Harper Adams University

Traffic and tillage effects
on soil health and crop growth

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MSc

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Declaration

I, Magdalena Anna Kaczorowska-Dolowy, hereby declare that this research work with the title "Traffic and tillage effects on soil health and crop growth” is my own, and solely composed by myself and that no help was provided from other sources as those allowed. Except where stated otherwise by reference or acknowledgment, the work presented is entirely my own.

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Publications

1. Kaczorowska–Dolowy, M., Godwin, R.J., Dickin, E.T., White, D.R. and Misiewicz, P.A. 2019. Controlled traffic farming delivers better crop yield of winter bean as a result of improved root development. Agronomy Research, 17 (3), pp. 725-740.
2. Kaczorowska–Dolowy M.A., Misiewicz P.A., Dickin E., White D.R., Millington W.A.J., Smith E.K., R. J. Godwin. 2020. The effect of traffic and tillage on soil biology and crop yields in a long-term experiment on sandy loam. ASABE meeting, Omaha, US.
3. Godwin, R., Misiewicz, P., White, D., Dickin, E., Grift, T., Pope, E., Millington, A., Shaheb, R. M. and Dolowy, M. 2019. The effect on crop yield and production economics of alternative traffic management systems for deep, shallow and zero tillage practices over an eight-year rotation. 7th international conference on trends in agricultural engineering 2019, TAE 2019. Czech University of Life Sciences, Prague.
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List of abbreviations

%CV – coefficient of variation

ANOVA – analysis of variance

m – metre

mc – moisture content

Mg – megagram (syn. metric tonne)

mm – millimetre

MPa – megapascal

p – p-value (probability)

SOM – soil organic matter

Treatment abbreviations:

CTF – Controlled Traffic Farming system

CTFut – Untrafficked soil

LTP – Low inflation pressure tyres

STP– Standard inflation pressure tyres

RLTP – Random traffic with low inflation pressure tyres system

RSTP – Random traffic with standard inflation pressure tyres system

Deep – deep tillage (250 mm)

Shallow – shallow tillage (100 mm)

Zero – zero tillage

Abstract

The growing world population demands rise of crop yields, which has resulted in agricultural intensification. This in turn has been accompanied by an increase in machinery size and weight, escalating degrees of soil compaction and has led to soil degradation of an area of 33 million ha in Europe. Compacted soil inhibits root development, water availability, nutrient uptake and causes yield loses. Remedial actions are expensive, and time consuming and require burning additional fossil fuels. Climate change is one of the most urgent problem and requires more sustainable approach to food production. Reducing fossil fuel consumption, whilst maintaining the soil in a good condition to facilitate water infiltration and carbon sequestration resulting from improved root development is of great importance.

This thesis reports on a three-year study conducted within a unique long-term 3x3 factorial experiment with four replicates, which started at Harper Adams University (UK) in October 2011. This study quantified the effects of absence of traffic (CTFut) vs traffic with standard and low tyre inflation pressure (STP and LTP respectively), influenced by different tillage depths (deep–250mm, shallow–100mm and zero–tillage) on soil physico-chemical and biological properties, as well as on crop growth and yields. Additionally, it investigated the effect of three common farming traffic systems: Controlled Traffic Farming with 30% of trafficked area (CTF), and two random traffic systems: with standard and low inflation pressure tyres (RSTP and RLTP) subject to three tillage depths (deep, shallow and zero) on plant establishment and combine harvested yields.

The analysed soil physico-chemical properties were: soil bulk density, porosity, penetration resistance, moisture content, field saturated hydraulic conductivity and instant infiltration rate, soil microbial carbon, soil organic matter and pH. The soil biological properties included soil fauna feeding activity, Collembola and earthworm abundance. The crop growth indicators included plant establishment, root growth and hand harvested and combine harvested yield.

The results from this study demonstrated that agricultural traffic, regardless tyre inflation pressure, had significant negative effects on soil physico-chemical and biological properties in comparison to unwheeled soil. The untrafficked soil (CTFut) featured significantly lower soil bulk density and penetration resistance, at the same time, significantly improved soil porosity, field saturated hydraulic conductivity and instant infiltration rate in comparison to soil trafficked with standard and low inflation pressure tyres (STP and LTP respectively). The absence of traffic also significantly improved soil biological properties namely soil fauna feeding activity, and Collembola abundance in

comparison to STP and LTP. The plant establishment and root growth were also significantly enhanced under untrafficked soil (CTFut) vs STP and LTP.

All these improvements in soil physico-chemical and biological properties led to the combine harvested yield increase by 4% under CTF system which in the experiment had 30% of trafficked area. This can be recalculated to additional 3% increase for CTF with 15% of trafficked area. Consequently, the adoption of CTF which restricts farming traffic to permanent wheelways covering in farming practice approximately 12-15% of the field area, brings significant improvements in soil physico-chemical and biological properties and as a result, it enhances crop growth and yield in comparison to non-controlled traffic systems (RSTP and RLTP) under which the majority of the field area is covered by at least one wheel pass every year.

The main effects of tyre pressures did not have a significant effect on soil physico-chemical properties. Nevertheless, LTP significantly improved soil fauna feeding activity (FA) in comparison to standard tyres pressures (STP).

Interactions between traffic system and tillage depth revealed that RLTP increased combine harvested yields on deeply tilled soils in comparison to RSTP (104% on average over the 8-year study).

The main effect of tillage and the interactions between traffic and tillage were not significant for soil physico-chemical characteristics. Tillage had however significant effects on soil biological properties. Nevertheless, the results do not conclusively indicate one tillage depth which could improve soil biology, as the SOM and similarly earthworms abundance were significantly greater under zero and shallow tillage than under deep tillage, however soil fauna feeding activity in 2019 on zero tillage was significantly lower than on remaining tilled treatments, similarly the Collembola density was significantly lower under zero tillage in comparison to shallow tillage, whereas deep tillage did not differ significantly from the remaining tillage depths. Nevertheless, in 2020 both reduced tillage treatments (zero and shallow tillage) featured significantly greater FA than deep tillage.

Interactions between tillage and time revealed that with time, under zero tillage, the crop yields improve and, in the year 7th and 8th yields from zero tillage were significantly greater than from deep tillage (105% and 103% in 2019 and 102% and 112% in 2020 respectively).

There was no single aspect of soil physico-chemical and biological properties, as well as crop growth and yields, which would indicate that deep tillage provided better results over shallow tillage, which might suggest that deep tillage is not a recommended practice on sandy loam in West Midlands, UK.

This leads to a conclusion that the optimal mechanisation system's approach (combination of traffic system and tillage depth) consists of CTF with shallow tillage; alternatively, zero tillage system, which is more resilient to agricultural traffic, with the caveat of yields penalties in the first years. The use of low inflation pressure tyres (LTP) is recommended, should deep tillage be required without CTF, as they reduce the impact of compaction and improve the crop yield.

This thesis also outlines additional environmental consequences, which in further studies might be developed in a robust environmental economics of traffic and tillage systems.

CHAPTER 1 INTRODUCTION

At the time of writing this thesis (autumn 2021) the world's human population is around 7.8 billion and is projected to reach 9.9 billion by 2050 (with a medium-fertility variant), an increase of more than 27% from the current state (UN, 2021). The significant increase in the population has been observed since 1950, with the year-to-year rise around 1.8% in 1950s and the highest so-far observed 1.98% in 1960. Although the pace of growth has slightly decreased since then and in the last 20 years it was on average 1.20%, the number of people is inevitably growing which in turn requires an increase in food production. On top of the growing population, the dietary requirements are also rapidly changing particularly in developing nations (Ray *et al.*, 2013), especially in Southeast Asia (Godfray, 2014).

The demand for reliable crop production has assisted humans since the beginning of farming era, with advances in chemical processes and agricultural technology after the Second World War allowing for the Green Revolution. Since then, the world food production has been increasing, providing food security and reducing food shortages around the world, and the improvements in food production are often indicated as the main factors that allowed for the boost in human population (Piesse and Thirtle, 2010). It has been estimated, that in the UK from 1960 to 2014, the wheat production increased 240%, barley 196% and oats 226% (Ritchie and Roser 2019). Nevertheless, Knight *et al.* (2012) reported that the yield improvements was observed only until 1996 with a yearly increase by 0.105 t/ha between 1980 and 1996. Since 1996 however, the yields have shown little improvement with by as little as 0.016 t/ha increase per year, and reached a plateau phase, which is presented in Figure 1.1.

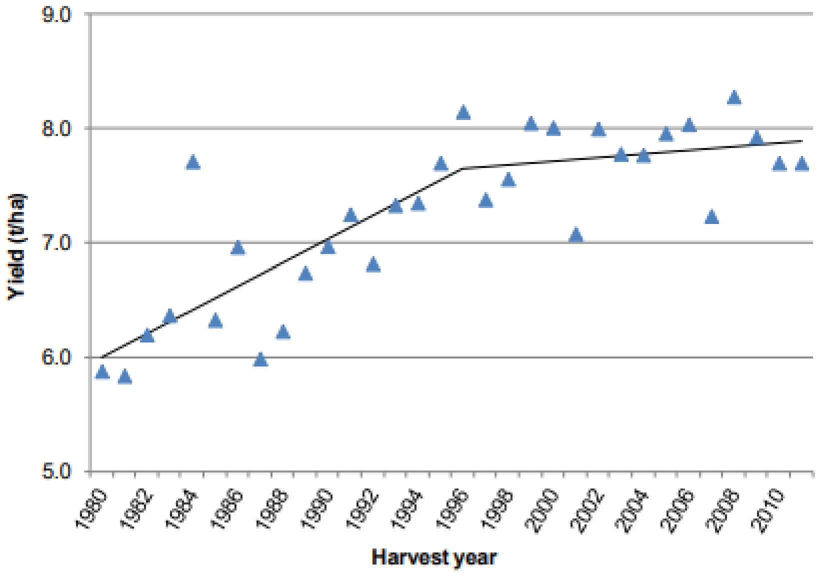


Figure 1.1 UK national average wheat yields from 1980 to 2011, after Knight et al. (2012)

