in standard tyre inflation pressure with deep tillage, and low tyre inflation pressure with zero tillage, with both treatments recording soil water contents 73% lower than on 4 April 2013. At a depth of 800 mm, the greatest percentage change in soil moisture at the end of the measurement period, for standard tyre inflation pressure and controlled traffic farming treatments, was observed in shallow tillage.

Rainfall events continued throughout measurement period (section 3.3, Figure 3.2). Increases in soil moisture content as a result of total rainfall in May 2013 of 90.0 mm were observed at a depth of 0 – 200 mm, with greatest differences in deep and shallow tillage treatments. Low tyre inflation pressure treatments with deep (Figure 6.12a) and shallow tillage (Figure 6.12b) did not however show any increases in soil moisture change as a result of rainfall, and reductions in soil water content were only evident between 0 – 200 mm. Soil water content measured between the 25 June and 19 July 2013 increased in the soil depths 0 – 200 mm, suggesting that uptake of water by crops in low ground pressure and zero tillage treatments was limited.

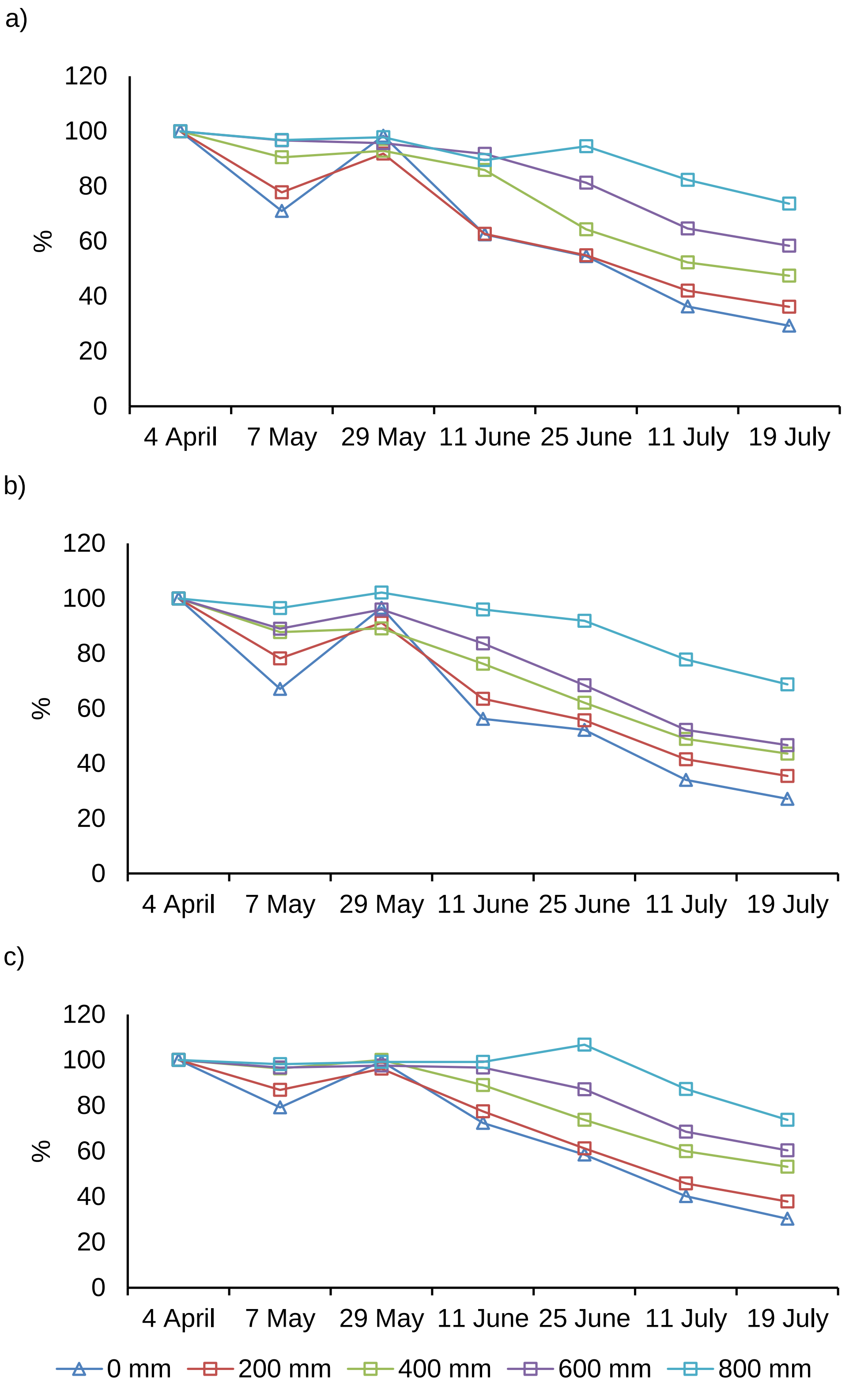


Figure 6.8. Temporal changes in volumetric soil moisture content from 0 to 800 mm under standard tyre inflation pressure traffic with a) deep, b) shallow and, c) zero tillage.

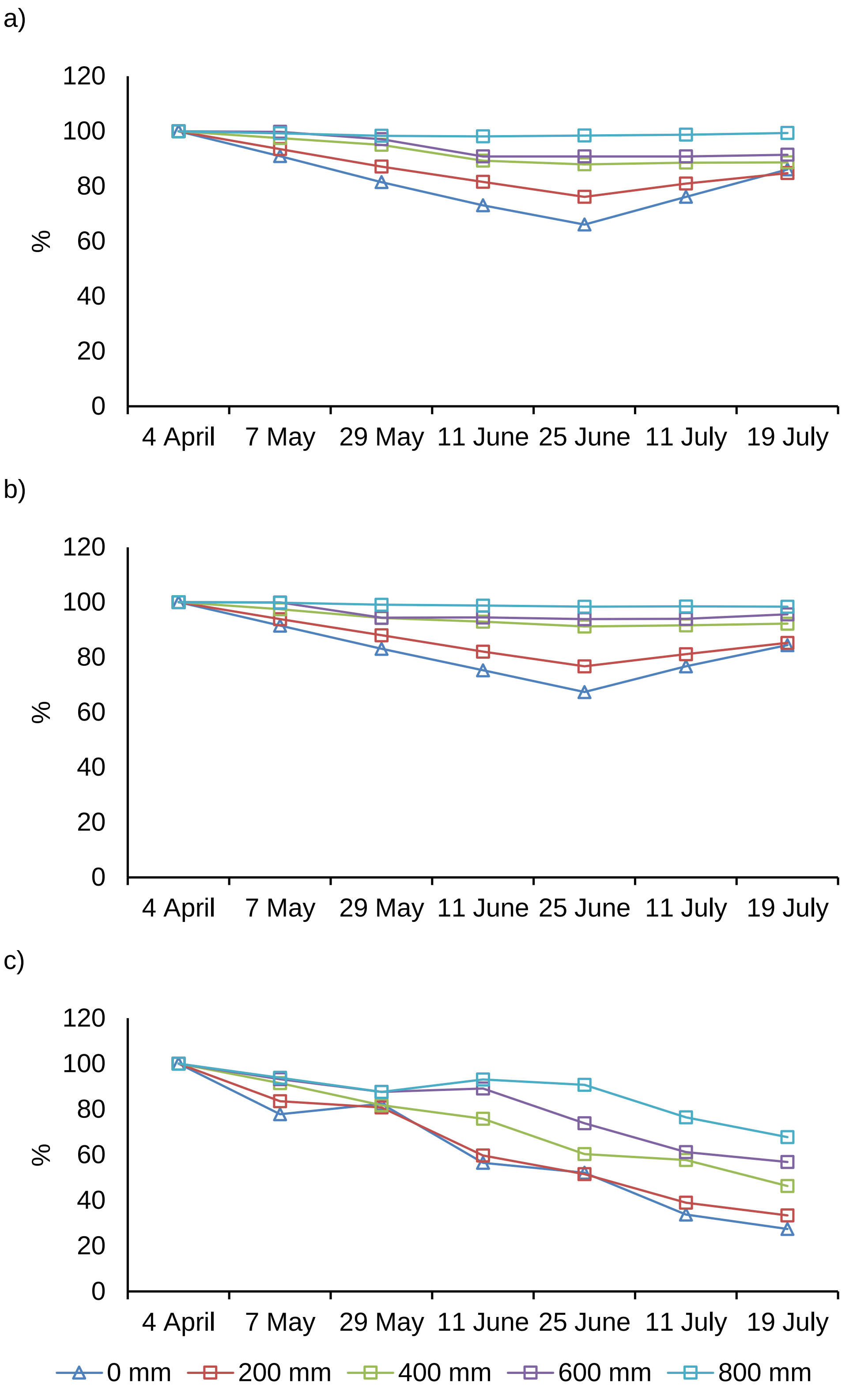


Figure 6.9. Temporal changes in volumetric soil moisture content from 0 to 800 mm under low tyre inflation pressure traffic with a) deep, b) shallow and, c) zero tillage.

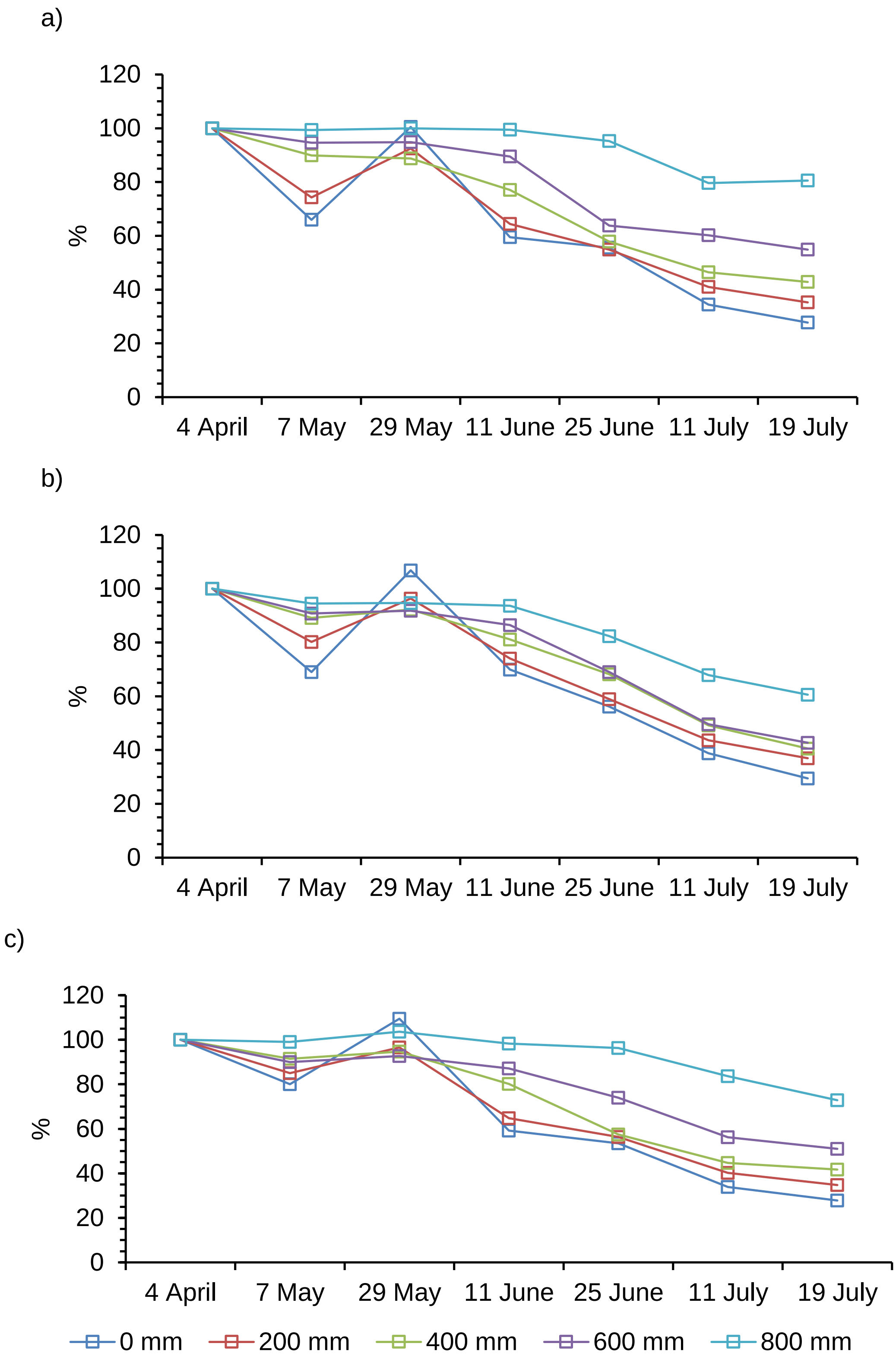


Figure 6.10. Temporal changes in volumetric soil moisture content from 0 to 800 mm under controlled traffic farming with a) deep, b) shallow and, c) zero tillage.

6.5.4. Hydraulic conductivity

Figure 6.11 illustrates the hydraulic conductivity measured in the first experimental year (2012-2013). Low tyre inflation pressure resulted in greater hydraulic conductivity (15.2 mm h^{-1}), compared to standard tyre inflation pressure (13.7 mm h^{-1}). An 11% decrease in hydraulic conductivity was measured when bulk density increased from 1.48 – 1.58 Mg m^{-3}. Low tyre inflation pressures recorded also greater hydraulic conductivity than controlled traffic farming wheelways (13.2 mm h^{-1}). Differences in means between traffic treatments were not significant (P = 0.917). This differs from research reported by Ankeny *et al*. (1995) who concluded that wheel traffic was more dominant in its effect of water movement than tillage. In the current study, differences in means between tillage treatments were significant (P = 0.009, LSD 5% = 10.17). Greater hydraulic conductivity was found in deep tillage (20.6 mm h^{-1}), compared to shallow (17.0 mm h^{-1}) and zero tillage (4.6 mm h^{-1}). A 349% decrease in hydraulic conductivity was measured when bulk density increased from 1.48 – 1.55 Mg m^{-3}. Other researchers, however, have reported that zero tillage increases water movement through the soil profile due to greater amounts of surface residue (Arshad *et al*., 1999). For the current study, differences in plant cover following cultivation are shown in Figure 6.12. Greater amounts of surface residue were observed in zero tillage plots, although results indicate that there was no benefit to hydraulic conductivity. There were no differences in surface residue between traffic systems.

Large variability within each tillage treatment, indicated by standard error of the means, is consistent with previously reported work (Jabro *et al*. 2016). Miriti *et al*. (2013) reported that hydraulic conductivity was lower under reduced tillage intensity, with differences between tillage treatments linked to reduced pore connectivity in cultivated soils (Osunbitan *et al*., 2004; Kargas *et al*., 2016).

For controlled traffic farming, differences in means between untrafficked and wheelways were significant (P < 0.001, LSD 5% = 12.96). Hydraulic conductivity of untrafficked soil (54.1 mm h^{-1}) was significantly greater than the wheelways (13.2 mm h^{-1}). The tillage effect for controlled traffic farming plots was different, in that differences in means between tillage treatments were significant (P = 0.016, LSD 5% = 15.87). Overall, deep tillage increased the hydraulic conductivity (29.6 mm h^{-1}), compared to shallow (41.3 mm h^{-1}) and zero tillage (16.6 mm h^{-1}). In the absence of traffic however, deep and shallow tillage resulted in a 40% and 116% increase in hydraulic conductivity compared to zero tillage respectively. Meek *et al*. (1992) reported findings that suggested the hydraulic conductivity of untrafficked soil did not improve due to tillage, and thus tillage should only occur within wheelway zones. The results presented in this current study however, indicate that in the absence of trafficking, tillage improves hydraulic conductivity of soils, which supports the recommendations presented by Hamza and Anderson (2005) to restrict traffic to permanent wheelways, as achieved in a CTF system, and the removal of compaction by deep ripping. It is important to note, however, that the results indicate that the benefit of the latter is only seen in the absence of subsequent trafficking, as reported by Voorhees and Lindstrom (1984). The authors concluded that deep tillage initially resulted in a more porous soil, but after 3 to 4 years, the soil porosity of reduced tillage was higher than deep tillage.

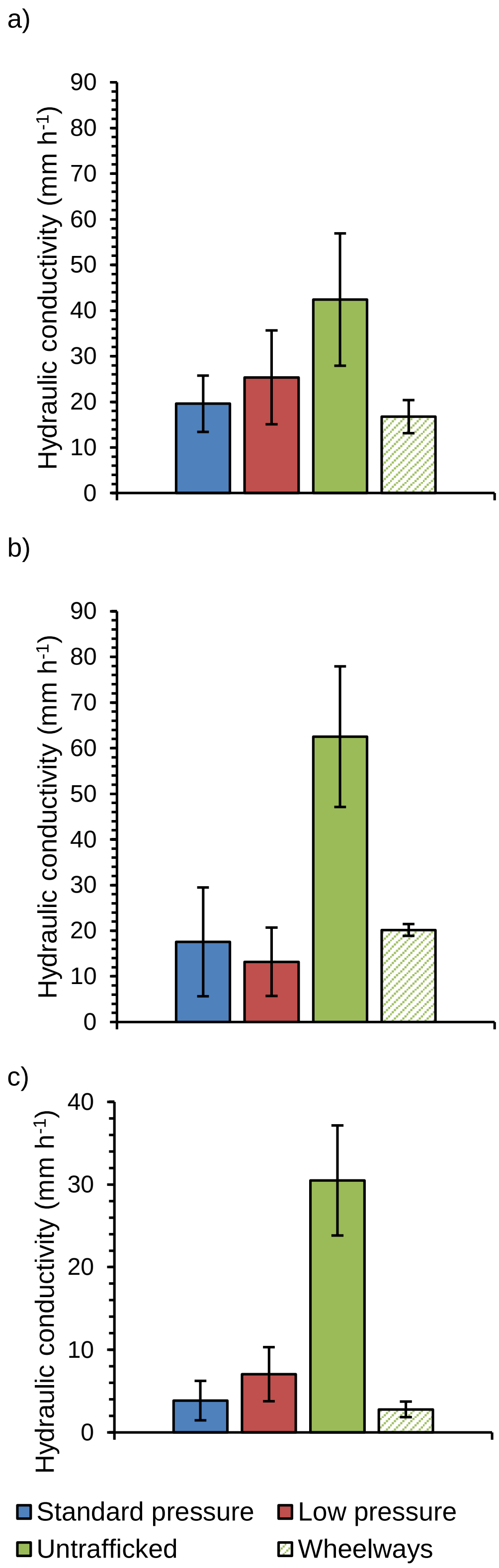


Figure 6.11. Mean hydraulic conductivity (mm h^{-1}) 2013-2014 under standard and low tyre inflation pressure and controlled traffic untrafficked and wheelways with deep tillage (a), shallow tillage (b), and zero tillage (c).

a)

b)

c)

Figure 6.12. Plant cover following seedbed preparation in a) deep, b) shallow, and c) zero tillage.

The results of this research shown that soil compaction was affected by traffic and tillage intensity. Traffic management systems, including a reduction in tyre inflation pressure and the use of controlled traffic farming reduced soil compaction, indicated by lower bulk density and penetration resistance. Lower bulk density has been shown to result in increased crop yields. At increased bulk density, root growth and therefore uptake of water and nutrients is inhibited (Raghavan *et al*., 1979). It should be noted however, that extremely low values of bulk density for a given soil, can be detrimental to crop yields (Raghavan *et al*., 1979). To manage the impact of trafficking on soil compaction and crop growth, it is essential that the local soil type is known, and threshold values for bulk density are utilised. In silt and silt loam soils, root restriction will occur at a bulk density of 1.55 Mg m^{-3} (Logsdon and Karlen, 2004); in sandy and sandy loam soils this critical threshold is increased to 1.6 Mg m^{-3} (Huber *et al*., 2008).

A reduction in tillage intensity increased soil bulk density and penetration resistance and reduced hydraulic conductivity. Increased soil bulk density and penetration resistance not only has a negative impact on crop growth, as discussed previously, but also limits the movement of water from the soil surface through the profile, evidenced in this research by a reduction in hydraulic conductivity. Restricted water infiltration results in soil degradation and erosion (Tullberg et al., 2007; Rowell, 1994). The use of reduced tillage systems to build healthier and more productive soil environments with minimal disturbance promotes the accumulation of soil organic matter. If reduced water infiltration in these systems occurs, shown in the research presented here, this will result in loss of organic matter and soil fertility (Tullberg et al., 2007; Rowell, 1994). The retention of surface residues in zero tillage systems protects the surface from rainfall erosion (Rowell, 1994) but could contribute to water being retained on the surface in poorer structural conditions, indicated by bulk density and penetration resistance, reduce the hydraulic conductivity. Ensuring that zero tillage promotes improved soil structure, therefore, is essential for the implementation of these systems in commercial practice.

6.6. Conclusions

The aim of this chapter was to determine the effect of a reduction in tyre inflation pressure and a reduction in traffic intensity, with deep, shallow and zero tillage systems on soil physical properties. Measurements of soil bulk density (Mg m^{-3}), penetration resistance

(MPa), soil moisture content (g g^{-1}; m^3/m^3) and hydraulic conductivity (mm h^{-1}) were used to determine the effect of treatments on soil physical properties, and to determine the effect of permanent wheelways and untrafficked soils in controlled traffic farming.

The following conclusions can be drawn after two years of agricultural traffic and tillage treatments studied in the field experiment.

A reduction in tyre inflation pressure, from standard (0.12 MPa front, 0.15 MPa rear) to low (0.07 MPa front and rear) resulted in a 2% and 13% decrease in bulk density and penetration resistance respectively. Differences in means were not significant. Soil water characteristics, including gravimetric moisture content between 0 – 300 mm, volumetric moisture content between 0 – 800 mm, and surface hydraulic conductivity were not significantly affected by a reduction in tyre inflation pressure.