The improved agricultural efficacy resulted from introduction and then a constant increase in farming machinery sizes leading to improved labour productivity and reduced operator's hazards (Cavallo, Ferrari, Bollani, & Coccia, 2014). This, together with modern breeds, artificial fertilizers and agro-chemicals as well as irrigation, resulted in improved yields and consequently relatively low food prices (Godfray, 2014). The growing agricultural machinery power was assisted with steadily increasing machinery weight. It is estimated that the wheel loads of tractors increased from about 1.5 Mg in 1960 to 4 Mg in 2000, the combine harvesters from 1.5 to almost 9 Mg over the period from 1958 to 2009 (Keller *et al.* 2019), and single-axle grain trailers in the U.S. characterise with an axle loads of 15 to 45 Mg (Schuler *et al.*, 2000). This in turn fortified the extent and severity of soil compaction, which is related to load, tyre pressure and contact area (Raper *et al.*, 1995; Soane and van Ouwerkerk, 1994) and leads to soil degradation. It has been already 30 years since the problem of soil degradation has been raised and was suggested to account for 30% of arable land in Europe which since then again increased (Oldeman *et al.* 1998, Keller et. Al. 2019). The increased loads applied to soil increase compaction of soil – both in the surface but also the subsoil, which is particularly difficult and expensive to remove (Kroulik *et al.*, 2009). For many years, tillage has been applied as a means to alleviate soil compaction, whist providing improved soil aeration and water infiltration (Sommer and Zach, 1992). Cultivated soil also features increased warming, soil-to-seed contact and facilitates root development (Hallett and Bengough, 2013). Nevertheless, cultivation is seen by many as another factor leading to soil structure degradation and erosion. Deep tillage is related to heavy traffic (Kroulik *et al.*, 2009) and consequently increased soil compaction. As a result of running two tractor wheels in the open furrow during ploughing there is a compacted stratum created in the soil at about 200-350 mm from the surface. To alleviate it, a sub-soiling is required but this again poses a risk of re-compaction from subsequent traffic (Morris *et al.*, 2010). Reduced tillage (non-inversion tillage), an alternative to conventional mouldboard ploughing (Warner *et al.*, 2016) is considered to be a solution for tillage induced soil degradation (Tullberg *et al.*, 2007). Apart from reduced tillage, much could be gained from controlled traffic farming practices (CTF) where field operations are focused on predetermined wheel ways and equipment widths and wheel track spacing are matched (Tullberg *et al.*, 2007). The global positioning satellite guidance and auto-steer systems with real time kinetic (RTK) make the controlled traffic farming (CTF) possible to adopt by many farmers. CTF due to the reduction in number of wheel ways reduces soil compaction, consequently its potential advantages are: improved crop yields, improved soil conditions and infiltration of rainfall/irrigation water, reduced draught forces/energy (Godwin at al., 2015). There are also many studies which identified the use of low ground pressure tyres as another method to avoid soil compaction (Alakukku *et al.* 2003, Antille *et al.* 2013, Chamen *et al.* 2015). Lower stresses in the soil under low ground pressure systems based on “Ultraflex” technology allow vehicle loads to be more evenly distributed over a larger area which in turn limits the negative effects of the vehicular traffic (Vermeulen and Perdock, 1994, Michelin, 2017).

Further development of agricultural systems to feed the growing population might be obtained by additional expansion into natural habitats clearing further large areas of rich in biodiversity tropical forests, grasslands etc. However, this approach would lead to many adverse effects on global climate and might be responsible for permanent loss of many habitats and species. It can potentially be achieved by further increase in intensification of crop production but as previously explained as a result of adverse effects of intensive tillage and heavy machinery traffic it leads to soil degradation which might result in permanent soil degradation and consequently loss of land suitable for crop production. Nevertheless, there are still opportunities to increase yields through improved efficiency of cultivated land and the propagation of best practice (Ray *et al.*, 2013), which would focus on maintaining soil in good condition, while expanding the full potential of increased crop yields.

It has become evident that the management of farming traffic and tillage requires optimisation to provide enough food for growing population without compromising soil quality. Sustainable managing of soil lies at the heart of the long-term experiment established at Harper Adams University, UK, which resulted already in two PhD researches (Smith, 2017 and Millington 2019) and this thesis presents results from the third consecutive study. The experiment started in 2011 by Smith (2017) on a uniform sandy loam field called Large Marsh within Harper Adams University campus (52°46'58.0"N 2°25'43.9"W). The aim of the experiment was to examine the effects of three traffic systems, namely random traffic with standard tyre inflation pressure (STP), random traffic with low tyre inflation pressure (LTP) and controlled traffic farming (CTF) subject to three different tillage depths (250 mm, 100 mm and zero tillage) on soil properties and crop yields. Smith’s work (2017) was an expansion of Chamen (2011) study to determine the effect of reduced trafficking on soil, yields and profitability. Addressing Chamen’s (2011) conclusions, that future research should establish methods of optimising conditions for crop growth and soil function, Smith (2017) designed the replicated field experiment and provided new information on the effects of tyre inflation pressures and running gear on soil compaction, as well as on the effects of traffic and tillage on soil physical properties (bulk density, penetration resistance, moisture, hydraulic conductivity) and crop yields (winter wheat and winter barley) in a typical UK crop rotation with grain as the main crop. Millington (2019) continued the study, with monitoring the crop yields and soil properties, with a particular interest in soil porosity – results obtained with X-ray tomography. The study which resulted in this thesis presents results on the cumulative effects of the long-term consequences of traffic and tillage systems on crop yields and soil physical properties. The novelty of this research constitutes the investigation of soil biological properties resulting from traffic and tillage systems, namely soil organic matter, soil microbial carbon, earthworms and Collembola abundance, as well as soil organisms feeding activity. This thesis also includes environmental-economic analysis which also has not been so-far undertaken for contrasting traffic and tillage systems.

Parallelly to these two studies, another researcher in the USA (Shaheb, 2019) looked into the effects of tyre inflation pressure systems on soil conditions, crop growth and yield for typical maize/soya bean rotation for 3 tillage systems namely: conventional deep tillage, shallow tillage and no-till on a silty clay loam and silt loam series in Illinois, U.S. In addition, another study has been investigating three traffic intensities, two tyre pressures subject to three tillage depths on crop growth and yields on heavy clay in Cambridgeshire, UK, as well as the possible application of ground penetrating radar (GPR) in detecting soil compaction (Dolowy, 2021). These studies expand understanding of the traffic and tillage effects on another soil types in different climate zones.

1.1 THE RESEARCH AIM, OBJECTIVES AND HYPOTHESES OF THE THESIS

All around the world there are several mechanisation systems, i.e., agricultural traffic and tillage systems which are associated with different traffic intensities (Kroulik *et al.*, 2009), however there are still gaps in knowledge what are the effects of those systems and their interactions, on soil properties and crop yields.

The overall aim of this long-term experiment - within which this 3-year study was conducted – is to provide an agricultural traffic and tillage systems optimisation. This can be achieved via quantification of impacts and benefits of: absence of traffic (CTFut) vs traffic with standard and low tyre inflation pressures (STP and LTP respectively) subject to three tillage depths (deep – 250 mm, shallow – 100 mm and zero tillage). The unique contribution of the study was the investigation of soil biology, namely: soil fauna feeding activity, the abundance of springtails and earthworms, as well as soil microbial carbon, crop root development and the connection between those aspects and the soil physico-chemical properties, crop growth and yield. The results of which, could in turn be translated into management guidelines and the systems optimisation for the agriculture community on the sustainable approach to managing field traffic for a range of tillage depths in a positive agronomic and environmental manner.

These guidelines should not only embrace the short-term gains expressed as the crop yields, but also take into consideration improvements to the carbon footprint of the agricultural activities as well as the maintenance of soil health, which is interchangeably used with “soil quality” term and integrates soil physical, chemical and biological properties. Doran (2002), defined soil health as “the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health”. This in turn would lead to meeting the demand of increased food production without compromising natural habitats.

This aim will be achieved by the following objectives:

1. To quantify the effects of: absence of vehicular traffic (CTFut), presence of traffic with low inflation pressure tyres (LTP) and presence of traffic with standard inflation pressure tyres (STP) on:
   a) soil physico-chemical properties, namely soil bulk density, porosity, penetration resistance, soil moisture content, soil field saturated hydraulic

    conductivity, infiltration rate; soil microbial carbon (SMC), soil organic matter (SOM) and pH,
    b) soil biological properties, i.e., soil fauna feeding activity, earthworm and springtails abundance,
    c) plant establishment, root growth and crop yield for typical arable rotation.

2. To determine the effects of tillage depth (deep – 250mm, shallow – 100mm and zero tillage) on:
    a) soil physico-chemical properties, namely soil bulk density, porosity, penetration resistance, soil volumetric moisture content, soil field saturated hydraulic conductivity, infiltration rate; soil microbial carbon (SMC), soil organic matter (SOM) and pH,
    b) soil biological properties, i.e., soil fauna feeding activity, earthworm and springtails abundance,
    c) plant establishment, root growth and crop yield for typical arable rotation
3. To determine the effects of interactions between traffic approaches (namely absence of traffic - CTFut, traffic with low tyre inflation pressures LTP and traffic with standard tyre inflation pressures STP) and three tillage depths (250mm, 100mm and zero tillage) on:
    a) soil physico-chemical properties, namely soil bulk density, porosity, penetration resistance, soil volumetric moisture content, soil field saturated hydraulic conductivity and infiltration rate; soil microbial carbon (SMC), soil organic matter (SOM) and pH,
    b) soil biological properties, i.e., soil fauna feeding activity, earthworm and springtails abundance,
    c) plant establishment, root growth and crop yield for typical arable rotation
4. To determine the effects of traffic systems: CTF (with 30% wheeled area) and random traffic systems with low and standard tyre inflation pressures (RLTP and RSTP respectively) subject to three different tillage depths (deep - 250 mm, shallow - 100 mm and zero tillage) and their interactions on combine harvested crop yield.

These analyses were conducted for typical arable rotation in a field-scale study on a sandy loam field in West Midlands, United Kingdom.

The central hypotheses are:

1. Agricultural traffic has a negative effect on soil physico-chemical and biological properties, as well as plant establishment, root development and crop yields.

Therefore, absence of traffic (CTFut) improves soil health and increases crop yields in comparison to trafficked soil (LTP and STP).

2. Reduced tillage (shallow and zero tillage) improves soil physico-chemical and biological properties, enhances plant establishment, root growth and consequently improves crop yields in comparison to deep tillage.
3. There are no significant interactions between traffic and tillage, and so STP significantly deteriorate soil physico-chemical and biological properties, plant establishment, root growth and crop yield for the range of tillage depths in comparison to absence of traffic (CTFut) and low inflation pressure tyres (LTP).

1.2 STRUCTURE OF THE THESIS

The thesis consists of the following chapters, an outline of which are given below:

Chapter 1 “Introduction” outlines this long-term experiment and explains the relationship between this research and two previously conducted studies within the long-term experiment (Smith, 2017 and Millington, 2019) on the effects of three traffic farming systems and three tillage depths (250 mm, 100 mm and zero tillage) on soil properties and crop yields. It also outlines the modern challenges of agriculture, specifically in the context of this research as well as identifies the gap in knowledge which this research addresses. The main research hypothesis, aim and objectives, as well as the structure of the thesis are presented.

Chapter 2 “Literature review” discusses the review of literature related to soil compaction, resulting from heavy machinery traffic, compares effects of low and high tyre pressures, tracked agricultural vehicles as well as controlled traffic farming subject to different tillage depths on soil physical and biological properties, as well as on crop growth and development. It presents the effects of traffic and tillage on soil properties, crop development and yields reported by two previous researchers (Smith, 2017 and Millington, 2019) who conducted their experiments within this long-term study at Harper Adams University, UK.

Chapter 3 “Overview of the long-term experiment” introduces the long-term experiment at Harper Adams University, outlines the crop rotation, experimental design, farm equipment and treatments.

Chapter 4 “Soil physico-chemical properties” describes and discusses the results of soil bulk density, penetration resistance, porosity and soil moisture, soil saturated connectivity and water infiltration, as well as soil microbial carbon (SMC), soil organic matter (SOM) and pH.

Chapter 5 “Soil biology” describes and discusses the results of soil fauna feeding activity expressed as the bait lamina score, as well as abundance of soil organisms – springtails and earthworms.

Chapter 6 “Crop growth and yield” presents the results and discussion on crop growth indicators namely plant establishment, root development and crop yields. It also presents the results of a long-term (since the start of the experiment) analysis of the crop yields resulting from 3 traffic systems subject to 3 tillage depths.

Chapter 7 “Discussion” provides the overall discussion of the results of soil properties and crop growth indicators and yields. It also outlines agronomic and economic implication and recommendation for policy.

Chapter 8 “Conclusions and management guidelines” summaries the conclusions from the results obtained within this study and provides management guidelines for managing agricultural traffic and tillage systems.

Chapter 9 outlines the limitations within this study and provides recommendations for further site management and future studies.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION TO SOIL COMPACTION

Soil is crucial for both crop production and global ecosystems functions. Its quality and crop potential are functions of its texture, structure, porosity, available water and biological soil life. Nevertheless, it is the soil management system which ultimately affects soil quality (Doran, 2002). Since the very beginning of crop production, farmers have undertaken different tillage application to maintain soil in good condition, these in turn required traffic operations. With the increasing demand for food from growing population, and changes in farm structures, the size and weight of farming machinery has increased significantly in the last 50 years: Chamen *et al.* (2006) reported that since 1966 average weight and power of farm vehicles has approximately tripled and the maximum wheel load has increased six times, whereas Schjønning *et al.* (2015) reported that the weight of the fully loaded machines increased by a factor of 6, from 4.3 Mg in 1958 to about 25 Mg in 2009. Increasing weight of farming machinery in turn causes increasing soil compaction, which is defined as “a process of densification in which porosity and permeability are reduced, strength is increased, and many changes induced in the soil fabric and in various behaviour characteristics” (Soane and van Ouwerkerk, 1994).

Soil compaction is considered to be a multi-disciplinary problem which has a significant economic and environmental consequences in the world agriculture (Soane and van Ouwerkerk, 1994). It can induce substantial changes in soil physical, chemical and biological processes, and affect many environmental issues, such as soil erosion, soil degradation and pollution of surface water, ultimately leading to reduction in crop production (Gupta *et al.,* 1989, Soane and van Ouwerkerk, 1994). Lal *et al.* (2015) suggested that the deterioration of soil quality and decrease in ecosystem services, is a major risk to achieving the increased agricultural productivity.

There are many causes of soil compaction identified by researchers, some are of natural characteristics like shrinkage of soil as a result of drying, trampling by grazing animals, but the most significant compaction results from the pressure induced by the wheels of farm vehicle. Depending on crop and agronomy measures, the trafficked area, that is, the area covered by wheel marks (wheel passes), might reach up to 90% (Soane *et al.*, 1980). Further surveys where global positioning system-tracking devices were applied revealed that random traffic farming practices, with conventional tyre inflation pressures, for wheat production covered some 86%, 65% and 45% of the field with at least 1 wheel-pass for conventional (plough based) tillage, minimum tillage and direct drilling/zero-till respectively (Kroulik *et al.,* 2011). These wheeled areas are at risk of soil compaction, since compaction is a result of stress upon the soil, and is related to load, tyre pressure and contact area (Raper *et al.,* 1995; Soane and van Ouwerkerk, 1994). According to Koolen *at al*. (1983) soil might behave in 3 different ways under stress. If the soil stress exceeds soil strength, the soil gets deformed and a new state of soil strength is reached as a result of soil compaction. When soil stress induces soil flow without volume change, he called it flow type behaviour. When the soil stress posed by a loaded wheel is lower than the soil strength, he described it as non-deforming situation.

Söhne (1958) reported that higher wheel loads cause stresses that reach to a greater depth below the soil surface (Figure 2.1). He also revealed that the pressure reaches greater depths in increasing soil moisture content.

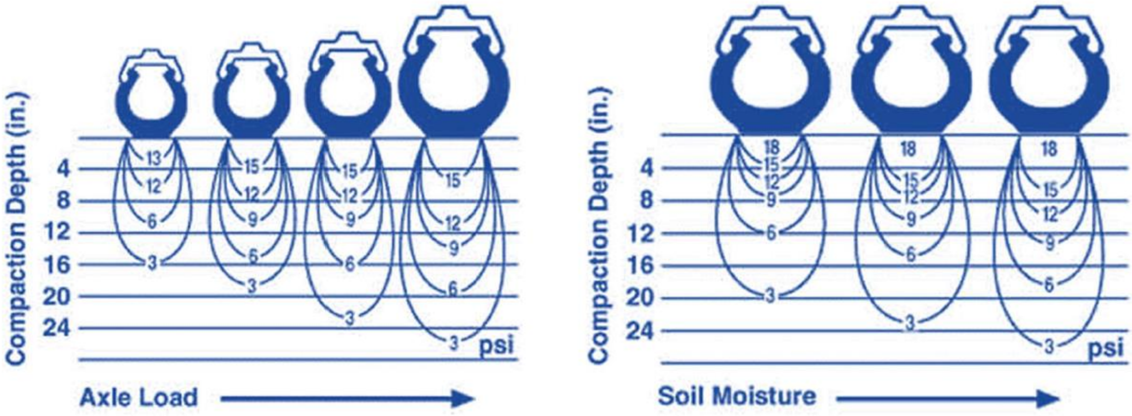


Figure 2.1 Curves of pressure under a range of tyres sizes, load and inflation pressures. Source: Söhne (1958)

Obour *et al.* (2017) revealed that on sandy loam four-wheel passes by a tractor-trailer combination with a wheel load of 8 Mg had significant effect on soil structural properties down to 0.65 m. In the same work he discovered that 3 Mg wheel load and five-wheel passes did not affect the soil structure in comparison to the control at any depth. In agreement, Arvidsson (2001) revealed that heavy traffic also affected the saturated hydraulic conductivity at 0.3 and 0.5 m and the soil bulk density at 0.5m.

Spoor (2003) related the contact pressure *Pc* with load and tyre contact area:

Equation 2-1

$$Pc = \frac{W}{A}$$

where W is the wheel load and A - contact area.

The Equation 2-1 however does not include carcass stiffness or tyre inflation pressure, thus often underestimates actual pressure. Misiewicz (2010) described a model that includes these factors:

Equation 2-2

$$Pc = Pi + Pcs$$

where *Pc* is calculated contact pressure, *Pi* – tyre inflation pressure and *Pcs* – tyre carcass stiffness.

2.2 EFFECT OF TYRE AND TRACK PRESSURES ON SOIL COMPACTION

Increased tyre inflation increases contact pressure as a result of the reduced contact area. Moreover, it accelerates tyre wear on the roads (Michelin, 2018) while on the field over-inflated tyres feature worse traction and a greater risk of wheel slip and rutting (Smith, 2017). This was confirmed by Raper *et al.* (1995) who reported that rut depth increased with an increase of tyre inflation pressure, confirming the relationship between high inflation pressure traffic and greater vertical impact on the soil profile. Alakukku *et al.* (2003) suggested to mount additional tyres to enlarge the tyre-soil contact area as a means of ground pressure reduction under high wheel loads and in turn to mitigate the soil compaction. Further works by Antille *et al.* (2013) focused on effects of a single pass of three sizes of combine harvester tyres at a fixed vertical load of 10.5 Mg. and confirmed that the least change in soil bulk density and vertical soil displacement was found when the combine was fitted with larger tyres size with the lowest tyre inflation pressure. Low tyre inflation pressure is not however the universal solution for compaction problems as under-inflated tyres feature quicker wear with an increase of the risk of failure (Smith, 2017). Raper *et al.* (1995) reported that the load is moved towards the edge of the tyre in case of under-inflated tyres, and therefore increases rolling resistance and makes manoeuvring in the field and on the road more difficult.