A reduction in tillage intensity significantly increased soil bulk density from 0 – 300 mm ($P = 0.042$) from 1.57 Mg m^{-3} to 1.66 Mg m^{-3}, and significantly ($P = 0.008$) increased penetration resistance from 0.619 MPa to 0.777 MPa. Gravimetric soil moisture content also decreased by 6%. Volumetric moisture content, from a depth of 0 – 800 mm was significantly ($P = 0.031$) higher under zero tillage compared to shallow tillage. A reduction in tillage intensity significantly ($P = 0.009$) reduced hydraulic conductivity from 20.6 mm h^{-1} in deep tillage to 4.6 mm h^{-1} in zero tillage.

Untrafficked soil recorded significantly lower soil bulk density ($P = 0.001$) and penetration resistance ($P = 0.006$) compared to wheelway zones in controlled traffic farming plots. Bulk density and penetration resistance of untrafficked soil were 14% and 27% lower than in the wheelways. The use of permanent wheelways and untrafficked soils had no effect on gravimetric soil moisture content between 0 – 300 mm. A reduction in traffic intensity, however, resulted in a significant ($P = 0.002$) reduction in volumetric soil moisture from 0 – 800 mm compared to intensively trafficking at standard and low tyre inflation pressures. The hydraulic conductivity of untrafficked soil was significantly ($P < 0.001$) greater than wheelway zones.

To reduce soil compaction, therefore, extensive traffic should be avoided by implementing a controlled traffic farming system. Where this is not possible, tyre inflation pressures should be reduced. Tillage systems had a greater effect than traffic on the interaction of soil and water properties which are key to supporting crop growth.

7. The effect of agricultural traffic and tillage on winter wheat (Triticum aestivum) and winter barley *(Hordeum vulgare)* crop yields

7.1. Introduction

Extensive compaction (Kroulík *et al*., 2011) that characterises agricultural production systems negatively affects crop yield as a result of increased soil pressure impeding root extension and crop growth (Raghavan *et al*., 1979). Low ground pressure systems have been shown to reduce the exerted pressure on the soil within the profile (Ansorge and Godwin, 2007), and result in improved soil structure for crop growth (Arvidsson and Håkansson, 2014). Chancellor (1977) reported the use of controlled traffic paths to minimise, offset or remove soil compaction effects. Crop performance within and bordering the permanent wheelways is reduced, but offset by increased yields in untrafficked, and therefore uncompacted, zones. Researchers have found increases in cereal crop yields up to 14% in Australia (Tullberg *et al*., 2007), 30% in Canada (Gamache, 2013) and 21% in Europe (Chamen *et al*., 1992a).

Tillage is the cultivation of soil to remove compaction and create seedbed structures for crop production. It is thus linked to the level of soil compaction and crop yield (Badlíková, 2010). The method of tillage used prior to seeding (Šíp *et al*., 2013) influences early crop development and can significantly affect rates of crop establishment (HGCA, 2008) and the rate at which the plant progresses through early development stages (HGCA, 2006). Ploughing is a traditional form of deep tillage and is central to 56% of UK farming systems. Developments in tillage technologies toward conservation approached, including reduced or direct drilling is now found on 30-40% and 4% of UK farms respectively (DEFRA, 2010a; Townsend *et al*., 2016). Conservation tillage systems seek to overcome the limitations of intensive cultivations by promoting shallow soil cultivations, the retention of crop surface residues and reduced trafficking by combining operations into fewer passes.

7.2. Research hypothesis and objectives

The hypothesis for this phase of research was that crop properties will be affected by traffic and tillage intensity, such that a reduction in traffic and tillage intensity using controlled traffic farming and reduced tillage will increase crop establishment, growth and harvestable yield.

The objectives of this research were:

1. To measure crop establishment, crop growth, and harvestable yield;
2. To measure crop yields of permanent wheelways and untrafficked soils in controlled traffic farming.

7.3. Materials and methods

7.3.1. Crop establishment

This research was completed in a randomised and replicated field experiment, as described in Chapter 3. In the years 2012 to 2013, the establishment of winter wheat was determined by counting the number of plants within a 0.1m^2 quadrat in the centre of each plot to calculate the number of plants m^{-2} at crop emergence (19 December 2012), and growth stage (GS) 20-main shoot (4 February 2013). In 2012, RTF_S and RTS_L plots were sampled from partially trafficked areas. In CTF plots, the area where the plant counts were taken was untrafficked. The establishment of winter barley in 2013 was also determined by plant counts, but the methodology was developed. Counts were taken on both sides of a 0.5 m length to calculate the number of plants in 1 m^2 based on the number of rows (8 rows) within 1 m. Furthermore, these measurements were taken from untrafficked and trafficked zones to allow for the determination of the effect of both traffic and tillage on crop establishment. In RTF_S and RTF_L deep tillage treatments, plant counts were measured from untrafficked (UT), one, two and three passes. In RTF_S and RTS_L shallow tillage and zero tillage treatments, measurements were obtained from untrafficked (UT), one and two passes. For the CTF plots, for all tillage systems, plant counts were taken from the untrafficked (UT) and wheelways (WW). Barley assessments were completed on 28 March 2014 at GS20 and thus it was the number of tillers that were measured. The yield of barley is chiefly determined by the amount of tillers (AHDB, 2015b), and these assessments were therefore made to quantify this.

7.3.2. Crop growth

In 2012 to 2013, NDVI was recorded along the centre (AB line) of each plot using a Crop Circle handheld system (Holland Scientific, Nebraska). The measurements were taken on 14 March 2013 and repeated on 1 July 2013 along the length of the plot (84 m). For the winter barley, on 14 May 2014, CS-45 RapidSCAN (Holland Scientific, Nebraska) was used to measure NDVI. A change in device was necessary due to equipment availability. Asebedo and Mengel (2017) reported that data collected using Rapid Scan and Crop Circle devices are closely correlated (R^2 = 0.93). Methodology including measurement height and speed, however, remained consistent. For RTF_S and RTS_L, the zone that had been exposed to two traffic passes was measured. Data was collected from these traffic zones as they are most representative of each of the traffic systems at all intensities of tillage (Figure 3.5). For controlled traffic farming, one untrafficked and one wheelway zone was measured. Three replications of each measurement were made for each plot and averaged.

7.3.3. Harvestable yield

For the years 2012 to 2013, hand samples were collected on 30 August 2013 from a 0.3 m wide transect across the width of each plot. For RTF_S and RTS_L treatments the samples were collected into one bag per plot. For the controlled traffic farming treatments, the crops from the untrafficked (UT) and wheelway (WW) areas were separated. This methodology was modified for the second experimental year. For the years 2013 to 2014, winter barley hand samples were collected on 18 July 2014. For RTF_S and RTS_L treatments, the crop from the zone exposed to 2x passes of traffic was separated from the remainder of the plot. For the controlled traffic farming plots, the crops from the untrafficked (UT) and wheelways (WW) areas were again separated.

Although it was anticipated that crop establishment growth and yield would be reduced in wheelway zones due to compaction, measurements were taken to quantify the impact of permanent wheelways on the overall plot yield. In UK commercial systems, due to narrow drill row spacings, CTF wheelways are cropped. In Australia, for example, it is not necessary to crop wheelways as crops are drilled at much wider row spacings, and therefore represent a smaller area of crop lost.

Mechanically harvestable grain yields were recorded for winter wheat on 31 August 2013 and 1 September 2013, and for winter barley on 22 September 2014. Each plot was harvested with a Claas Dominator 85 combine with 4 m cutter bar, at a forward speed of 5 km h^{-1} (Chapter 3, Figure 3.13a). Individual total plot yields (Mg ha^{-1}) were calculated from the weight of the grain removed by the combine harvester measured in-field with a load cell (Chapter 3, Figure 3.13b). The grain specific weight (kg/hl) was measured in-field and a sample of grain was obtained to determine grain moisture content. Plots were harvested at grain moisture content 14-16.5 % and yields adjusted to 15% grain moisture content (MC).

7.4. Statistical analyses

For the winter wheat emergence and establishment data, repeated measures ANOVA was used. Replications of data (n = 4) were averaged for each treatment and are presented with the SEM. For the winter barley establishment data, a blocked (n=4) unbalanced ANOVA using regression was used to analyse the effect of traffic, tillage and traffic intensity (untrafficked and repeated passes). Replications of data collected from each traffic intensity (n = 4) were averaged for each treatment and are presented with the SEM.

For the winter wheat NDVI data, repeated measures ANOVA was used. Replications of data (n = 4) collected from the centre of each plot were averaged for each treatment and are presented with the SEM. For the winter barley NDVI data, two-way ANOVA was used to determine the effect of traffic management system on crop growth, and the effect of untrafficked and wheelway zones in controlled traffic farming.

Prevalence of winter wheat volunteers in the winter barley crop were converted into a score based on weight (Mg ha^{-1}), and plotted against barley yield (Appendix K). No correlation was found between the wheat and barley yields, and therefore the wheat yield data was removed from statistical analyses.

Statistical analysis on combine harvested and hand harvested yields were completed using two-way ANOVA to determine the effect of traffic management system on combine harvested and hand harvested yield, and the effect of untrafficked and wheelway zones in controlled traffic farming.

The effect of traffic and tillage on harvest index was analysed by multivariate analysis using a MANOVA.

7.5. Results and discussion

7.5.1. Crop establishment

Figure 7.1 shows the effect of traffic and tillage on plant numbers/m^2 of winter wheat at emergence (November 2012) and establishment (February 2013). For RTF_S and RTS_L, the area from which the measurements were obtained had been partially trafficked once, with standard and low inflation pressure tyres respectively. The measurements for controlled traffic farming were taken in untrafficked soil.

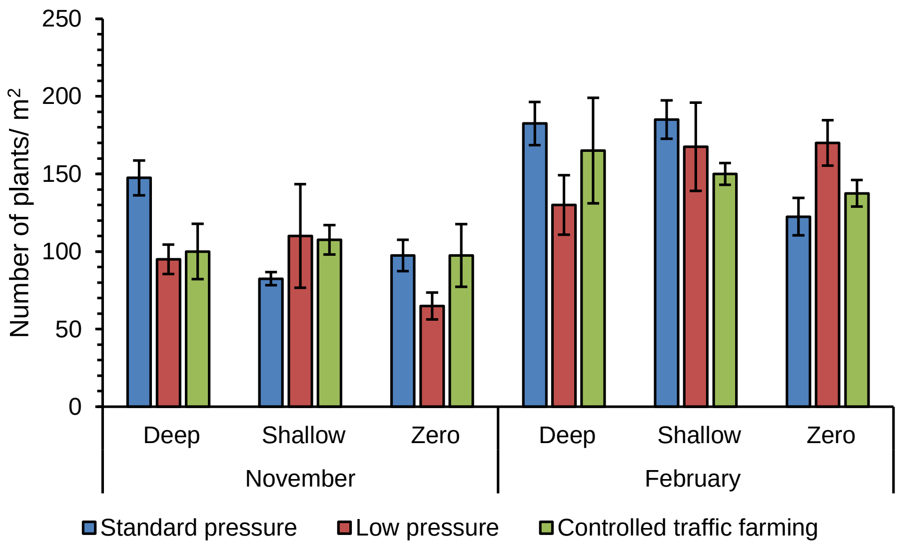


Figure 7.1. The effect of traffic and tillage on plants/m^2 (± SEM) of winter wheat at emergence (November 2012) and establishment (February 2013) under standard tyre inflation pressure, low tyre inflation pressure, and controlled traffic farming.

Traffic (P = 0.536), tillage (P = 0.181), and their interaction (P = 0.287) had no significant effect on the number of winter wheat plants/m^2. As expected, there was a significant increase in the number of plants/m^2 between emergence (100 plants/m^2, November 2012) and establishment (157 plants/m^2, February 2013) (P < 0.001, LSD 5% = 16.74). The interaction of time, traffic and tillage had no significant effect on winter wheat plants/m^2 (P = 0.076, time.traffic.tillage LSD 5% = 47.74, means at the same level of time.tillage LSD 5% = 50.23). A reduction in tyre inflation pressure reduced the number of plants/m^2 by 11%. For soil cultivated with deep tillage, standard tyre inflation pressures resulted in the highest plant numbers at emergence and establishment, and low tyre inflation pressures resulted in the lowest plant numbers at both times. This could be attributed to increased seed to soil contact under increased tyre inflation pressure, and therefore soil pressure, compared to low tyre inflation pressures. For shallow tillage, emergence (November) was highest under low tyre inflation pressure and controlled traffic farming. By February however, the highest plant populations were observed in the standard tyre inflation pressure treatments. Increased plant emergence could lead to lower over winter survival as plants compete for space. Conversely, in zero tillage, low tyre inflation pressures resulted in the lowest level of plant emergence, but by establishment in February recorded the highest. Overall, a reduction in tillage resulted in a 19% reduction in the number of plants/m^2.

Figure 7.2 illustrates the effect of traffic passes and tillage on number of tillers/m^2 of winter barley at establishment under a) standard tyre inflation pressure, b) low tyre inflation pressure and, c) controlled traffic farming. Differences in means between traffic (P = 0.949) and tillage (P = 0.844) were not significant. Overall, a reduction in tyre inflation pressure reduced number of tillers/m^2 by 3%. A reduction in tillage resulted in a 0.3% reduction in number of tillers/m^2. Chamen and Longstaff (1995) also reported that traffic and tillage treatments had no significant effect on the establishment of winter wheat, although differences in yield were observed (section 7.6.4). Other researchers, however, have shown that germination and emergence of winter wheat is affected by soil strength as a result of surface applied stresses (Collis-George and Yoganathan, 1985), although the loads applied were in excess of those used in the current study which are typical of UK agricultural production systems.

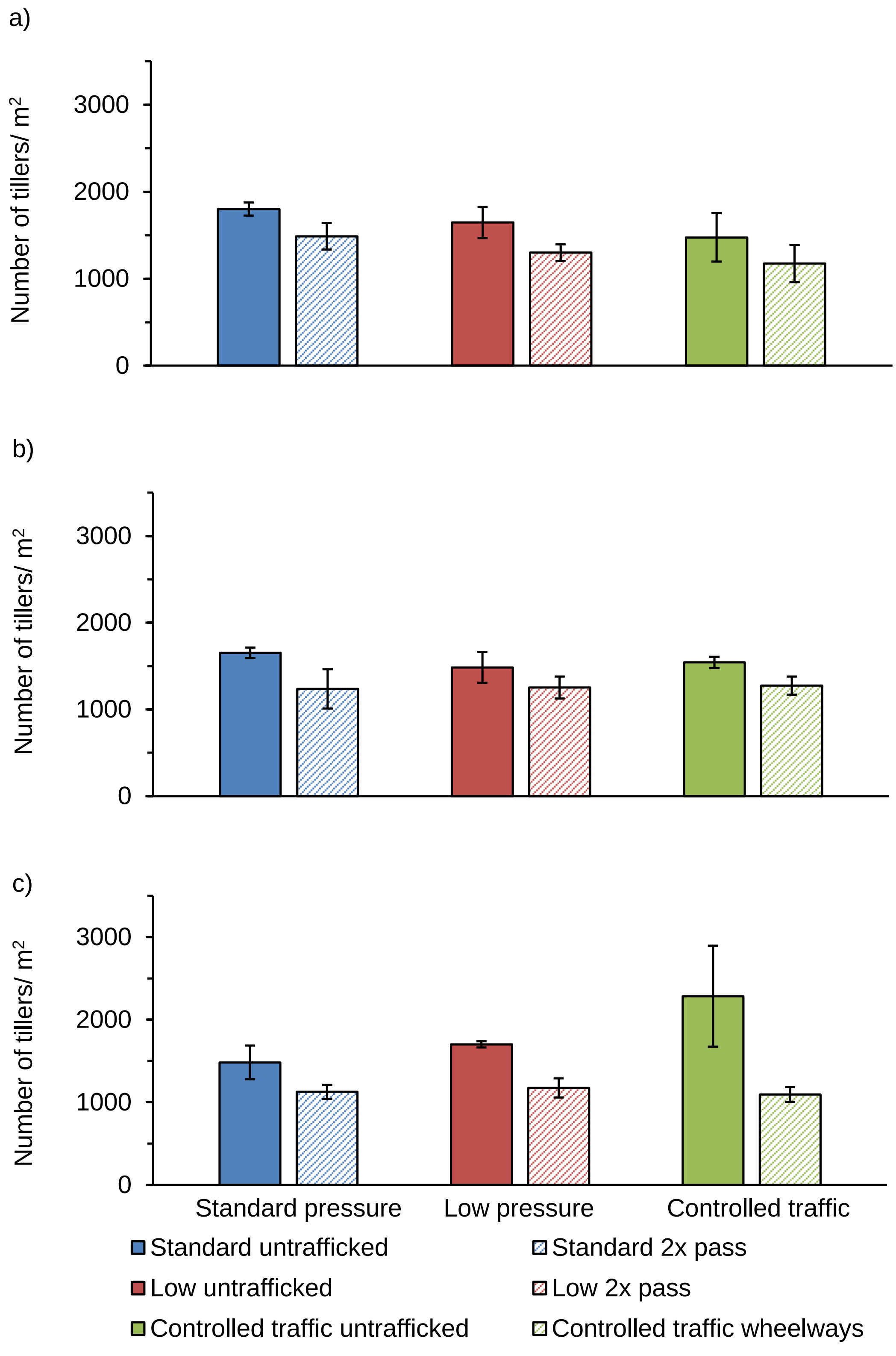


Figure 7.2. The effect of multiple traffic passes and tillage on number of tillers/m^2 (± SEM) of winter barley at establishment under a) deep, b) shallow, and c) zero tillage systems.

7.5.2. Crop growth

Figure 7.3 shows the effect of traffic and tillage on NDVI of winter wheat crops in March 2013 and July 2013. For winter wheat, the effect of tillage was significant (P < 0.001, LSD 5% = 0.00677). Deep tillage recorded the lowest NDVI (0.5912), shallow (0.59950) and zero tillage (0.6119). These results differ from those reported by Atkinson *et al*. (2009) who concluded that crop establishment increased as tillage intensity increased and produced finer seedbeds, although these results did not consider the effect of wheel traffic.

Controlled traffic farming resulted in highest values of NDVI (0.6043) and low ground pressure recorded the lowest (0.5990). However, the effect of traffic (P = 0.214), and the interaction of traffic and tillage (P = 0.124) were not significant. As expected NDVI increased significantly (P < 0.001, LSD 5% = 0.00889) between March (0.4199) and July (0.7818). The interaction of time and tillage was significant (P = 0.033, LSD 5% = 0.01258, means at same level of tillage LSD 5% = 0.01541) whereby deep tillage resulted in lowest NDVI at both times, and zero tillage resulted in the highest NDVI values at both times.

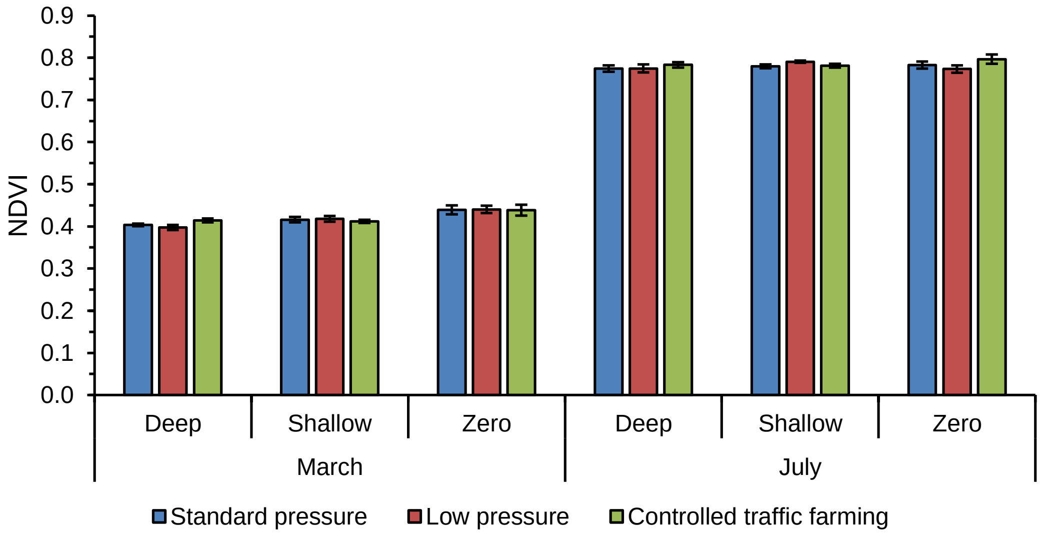


Figure 7.3. Normalised difference vegetation index (± SEM) of winter wheat in March 2013 and July 2013.

The effect of traffic and tillage on NDVI of winter barley in May 2014 is shown in Figure 7.4. Differences in means between traffic treatments were not significant (*P* = 0.872). Shallow tillage recorded lower NDVI (0.7981) compared to zero (0.8014) and deep tillage (0.8186). Differences in means between tillage treatments were significant (*P* = 0.005, LSD 5% = 0.01242). The interaction of traffic and tillage was significant (*P* = 0.025, LSD 5% = 0.02151). For controlled traffic farming, differences in means between the untrafficked and wheelway zones were not significant (*P* = 0.504). Differences in means between tillage treatments were significant (*P* = 0.034, LSD 5% = 0.01589).

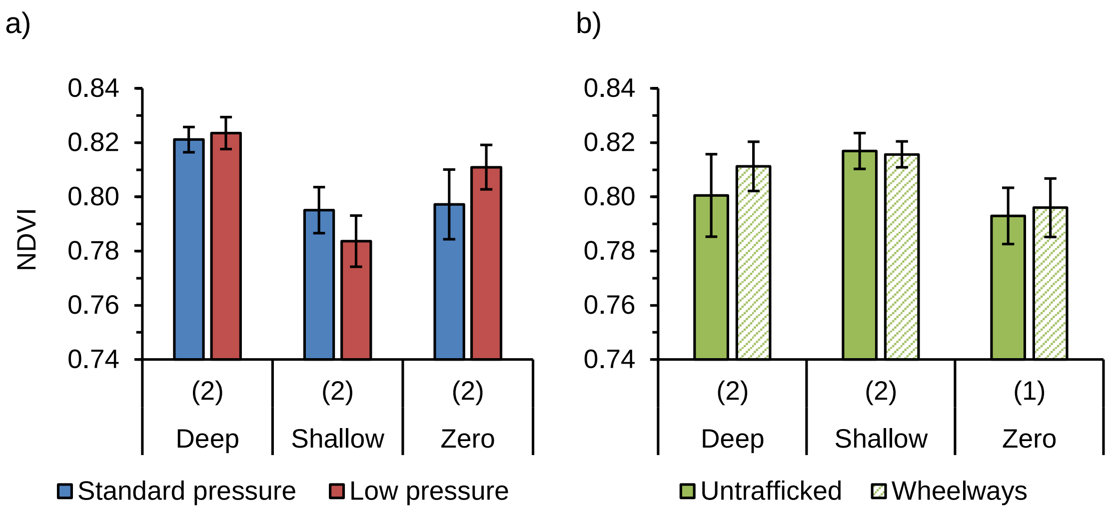


Figure 7.4. Normalised difference vegetation index (± SEM) of winter barley (May 2014) for a) standard tyre inflation pressure and low tyre inflation pressure, and b) controlled traffic farming. The number of passes, shown in brackets, refer to the total amount of vehicle passes.