The results of many studies on the effects of tyre pressures on soil degradation triggered the development of low ground pressure (LGP) tyres and tracks (Tijink *et al.,* 1995). Since additional tyres mounted on the tractor caused problems with the external width of a vehicle moving on a highway, tyres of larger volume but the same external diameter as the standard equivalent became an option (Michelin, 2018). Moreover, Michelin has developed a range of improved flexion tyres (IF) and of very high flexion tyres (VF) that are suitable for many agricultural machines. According to the manufacturer, these tyres feature even load distribution thanks to a wider footprint of the tractor wheel, which in turn offers increased soil protection and improves longevity and fuel and time efficiency (Michelin, 2018).

Another approach to minimise contact pressure is to equip the vehicle with tracks. The development of rubber tracked vehicles dates back to 1987 (Cousins *et al.,* 2016). Blunden *et al.* (1994) in his study on the effects of a rubber-tracked Caterpillar Challenger on sandy soil revealed that there were high stresses under the sprockets of the track construction. There was no significant difference in the maximum stress from the rubber-tracked vehicle and dual tyres at the depth of 0.3 m, nevertheless deeper in the soil profile, at 0.4 and 0.5 m, the tyres resulted in significantly higher maximum stress, which suggested that the stresses under the tracked vehicle do not extend as deep in the soil profile. Additionally, Alakukku *et al.* (2003) concluded that the uneven load distribution from tracked vehicles is only evident in the soil surface layers. On the other hand, Bashford *et al.* (1998) who also studied the effect of tracks and tyres on soil compaction, found no significant differences in soil bulk density in the topsoil and subsoil.

Ansorge and Godwin (2007) found out that wheels resulted in greater soil deformation than tracks. They also suggested that the cone penetrometer resistance is minimal under tracks. The authors however concluded that the pressure distribution is not constant and continues for a longer duration of time. In agreement, Arvidsson (2014) found out that the stresses were more variable along the length of the track in comparison to the wheels, however the highest soil stress was caused by single wheel tyre vehicles.

2.3 Introduction to traffic management systems

In agricultural production, the area over which the stress is applied is determined by the intensity of farming traffic (Kroulík *et al.,* 2009). Figure 2.2 a) illustrates the intensity of traffic on a 1-hectare field resulting from random traffic farming (RTF) with conventional tillage system during one season of cereal production (Kroulík *et al.,* 2009). At the field scale, this ultimately leads to 86% of the field subjected to at least one wheel pass every growing year (Figure 2.2 b). Reducing the depth of tillage leads to a decrease in the trafficked area which is a consequence of lower number of field operations required to prepare seed bed. Consequently, the use of shallow tillage and zero tillage reduces the total wheeled area to around 65% and 43% respectively which is presented in Figure 2.3 and Figure 2.4 respectively (Kroulík *et al.,* 2009).

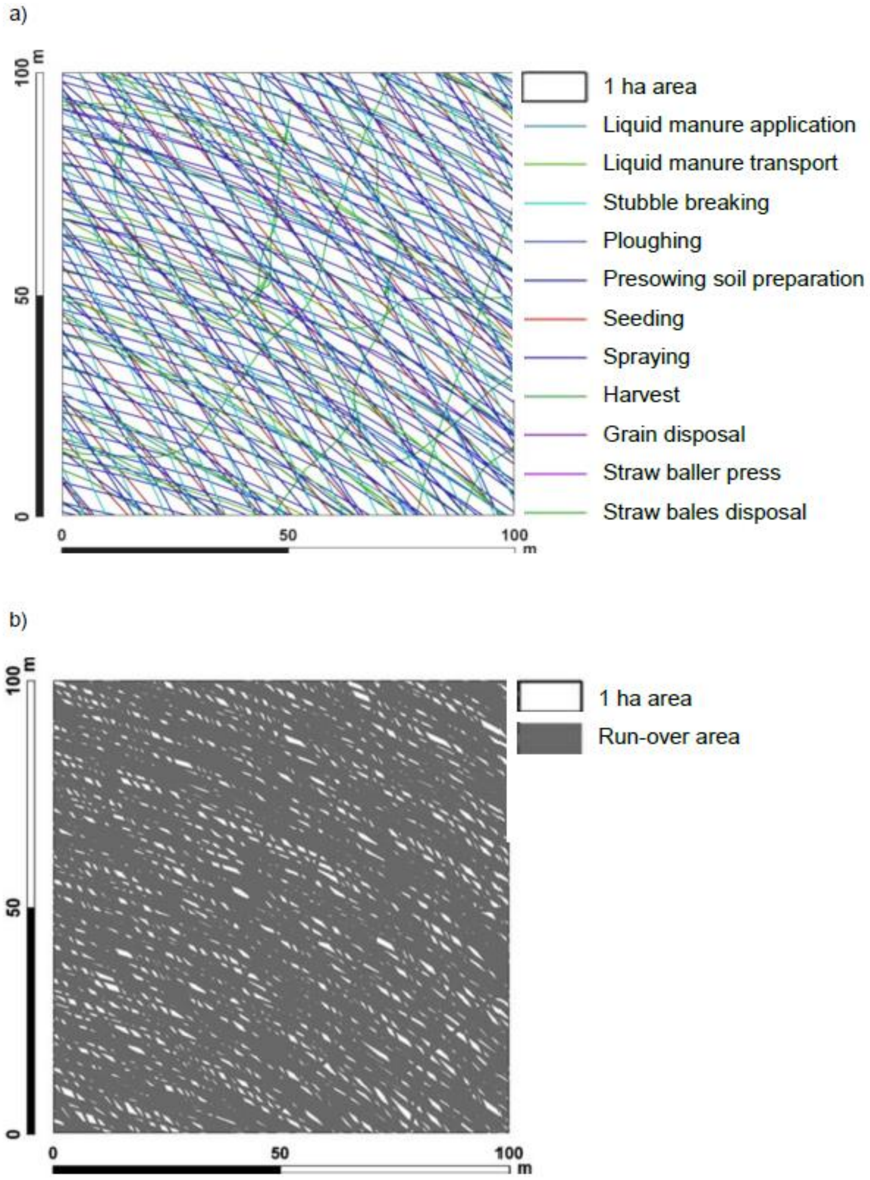


Figure 2.2 Graphic representation of (a) machinery trajectories, and (b) total trafficked area for random traffic farming with conventional mouldboard ploughing. Reproduced from source: Kroulik et al. (2009)

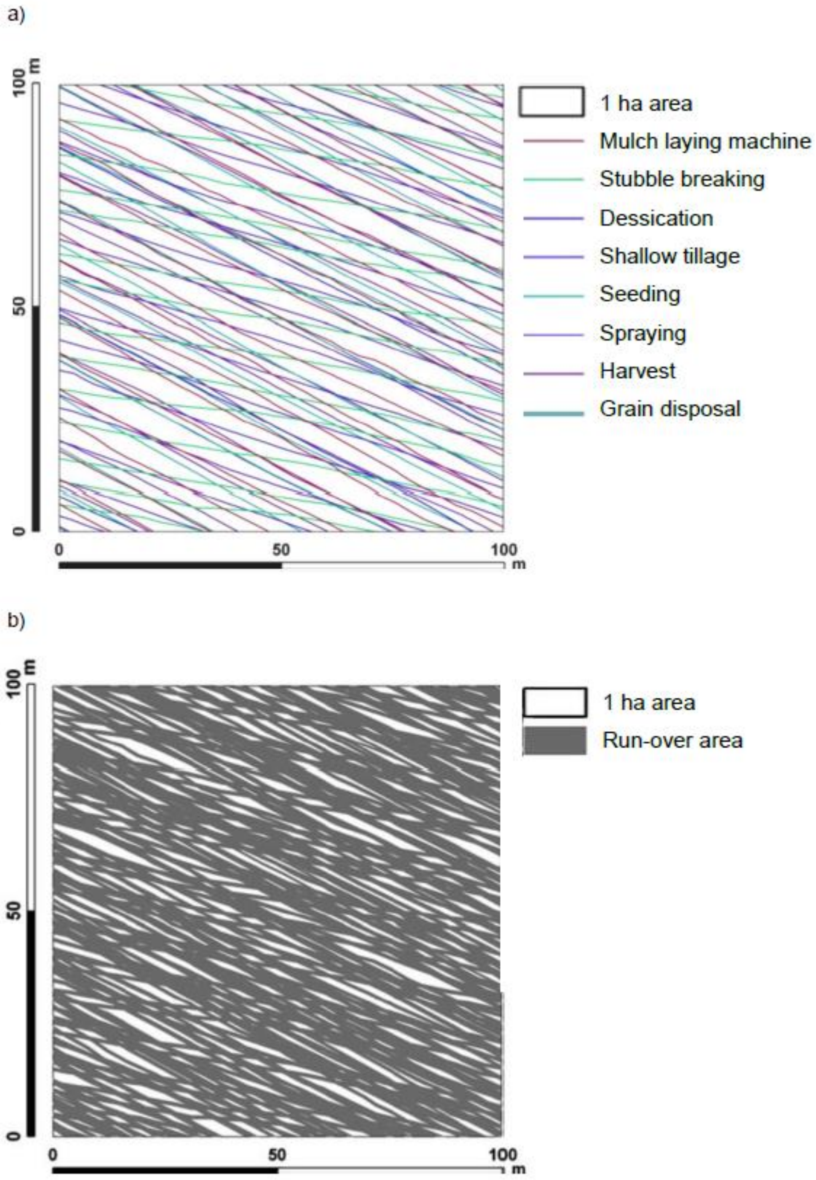


Figure 2.3 Graphic representation of (a) machinery trajectories, and (b) total trafficked area, for random traffic farming with shallow tillage. Reproduced from source: Kroulik et al. (2009)