Masle and Passioura (1987) reported that high soil strength, indicated by measurements of penetration resistance, resulted in lower crop biomass measured as leaf area of wheat plants 22 day post-emergence. In the current study, however, no consistent effect of penetration resistance values and NDVI were observed. In the first experimental year, the greatest tillage differences in penetration resistance were observed between deep (1.27 MPa) and shallow (1.18 MPa). Differences in NDVI of winter wheat, however, were minimal at 1%. The highest values of NDVI were recorded in zero tillage, an increase of 3.5% compared to deep tillage, yet the penetration resistance was 1.213 MPa. In the second experimental year, the penetration resistance of zero tillage (0.78 MPa) was 12% higher than shallow tillage (0.62 MPa), yet NDVI values from the former were higher.

7.5.3. Combine harvestable crop yield

The combine harvest yield (Mg ha^{-1}) of winter wheat is shown in Figure 7.5. Controlled traffic farming resulted in a 6.87% yield increase compared to RTF_S, and a 3.05% yield increase compared to RTF_L. Differences in means between traffic treatments were not significant ($P = 0.073$). Compared to conventional traffic, other researchers have reported yield increases of between 7.3 – 10% with controlled traffic farming (Lamers *et al*., 1986; Li *et al*., 2007), and up to 30% with low ground pressure tracks (Vermeulen and Mosquera, 2009). The use of low ground pressure systems in the current study resulted in smaller yield differences than those previously reported by Vermeulen and Mosquera (2009), although results are not directly comparable as the authors investigated the effect of traffic on vegetable yields. Differences in means between tillage treatments were found to be significant ($P < 0.001$). Shallow tillage resulted in a 4.71% yield increase compared to deep tillage, which supports previous research (Šíp *et al*., 2013). Shallow tillage resulted in a 14.78% yield increase compared to zero tillage.

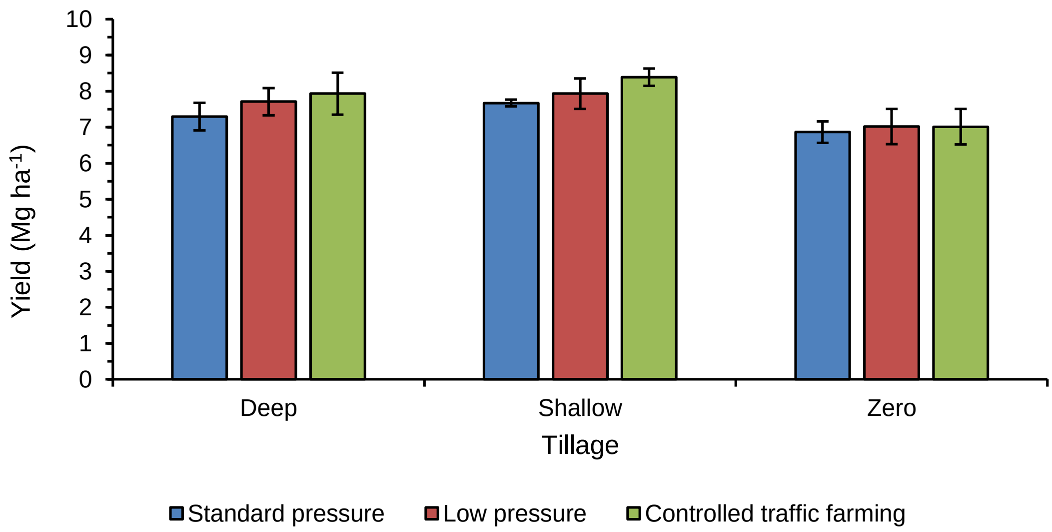


Figure 7.5. Combine harvested grain yield (± SEM) of winter wheat (2012-2013).

The combine harvest yield (Mg ha^{-1}) of winter barley is shown in Figure 7.6. Both RTF_S and CTF resulted in a 2% yield increase compared to RTF_L. Differences in means were not found to be significant (P = 0.682). Barraclough and Weir (1988) reported that even in conditions of increased bulk density, where soil moisture is not a limiting factor, compensatory crop rooting results in minimal yield effects, as seen in the current study. Other researchers, however, have reported 17% and 14% barley yield increases under controlled traffic farming compared to conventional and reduced ground pressure traffic respectively (Dickson and Ritchie, 1996). Similarly, Ball and Ritchie (1999) reported a 24% reduction in yield as a result of traffic-induced compaction.

In the second experimental year, shallow tillage resulted in a 2% increase in winter barley yields compared to deep tillage, and a 0.5% increase compared to zero tillage. Differences in means between tillage treatments were not significant (P = 0.857). Zero tillage did not result in significant winter barley yield reductions compared to deep and shallow cultivated soil, which is consistent with other research (Vermeulen and Klooster, 1992). Other research, however, has found that averaged over three years, the zero tillage resulted in a 13.4% reduction in barley yield compared to conventional tillage (Małecka and Blecharczyk, 2008). Yield loss, which has been widely reported in the literature in the short-term following the implementation of zero tillage, and as seen in the results from the first experimental year of this current project, has resulted in its limited uptake (Jones *et al*., 2006), Following the implementation of a zero tillage system, Clutterbuck and Hodgson (1984) reported yield decreases. These reductions in yield, however, were only experienced in the first year. Across a period of three years, differences were not found to be significant. Similarly, Knight (2003) reported yield reductions from uncultivated treatments in the range of 25-40% lower than conventionally cultivated soil. Timeliness to ensure appropriate soil moisture conditions is critical for the success of zero tillage (Carter *et al*., 2003), and caution must be taken to ensure that, in the absence of soil drying cultivation practices, moisture conditions are monitored. Furthermore, Keeble (2008) reported that zero tillage yields in tillage experiments can be compromised due to the drill choice. In the first two years following the implementation of zero tillage, yields of winter wheat and winter barley were 27% and 12% lower respectively, compared to deep tillage. The use of a specialist zero tillage drill in the third year of the experiment, resulted in a 10% increase in zero tillage yields compared to deep tillage (Keeble, 2008). Other research has also shown that zero tillage increased grain yield by 28% compared to conventional tillage, although results were not consistent across study sites (Trethowan *et al*., 2012).

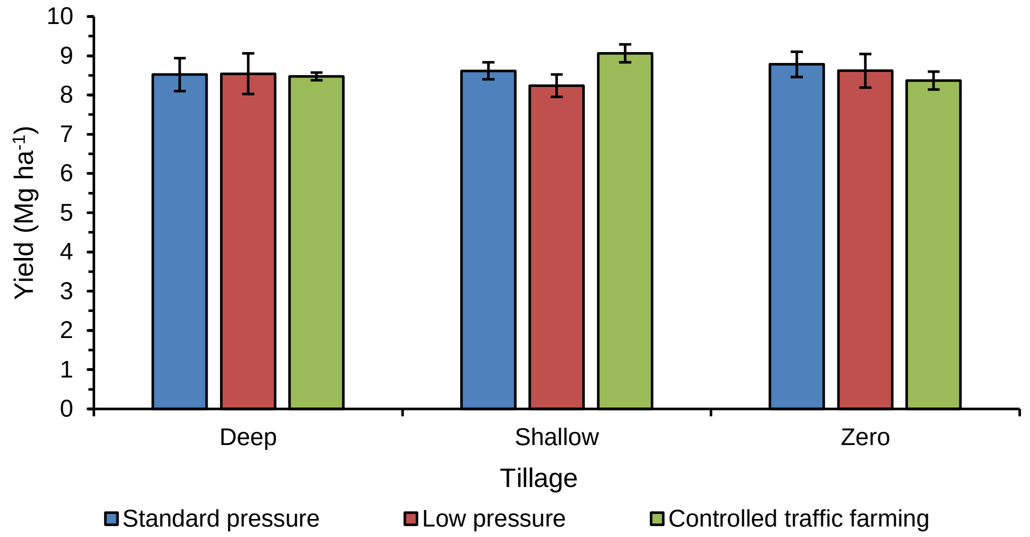


Figure 7.6. Combine harvested grain yield (± SEM) of winter barley (2013-2014).

7.5.4. Hand sampled crop yield

Hand samples were separated to calculate winter wheat grain yield (Figure 7.7). Controlled traffic farming resulted in the highest average yield (8.28 Mg ha^{-1}) and RTF_S the lowest (7.71 Mg ha^{-1}). Controlled traffic farming resulted in a 7.47% yield increase compared to RTF_S, and a 3.81% yield increase compared to RTF_L.

Shallow tillage resulted in the highest yield (8.41 Mg ha^{-1}) and zero tillage the lowest (7.51 Mg ha^{-1}). Shallow tillage resulted in a 4.4% yield increase compared to deep tillage, and a 11.95% yield increase compared to zero tillage. Traffic (P = 0.640), tillage (P = 0.342) and their interaction (P = 0.306) had no significant effect on whole plot hand harvested grain yield.

In deep, shallow and zero tillage, winter wheat yields declined in conditions below the soil bulk densities lower threshold of 1.6 Mg m^{-3} (Huber *et al*., 2008). Alvarez and Steinbach (2009) found that although bulk density values did not reach critical threshold values, winter wheat yields were negatively affected. Other researchers, however, have reported that crop yields were not significantly affected by bulk densities greater than threshold values. The researchers attributed this to the effect of natural restructuring and weathering processes over winter, known as freeze-thaw. Former root channels also support macropore pathways through the soil that reduces the effect of high bulk density on crop yield (Logsdon and Karlen, 2004).

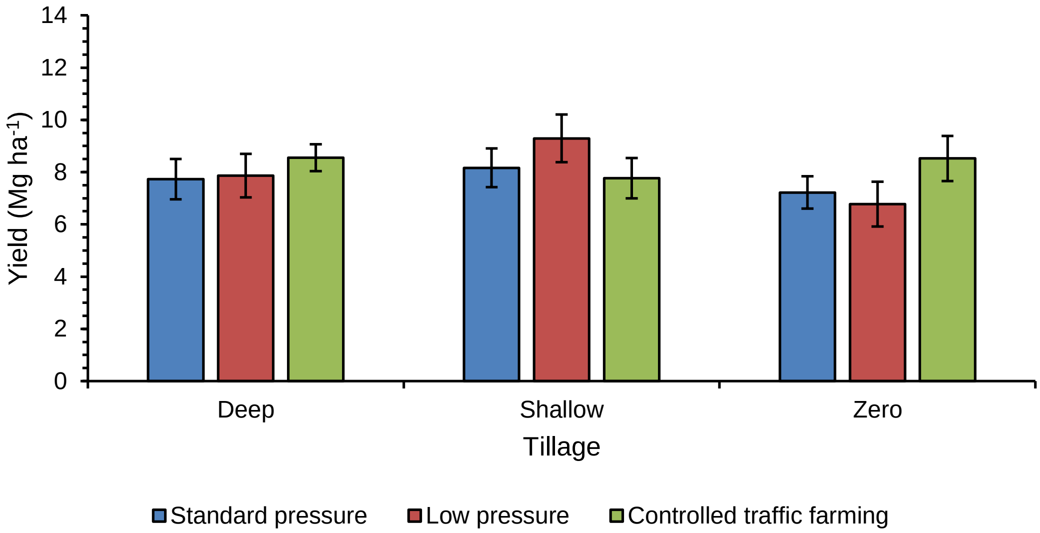


Figure 7.7. Hand sampled whole plot grain yield (± SEM) of winter wheat (2012-2013).

In 2013-2014, volunteer wheat from the previous cropping year was quantified from the hand-harvested samples, as shown in Figure 7.8. Statistical evaluation included winter barley yields only. Random traffic farming with low tyre inflation pressures resulted in a 16% yield increase compared to random traffic farming with standard tyre inflation pressures, and a 10.5% yield increase compared to controlled traffic farming. Deep tillage resulted in a 9.58% yield increased compared to shallow tillage, and a 13.98% yield increase compared to zero tillage. Differences in means between traffic (P = 0.207) and tillage (P = 0.285) were not significant.

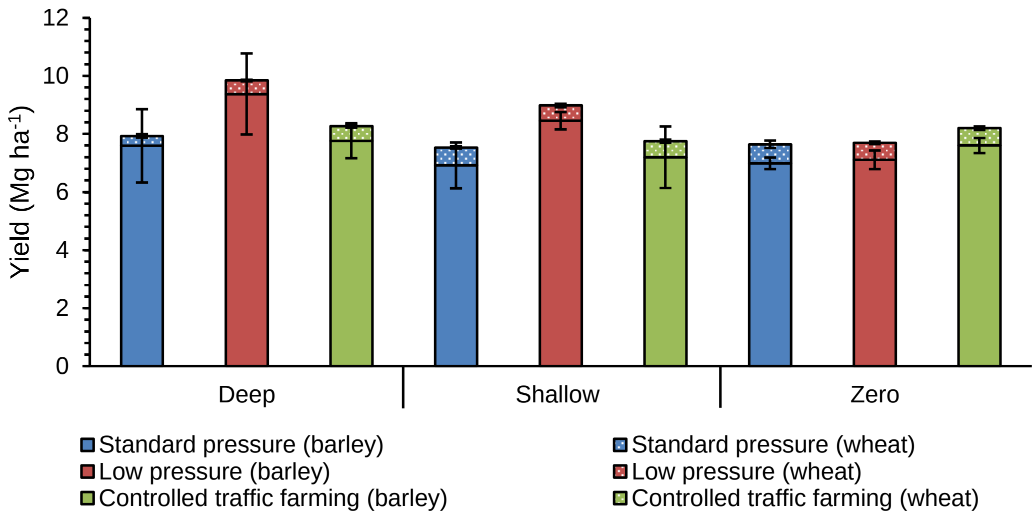


Figure 7.8. Hand sampled whole plot grain yield (± SEM) of winter barley (2013-2014), including winter wheat volunteers.

The crop from controlled traffic farming plots was separated at the time of sampling, to differentiate between the untrafficked and the wheelway zones. Figure 7.9 shows that the winter wheat grain yield from untrafficked zones was significantly (P = 0.003, LSD 5% = 1.778) higher compared to the wheelways. Grain yields from controlled traffic farming untrafficked zones were 45.73% higher than yields from the wheelway zones. Other researchers have similarly reported increases in penetration resistance in controlled traffic farming wheelways. Lamers *et al*. (1986) reported penetration resistance values of 3.5 MPa, which was found to improve vehicle tractive efficiency, in permanent traffic lanes. The author does not, however, provide any information on the structure of untrafficked soil.

In controlled traffic farming plots, deep tillage resulted in a 10% increase in yield compared to both shallow and zero tillage. Differences in means between tillage treatments were not significant (P = 0.684). The interaction of traffic and tillage was significant (P = 0.033, LSD 5% = 3.079). The mean zero tillage wheelways yield (4.34 Mg ha^{-1}) was significantly lower than the yield from all other zones (P = 0.033, LSD 5% = 3.079). Photographic evidence of poor plant establishment and growth in the cultivation and seeding wheelways was identified in all plots, not just the controlled traffic farming plots, and are provided in Appendix L. For controlled traffic farming with zero tillage, a 147% reduction in yield was found, as trafficking increased penetration resistance by 14%. Across all tillage systems in controlled traffic farming, trafficking reduced winter wheat grain yield by 46%.

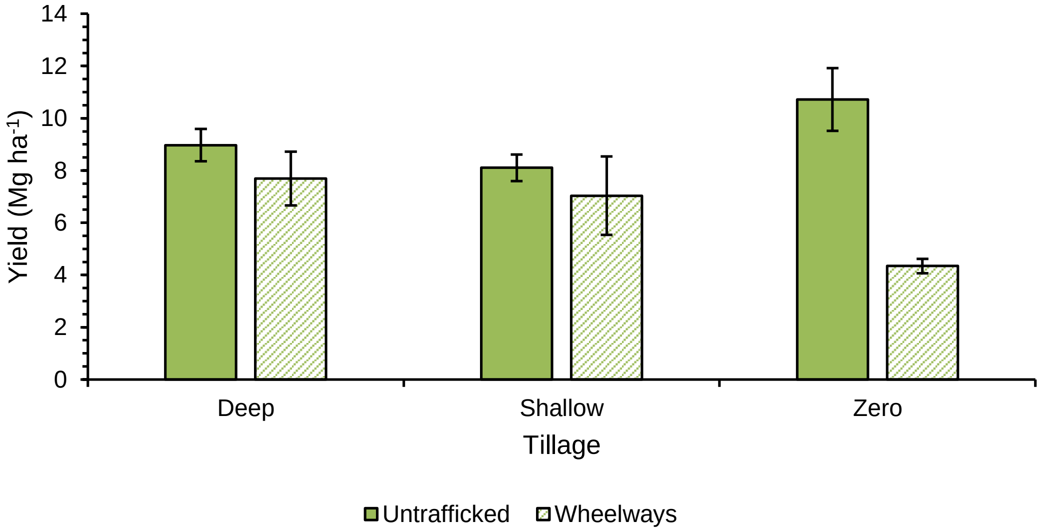


Figure 7.9. The effect of controlled traffic farming on hand sample grain yield (±SEM) of winter wheat (2012-2013).

Figure 7.10 shows that winter barley grain yield from untrafficked (8.15 Mg ha^{-1}) zones were significantly (P = 0.009, LSD 5% = 1.273) higher compared to the wheelways (6.36 Mg ha^{-1}), and were associated with a 27% increase in penetration resistance. Grain yields from controlled traffic farming untrafficked zones were 28.13% higher than yields from the wheelway zones. Previous research has reported that following the removal of soil compaction by deep ripping, and in the absence of any subsequent vehicle traffic, yields increased by 20% (Chan *et al*., 2006). Chamen and Longstaff (1995) reported that, although plant establishment was not significantly affected by traffic, final yield from wheelway zones was 25% lower than untrafficked soil.

Zero tillage resulted in a 0.71% increase in yield compared to deep tillage, and a 6.83% increase in yield compared to shallow tillage. Differences in means between tillage treatments were not significant (P = 0.780).

Figure 7.10. The effect of controlled traffic farming on hand sample grain yield (±SEM) of winter barley (2013-2014).

7.5.5. Harvest index

The quantity of dry matter (Mg ha^{-1}) (Appendix L) was converted into harvest index (%) using Equation 3.7.

7.5.5.1. Winter wheat harvest index

Winter wheat harvest index is shown in Figure 7.11. Differences in means of grain harvest index between traffic treatments were significant (P = 0.011). Controlled traffic farming resulted in the highest grain harvest index (51.58%) compared to low (48.11%) and standard (47.06%) tyre inflation pressure. Increased harvest index could be due to lower soil moisture conditions (Zhang *et al*., 2008). Where soil moisture is lower, the time at which the crop progresses through head emergence and flowering growth stages is earlier, providing a longer length of time for grain-filling and thus producing a higher grain harvest index (%). In the current study the lowest volumetric soil moisture conditions were found in the controlled traffic farming treatment (section 6.6.3), and the highest grain harvest index for winter wheat was observed under controlled traffic farming. Similarly, deep tillage resulted in lower volumetric soil moisture content, and higher winter wheat grain harvest index (49.43%), compared to zero tillage (48.91%) and shallow (48.41%), but differences in means were not significant (P = 0.775). The interaction of traffic and tillage was found to be significant (P = 0.014).

Controlled traffic farming, as shown in Figure 7.12, with deep and zero tillage were the only treatments to reach the winter wheat grain benchmark of 51% (AHDB, 2015a). Overall, the differences in means of grain harvest indexes between controlled traffic farming untrafficked and wheelway zones were not significant (P = 0.500). Similarly, differences in means of harvest indexes between tillage systems were not significant (P = 0.098). Untrafficked zones resulted in higher grain (50.8%) harvest index compared to the wheelways (49.3%). Zero tillage resulted in higher grain harvest index (53.3%) compared to deep and shallow tillage.

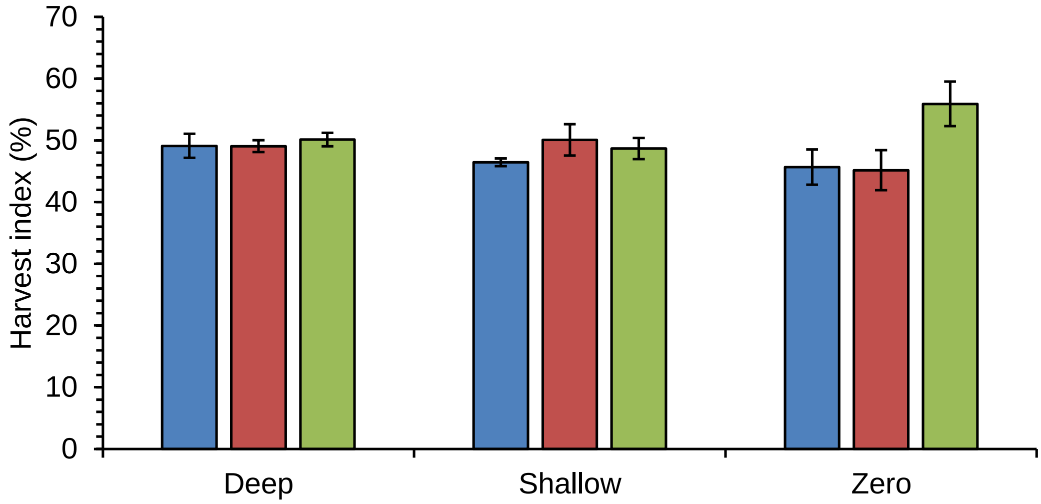


Figure 7.11. Grain harvest index (%) (± SEM) of winter wheat.

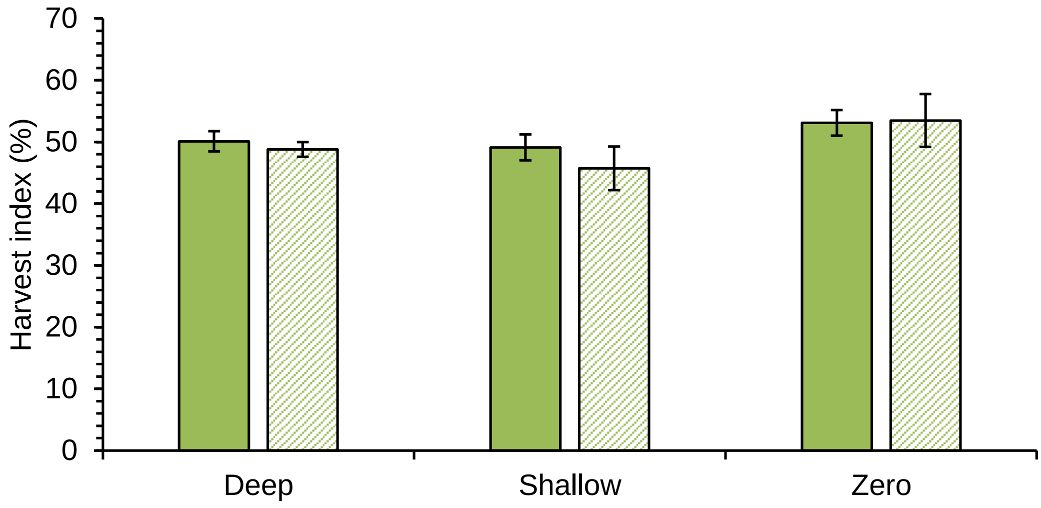


Figure 7.12. Grain harvest index (%)(± SEM) of winter wheat in controlled traffic farming.

7.5.5.2. Winter barley harvest index

The winter barley harvest index is shown in Figure 7.13. All treatments exceeded the grain harvest index of 51% (AHDB, 2015b). Controlled traffic farming resulted in the highest grain harvest index (60.52%) compared to random traffic farming with low tyre inflation pressure (59.55%) and standard tyre inflation pressure (58.66%). Zero tillage resulted in the highest grain harvest index (60.36%) compared to shallow (60.09%) and deep (58.28%) tillage. There were no significant differences in means of winter barley grain harvest index between traffic (P = 0.374) and tillage (P = 0.241) treatments. The interaction of traffic and tillage was not significant (P = 0.625).

For controlled traffic farming, untrafficked zones resulted in higher grain (60.87%) harvest index compared to the wheelways (59.60%). Zero tillage resulted in higher grain (60.76%) harvest index compared to deep and shallow tillage.

In the first experimental year, significant differences in winter wheat harvest indexes were found. In the second experimental year, however, only small differences in winter barley harvest index were found. Asgari *et al*. (2014) reported similar findings, and concluded that this was due to the association between grain and total dry matter yields and a consistent change in both parameters.

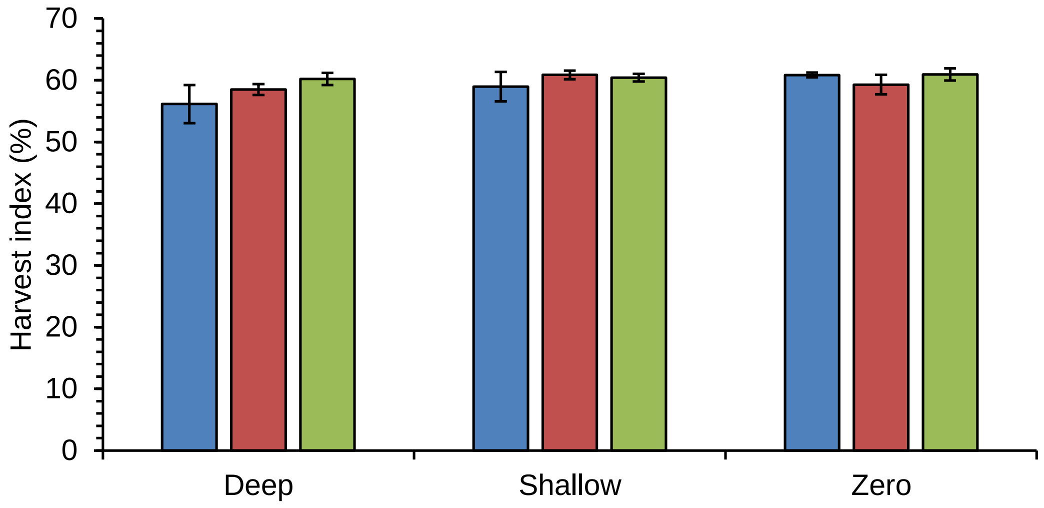


Figure 7.13. Grain harvest index (%)(± SEM) of winter barley.

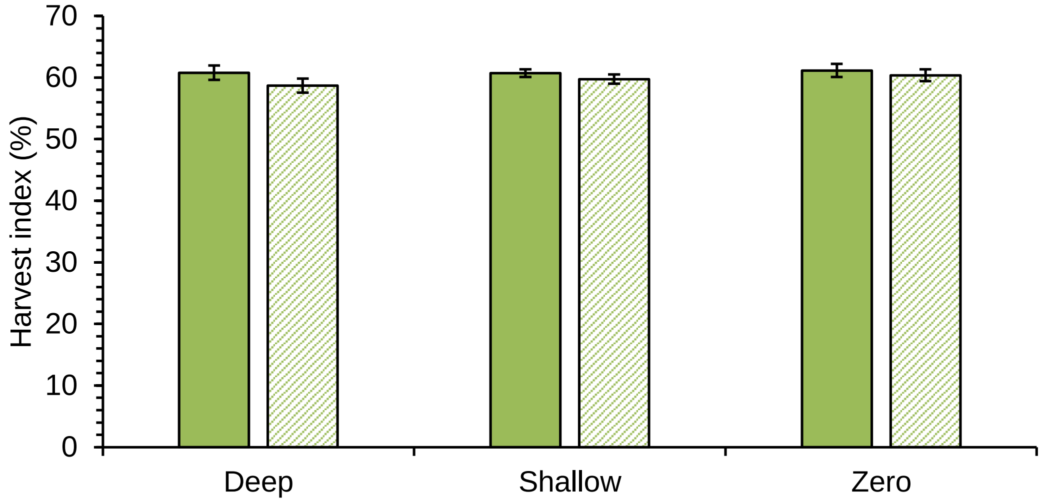


Figure 7.14. Grain harvest index (%) (± SEM) of winter barley in controlled traffic farming.

The components of yield, ear number/m^2, grains per ear and grain weight, were not measured in the current study, but evidence in the literature could provide insight into their effect on grain yield, and thus harvest index that were observed. Soil compaction has been shown to reduce grain yield compared to uncompacted soil, and also reduce grain weight, grains per ear, and number of tillers per plant (Saqib *et al*., 2004).

Tillage has been shown to have a significant impact on yield, due to differences in number of plants (Rashidi and Keshavarzpour, 2007). In the first year of the current experiment, deep tillage resulted in the highest recorded harvest index, which supports results presented by Rashidi and Keshavarzpour (2007). In the second year, although zero tillage resulted in lower tillering (Figure 7.2), it increased harvest index of winter barley. This could be due to the crops ability to compensate for fewer plants, by producing more grains per ear (AHDB, 2015b).

Larger differences in harvest index where observed in the first year compared to the second. Zero tillage has been shown to reduce soil temperatures (Wall and Stobbe, 1984), which results in delayed emergence, tillering and leaf extension (AHDB, 2015b), which leads to yield reductions as observed in the first experimental year. Improvements in soil physical properties under zero tillage in the second experimental year, indicated by increased soil moisture (Figure 6.7), could have offset differences in soil temperature, and permitted greater access to water and nutrients, resulting in smaller differences in harvest index between tillage systems.

7.6. Conclusions

The aim of this chapter was to determine the effect of a reduction in tyre inflation pressure and a reduction in traffic intensity, with deep, shallow and zero tillage systems on crop yields. Measurements of crop establishment (plants/m^2), crop growth (NDVI) and harvestable yield (Mg ha^{-1}) were used to determine the effect of treatments on crop yields, and to determine the effect of permanent wheelways and untrafficked soils in controlled traffic farming.

The following conclusions can be drawn after two years of agricultural traffic and tillage treatments studied in the field experiment.

Agricultural traffic system had no significant (P > 0.05) effect on winter wheat and winter barley establishment, growth and yield. A reduction in tyre inflation pressure resulted in a 4% increase in winter wheat combine harvested yield, but in the following year resulted in a 2% reduction in winter barley yield.

Tillage had no significant (P > 0.05) effect on winter wheat and winter barley establishment. A reduction in tillage however resulted in a significant increase in winter wheat and winter barley crop growth (NDVI) ($P < 0.05$). Zero tillage recorded up to 4% increases in NDVI compared to intensively cultivated treatments. For combine harvestable yields, a reduction in tillage intensity, from deep to shallow, increased winter wheat yields by 5%. The use of zero tillage, however, resulted in a significant reduction in yields ($P < 0.001$). A reduction in tillage intensity for winter barley, however, resulted in a 1% increase in yields. Tillage had no significant effect on winter barley yields ($P = 0.857$).

A reduction in traffic intensity using controlled traffic farming, decreased the number of winter wheat plants/m^2 at establishment, but increased the number of winter barley plants/m^2 at tillering. Controlled traffic farming increased winter wheat and winter barley crop growth but differences in means were not significant ($P > 0.05$). Harvestable yield of winter wheat increased by 5% compared to intensively trafficked treatments, although differences in means were not significant ($P > 0.05$). Harvestable yield of winter wheat and winter barley was significantly lower in the controlled traffic farming permanent wheelways, a reduction on 46% and 28% respectively, compared to the untrafficked zone.

To increase yields in commercial agricultural production systems, therefore, soil compaction should be minimised either by reducing the inflation pressure of standard agricultural tyres or by minimising the area covered by traffic by implementing a controlled traffic farming system. The effects of a reduction in tillage using zero tillage could require a longer-term approach before yield benefits are realised.

8. Discussion

In order to determine the effect of agricultural traffic and tillage systems on soil physical properties and crop yields, measurements of tyre and soil interactions under different running gear and tyre inflation pressures were taken using strain gauge transducers and penetration resistance. Misiewicz (2010) suggested that the use of pressure transducers in the soil profile may affect soil conditions, and therefore pressure measurements. As such there is an argument instead to use a Tekscan, a piezo-electric pressure mapping system, in order to measure pressures within the soil profile as the sensors have similar flexibility response characteristics to soil. Tekscan was not used in the current study as it could only be used in a soil bin, as described by Miziewicz (2010), where tyre treatments are mounted within a loading frame. Teckscan therefore could not be used in field or soil hall conditions to measure pressure under conventional agricultural traffic. Using strain gauge transducers it was possible to measure pressures within the soil profile at a depth of 150 mm and 300 mm. This study illustrated how pressure generated under different running gear distributes in the soil.

Contact pressure, determined from load and contact area between the running gear and the soil surface, was found to be lower under increased flexion tyres compared to standard agricultural tyres. The pressure transducers showed that use of increased flexion tyres resulted in overall lower soil pressures within the profile, but this is not consistent at all depths. Söhne (1958) suggested that the propagation of pressure within the soil profile can be affected by tyre size, load, and soil moisture. Based on the review of literature (Chapter 2), and estimations of carcass stiffness using tyre manufacturer data, the results of this research are likely attributable to the increased tyre carcass stiffness of increased flexion tyres. The manufacturers claim that the benefit of these tyres is that they can carry increased load at low inflation pressures, or the same load at a lower inflation pressure (Michelin, 2014b). From the results presented in this research, carcass stiffness in increased flexion tyres could be reducing the benefit of low tyre inflation pressures at shallow depths, as suggested by van den Akker *et al*. (1994) who reported the role of carcass stiffness in moderating the benefits of a reduction in tyre inflation pressure.

In a controlled environment, a reduction in tyre inflation pressure resulted in a reduction in soil pressures and penetration resistance. This indicates that in order to minimise soil compaction below agricultural tyres it is necessary to reduce tyre inflation pressures. This study was conducted in a controlled environment with a low soil moisture content (7 MBV%), and it was suggested by Söhne (1958) that under increasing soil moisture the effect of agricultural traffic on soil pressures increases and reaches to greater depths in the soil profile. In the subsequent field experiment, with higher soil moisture contents of up to 25% MBV, a reduction in tyre inflation pressure also reduced soil bulk density and penetration resistance. A reduction in tyre inflation pressures, therefore, is an effective approach that farmers can easily use to reduce in field soil pressures when cultivating and seeding without any machinery modification or investment. This method of reducing soil pressures and thus compaction has been confirmed by other researchers and attributed to both an increase in contact area and a reduction in ground pressure (Veremeulen and Klooster, 1992; Spoor *et al*., 2003; Antille *et al*., 2013).

Crop responses to a reduction in tyre inflation pressure were mixed. Winter wheat, grown in the first experimental year, responded positively to a reduction in tyre inflation pressure. Yields of winter barley, however, reduced, although differences in means between traffic treatments were not significant. In the first experimental year, compaction treatments were applied on 18 October 2012, when rainfall in the month preceding totalled 109.4 mm. In the second experimental year compaction treatments were applied on 7 September 2013 and rainfall in the preceding month was 50.4 mm, half of what it had been in the previous year. Bulk densities that were observed in the field under increased tyre inflation pressure never exceeded the critical threshold of 1.6 Mg m^{-3} for the sandy loam soil type, as suggested by Huber et al. (2008). The results of this research suggest that where soil moisture is low, the effect of agricultural tyres on soil compaction is reduced, but as soil moisture increases, the inflation pressure of agricultural tyres should be lowered to avoid soil compaction, as suggested by Söhne (1958). These findings suggest that when soil moisture content does not create a greater risk of compaction, the use of low tyre inflation pressures is of no benefit in terms of crop yields compared to standard tyre inflation pressures. Soil conditions at depth however can still be affected by traffic-induced compaction, even in drier field conditions. If soil moisture then becomes a limiting factor later in the season, greater yield effects could be seen (Barraclough and Weir, 1988). The association between soil moisture and compaction, therefore, is an important factor over the duration of growing season, and not just at the time of agricultural trafficking, which has previously been the focus of research (Söhne, 1958; Spoor *et al*., 2003).

In the current study agricultural traffic compaction intensities were applied at the end of each growing season following harvest, prior to cultivation and seeding for the following crop. This methodology was used to account for all of the traffic that would have entered a commercial field within one growing year, applicable to each tillage intensity, as defined by Kroulík *et al*. (2009). The resilience of soil to compaction at this time of year is greater, as a result of lower soil moisture content (Söhne, 1958) and lack of preceding soil disturbance (Ankeny *et al*., 1995; Botta *et al*., 2009; Antille *et al*., 2013). Therefore, it is anticipated that differences in soil and crop properties between agricultural traffic and tillage treatments would be greater if the compaction intensities had been applied when the soil moisture content was higher, and the soil therefore more vulnerable. In commercial agricultural production systems, for example, agri-chemical spray applications for crop protection and crop performance are often completed when soil moisture is high, and the risk of compaction therefore is increased. One of the driving forces behind the uptake of conservation agriculture, including CTF, in commercial practice in Australia has been to improve soil water conservation and availability (Belloti and Rochecouste, 2014). In the current study, however, differences in means of soil moisture content between traffic systems were not significant. The UK does not experience the same water shortages as in Australia, yet the risk and resilience of crop yields under increasingly variable weather conditions could be affected by soil compaction resulting from loads applied during tillage and seeding. The adaptation of agricultural cropping systems to climate change should conserve soil moisture and manage it to prevent water logging and erosion (Howden *et al*., 2007).

Although the soil pressure measured under the Challenger tracks was lower than that measured under the tyres, the pressure distribution along the length of the tracks was not uniform, as reported by Reaves and Cooper (1960). The use of strain gauge pressure transducers provided measurements of soil pressure within the profile but this method does not allow for the use of ground engaging equipment, which increases the uniformity of pressure distribution, as suggested by Blunden *et al*. (1994). Track design has also changed from flat steel tracks, to rubber tracks with multiple sprockets constructed to be hard wearing with larger casings for lasting strength and reliability (Challenger-Ag, 2014). Therefore, comparisons within the literature of the benefits of tracks need to take account of the effect of track design. Results from the current study, indicate that the distribution of load across multiple sprockets on modern machinery results in higher pressures being applied over a longer period compared to the tyre treatments, as suggested by Blunden *et al*. (1994) and Alakukku *et al*. (2003).

The assessment of running gear and tyre inflation pressure did however provide a methodology for implementing differential pressure treatments in a field experiment, whereby the impact of both traffic and tillage could be fully evaluated using measurements of soil physical and crop properties. The field experiment was designed to be located on a uniform site, based on measurements of soil and crop properties, namely elevation, soil type, electrical conductivity, soil moisture, penetration resistance, crop establishment, growth and yield. This methodology represents the first of its kind in terms of site preparation and assessment prior to the establishment of an agricultural traffic and tillage study (Chamen, 2011). The current research, therefore, provides a methodology for the design of future research. Furthermore, it provides a methodology by which farmers themselves can use commercially available technologies, in addition to information available on farm such as crop yields, to inform management decisions or zonal management of fields. McBratney *et al*. (2005) suggested that the use of yield maps on farm should not only focus on the delineation of variation within a field but also to assess changes over time. It is recommended, therefore, that historical field information are used in combination with continued measurements to assess the impact of management decisions on agricultural productivity. The models used within yield mapping software, however, require development and improvement to deliver cost-effective and reliable decision-making tools to farmers (Henly, 2015).

The timing of cultivation and seeding plays a role in the risk of soil compaction and the impact on crop establishment and yield in the UK (AHDB, 2017a). In commercial systems, farmers are principally governed by rotations, variety choice and the weather. If a late harvest occurs, due either to late maturing crops or varieties, or poor weather conditions, this can impact on establishment of the following crop. The later that this is pushed into the winter, the more vulnerable the soil becomes to compaction due largely to higher soil moisture contents. The tillage system that is then necessary to use to establish a successful crop is often more intensive in order to achieve a drying action, through ploughing for example.

Bulk density and penetration resistance of untrafficked soil was significantly lower than in the wheelways of controlled traffic farming, and yields of both winter wheat and winter barley were higher in the untrafficked zone. Controlled traffic farming could allow UK farmers to make potential cost savings of up to £130/ha, as suggested by Redman (2016) by reducing soil compaction and the need for intensive tillage. Furthermore, CTF could increase income due to increased crop yields, equating to an additional £53.64/ha (based on May 2017 feed wheat price of £149.20/tonne and a yield increase of 0.36 t/ha) (AHDB, 2017b). To adopt controlled traffic farming, and the use of accurately located permanent wheelways, however, requires investment in reliable global positioning systems. Godwin *et al*. (2017)

reported that the annual cost of a high-accuracy RTK system, with an initial investment cost of £15,000, is approximately £4000. The usability and uptake of these systems on commercial farms is increasing, but the applicability of these high cost systems on smaller sized farms could be uneconomical; the adoption of lower cost systems based on telephone signal or physical crop line markers could be more viable (Godwin *et al*., 2017).

The introduction of alternative traffic and tillage management systems can have beneficial impacts on the environment, but only when managed appropriately. In the current study, the poor soil structure in the wheelways, indicated by increased bulk density and penetration resistance, resulted in restricted water movement, which during times of high rainfall could lead to surface ponding and subsequent soil erosion and run off, especially on downhill slopes. Adopters of controlled traffic farming, therefore, should implement their traffic lanes to avoid steep land gradients, especially on heavy soils which are prone to waterlogging (Chamen, 2006b). Erosion and soil degradation in Australian agricultural controlled traffic farming systems, however, is driven by the effects of tillage rather than the effects of agricultural traffic (Tullberg *et al*., 2007).

A lack of consistency in yields from zero tillage systems agrees with Seehusen *et al*. (2014), who concluded that wheat yields are strongly dependent on tillage, and that in the first few years following its adoption zero tillage can negatively affect crop yields. Furthermore, the soil type used in this research, a sandy loam, was deemed “risky” by Butterworth *et al*. (1980) and represents the most challenging conditions in which to establish a zero tillage system. The literature does contain evidence of increased crop yields from zero tillage systems, which have been attributed to suitability of soil types for the adoption of zero tillage to increase crop yields (De Vita *et al*., 2007). Butterworth *et al*. (1980) suggested that chalk, limestone, well drained loams, calcareous clays are favourable for the adoption of zero tillage, followed by well drained loams, calcareous clays, other clays. It is recommended that drill selection is critical in more risky conditions, being sandy, silty and wet alluvial soils (Butterworth *et al*., 1980). In the current study, all treatments were drilled with the same disc and tine drill, although the drill model changed between the first and second experimental years due to machinery availability and suitability (Dines, 2013. Pers. Comm. Mr. R. Dines is the Central Territory Sales Manager for Väderstad UK). Previous research has reported that the reduction in yields of zero tillage systems can be attributed to the use of non-specialist drills (Keeble, 2008). Where drills have been used that have been specifically designed for drilling directly into uncultivated stubble, zero tillage yields have increased. Therefore, traffic and tillage management systems should be implemented in combination with good understanding and management of both machinery and soils, including drainage and drainage maintenance, to avoid soil degradation and yield losses. In controlled traffic farming systems, soil structure and performance should be monitored in both the untrafficked and permanent wheelway zones, with appropriate and timely action taken where necessary.