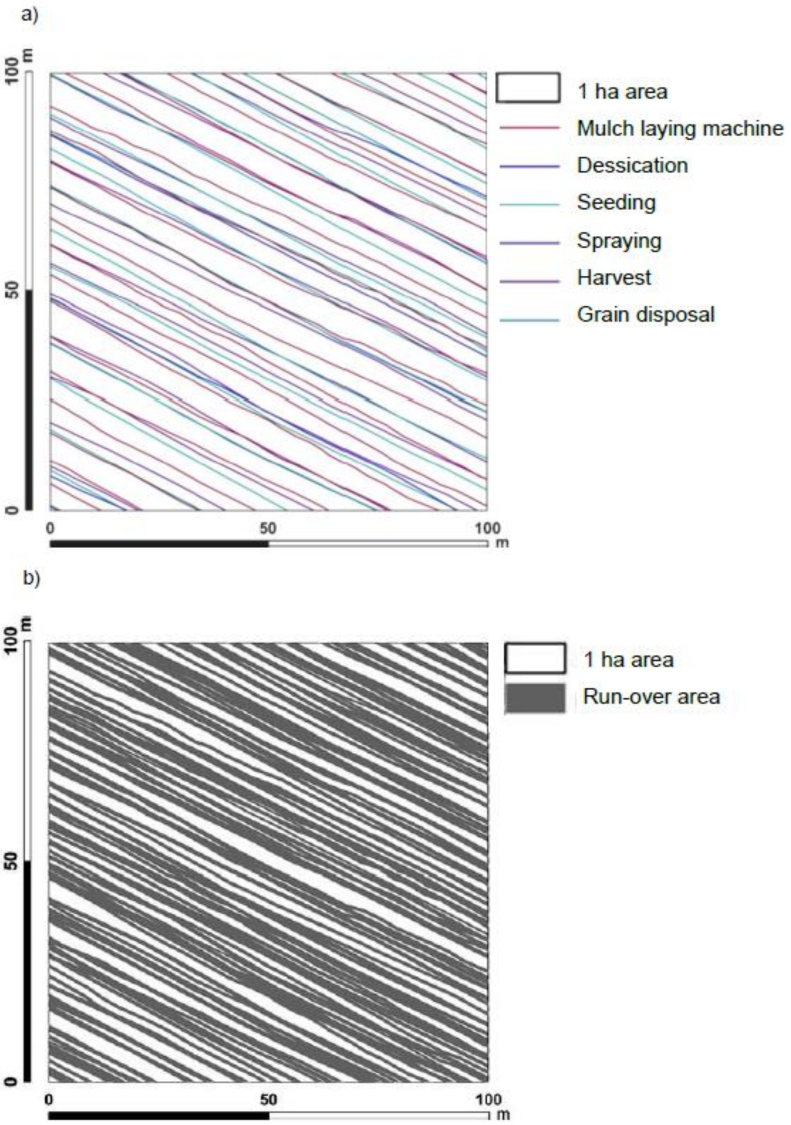


Figure 2.4 Graphic representation of (a) machinery trajectories, and (b) total trafficked area, for random traffic farming with zero tillage. Reproduced from source: Kroulik et al. (2009)

Soil compaction as a result of farming traffic has been suggested as the main reason for crop yield penalty by many researchers (Raghavan *et al.,* 1979; Horn *et al.,* 2003; Hula *et al.* 2009; Chamen *et al.,* 2011; Chyba, 2012). The yield reduction on trafficked soil is related to restricted root growth and lower access to nutrients as a result of increased bulk density and reduced pore size in trafficked areas (Kaspar *et al.*, 2001, Nawaz *et al.*, 2013). This suggests that much could be gained from reducing trafficked areas and a “zero-traffic system” started to be explored where vehicle wheelings are removed from the cropped area. This led to a development of wide-span gantry systems. This system relies on a frame mounted on a wide track gauge, between which implements attach onto sections that can move independently of each other as presented in Figure 2.5.

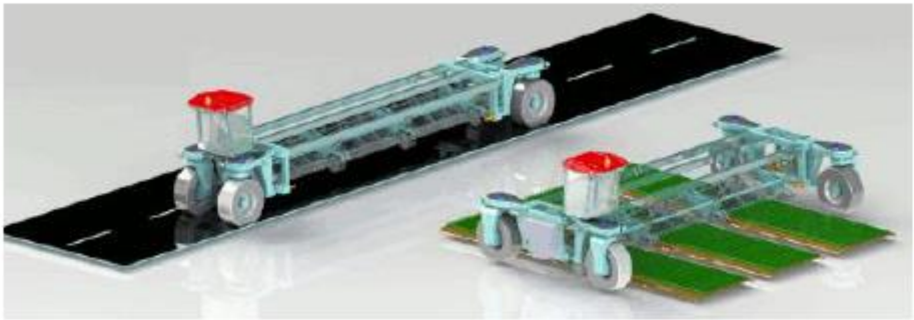


Figure 2.5 Wide span gantry system transport on the highway and working in the field. Adapted from source: CTF Europe (2020)

Chamen *et al.* (1992a) who investigated the effects of a partial 12 m-wide gantry system on energy consumption concluded that it reduced fuel consumption by up to 44%, reduced the trafficked area by 50%, and increased yield by 19% in comparison to conventional practice, although the gantry system was used for secondary cultivations and chemical applications only. However, there is no evidence that the experiment was fully randomised and replicated hence these results need to be considered carefully. Pedersen (2013) continued the research on the gantry system on a Danish vegetable farm where a 9.6 m prototype was implemented. This resulted in a reduction of trafficked area from 21% to 6%. Moreover, the same author indicated that there are no restrictions in movement of the gantry on a highway, as its transport width does not exceed 2.5 m. Additional benefits of this system highlighted by Pedersen (2013) included flexible working widths, lighter implements, and greater efficiency in a variety of crop production systems.

An alternative method of implementing a “zero traffic system” is to restrict all farming traffic to permanent wheelways or traffic lanes using controlled traffic farming system (CTF) as CTF is an agricultural management system which aims to minimise traffic-induced soil compaction (Raper, 2005). To confine farming traffic to permanent traffic lanes, the use of in-field machinery equipped with navigation aids and auto-steering systems is required. RTK-GPS (Real Time Kinematic Global Positioning System) provides accuracy to below 20 mm, which allows to drive farm vehicles on the same permanent traffic lanes every year. This in turn allows the crop zones in-between to remain untrafficked (Gasso *et al.* 2013, Bochtis and Vougioukas, 2008, Raper, 2005). Since permanent traffic lanes are separated from distinct crop zones, CTF keeps the crop zone unaffected by the wheels whereas the compacted permanent traffic lanes improve the draught efficiency (Taylor, 1992). CTF can reduce the trafficked area when compared with random traffic farming (RTF) from up to 85% in case of random traffic and mouldboard ploughing (Kroulik 2012) to only 10–20% of the total field area, regardless of the tillage intensities (Antille *et al.* 2016, Gasso *et al.* 2013, Soane and van Ouwerkerk, 1994, Tullberg, 2010, Wang *et al.,* 2009). Researchers in Australia reported on economic benefits of this system: Tullberg *et al.,* (2007) indicated a potential increase of farm profits by as much as 50% when CTF was in place, and this system has been adopted by the Australian sugar industry as a method of improving the sector's sustainability. Bell *et al.* (2003) suggested that the greatest benefits of CTF systems are achieved when the width of all track gauges match, that is, when the distance from wheel centre to wheel centre across all equipment is the same. Figure 2.6 illustrates the preferred ratio of the implements width, called "3:1 ratio" layout (Australian terminology) or "ComTrac" system (European terminology). This layout is suitable for implements less than 12 metres (Isbister *et al.,* 2013), where a single wheel track is used and implement width and the chemical application is a direct multiplication.

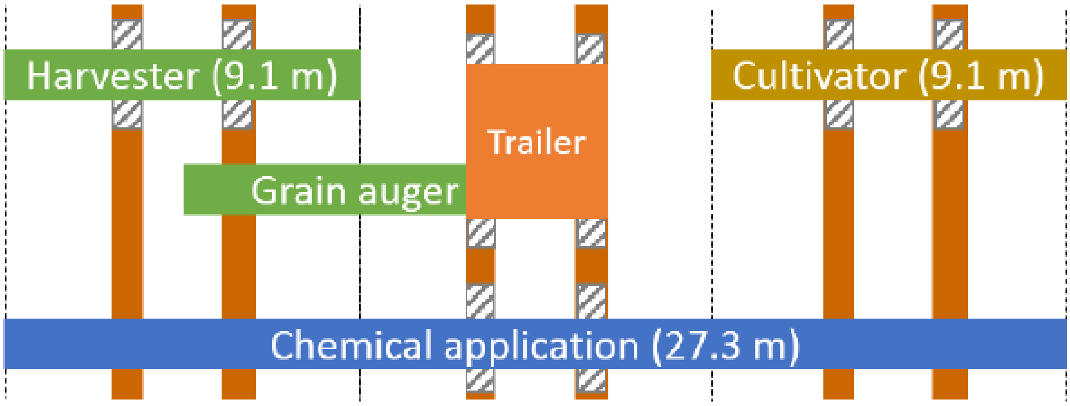


Figure 2.6 Layout of a "3:1 ratio" or "Com Trac" controlled traffic farming system. Adapted from source: Chamen, 2011

There is however no universal CTF track layout in UK and Europe as a result of a diverse range of agricultural machinery and road traffic restrictions. Nevertheless, as the combine harvester is usually the most expensive piece of equipment to replace, the most popular solution is an 'OutTrac' system where all other machines are adapted or replaced to run the same track gauge and the combine harvester runs on its own track gauge Other potential systems are TwinTrac where a tractor with a narrower gauge straddles adjacent passes of vehicles harvester with a wider gauge, as presented in Figure 2.7 and AdTrac where one track of the wider gauge, i.e. harvester coincides with narrower gauge of tractor, as presented in Figure 2.8 (Hargreaves *et al.,* 2016). Slow progress in adoption of CTF across the world is suggested to derive from the lack of compatibility of implements' working widths between the different agricultural equipment (Tullberg, 2010), nevertheless Galambošová *et al.* (2017) successfully implemented a CTF system using existing equipment (without modification) on a 16-ha site at Slovak University of Agriculture and managed to reduce the trafficked area from 64% to 45% in a 6-m wide CTF system. The same authors suggested that it was achievable to increase the crop yields by 0.5 t ha^{-1} which was associated with a decrease in soil bulk density. Godwin *et al.* (2017) suggested a breakeven area of 168 ha to pay for the annual costs for three RTK guidance systems, assuming the 0.61 t ha^{-1} increase in yields from a 15% CTF system and 312 ha for 30% trafficked area.