Tillage plays an important role in weed management. A challenge facing farmers at the present time is the future uncertainty over the use of glyphosate (Lyddon, 2016). Due to the lack of cultural controls available to zero tillage farmers, the use of glyphosate is integral to the success of this system, and there are currently no alternatives for effective weed control. The de-registration of glyphosate could have a major impact on the range of cultivation systems used in the UK, and could see a return to more intensive tillage operations. Deep tillage, for example rotational ploughing in minimum and zero tillage systems, is used in commercial practice to control black-grass. The benefits to soil structure, achieved from using zero tillage systems would be lost as the vulnerability of soils to compaction would increase under increased tillage (Ankeny *et al*., 1995; Chan *et al*., 2006; Botta *et al*., 2009). Increasing awareness of the risk of soil compaction in these systems would become critical to soil conservation. The role of traffic management systems, such as controlled traffic farming, could offer a compromise whereby deep tillage is used in conjunction with repeatable wheelways.

Improvements to this research could have been made by taking additional measurements on the effect of traffic and tillage on the biological component of the soil, including macro and microbial diversity and abundance. The assessment of earthworm populations, for example, provides an indicator of soil quality and the impact of management practices, primarily tillage. Earthworms play an important role in breaking down organic matter and increasing plant available nutrients (Doran and Zeiss, 2000). A reduction in tillage, however, can reduce nutrient availability (Garcia *et al*., 2007). Additional measurements of soil organic matter and available nutrients could have investigated whether they are linked to soil biological activity and are affected by traffic and tillage. To complement the additional measurements of the soil's biological and nutrient status, measurements of crop root architecture could serve as an explanation for observed variations in yield, due to differences in access and uptake of water and crop available nutrients (Dal Ferro *et al*., 2014; Li *et al*., 2016).

To minimise soil compaction in commercial agricultural production systems, it is recommended to keep tyres at low inflation pressures or to implement a controlled traffic farming system where both financial and management investment allows. A change in traffic management results in a change in the extent of soil compaction, and the selection of tillage system therefore should be based on the requirement to remove compaction and to create a soil environment that is conducive to crop growth.

9. Conclusions

The results of this research, conducted on a uniform field site, suggest that field practices in commercial agricultural operations should seek to reduce soil compaction. This can be achieved by reducing tyre inflation pressures of standard agricultural tyres, or using controlled traffic farming, in combination with reduced tillage systems.

Tyre inflation pressure of standard agricultural tyres should be reduced. Results presented here show that reduced tyre inflation pressure results in an increase in the soil contact area and reduced soil pressures within the profile. Reduced soil pressure in-turn results in reduced soil compaction shown here by lower soil bulk density, penetration resistance and increased hydraulic conductivity. Using lower tyre inflation pressures resulted in yield benefits of up to a 4% increase compared to standard tyre inflation pressures.

Tyre selection is critical to minimising soil compaction, but this does not eliminate the need for appropriate tyre inflation pressures. An understanding of the interaction between tyres and the depth of soil compaction could aid manufacturers to design tyres which reduce the depth at which compaction occurs. Farmers need to fully understand the depth within the soil profile where increased soil compaction is occurring to inform appropriate tillage depth to target the removal of compaction. This research showed that differences in tyre construction, using increased flexion tyres, increased the soil/tyre contact area and resulted in soil pressures which were 52% lower at a depth of 300 mm than when conventional tyres were used. At a depth of 150 mm, however, the use of increase flexion tyres resulted in soil pressures which were 38% higher than when standard tyres were used.

Controlled traffic farming has the potential to increase commercial crop yields due to improved soil properties of untrafficked soil due to less soil compaction. The yield of winter wheat (*Triticum aestivum*) and winter barley (*Hordeum vulgare*) from untrafficked soil in the replicated plot experiment increased by 1.5 Mg ha^{-1} and 0.98 Mg ha^{-1} compared to random traffic farming (RTF). After two years of the field experiment, there was evidence to suggest that differences in crop yields between traffic treatments resulted from 14% lower soil bulk density and 27% lower penetration resistance of untrafficked soil.

Tillage management has the potential to increase crop yields, but farmers need to have a long-term and whole system approach to improving soil management by reduced tillage. The results presented here show that crop yields from zero tillage plots varied between the two experimental years, -9% and +1% compared to conventional deep tillage, respectively.

There was also evidence to suggest that the potential of zero tillage systems is dependent on agricultural traffic. When using zero tillage systems, the intensity of traffic should therefore be kept to a minimum by implementing controlled traffic farming systems. This was shown by an increased effect of agricultural traffic on crop yields in zero tillage plots, with yield losses from random traffic farming of between 1.01 Mg ha^{-1} and 3.72 Mg ha^{-1} compared to untrafficked soil.

To give farmers the confidence to adopt alternative traffic and tillage practices to reduce soil compaction in commercial systems, longer-term and further robust data on soil and plant interactions are required. Crucially effective knowledge exchange is needed between researchers, machinery and tyre manufacturers and end-users if widespread adoption is to occur.

10. Recommendations for further work

This research represents the design and establishment of the first three years of a long-term experiment to determine the impacts of controlled traffic farming and low ground pressure with reduced tillage systems. As such, this is the first long-term experiment of its type. In addition to the on-going experiment, which is utilising computed tomography (CT) to gain a better understanding of plant and soil interactions under a wider rotation of spring and autumn sown crops, the limitations of the research presented in this thesis has highlighted areas where further work would be beneficial. The investigation of the effect of traffic and tillage on soil biology, and in turn the effect of soil biology on plant available nutrients, could provide information on the timescales required to achieve the benefits of reduced tillage systems for increasing crop yields. Further investigations could consider whether the incorporation of additional organic matter, using cover cropping or applications, stimulates the rate of biological activity under different tillage systems, such as zero tillage.

Although sub-surface water characteristics were quantified in the current study, further work on the extent to which compaction effects crop root architecture would provide information on characteristics of soil structure and rooting within the soil profile. The degree to which different crops respond to soil compaction could help inform crop selection in commercial systems, whereby rotations are designed to exploit, or rectify, soil structural conditions.

In the current study, all treatments were drilled with the same disc and tine drill, and the use of non-specialist drills in zero tillage systems can lead to lower yields. Further work could consider the design of drill machinery to allow for greater flexibility of tillage using one piece of equipment. This would allow farmers to more effectively use a range of appropriate tillage intensities based on the prevailing conditions.

There are areas for further development and applications of methodologies used for this research. The technique of assessing field uniformity using within field and remote sensing technologies could be applied in further experimental research and commercial agricultural production systems. This would provide a protocol and allow comparison between results of different traffic and tillage studies.

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Appendix A. Field experimental design – layout of treatments

Block	Plot	Traffic	Tillage	Width (m)
1	1	Standard tyre pressure	Deep	3.935
	2	Low tyre pressure	Deep	3.885
	3	Controlled traffic farming	Zero	3.935
	4	Controlled traffic farming	Deep	3.975
	5	Low tyre pressure	Shallow	3.965
	6	Standard tyre pressure	Zero	3.980
	7	Low tyre pressure	Zero	3.995
	8	Controlled traffic farming	Shallow	3.965
	9	Standard tyre pressure	Shallow	3.995
2	10	Low tyre pressure	Deep	3.935
	11	Controlled traffic farming	Shallow	3.955
	12	Low tyre pressure	Shallow	3.955
	13	Standard tyre pressure	Shallow	3.950
	14	Controlled traffic farming	Zero	3.960
	15	Standard tyre pressure	Zero	3.920
	16	Low tyre pressure	Zero	3.955
	17	Controlled traffic farming	Deep	4.000
	18	Standard tyre pressure	Deep	3.945
3	19	Controlled traffic farming	Shallow	3.945
	20	Standard tyre pressure	Zero	4.045
	21	Low tyre pressure	Deep	3.840
	22	Controlled traffic farming	Deep	3.625
	23	Standard tyre pressure	Shallow	4.025
	24	Controlled traffic farming	Zero	3.865
	25	Standard tyre pressure	Deep	3.825
	26	Low tyre pressure	Zero	3.945
	27	Low tyre pressure	Shallow	3.755
4	28	Controlled traffic farming	Shallow	3.770
	29	Standard tyre pressure	Zero	3.905
	30	Low tyre pressure	Zero	3.810
	31	Standard tyre pressure	Deep	3.825
	32	Low tyre pressure	Deep	3.910

33	Standard tyre pressure	Shallow	3.795
34	Controlled traffic farming	Zero	3.780
35	Low tyre pressure	Shallow	3.810
36	Controlled traffic farming	Deep	3.900

Appendix B. Skeleton ANOVA

Source of variation	n	d.f.
Block	4	3
Traffic	3	2
Tillage	3	2
Traffic x tillage		4
Residual		24
Total	36	35

Appendix C. Compaction protocol

The compaction protocol was designed by the researcher to apply differential traffic compaction in the experiment. The most appropriate route was investigated based on turning circle of the tractor and logistics of changing tyre pressures when necessary. Compaction was applied on 18 October 2012 and 7 September 2013.

Driving instructions	**Check**	**Speed (k h^{-1})**	**Accuracy**
Check tyre pressures are 0.12 MPa front and 0.15 MPa rear	✓		
Enter field	✓		
Got to plot 1	✓		
Drive AB line once	✓	7.0	<0.01
Back to plot 1	✓		
Offset LEFT from AB 0.6m	✓		
Drive first time (offset LEFT 0.6 m)	✓	8.0	<0.01
Back to plot 1	✓		
Drive second time (offset LEFT 0.6 m)	✓	7.5	<0.01
Go to plot 6	✓		
Drive AB line once	✓	7.0	<0.01
Go to plot 9	✓		
Offset LEFT from AB 0.6m	✓		
Drive once (offset LEFT 0.6m)	✓	7.0	<0.01
Go to plot 14	✓		
Offset LEFT from AB 0.6 m	✓		
Drive once (offset LEFT 0.6 m)	✓	7.0	0.00
Go to plot 19	✓		
Drive AB line once	✓	7.4	<0.02
Back to plot 19	✓		
Offset LEFT from AB 0.6 m	✓		
Drive first time (offset LEFT 0.6 m)	✓		<0.01
Back to plot 19	✓		
Drive second time (offset LEFT 0.6 m)	✓		<0.01
Back to plot 19	✓		
Offset LEFT from AB 1.4 m	✓		<0.01
Drive once (offset LEFT 1.4 m)	✓		
Go to plot 22	✓		
Drive AB line once	✓	7.4	<0.01
Go to plot 25	✓		
Offset LEFT 0.6 m	✓		

Drive once (offset LEFT 0.6 m)	✓	7.6	<0.01
Go to plot 27	✓		
Drive AB line once	✓	7.0	<0.01
Back to plot 27	✓		
Offset LEFT 0.6m (offset LEFT 0.6 m)	✓		
Drive first time (offset LEFT 0.6 m)	✓	5.0	<0.01
Back to plot 27	✓		
Drive second time (offset LEFT 0.6 m)	✓	6.4	<0.01
Go to plot 32	✓		
Drive AB line once	✓	7.0	<0.01
Go to plot 34	✓		
Drive AB line once	✓	7.2	<0.01
Offset LEFT 0.6 m	✓		
Drive first time (offset LEFT 0.6 m)	✓	6.2	<0.01
Back to plot 34	✓		
Drive second time (Offset LEFT 0.6 m)	✓	7.0	<0.01
Go to plot 36	✓		
Offset LEFT 0.6 m	✓		
Drive once (offset LEFT 0.6 m)	✓	6.2	<0.01
Check tyre pressure are 0.07 MPa front and rear	✓		
Go to plot 2	✓		
Drive AB line once	✓	6.5	<0.01
Back to plot 2	✓		
Offset LEFT 0.6 m	✓		
Drive first time (offset LEFT 0.6 m)	✓	6.5	<0.01
Back to plot 2	✓		
Drive second time (offset LEFT 0.6 m)	✓	6.6	<0.01
Go to plot 5	✓		
Offset LEFT 0.6 m	✓		
Drive once (offset LEFT 0.6 m)	✓	6.4	<0.01
Go to plot 7	✓		
Drive AB line once	✓	6.8	<0.01
Go to plot 11	✓		
Drive AB line once	✓	7.4	<0.01

Back to plot 11	✓		
Offset LEFT 0.6 m	✓		
Drive first time (offset left 0.6 m)	✓	8.0	<0.01
Back to plot 11	✓		
Drive second time (offset left 0.6 m)	✓	6.4	<0.01
Go to plot 13	✓		
Offset LEFT 0.6 m	✓		
Drive once (offset 0.6 m)	✓	7.2	<0.01
Go to plot 17	✓		
Drive AB line once	✓	7.9	<0.01
Go to plot 23	✓		
Drive AB line once	✓	7.5	<0.01
Back to plot 23	✓		
Offset LEFT 0.6 m	✓		
Drive first time (offset 0.6 m)	✓	6.9	<0.01
Back to plot 23	✓		
Drive second time (offset 0.6 m)	✓	8.0	<0.01
Go to plot 28	✓		
Drive AB line once	✓	6.0	<0.01
Go to plot 29	✓		
Offset LEFT 0.6 m	✓		
Drive once (offset 0.6 m)	✓	7.0	<0.01
Go to plot 33	✓		
Drive AB line once	✓	6.0	<0.01
Go to plot 35	✓		
Drive AB line once	✓	6.7	<0.01
Back to plot 35	✓		
Offset LEFT 0.6 m	✓		
Drive first time (offset 0.6 m)	✓	7.0	<0.01
Back to plot 35	✓		
Drive second time (offset LEFT 0.6 m)	✓	7.2	<0.01
Go to plot 38	✓		
Offset LEFT 0.6 m	✓		
Drive once (offset LEFT 0.6 m)	✓	7.9	<0.01
Change tyre pressures:	✓		

LEFT tyres = 0.07 MPa front and rear RIGHT tyres = 0.12 MPa front and 0.15 MPa rear			
Go to plot 1	✓		
Offset LEFT 1.4 m	✓		
Drive once	✓	6.7	<0.01
Go to plot 6	✓		
Offset LEFT 1.15 m	✓		
Drive once	✓	6.5	0.01
Go to plot 10	✓		
Offset LEFT 1.30 m	✓		
Drive once	✓	7.0	<0.01
Go to plot 16 (Offset LEFT 1.15 m)	✓		
Offset LEFT 1.15 m	✓		
Drive once	✓	6.7	<0.01
Go to plot 22	✓		
Offset LEFT 1.15 m	✓		
Drive once	✓	7.9	<0.01
Go to plot 27	✓		
Offset LEFT 1.15 m	✓		
Drive once	✓	7.0	<0.01
Go to plot 32	✓		
Offset LEFT 1.15 m	✓	7.6	<0.01
Go to plot 34	✓		
Offset LEFT 1.25 m	✓		
Drive once	✓	7.1	<0.01

Appendix D. Tillage and seeding protocol.

1. Tillage protocol

Instruction	Plot number	Traffic	Tillage	Action
Set TopDown to deep tillage				
Go to plot	1	RTF standard	Deep	Cultivate deep tillage
Go to plot	10	CTF	Deep	Cultivate deep tillage
Go to plot	2	RTF low	Deep	Cultivate deep tillage
Go to plot	17	CTF	Deep	Cultivate deep tillage
Go to plot	4	CTF	Deep	Cultivate deep tillage
Go to plot	18	RTF standard	Deep	Cultivate deep tillage
Go to plot	21	RTF low	Deep	Cultivate deep tillage
Go to plot	31	RTF standard	Deep	Cultivate deep tillage
Go to plot	22	CTF	Deep	Cultivate deep tillage
Go to plot	32	RTF low	Deep	Cultivate deep tillage
Go to plot	25	RTF standard	Deep	Cultivate deep tillage
Go to plot	36	CTF	Deep	Cultivate deep tillage
Set TopDown to shallow tillage				
Go to plot	5	RTF low	Shallow	Cultivate shallow tillage
Go to plot	11	CTF	Shallow	Cultivate shallow tillage
Go to plot	12	RTF low	Shallow	Cultivate shallow tillage
Go to plot	9	RTF standard	Shallow	Cultivate shallow tillage
Go to plot	13	RTF standard	Shallow	Cultivate shallow tillage
Go to plot	19	CTF	Shallow	Cultivate shallow tillage
Go to plot	28	CTF	Shallow	Cultivate shallow tillage
Go to plot	23	RTF standard	Shallow	Cultivate shallow tillage
Go to plot	33	RTF standard	Shallow	Cultivate shallow tillage
Go to plot	27	RTF low	Shallow	Cultivate shallow tillage
Go to plot	35	RTF low	Shallow	Cultivate shallow tillage

2. Seeding protocol

Order	Start		Plot	Traffic	Tillage
1		Engineering building	7	RTF low	Zero
2	Off-road track		3	CTF	Zero
3		Engineering building	6	RTF standard	Zero
4	Off-road track		16	RTF low	Zero
5		Engineering building	20	RTF standard	Zero
6	Off-road track		15	RTF standard	Zero
7		Engineering building	24	CTF	
8	Off-road track		14	CTF	Zero
9		Engineering building	26	RTF low	Zero
10	Off-road track		30	RTF low	Zero
11		Engineering building	34	CTF	Zero
12	Off-road track		29	RTF standard	Zero
13		Engineering building	33	RTF standard	Shallow
14	Off-road track		35	RTF low	Shallow
15		Engineering building	28	CTF	Shallow
16	Off-road track		27	RTF low	Shallow
17		Engineering building	23	RTF standard	Shallow
18	Off-road track		19	CTF	Shallow
19		Engineering building	13	RTF standard	Shallow
20	Off-road track		9	RTF standard	Shallow
21		Engineering building	12	RTF low	Shallow
22	Off-road track		8	CTF	Shallow
23		Engineering building	11	CTF	Shallow
24	Off-road track		5	RTF low	Shallow
		Engineering building	31	RTF standard	Deep
26	Off-road track		36	CTF	Deep
27		Engineering building	25	RTF standard	Deep
28	Off-road track		32	RTF low	Deep
29		Engineering building	Plot 21	RTF low	Deep
30	Off-road track		Plot 18	RTF standard	Deep
31		Engineering building	Plot 22	CTF	Deep
32	Off-road track		Plot 17	CTF	Deep
33		Engineering building	Plot 10	RTF low	Deep

34	Off-road track		Plot 2	RTF low	Deep
35		Engineering building	Plot 4	CTF	Deep
36	Off-road track		Plot 1	RTF standard	Deep

Appendix E. Agronomy

1. Agronomy 2011-2012

Date	Application	Product (active)	Rate
15/09/2011	Herbicide	Azural (glyphosate)	3 l ha^{-1}
10/11/2011	Seed	Duxford C2 Jockey	180 kg ha-1
6/03/2012	Herbicide	Othello diflufenican+iodosulfuron-methyl-sodium	0.9 l ha^{-1}
	Adjuvant	Biopower	1 l ha^{-1}
	Instecticide	Toppel 100 EC cypermethrin	0.25 l ha^{-1}
17/03/2012	Fertiliser	Muriate of Potash	158 kg ha^{-1}
		Top Crop 26N 37SO3	N = 29.61 kg ha^{-1} SO3 = 42.2 kg ha^{-1}
29/03/2012	Fungicide	Justice proquinazid	0.1 l ha^{-1}
	Growth Regulator	Tempo trinexapac-ethyl	0.1 l ha^{-1}
	Chemicals	Cherokee cyproconazole chlorothalonil propiconazol	1 l ha^{-1}
	Growth Regulators	Mirquat 730 chlormequat	1 l ha^{-1}
05/04/2012	Fertiliser	Lithan 34.5% N	65 kg ha^{-1} of N
24/04/2012	Herbicide	Presite Sx metsulfuron-methyl + thifensulfuron	74.99 g ha^{-1}
	Fungicide	Proline 275	0.43 l ha^{-1}
	Fungicide	Justice proquinazid	0.1 l ha^{-1}
	Growth Regulator	Chloremequat (BASF)	1.25 l ha^{-1}
	Chemical	Cherokee cyproconazole chlorothalonil propiconazol	1 l ha^{-1}
08/05/2012	Fertiliser	Top Crop 26N 37SO3	N = 45.74 kg ha^{-1} SO3 = 65 kg ha^{-1}
16/05/2012	Fungicide	Osiris Pepoxiconazole metconazole	0.4 l ha^{-1}
	Fungicide	Adexar epoxiconazole fluxapyroxad	0.72 l ha^{-1}

10/06/2012	Fungicide	Prosaro Prothioconazale+Tebuco	0.5 l ha^{-1}
01/09/2012	Herbicide	Azural (glyphosate)	3 l ha^{-1}

2. Agronomy 2012-2013

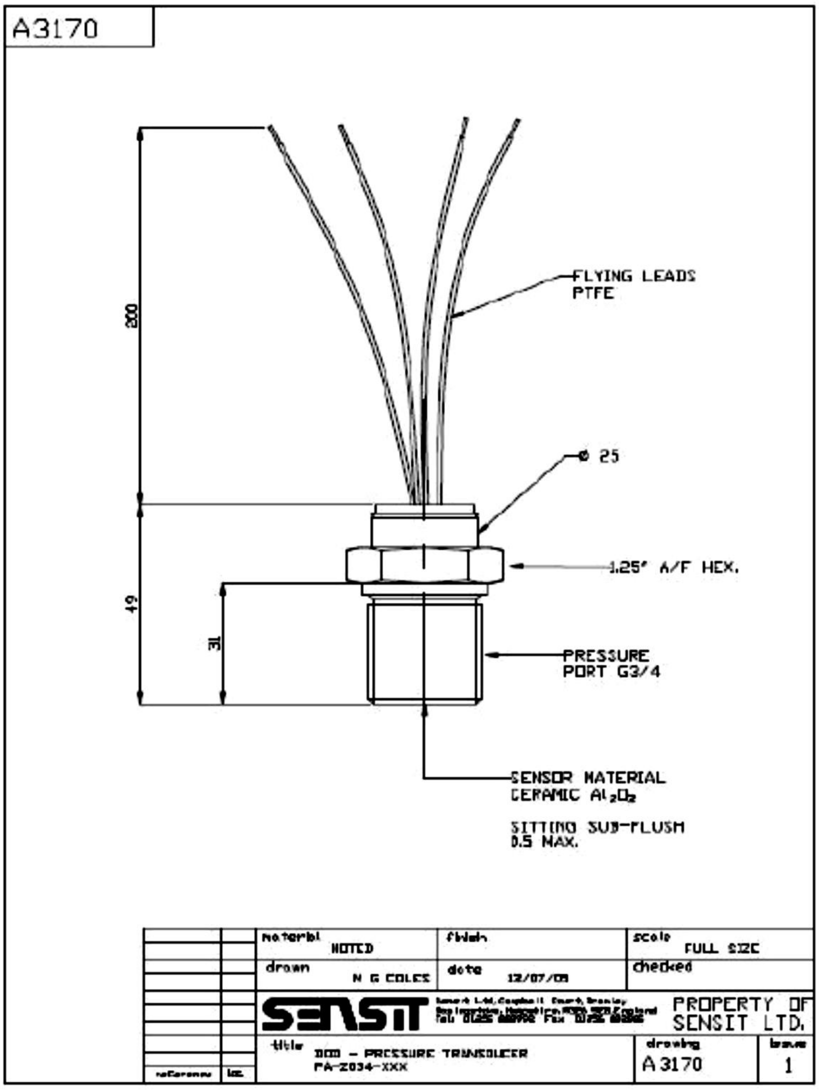
Date	Application	Product (active)	Rate
01/09/2012	Herbicide	Azural (glyphosate)	3 l ha^{-1}
07/01/2013	Molluscicide	Slug pellets Sluxx	5 kg ha^{-1}
05/03/2013	Fertiliser	Top Crop 26N 37SO3 (del Aug 11)	148 kg ha^{-1}
02/05/2013	Herbicide	Starane XL fluroxypyr + florasul	1 l ha^{-1}
	Fungicide	Chord boscalid + epoxiconazole	1 l ha^{-1}
		Cherokee cyproconazole chlorothalonil propiconazol	1 l ha^{-1}
	Growth regulator	Tempo trinexapac-ethyl	0.1 l ha^{-1}
	Fungicide	Justice proquinazid	0.1 l ha^{-1}
	Herbicide	Presite Sx metsulfuron-methyl + thifensulfuron	50 Gms ha^{-1}
07/05/2013	Fertiliser	Growham Nitram 34.5%	218 kg ha^{-1}
20/05/2013	Fertiliser	Growham Nitram 34.5%	218 kg ha^{-1}
25/05/2013	Trace element	Sedema Manganese Sulphate	5 kg ha^{-1}
	Adjuvant	Activator 90	0.05 l ha^{-1}
03/06/2013	Fungicide	Prosaro Prothioconazole+Tebuco	0.75 l ha^{-1}
		Vertisan penthiopyrad	0.75 l ha^{-1}
24/06/2013	Fungicide	Prosaro Prothioconazole+Tebuco	0.6 l ha^{-1}
12/08/2013	Herbicide	Azural (glyphosate)	3 l ha^{-1}

3. Agronomy 2013-2014

Date	Application	Product (active)	Rate
08/11/2013	Insecticide	Permasect C (cypermethrin)	0.25 l ha^{-1}
	Herbicide	Liberator (flufenacet diflufenican)	0.6 l ha^{-1}
17/03/2014	Fertiliser	Origin sulphur N26N-0P-35SO3	100 kg ha^{-1}
29/03/2014	Trace element	Headland stem	0.73 l ha^{-1}
	Fungicide	Kayak (cyprodinil)	0.55 l ha^{-1}
	Growth regulator	Tempo trinexapac-ehtyl	0.05 l ha^{-1}
	Trace element	Manganese Sulphate Norken Superior	2.73 kg ha^{-1}
09/04/14	Fertiliser	Yara Bella 34.5% N	173 kg ha^{-1}
14/04/2014	Herbicide	Gala fluroxypr	0.75 l ha^{-1}
	Fungicide	Rubric epoxiconazole	0.6 l ha^{-1}
		Justice proquinazid	0.1 l ha^{-1}
		Vertisan penthiopyrad	0.7 l ha^{-1}
	Herbicide	Jubilee Sx metsulfuron-methyl	20 Gms ha^{-1}
	Growth regulator	Tempo trinexapac-ethyl	1.46 l ha^{-1}
02/05/2014	Fertiliser	Yara Bella prilled del April 2014	144 kg ha^{-1}
05/05/2014	Fungicide	Siltra Xpro Prothioconazole + Bixafen	0.50 l ha^{-1}
	Fertiliser	Bittersalz Epsotop foliar magnesium and sulphur	3.73 kg ha^{-1}
15/07/2014	Herbicide	Roundup Flex glyphosate	1.25 l ha^{-1}

Appendix F. Pressure transducer specification

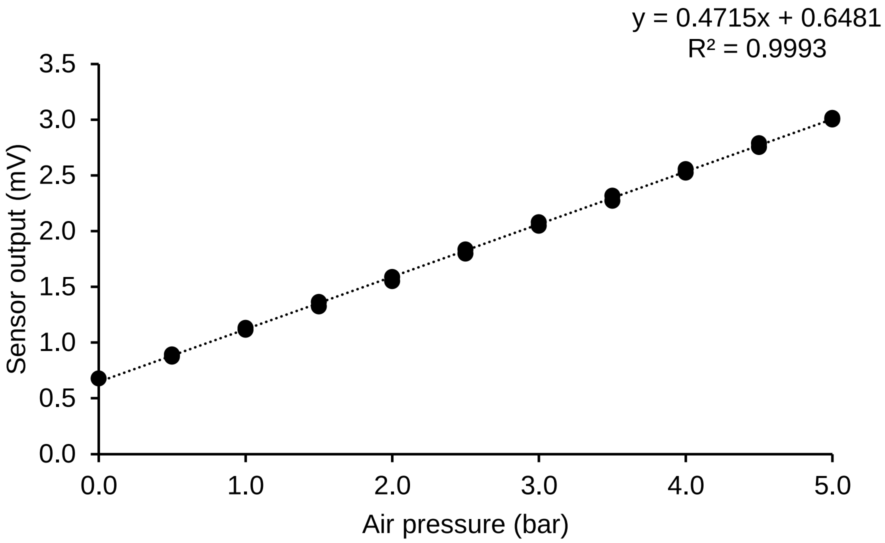
General description			
This is a mV output sensor in a stainless steel housing with ¾” male pressure port. The sensor is sub-flush mounted with the pressure port and potted.			
Input specification			
Pressure range	0 bar abs to 5 bar abs 0 bar abs to 10 bar abs	**Electrical excitation**	10 V
Over pressure	x 1.5 of cal pressure	**Input current**	
Burst pressure	> x 3 cal pressure	**Input resistance**	10 Kohms ± 30%
Reverse polarity protection	N/A	**Supply voltage effect**	N/A
Pressure media	Fluids compatable with 316SS, 96% alumina and ESP109 potting compound		
Output specification			
Sensitivity	0-5 bar 4mV/V ± 30% 0-10 bar 4mV/V ± 30%	**Repeatability**	0.1% FRO
Residual unbalance	0mV ± 2mV with zero applied pressure, rated excitation and at room temperature	**Output resistance**	10 Kohms ± 30%
Non-linearity & hysteresis	< ± 0.25% FRO (BSL)	**Electrical relationship of strain gauges to capsule**	Isolated
Environmental performance			
Temperature range	-55 to +125ºC	**Thermal sensitivity**	<-0.04%/ºC
Temerpature zero shift	5 bar <0.05% FRO/ºC 20 bar <0.04% FRO/ºC	**Mechanical shock**	100g half peak wave pulse for a duration of 11 milliseconds will not damage the sensor
Physical characteristics			
D.O.D	A3170	**Electrical connection**	7 x 0.2mm PTFR wire attached, length 200mm
Pressure port	¾” BSP male flush mount	**Positive supply**	Red
Materials of construction	316L st.st.	**Negative supply**	Blue
Method of installation	1 ¼” A/F hex	**Positive output**	Green
Nominal diameter	25mm	**Negative output**	Yellow
Nominal length	See A3170	**Weight**	TBA


A3170
FLYING LEADS
PTFE
200
⌀ 25
1.25" A/F HEX.
49
31
PRESSURE
PORT G3/4
SENSOR MATERIAL
CERAMIC Al_2O_3
SITTING SUB-FLUSH
0.5 MAX.
material
NOTED
finish
scale
FULL SIZE
drawn
N G COLES
date
checked
PROPERTY OF
SENSIT LTD.
title
PRESSURE TRANSDUCER
PA-2034-XXX
drawing
A 3170
issue
1
reference

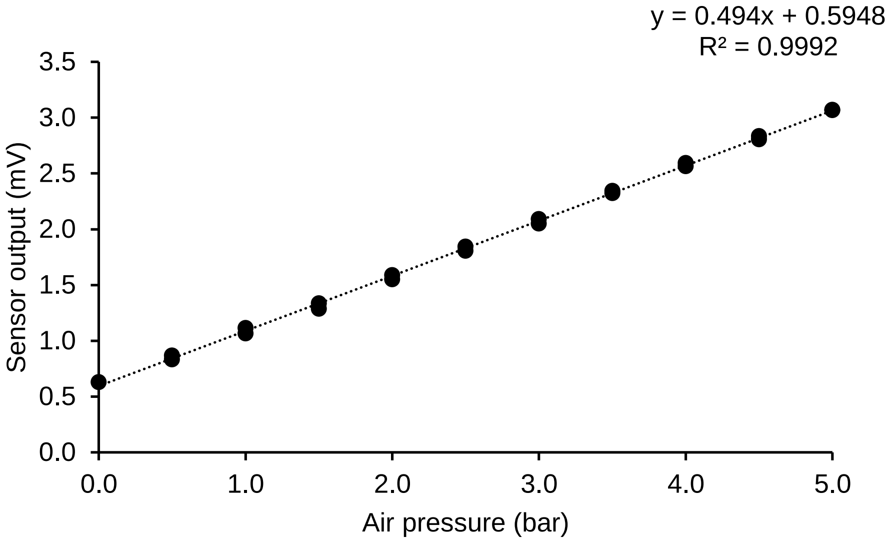
Appendix G. Calibration of Roxspur strain gauge transducers

The strain gauge pressure transducers were calibrated using an air calibrator. These were then used to apply calibrations to the values recorded under trafficking.

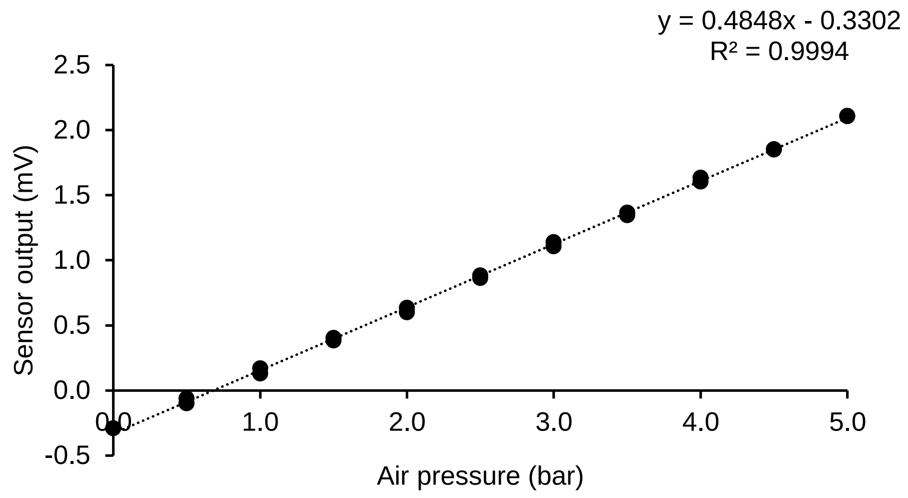
1. Transducer 1



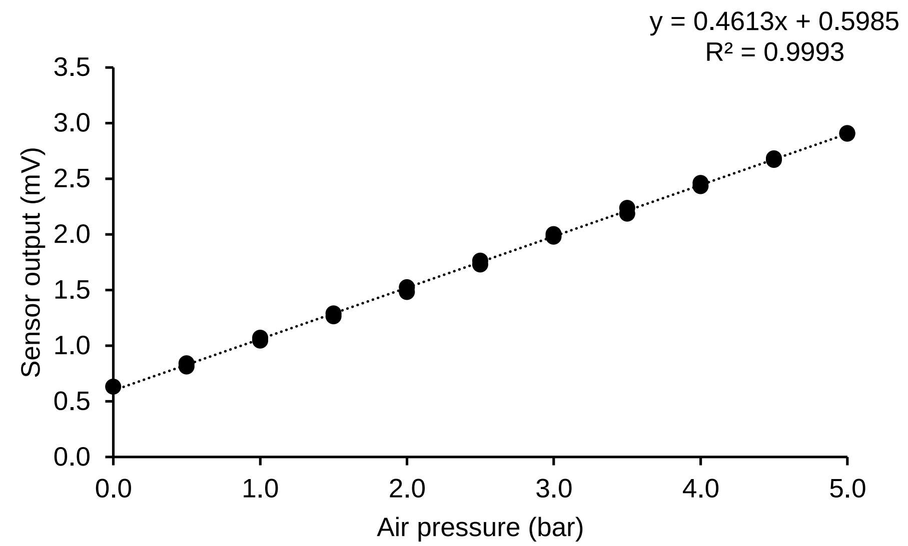
2. Transducer 2



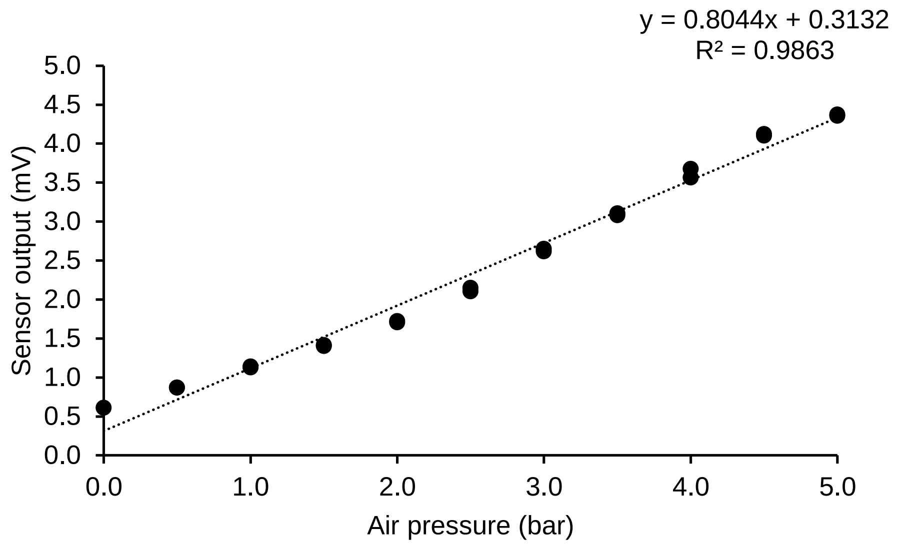
3. Transducer 3



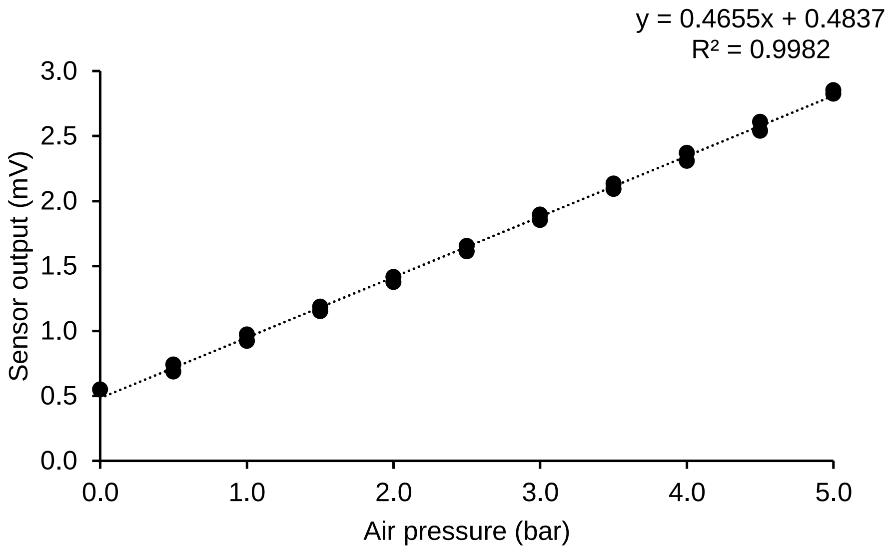
4. Transducer 4



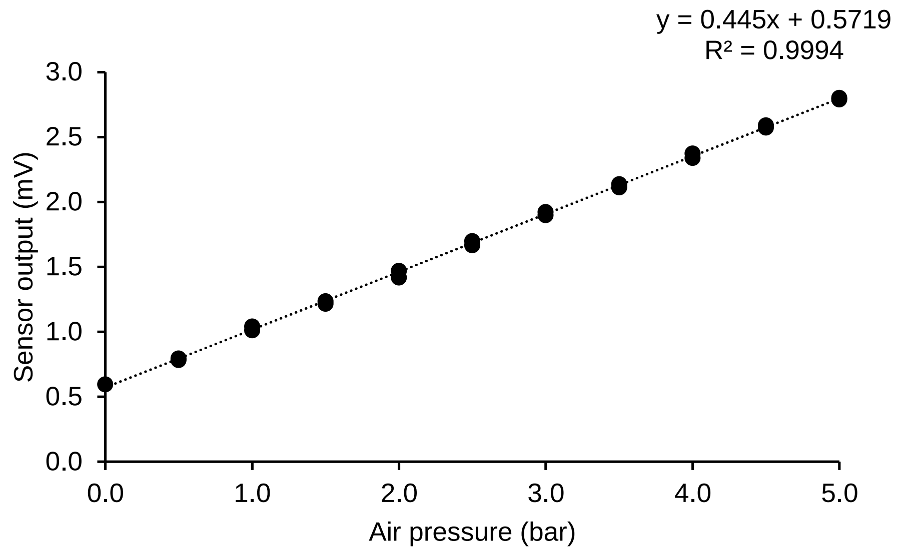
5. Transducer 5



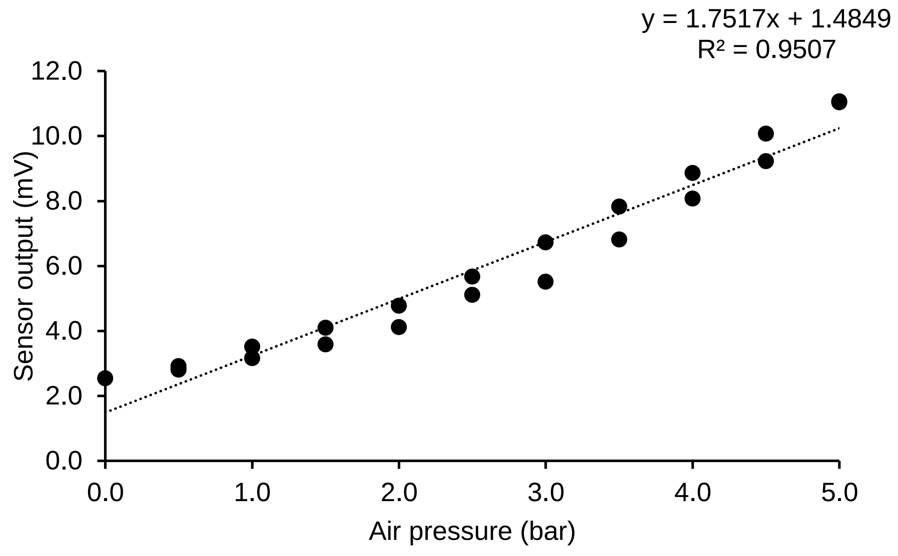
6. Transducer 6



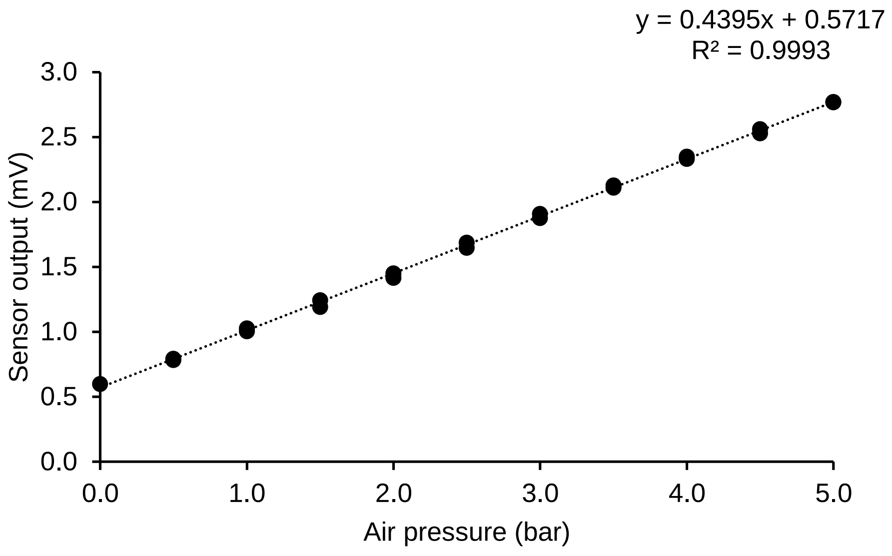
7. Transducer 7



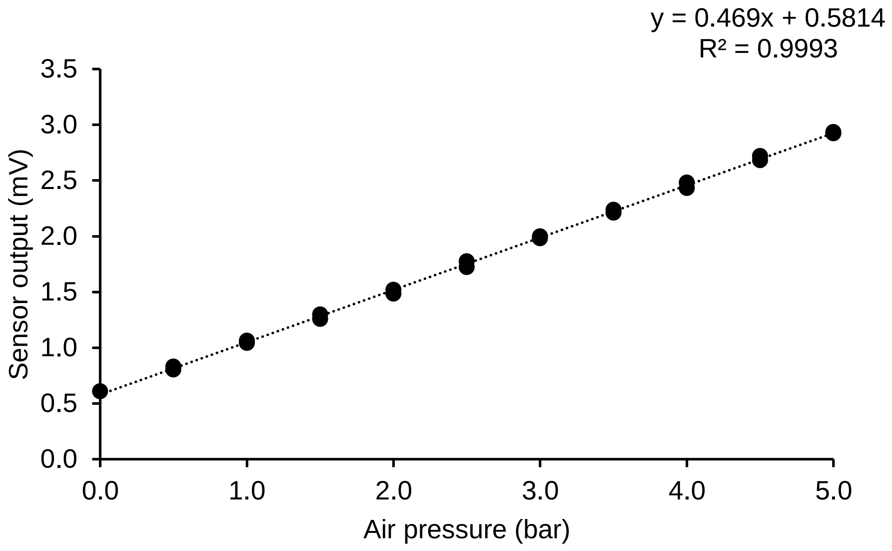
8. Transducer 8



9. Transducer 9



10. Transducer 10



Appendix H. Plot photographs

1. Block 1 (Compaction, September 2012)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage

2. Block 2 (Compaction, September 2012)

	Standard tyre pressure	Low tyre pressure	Controlled traffic farming
Deep tillage			
Shallow tillage			
Zero tillage			