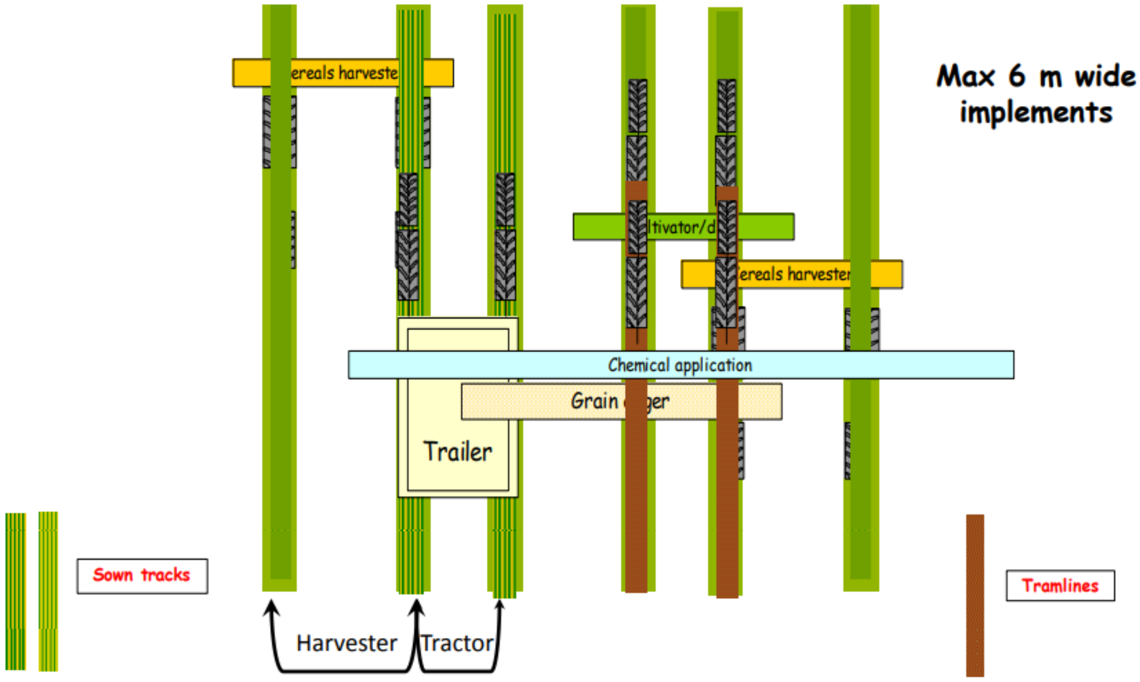


Figure 2.7 Twin Track CTF system where tractor straddle harvester passes. Adapted from source: Chamen, 2011

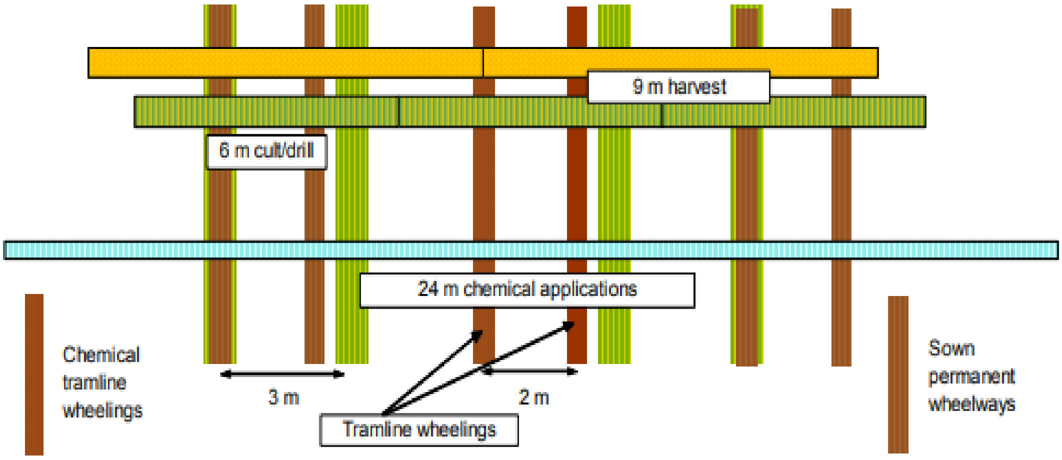


Figure 2.8 Ad2Trac CTF system with two track and two implement widths. One wheel of the narrower track (e.g. tractor) coincides with the harvester track. Adapted from source: Chamen, 2011

The potential advantages of CTF include improved crop yields, improved soil conditions, infiltration of rainfall/irrigation water, reduced tillage and crop establishment draught forces/energy (Godwin *at al*., 2015). The experiment on Large Marsh at Harper Adams University focused on three traffic systems subjected to three tillage systems revealed that CTF delivered higher crop yield than random traffic with standard tyre pressures (STP) (Smith, 2017). This is in agreement with other studies: Chamen *et al.* (2011) reported yield improvements between 7% and 35% for CTF, while Godwin, *et al.* (2015) reported yield increases of between 7.3 -10% when controlled traffic farming was applied. Gasso *et al.* (2013) in their review of the environmental impacts reported that the lack of soil compaction in the crop zones also lead to a significant reduction of draft force and fuel consumption (by 23%). In agreement, Godwin *et al.* (2019) reported an increase in energy requirements of 200-300% for tillage operations on heavily compacted soils.

Soil compaction can also affect soil aeration and can increase the release of greenhouse gases (GHGs) from fertilised soils, which explains why reducing the trafficked area via implementing CTF system can bring additional environmental benefits, as reported by Gasso *et al.* (2013). Their modelled data estimated a reduction of fluxes of nitrous oxide (21–45%) and methane (372–2100%), as well as water runoff (27–42%) from CTF in comparison to random traffic. This was supported by results of a 3-year study in Australia (Tullberg *et al.,* 2018) where the observed N_2O emissions from untrafficked soil under CTF were lower by a factor of 2.2 in comparison to those from trafficked soils. The same authors also reported a decrease of methane emissions from untrafficked soil and concluded that the adoption of CTF might reduce total soil emissions by 30%–50% while bringing other benefits described above. Taylor (1983) reported reduced runoff due to increased water infiltration rates on untrafficked soil.

In the CTF system, the detrimental effect of repeated wheel passes described earlier is limited to the permanent wheelways only. The increased compaction in permanent wheel passes can be beneficial as it improves trafficability, allowing to access fields up to eight days earlier than in conventional systems which is of particular importance after heavy rainfall (McPhee *et al.,* 1995 as well as Dickson and Ritchie, 1996). Li *et al.* 2009 suggested that improving the tractive efficiency (the ratio of output power at the drawbar to input power of the tyres or tracks) leads to improved timeliness of field operations.

2.4 EFFECTS OF TILLAGE ON SOIL CONDITIONS

The purpose of tillage is to produce favourable soil conditions for good crop establishment and growth. Tillage is also used to incorporate crop residues and nutrients and to destroy weeds (Godwin, 2014). Widely adopted conventional tillage relies on mouldboard ploughing which is followed by secondary cultivation to prepare the seedbed as larger aggregates resulting from mouldboard ploughing need to be divided into smaller aggregates with tine- or disc-harrows (Morris *et al.,* 2010; Hallett and Bengough, 2013). In England, the conventional tillage is still a prevailing method of cultivation with around 65% of arable land under this system (Townsend *et al.*, 2016). Cultivation also alleviates soil compaction by providing improved soil aeration and water infiltration (Sommer and Zach, 1992). Cultivated soil features increased warming, improved soil-to-seed contact and facilitates root development (Hallett and Bengough, 2013). On the other hand, intensive tillage is suggested to have a severe negative environmental effect (Foley *et al.,* 2011). Deep tillage is related to increased field traffic (Kroulik *et al.,* 2009) and consequently increases the area of compacted soil. As a result of running two tractor wheels in the open furrow during ploughing there is a compacted stratum created in the soil at about 200-350 mm from the surface. To alleviate it, sub-soiling is required but this again poses a risk of re-compaction from subsequent traffic (Morris *et al.,* 2010). Alakukku (1996) reported that the effects of soil compaction below 0.1 m on the clay soil were long-lasting and persisted for 3 years despite annual ploughing to 0.2 m. In agreement, Soane *et al.* (1986) suggested that a significant re-compaction was a result of trafficking of soil that had been deep loosened and then ploughed. Other negative consequences of conventional inversion tillage include accelerated erosion by wind and water runoff whenever the soil is left bare till the next season (Lal, 2007). Huggins and Reganold (2008) related the 1930s 'Dust Bowl' in the USA to the plough cultivation. Bogunovic *et al.* (2018) in his study on the effects of tillage systems in Croatia reported that conventional tillage resulted in an annual soil loss of up to 46.2 t ha^{-1} in case of maize production. Those soil particles which are blown away contain nutrients and pesticides causing water pollution (Rickson, 2014). Bogunovic *et al.* (2018) concluded that residue cover is key factor in controlling erosion and attributed main soil loss to the seedbed preparation which was especially relevant during intense rainfall.