3. Block 3 (Compaction, September 2012)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage

4. Block 4 (Compaction, September 2012)

5. Block 1 (Compaction, September 2013)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage / Shallow tillage / Zero tillage

6. Block 2 (Compaction, September 2013)

7. Block 3 (Compaction, September 2013)

	Standard tyre pressure	Low tyre pressure	Controlled traffic farming
Deep tillage			
Shallow tillage			
Zero tillage			

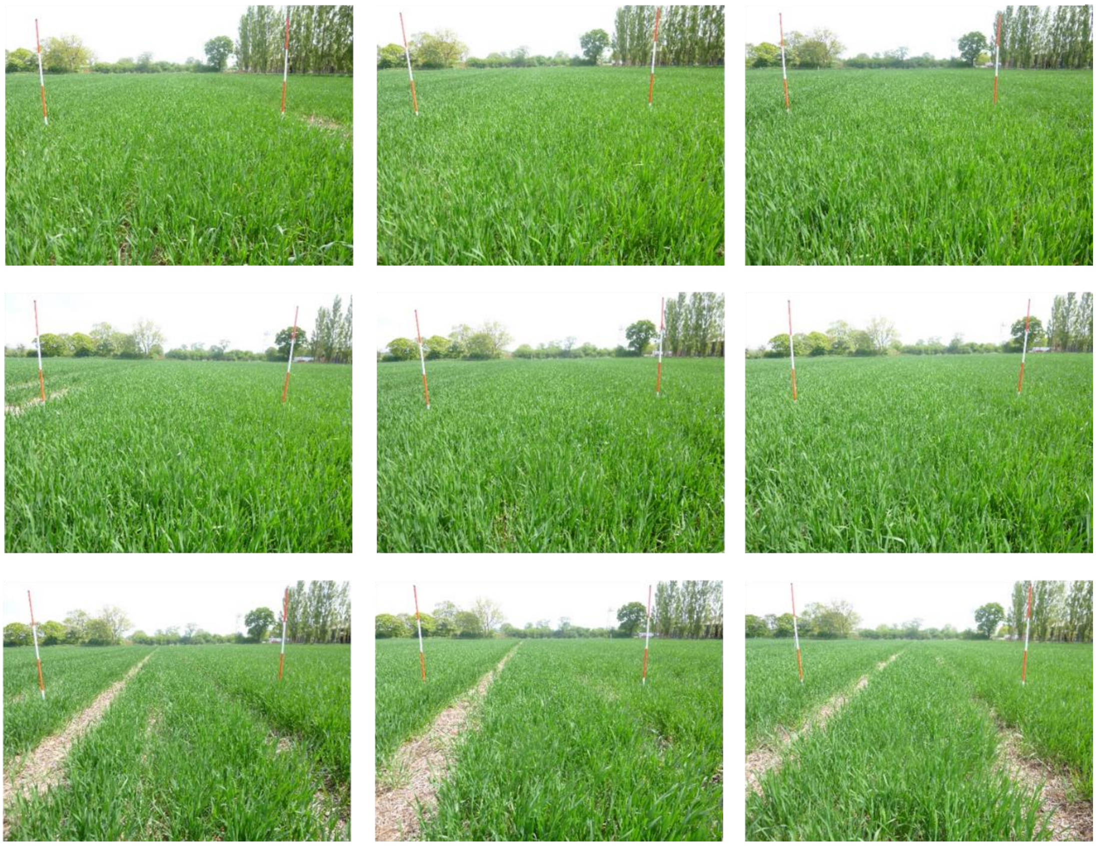
8. Block 4 (Compaction, September 2013)

	Standard tyre pressure	Low tyre pressure	Controlled traffic farming
Deep tillage			
Shallow tillage			
Zero tillage			

9. Block 1 (May 2013)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage | Shallow tillage | Zero tillage



10. Block 2 (May 2013)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

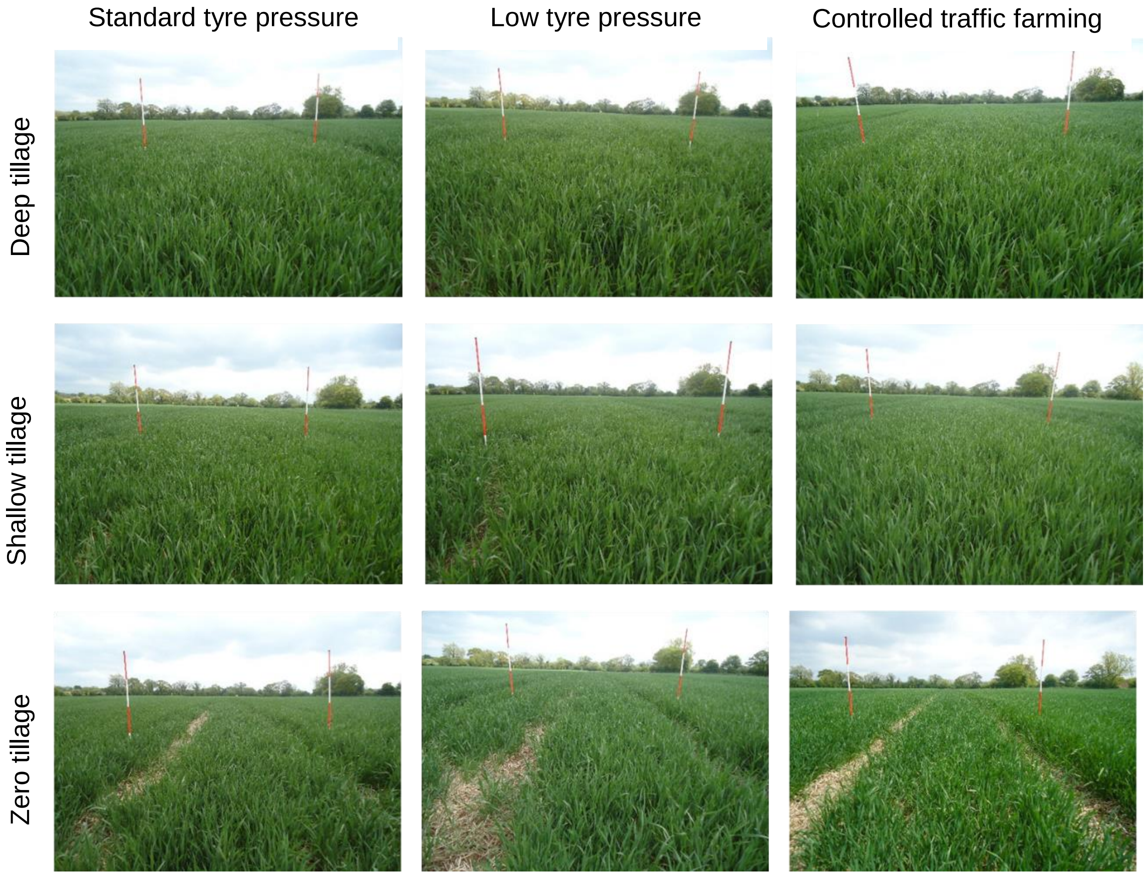
Zero tillage

11. Block 3 (May 2013)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage | Shallow tillage | Zero tillage

12. Block 4 (May 2013)



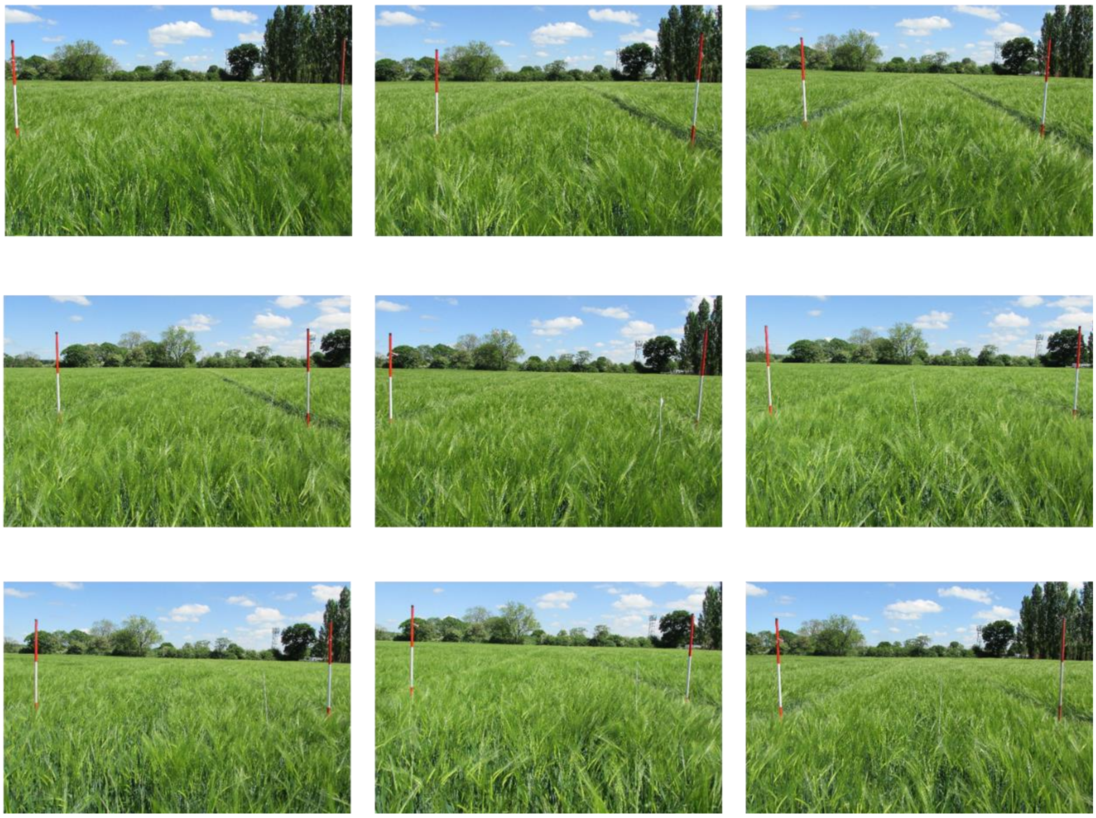
13. Block 1 (May 2014)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage



14. Block 2 (May 2014)

	Standard tyre pressure	Low tyre pressure	Controlled traffic farming
Deep tillage			
Shallow tillage			
Zero tillage			

15. Block 3 (May 2014)

	Standard tyre pressure	Low tyre pressure	Controlled traffic farming
Deep tillage			
Shallow tillage			
Zero tillage			

16. Block 4 (May 2014)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage

17. Block 1 (Pre-harvest, 27 August 2013)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage

18. Block 2 (Pre-harvest, 27 August 2013)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage

19. Block 3 (Pre-harvest, 27 August 2013)

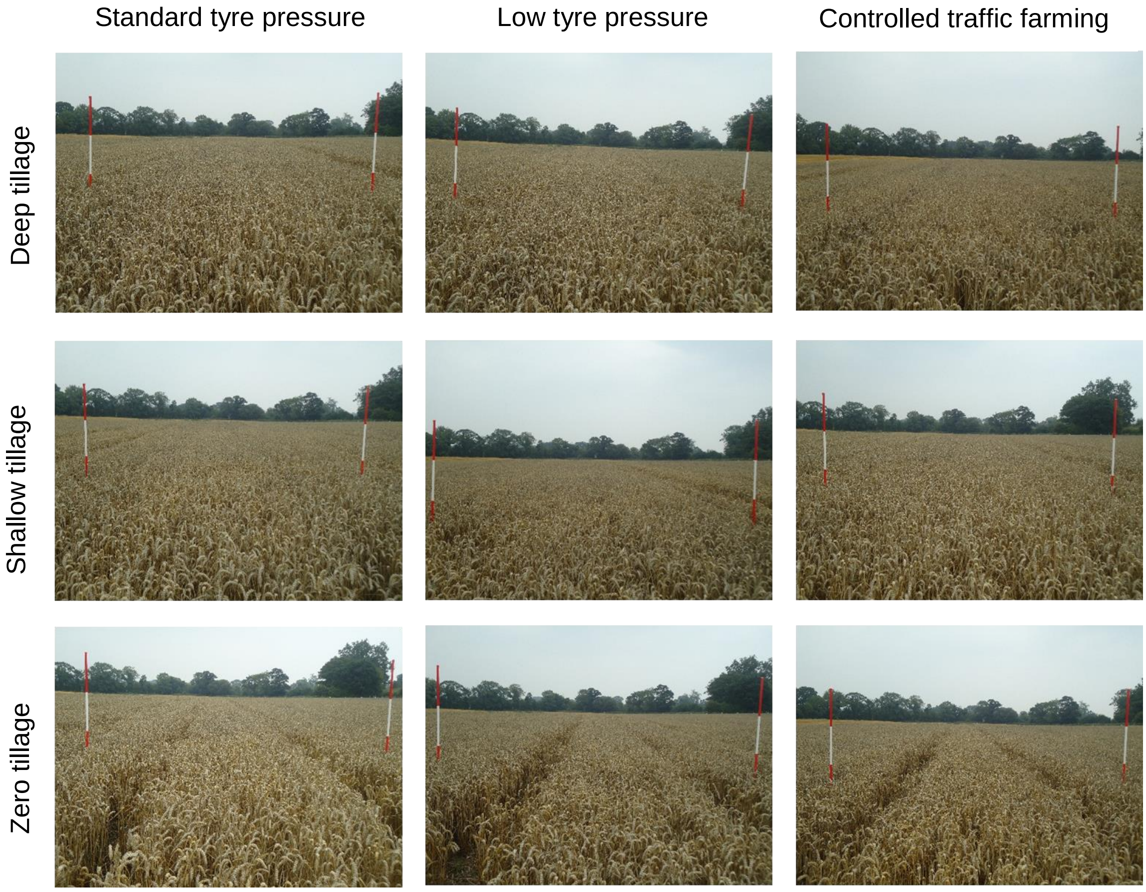
Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

Shallow tillage

Zero tillage

20. Block 4 (Pre-harvest, 27 August 2013)



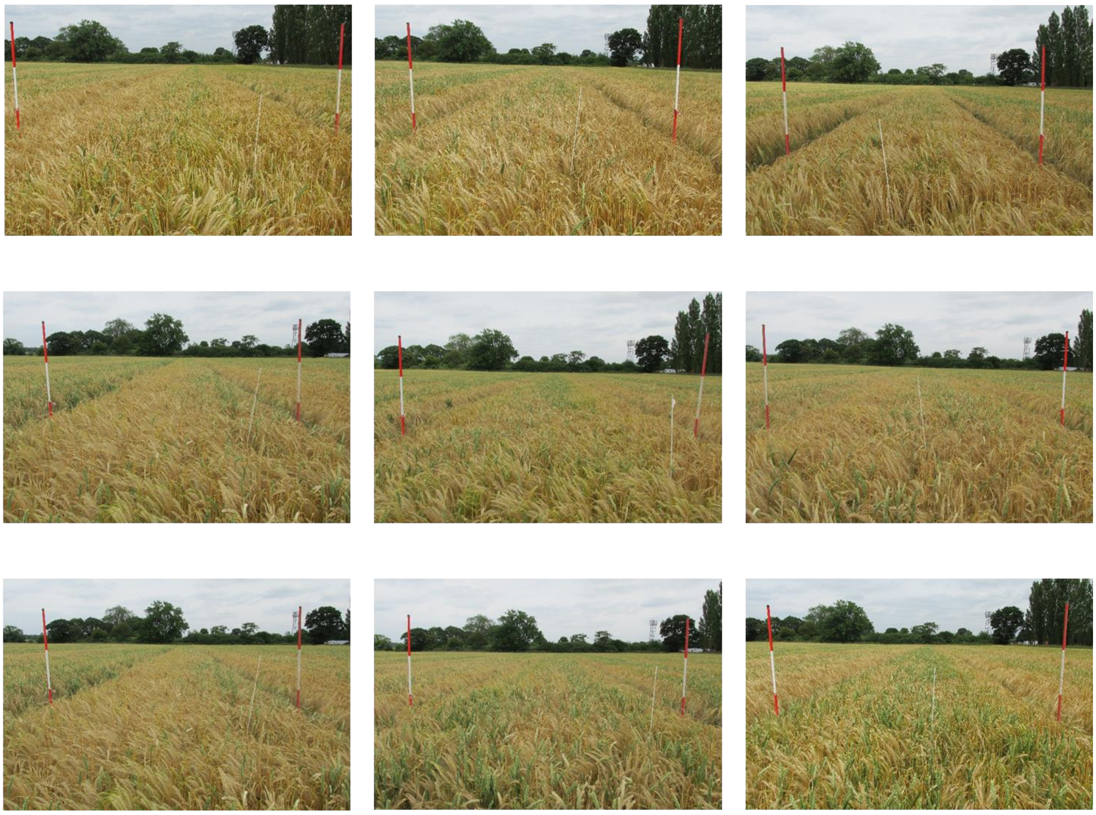
21. Block 1 (Pre-harvest, 2014)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