To mitigate the negative environmental consequences of ploughing, many scientists point to “no-tillage” as an alternative. The expansion of this approach has occurred since the mid- to late-1990s as a result of available broad-spectrum herbicides and improved no-till technologies (Derpsch *et al.,* 2010). Reduced tillage together with retention of residues and crop rotation is defined as conservation agriculture and is described by FAO as ‘climate smart’ (FAO, 2013). The conservation agriculture is suggested to increase soil fertility as well as water infiltration (Verhulst *et al.,* 2010), on the other hand it decreases evaporation in cooler soil temperatures (Gauer *et al.,* 1982). It is however suggested that the majority of positive effects of no-till derive from the plant cover and there are many variabilities between the results of reduced tillage alone (Kjell B. Esser, 2017). Munkholm *et al.* (2003) reported that the conversion from mouldboard ploughing to no-till on sandy loam soil in moist and cool Scandinavian climate resulted in significant increase of soil bulk density and penetration resistance.

That trend was confirmed on sandy loam soil in UK by Smith (2017). Similarly, Singh and Malhi (2006) reported that six years of no-till without soil cover on Black Chernozem resulted in reduced infiltration rates. Kjell (2017) focused on soil moisture in conservation and conventional tillage small scale fields in Zambia and reported increased ponding and runoff as well as significantly shorter saturation time on conservation tillage fields comparing to conventional ones. At the same time, the soil moisture at the depth of 0-60 mm was found significantly smaller on conservation fields.

Some researchers reported an increase in crop yields under no-till compared to mouldboard ploughing (Lal, 1997, Singh *et al.,* 2016). Other researchers reported no differences in crop yields between those two tillage systems (Shipitalo and Edwards, 1998; Alvarez and Steinbach, 2009), or even crop yield penalty (Smith 2017). Buschiazzo *et al.* (1998) suggested that no-till might bring much benefits in semi-arid regions, as it retains more water in the soil when compared to deep tillage, whereas in wet conditions, deep tillage can deliver higher crop yields due to better infiltration as suggested by Alvarez and Steinbach (2009). Bogunovic *et al.* (2018) concluded that crop yields were more affected by crop rotation, soil properties and climate than by tillage. Many scientists also suggest that there might be a limited period of soil deterioration as a result of transition from conventional to conservation agriculture, but it is followed by a gradual improvement resulting in good crop development and yield (Chamen, 2011; Kaczorowska-Dolowy *et al.*, 2020). Rhoton *et al.* (2000) concluded that no-till practices can improve some soil properties, namely soil organic matter, aggregate stability, exchangeable Ca, within a 4-year period, thus enhancing soil sustainability.

2.5 EFFECT OF FARM VEHICLE TRAFFIC AND TILLAGE ON SOIL PHYSICO-CHEMICAL PROPERTIES

Soil compaction due to wheel traffic deteriorates soil structure both at the top soil and deeper in the soil profile (Domżał *et al.,* 1991). As it was mentioned before, compaction disrupts soil structure, accelerates water run-off, wind and water erosion, it also damages soil balance with other components of the environment (Houšková & Montanarella, 2008).

2.5.1 Effects of traffic and tillage on penetration resistance and bulk density

Domżał *et al.,* 1991 reported on increased penetration resistance, shear resistance of soil, increased cohesion and crushing strength of soil aggregates of compacted soil. Many authors reported on increased soil bulk density (Millington, 2019; Shaheb, 2019; Smith, 2017; Lipiec *et al.,* 2003). The changes in soil bulk density however are not linear. Antille *et al.* (2013) and Stranks (2006) suggested that the increase in soil bulk density decreases progressively as the initial soil bulk density increased. Antille *et al.* (2013) who investigated three different sizes of combine tyres at three inflation pressures reported higher values of soil bulk density under higher inflation pressure tyres with a smaller contact area. Ahmadi and Ghaur (2015) reported that an increase of the tractor wheeling intensity from 0 to 4 passes resulted in an increased bulk density by 13%. Similarly to the effect of farming traffic and tyres pressures on BD, many researchers reported on increased penetration resistance (PR) under compacted soil. Arvidsson *et al.* (2001) reported a significant increase of PR two to four years after the traffic was applied in comparison to untrafficked soil. The effect of tyres pressures (in the range of 150-300kPa) on PR were investigated by Schjønning *et al.* (2016) who found that lower tyre pressures produced lower stresses in the upper soil profile resulting in lower penetration resistance but for deeper layers penetration resistance was correlated to vehicle load. On the other hand, Millington (2019), and Smith (2017) who investigated effects of tyres pressures in the range of 70 kPa - 110 kPa on the front and rear axis for LTP and STP respectively on PR reported on lack of significant differences between LTP and STP.

The effects of tillage on soil bulk density are not coherent. Franzluebbers *et al.* (1995) observed reduced soil BD shortly after tillage, however with the growing season the differences between tiled and no-tilled soil decreased regardless the crop. On the other hand, Alvarez and Steinbach (2009) in their review of the effects of tillage systems on some soil physical in Argentine Pampas concluded that soil BD and cone PR of the 0–20 cm layer were higher under limited tillage (zero and shallow) systems than under mouldboard ploughing system (by 4% and up to 50% respectively on average, depending on the soil type), nevertheless, none of those results reached critical threshold for roots development (1.5 g ml^{-1} for soil bulk density after Hassan *et al.,* 2007; and 2.5–3.0 MPa for cone resistant (after Hakansson and Lipiec, 2000; Hamza and Anderson, 2005). Millington (2019) reported on the lack of significant effects of tillage systems on BD, which is in agreement with Burch *et al.* (1986); Taboada *et al.* (1998); Logsdon and Cambardella (2000). Also, Jabro *et al.* (2016), as well as Martínez *et al.* (2008), reported that tillage did not significantly influence soil bulk density, and suggested that the bulk density was associated with the role of soil texture governing total porosity, rather than changes as a result of tillage practice.

Apart from soil bulk density and penetration resistance, another characteristic of soil physical condition is porosity which is defined as the fraction of the total soil volume that is taken up by the pore space, hence it is a quantification of the amount of space available to water or other fluids (Nimmo 2013). The same author suggested that the value of porosity in soil falls in the range of 30-70% and hardly ever is lower than 26%.

2.5.2 Effects of traffic and tillage on soil porosity

Changes in pore size distribution can be indirectly obtained from water retention curves, when the saturated soil samples are drained to increase water suctions (Dexter and Bird, 2001), however this method does not identify the complex changes to soil pore structure resulting from different stress during wheeling (Peth *et al.* 2010). Another method to analyse the pore systems is a 2-D image analysis of thin slices of undisturbed soil samples as used by Pagliai *et al.* (2003), where dried samples are impregnated by polyester resin and then sliced into thin sections and then analysed with e.g. Image Pro-plus software (Pagliai *et al.* 2003), nevertheless this method of porosity analysis is time consuming and costly and the technique requires specialist training (Lipiec and Hatano, 2003). To overcome these limitations many scientists started to investigate the potential of X-ray CT technique and concluded that it is an effective method to quantify pore size and its distribution in soil (Rab *et al.* 2014; Beckers *et al.* 2014). Udawatta & Anderson (2008) in their field study in Missouri, USA, concluded that X-ray computer tomography (CT) can be used to quantify the effects of different soil managements systems, and reported on the relationship between saturated hydraulic conductivity and CT measured pore parameters. Kim *et al.* (2010) investigated the effect of compaction using medical X-ray CT scanner on a silty loam soil in Missouri, USA and found that the porosity in the compacted soil was reduced by 64 % in comparison to the un-compacted soil, at the same time the number of pores decreased by 71%. The same authors reported an increase by 8% in bulk density of the compacted vs uncompacted soils. In agreement, Kim *et al.* (2010) and Berisso *et al.* (2012) reported that soil compaction reduces number of larger pores and thus affects total porosity. This in turn increases waterlogging and eventual anaerobic conditions leading to denitrification and reduction in root growth as small pores are more susceptible to waterlogging (Czyż, 2004b). Dal Ferro *et al.* (2014) in a study on the influence of tillage and no-till systems on soil structure, root morphology and dynamics of maize in Italy using X-ray CT and mercury intrusion porosimetry (MIP) reported that that the macro porosity of soil was significantly affected by tillage systems while micro porosity measured by MIP, did not significantly differ between treatments. Millington *et al.* (2017) reported that the soil compaction resulting from farming traffic results in reduced porosity which was in agreement with Soane and van Ouwerkerk (1994) who suggested that farming traffic results in homogenisation of the pore systems and stability index. The system of pores within the soil is essential for the transport of air water and nutrients necessary for the growing plant (Eden *et al.,* 2011). The reduction in macro-porosity from soil compaction may limit root development (Rab *et al.,* 2014) resulting in the reduction of crop yield (Czyz, 2004). Analysis of soil pore structure (size and distribution) using X-ray CT technique showed that soil percentage porosity is higher in untrafficked treatments. It decreased with depth in case of deep tillage, at the same time small pores were more frequent (Millington *et al.,* 2017). The same authors revealed that shallow tillage treatments increased the percentage porosity with depth whilst providing the lowest penetration resistance. Similarly, Shaheb (2019) reported on almost twofold greater macro porosity in untrafficked soil in comparison to trafficked.