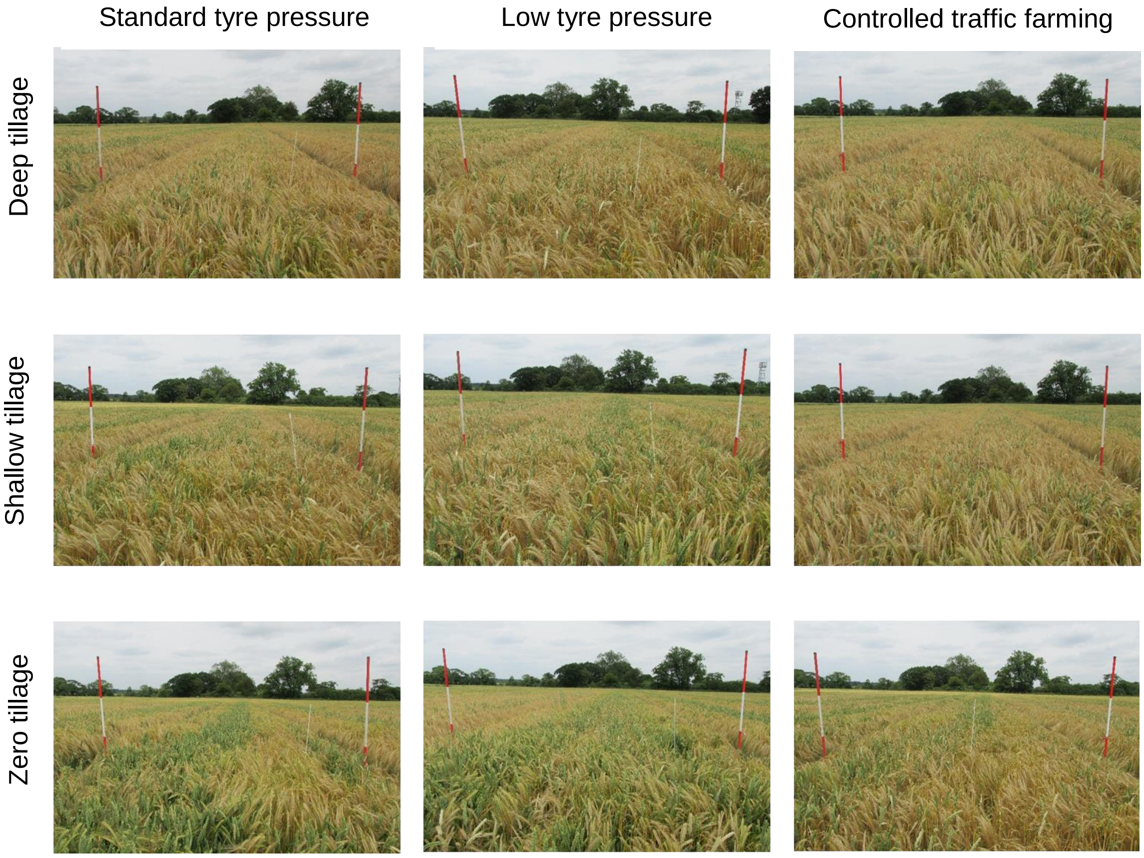
Deep tillage

Shallow tillage

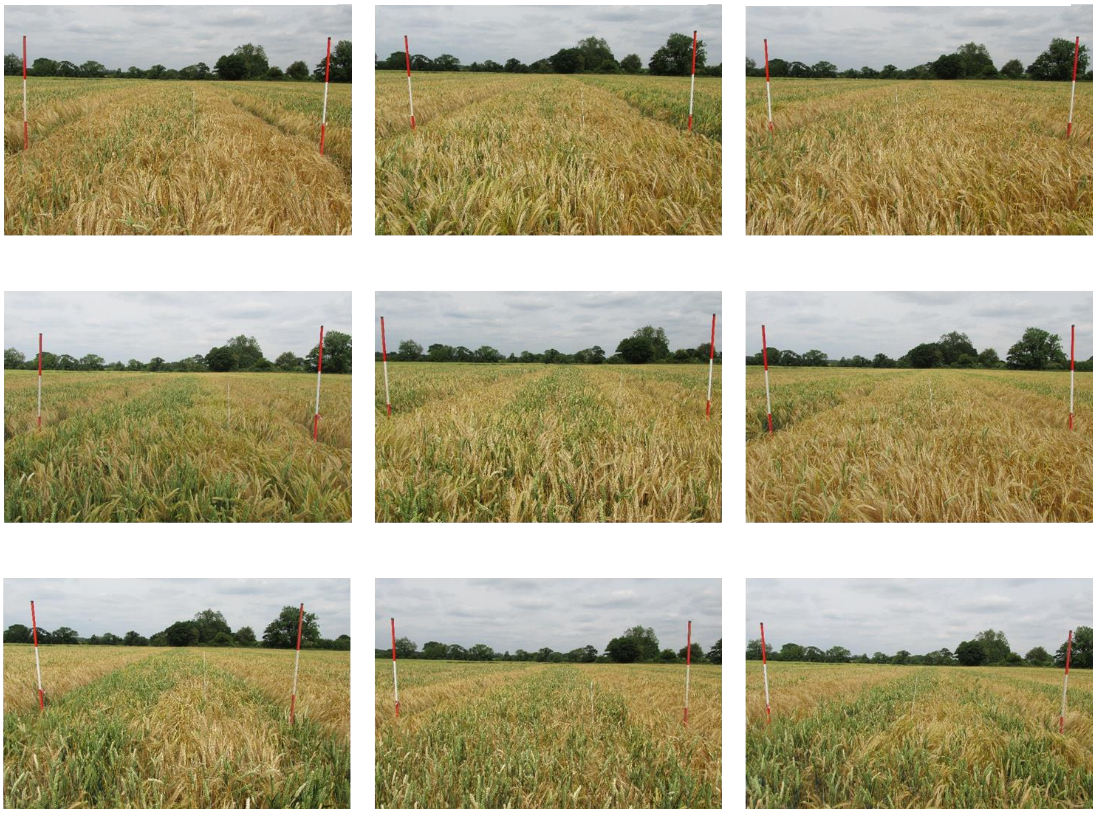
Zero tillage



22. Block 2 (Pre-harvest, 2014)



23. Block 3 (Pre-harvest, 2014)



24. Block 4 (Pre-harvest, 2014)

Standard tyre pressure | Low tyre pressure | Controlled traffic farming

Deep tillage

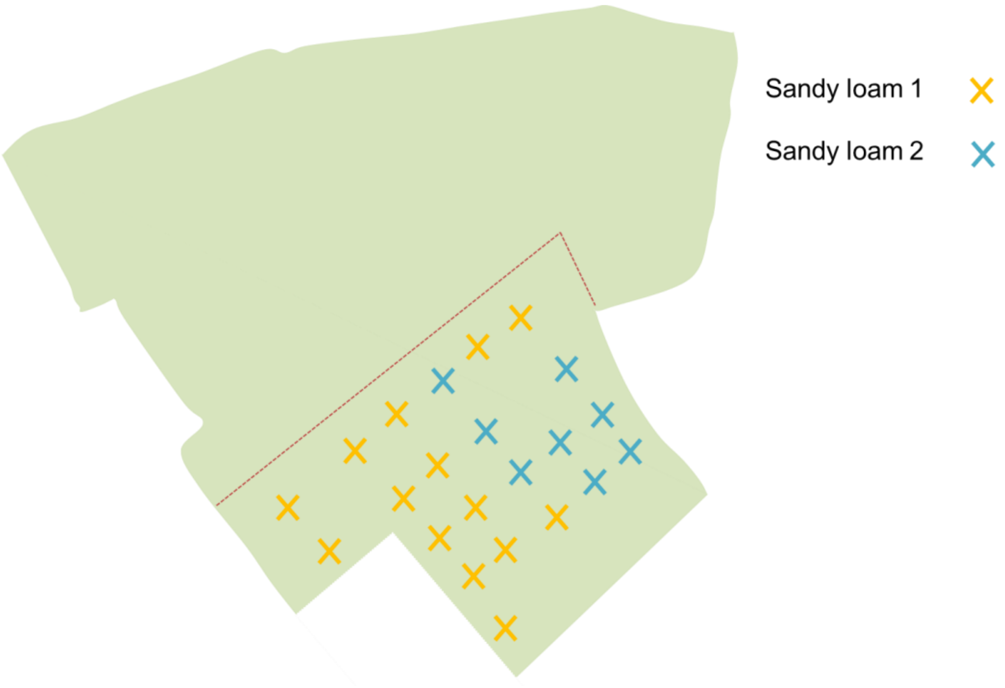
Shallow tillage

Zero tillage

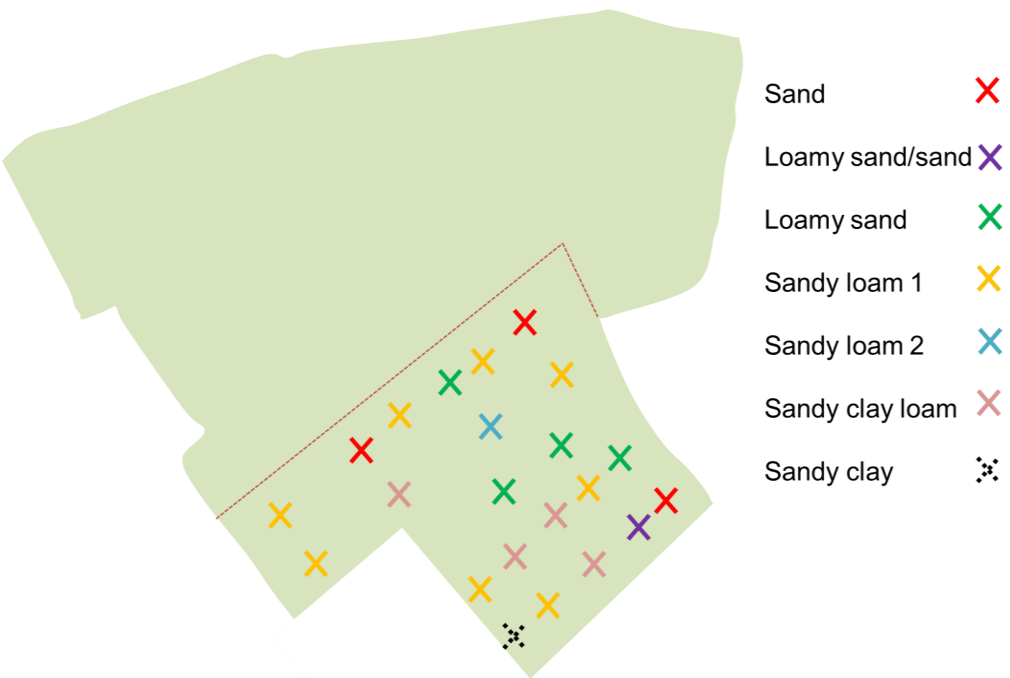
Appendix I. In-field hand texture analysis

Soil samples were collected from the locations indicated and analysed in the laboratory.

10.1 Topsoil



2. Subsoil



Appendix J. Means of data collected on soil properties during Phase 3

Bulk density (Mg m^{-3})

Table of means 2012-2013				
Deep tillage			**CTF**	
Depth (mm)	**RTF_S**	**RTF_L**	**Untrafficked**	**Wheelways**
100	1.64	1.38	1.53	1.57
200	1.71	1.48	1.47	1.58
300	1.66	1.42	1.69	1.49
Mean	1.67	1.43	1.56	1.55
Shallow tillage				
100	1.45	1.46	1.35	1.60
200	1.60	1.38	1.49	1.49
300	1.68	1.58	1.53	1.75
Mean	1.58	1.48	1.46	1.62
Zero tillage				
100	1.54	1.47	1.47	1.34
200	1.45	1.57	1.46	1.46
300	1.45	1.61	1.50	1.39
Mean	1.48	1.55	1.48	1.40

Table of means 2013-2014				
Deep tillage			**CTF**	
Depth (mm)	**RTF_S**	**RTF_L**	**Untrafficked**	**Wheelways**
100	1.46	1.50	1.31	1.45
200	1.52	1.54	1.49	1.65
300	1.69	1.65	1.61	1.65
Mean	1.56	1.56	1.47	1.58
Shallow tillage				
100	1.63	1.53	1.31	1.61
200	1.67	1.62	1.44	1.65
300	1.74	1.63	1.54	1.83
Mean	1.68	1.59	1.43	1.70
Zero tillage				
100	1.64	1.64	1.49	1.70
200	1.58	1.52	1.49	1.70
300	1.61	1.65	1.61	1.61
Mean	1.61	1.60	1.53	1.67

Penetration resistance (MPa)

Table of means 2012-2013				
Deep tillage			**CTF**	
Depth (mm)	**RTF_S**	**RTF_L**	**Untrafficked**	**Wheelways**
100	0.60	0.73	0.64	0.60
200	1.07	0.96	0.78	0.97
300	1.32	1.21	1.18	1.30
400	2.02	2.15	1.81	2.26
Mean	1.25	1.26	1.10	1.28
Shallow tillage				
100	0.48	0.68	0.63	0.58
200	0.94	1.08	0.99	1.01
300	1.15	1.09	1.02	1.29
400	1.72	1.99	1.81	2.12
Mean	1.07	1.21	1.11	1.25
Zero tillage				
100	0.50	0.68	0.40	0.51
200	1.03	1.08	0.67	1.04
300	1.18	1.21	1.02	1.22
400	2.09	2.21	1.92	1.81
Mean	1.20	1.29	1.00	1.15

Table of means 2013-2014				
Deep tillage			**CTF**	
Depth (mm)	**RTF_S**	**RTF_L**	**Untrafficked**	**Wheelways**
100	0.17	0.12	0.12	0.16
200	0.51	0.45	0.39	0.55
300	0.71	0.57	0.48	0.68
400	1.34	1.02	0.93	1.14
Mean	0.68	0.54	0.48	0.64
Shallow tillage				
100	0.15	0.13	0.14	0.16
200	0.62	0.58	0.54	0.67
300	0.86	0.74	0.63	0.73
400	1.26	1.25	1.00	1.17
Mean	0.72	0.68	0.58	0.68
Zero tillage				
100	0.13	0.13	0.14	0.13
200	0.64	0.64	0.57	0.72
300	0.78	0.81	0.63	0.90
400	1.33	1.26	1.19	1.57
Mean	0.72	0.71	0.63	0.83

Soil moisture content (%)

Table of means 2012-2013				
Deep tillage			**CTF**	
Depth (mm)	**RTF$_S$**	**RTF$_L$**	**Untrafficked**	**Wheelways**
100	14.67	16.00	15.33	16.41
200	12.22	13.22	13.76	11.50
300	8.79	7.61	8.15	9.27
Mean	11.89	12.27	12.42	12.39
Shallow tillage				
100	15.91	14.72	14.02	14.17
200	12.91	14.84	12.33	13.68
300	8.15	10.47	9.18	9.15
Mean	12.32	13.34	11.84	12.33
Zero tillage				
100	15.60	14.98	8.19	24.87
200	11.62	11.39	11.34	15.39
300	8.01	4.65	5.01	14.30
Mean	11.75	10.34	8.18	18.19

Table of means 2013-2014				
Deep tillage			**CTF**	
Depth (mm)	**RTF$_S$**	**RTF$_L$**	**Untrafficked**	**Wheelways**
100	21.26	20.39	21.66	21.10
200	20.81	20.47	21.29	24.46
300	16.53	18.06	18.74	17.97
Mean	19.53	19.64	20.56	21.18
Shallow tillage				
100	24.23	24.16	23.05	21.51
200	20.33	20.77	20.48	21.46
300	18.08	17.75	19.54	16.88
Mean	20.88	20.89	21.02	19.95
Zero tillage				
100	19.79	18.34	22.74	20.45
200	22.28	20.28	23.02	19.23
300	16.46	19.57	17.81	15.25
Mean	19.51	19.40	21.19	18.31

Volumetric soil moisture (m^3/m^3)

Table of means 04.04.2013	Deep tillage			Shallow tillage			Zero tillage		
Depth (mm)	**RTF_S**	**RTF_L**	**CTF**	**RTF_S**	**RTF_L**	**CTF**	**RTF_S**	**RTF_L**	**CTF**
0	33.58	30.54	31.84	33.74	31.86	32.36	32.34	31.54	32.71
200	41.06	37.97	37.86	38.29	38.18	38.29	40.37	39.24	37.47
400	29.40	33.00	29.01	29.93	33.40	30.65	33.55	31.15	28.85
600	31.28	33.40	32.21	31.81	33.16	29.30	33.05	31.84	30.67
800	33.03	32.71	35.56	31.92	32.23	33.87	33.79	35.80	32.52
Mean	33.67	33.52	33.29	33.14	33.77	32.89	34.62	33.91	32.44
07.05.2013									
0	23.93	20.21	20.95	22.64	21.45	22.32	25.65	24.51	26.18
200	31.97	28.88	28.11	29.96	29.27	30.73	35.11	32.76	31.84
400	26.65	29.09	26.05	26.31	30.41	27.29	32.29	28.53	26.42
600	30.36	30.36	30.65	28.21	31.04	26.52	31.92	29.69	27.77
800	31.94	32.18	35.35	30.78	31.70	31.70	33.08	33.32	32.23
Mean	28.97	28.14	28.22	27.58	28.77	27.71	31.61	29.76	28.89
29.05.2013									
0	32.95	30.83	31.97	32.60	32.21	34.53	32.13	25.89	35.72
200	37.70	34.90	35.01	34.88	35.30	36.81	38.87	31.92	36.17
400	27.37	30.33	25.68	26.63	30.73	28.24	33.58	25.28	27.37
600	30.04	32.34	30.67	30.75	31.65	26.84	32.23	27.74	28.53
800	32.31	32.60	35.54	32.39	31.60	31.76	33.42	31.15	33.69
Mean	32.07	32.20	31.77	31.45	32.30	31.63	34.05	28.39	32.30
11.06.2013									
0	21.21	17.75	18.91	18.99	19.07	22.58	23.46	17.91	19.36
200	25.73	24.01	24.38	24.36	24.59	28.16	31.44	23.38	24.28
400	25.12	25.89	22.21	23.01	26.97	24.91	29.96	23.64	23.17
600	28.53	30.59	29.09	26.50	29.83	25.36	31.94	28.35	26.92
800	29.64	32.10	35.35	30.59	30.96	31.54	33.40	33.05	31.99
Mean	26.05	26.07	25.99	24.69	26.28	26.51	30.04	25.26	25.14
25.06.2013									
0	18.33	16.50	17.69	17.64	18.04	18.17	18.96	16.56	17.46
200	22.53	21.18	20.79	21.34	22.24	22.58	24.78	20.18	21.13
400	18.96	22.40	16.80	18.75	23.35	20.95	24.80	18.86	16.58
600	25.60	26.07	20.73	21.76	26.05	20.31	28.90	23.64	22.93
800	31.20	30.75	33.79	29.30	29.35	27.32	35.69	32.13	31.33
Mean	23.32	23.38	21.96	21.76	23.81	21.87	26.63	22.27	21.89
11.07.2013									
0	12.20	11.14	10.95	11.43	14.71	12.57	13.02	10.66	11.03
200	17.27	16.27	15.53	15.87	17.32	16.64	18.51	15.29	15.02
400	15.50	17.30	13.54	14.79	17.77	15.02	20.10	17.98	12.91
600	20.47	20.97	20.18	16.58	21.18	14.58	22.77	19.62	17.40
800	27.18	27.26	28.64	24.96	26.21	22.58	29.35	27.02	27.21
Mean	18.52	18.59	17.77	16.73	19.44	16.28	20.75	18.12	16.72

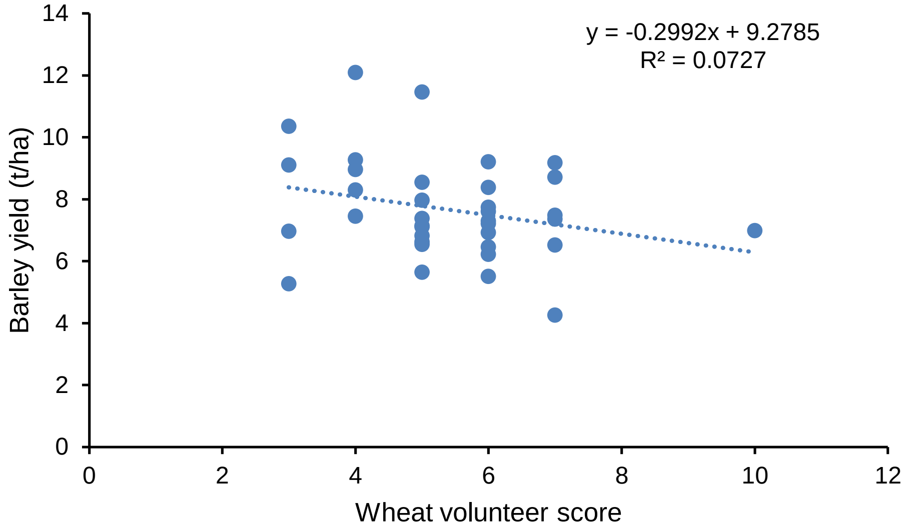
19.07.2013									
0	9.87	9.16	8.84	9.10	9.84	9.53	9.76	8.63	9.08
200	14.84	13.86	13.36	13.54	14.44	14.10	15.26	13.07	12.96
400	14.05	15.87	12.51	13.15	15.32	12.38	17.77	14.50	12.06
600	18.51	19.10	18.43	14.79	18.80	12.51	20.02	18.25	15.82
800	24.33	24.94	28.80	22.08	23.69	20.18	24.80	24.01	23.67
Mean	16.32	16.58	16.39	14.53	16.42	13.74	17.52	15.69	14.72

Percentage change in soil moisture (%)

Table of means 04.04.2013									
	Deep tillage			**Shallow tillage**			**Zero tillage**		
Depth (mm)	**RTF_S**	**RTF_L**	**CTF**	**RTF_S**	**RTF_L**	**CTF**	**RTF_S**	**RTF_L**	**CTF**
0	100	100	100	100	100	100	100	100	100
200	100	100	100	100	100	100	100	100	100
400	100	100	100	100	100	100	100	100	100
600	100	100	100	100	100	100	100	100	100
800	100	100	100	100	100	100	100	100	100
Mean	100	100	100	100	100	100	100	100	100
07.05.2013									
0	71	91	66	67	91	69	79	78	80
200	78	93	74	78	94	80	87	83	85
400	91	97	90	88	97	89	96	91	91
600	97	100	95	89	100	91	97	93	90
800	97	99	99	96	100	94	98	94	99
Mean	87	96	85	84	96	85	91	88	89
29.05.2013									
0	98	81	100	97	83	107	99	82	109
200	92	87	92	91	88	96	96	81	97
400	93	95	89	89	94	92	100	82	95
600	96	97	95	96	94	92	97	88	93
800	98	98	100	102	99	95	99	88	104
Mean	95	92	95	95	92	96	98	84	100
11.06.2013									
0	62	73	59	56	75	70	72	56	59
200	63	82	64	64	82	74	77	60	65
400	86	89	77	76	93	81	89	76	80
600	92	91	89	84	94	86	97	89	87
800	89	98	99	96	99	94	99	93	98
Mean	78	87	78	75	89	75	87	75	78
25.06.2013									
0	54	66	56	52	67	56	58	52	53
200	55	76	55	56	77	59	61	52	56
400	64	88	58	62	91	68	74	60	57
600	81	91	64	68	94	69	87	74	74
800	95	98	95	92	98	82	107	91	96
Mean	70	84	66	66	85	66	77	66	67
11.07.2013									
0	36	76	34	34	77	39	40	34	34
200	42	81	41	42	81	44	46	39	40
400	52	89	46	49	92	49	60	58	45
600	65	91	60	52	94	50	68	61	56
800	82	99	80	78	98	68	87	76	84
Mean	55	87	52	51	88	54	60	54	52

19.07.2013									
0	29	86	28	27	84	29	30	27	28
200	36	85	35	35	85	37	38	33	35
400	47	89	43	44	92	41	53	46	42
600	58	91	55	47	96	43	60	57	51
800	74	99	81	69	98	61	74	68	73
Mean	49	90	48	44	91	46	51	46	46

Appendix K. Wheat volunteer score and barley yield.



Appendix L. Dry matter distribution.

1. Average distributions of grain, chaff and straw yield (Mg ha^{-1}) of hand-harvested winter wheat samples (2012-2013).

		Yield (Mg ha^{-1})		
Traffic	Tillage	Grain	Chaff	Straw
Standard pressure	Deep	7.74	2.99	5.03
	Shallow	8.16	3.58	5.90
	Zero	7.22	3.88	4.74
Low pressure	Deep	7.86	2.86	5.32
	Shallow	9.29	3.25	5.89
	Zero	6.78	3.17	4.88
Controlled traffic farming	Deep	8.55	2.81	5.70
	Shallow	7.77	2.65	5.43
	Zero	8.53	2.19	4.55

2. The effect of controlled traffic farming on average distributions of grain, chaff and straw yield (Mg ha^{-1}) of hand-harvested winter wheat samples (2012-2013).

		Yield (Mg ha^{-1})		
	Tillage	Grain	Chaff	Straw
Untrafficked	Deep	8.97	2.92	5.96
Untrafficked	Shallow	8.10	2.64	5.70
Untrafficked	Zero	10.72	2.84	6.60
Wheelways	Deep	7.69	2.70	5.44
Wheelways	Shallow	7.04	2.65	5.15
Wheelways	Zero	4.34	1.53	2.49

3. Average distributions of grain, chaff and straw yield (Mg ha^{-1}) of hand-harvested winter barley samples (2013-2014).

		Yield (Mg ha^{-1})		
Traffic	Tillage	Grain	Chaff	Straw
Standard	Deep	7.59	1.19	4.65
Standard	Shallow	6.92	1.13	3.62
Standard	Zero	6.99	1.05	3.45
Low	Deep	9.38	1.40	5.20
Low	Shallow	8.45	1.19	4.27
Low	Zero	7.11	1.00	3.86
Controlled traffic farming	Deep	7.76	1.26	3.85
Controlled traffic farming	Shallow	7.20	1.30	3.43
Controlled traffic farming	Zero	7.60	1.16	3.74

4. The effect of controlled traffic farming on average distributions of grain, chaff and straw yield (Mg ha^{-1}) of hand-harvested winter barley samples (2013-2014).

		Yield (Mg ha^{-1})		
	Tillage	Grain	Chaff	Straw
Untrafficked	Deep	8.69	1.22	4.37
Untrafficked	Shallow	7.68	1.22	3.74
Untrafficked	Zero	8.06	1.12	4.02
Wheelways	Deep	6.06	1.33	2.90
Wheelways	Shallow	6.22	1.43	2.80
Wheelways	Zero	6.79	1.23	3.24