The effects of tillage on porosity has been investigated by many researchers who examined the hydraulic properties and concluded on macroporosity, nevertheless the conclusions are often contradictory. Capowiez *et al.* (2009) reported that mouldboard ploughing lead to a significant decrease in the total number of pores and their continuity in comparison to reduced tillage. Similarly, Strudley *et al.* (2008) reviewed tillage effects on soil hydraulic properties and concluded that zero tillage increases macropore connectivity, however the effect of tillage on total porosity is inconsistent when comparing with conventional tillage system. On the other hand, some investigations in Argentina found, that no-tillage lead to lower values of hydraulic conductivity and water-conducting macroporosity in comparison to conventional ploughing system (Ferreras *et al.,* 2000; Fabrizzi *et al.,* 2005; Sasal *et al.,* 2006, Villarreal *et al.* 2020). Derpsch *et al.* (2014) suggested that NT could have a negative impact on soil properties when some of their best-practice principles are not achieved (e.g. lack of crop rotation, extended fallow periods, and insufficient mulch cover).

2.5.3 Effects of traffic and tillage on soil moisture

The effect of farming traffic on soil moisture was investigated by Raghavan and McKyes (1978) who suggested that farming traffic increases soil moisture in the top 200mm. Similarly, Evans *et al.* (1996) concluded that volumetric soil moisture content increased together with an increase of soil bulk density hence in compacted soil it was greater. As a result of increased compaction in permanent wheelways under CTF system the water is less available to plants, but this is limited to the trafficked area which is enclosed by areas of improved water regime (Li *et al.,* 2007). The same author reported that in the 0-0.5 m depth of soil profile, CTF increases plant available water by 11.5% in comparison to trafficked areas. McHugh *et al.* (2009) confirmed that on untrafficked soil, water holding capacity and plant available water were improved which led to elimination of water ponding which is of great importance during periods of water deficits. The effects of tillage however on soil water content are not coherent. Oorts *et al.* (2007) who reported on a study in Northern France found no significant differences in soil moisture between different tillage systems. Similarly, Smith (2017) did not find any significant differences in gravimetric soil moisture between contrasting tillage and traffic treatments. Contradictory findings however were reported by Wuest *et al.* (2010) who found out that in U.S. Pacific Northwest, tillage to depths of 100 and 150 mm preserved up to 0.01 kg kg^{-1} greater water content than zero-tillage or shallow tillage (50mm). On the other hand, Alvarez and Steinbach (2009) for Argentine Pampas, Gruber *et al.* (2011) in Germany, Rasmussen (1999) for Scandinavia and Fuentes *et al.* (2003) for North America drylands observed an increase in soil moisture under no-tillage in comparison to cultivated soil. Gruber *et al.* (2011) indicated that the differences were slight but significant (by 0.4–1.2 percentage points). Similarly, Slawinski *et al.* (2012) in their study in Poland reported higher soil moisture under zero-tillage than conventionally- ploughed, nevertheless the differences were not always significant, and the differences varied across season and years and depth, with some observations of higher soil moisture in 300 mm under ploughed-based soil. Wuest *et al.* (2010) suggested t it is often difficult to discern significant differences between treatments because of high variability across time points.

2.5.4 Effect of traffic and tillage on water infiltration and soil hydraulic conductivity

As previously mentioned, intensive agricultural traffic is linked with an increased soil erosion and surface run-off (Kroulik *et al.,* 2007), hence controlling them also significantly reduces leaching of pesticides and nutrients from the soil, which are suggested to be two of the main contaminants deriving from agriculture (Bagarello, *et al.,* 2004). The rate at which water enters the soil from the surface to the profile is known as infiltration, and the higher the infiltration rate, the less susceptible the soil is to the surface runoff and erosion (Barthes and Roose, 2002). The effect of soil saturation on infiltration is significant, and the rate at which saturated soil can absorb water depends on the texture and structure of the soil (Bagarello, *et al.,* 2004). The same authors suggested that "The hydraulic conductivity (Kfs) of saturated soil is one of the most important soil properties controlling water infiltration and surface runoff". The value of Kfs is governed by cracks, root holes, as well as by aggregate stability (Kirkham 2014). It is also dependent on soil structure and texture (Bagarello *et al.,* 2004), as well as on organic matter content and population of earthworms which build the vertical holes facilitating water movement down the soil profile as suggested by Unger (1996). Given those many factors affecting this soil characteristic, it can vary significantly across both - field and region scale. Kirkham (2014) reported that the value of Kfs in natural soils varies significantly depending on the soil texture from 30 m day^{-1} (1250 mm h^{-1}) on silty clay loam to 0.05 m day^{-1} (2.08 mm h^{-1}) for a clay, whereas Bagarello *et al.* (2012) in his investigation of the simplified falling head (SFH) method in Italy reported values of Kfs from 7424 mm h^{-1} under vineyard on clay to 1.7 mm h^{-1} under pasture on clay loam. The application of the SFH method was previously investigated and compared to the traditional constant head technique in a previous work of the same author Bagarello *et al.* (2004) who reported an increase of the value of Kfs obtained by the SFH method by factor of 1.8. Nevertheless, the authors concluded that the results from those two methods were statistically significantly correlated (p = 0.05, coefficient of determination, r^2 = 0.65). Furthermore, practically many authors have suggested that an error of the estimate of K_{fs} by a factor of two or three can be considered acceptable for many practical purposes (Elrick and Reynolds, 1992, Reynolds, 1996). The SFH method calculates the *Kfs* according to Equation 4-2 (after Bagarello *et al.*, 2004 – see Chapter 4.2.6).

The effects of traffic and tillage on soil saturated hydraulic conductivity were investigated by many researchers. Traffic is suggested to have detrimental effect on hydraulic conductivity. Ankeny *et al.* (1995) in his study on the effect of traffic and tillage on hydraulic properties of soils in Missouri reported that the wheel traffic reduced ponded infiltration rates regardless the tillage systems (chisel plough and no-till) by 33 and 64% depending on location. Chyba (2012) concluded that the first pass of traffic is responsible for the greatest decrease in surface water infiltration rate by approximately 82%. Similarly, Silburn and Glanville (2002) found that rates of water infiltration were 29% higher on untrafficked soils when compared to trafficked. In a later study, Chamen (2011) reported on 400% increase of the infiltration rates on untrafficked vs trafficked soil.

The results of studies on the effects of tillage on water infiltration rates and hydraulic conductivity contradict depending on the soil textures, and geographical location: Nielsen *et al.* (2005) reported an increase of infiltration rates under no-till, but Rasmussen (1999) found greater water infiltration in tilled soil. These conflicting results can be attributed in some cases to temporal variability of the soil infiltration rate as suggested by Strudley *et al.* (2008) which is very high immediately following tillage application, but decreases with time. The same authors concluded that water infiltration under no-till can be greater than in tilled soil after the first wetting-drying cycle.

2.5.5 Soil carbon and soil organic matter

Soil organisms play a crucial role in nutrient cycling and decomposition of plant residues which in turn capture carbon (C) in the soil, which plays a crucial role in improving soil properties, including drainage, soil structure, water holding capacity, and consequently productivity (Lal, 2007). It is suggested that soils hold approximately 75% of the C stored on land in the form of vegetation and about twice that stored in the atmosphere (Syswerda *et al.,* 2011). With the onset of global warming, the capture and storage of atmospheric carbon dioxide (CO_2) is vitally important and soil has the greatest potential for carbon sequestration (Kravchenko *et al.,* 2019). Syswerda *et al.* (2011) suggested that carbon sequestration takes place when the pace of organic matter accumulation exceeds loses resulting from soil microorganisms' respiration, leaching and erosion. Depending on the complexity of the organic compounds of organic matter, resistance to microbial decomposition varies: compound lignified materials may last millennia whereas simple sugars last for hours (Kononova, 1975; VanVeen and Paul, 1981; Coleman and Jenkinson, 1996).

The strategy to increase soil C includes reducing soil disturbance (West and Post, 2002), increasing the incorporation of plant residues into the soil followed by an increase in plant diversity and the percentage of perennial plants in the crop rotation. Houghton (1999) suggested that after changing land use from forest to arable land, the soil C content decreases as a result of C flux to the atmosphere by 15-20%, while other studies suggest even greater C losses up to 30-40% (Poeplau and Don, 2015). This carbon flux is mainly a result of tillage that causes physical disruption of soil aggregates and the carbon that had previously been stored in the soil is exposed for oxidation and lost as a CO_2 flux to the atmosphere (West *et al.,* 2004).

Change in farming practice from conventional tillage to zero-tillage is suggested as another measure to increase soil C sequestration (West and Post, 2002). The same study suggests that the maximum carbon sequestration rate occurs in the period of 5-10 years since conversion from CT to NT and the soil organic carbon (SOC) reached new equilibrium after 15-20 years. Reducing tillage intensity is also suggested to increase soil microbial abundance (or biomass) (Valpassos, *et al.* 2001; Guo *et al.,* 2016; Doran, 1980). Doran (1980) in his study of US soils found that the top soil (0-70mm layer) of no-till soils had more abundant aerobic microorganisms, facultative anaerobes, and denitrifiers in comparison to mouldboard ploughed soils. However, the trend was reversed in the deeper layer of soils (70–300 mm). In agreement, van Groenigen *et al.* (2010) found in a study in Ireland that reduced tillage featured increased total biomass of both bacteria and fungi in the 0–50 mm soil layer; however, in the deeper soil layer (50–200 mm) the bacterial biomass decreased.

There are however many studies that deliver contradictory findings. Despite intensive tillage, row crop systems, with cover crops successfully accumulate carbon, while some perennial bioenergy systems such as switchgrass (*Panicum virgatum*) does not feature rapid increase of soil organic matter (SOM) despite large below ground biomass and lack of cultivation (Sprunger and Robertson, 2018). These inconsistencies indicate that there is a need for a greater understanding of the interaction between plant species, soil condition and microbial interactions with farming practices that determine their effect on carbon sequestration.

2.6 EFFECTS OF TRAFFIC AND TILLAGE ON SOIL BIOLOGY

Soil health is a term which is widely used to describe the general quality of the soil resource and embraces both the provision for agricultural crop production and the provision of other ecosystem services (Kibblewhite *et al.,* 2007). These authors put great emphasis on the necessity of integrating the interaction approach between different processes and properties (biological, physical and chemical), since those interactions might enhance some processes in soils, on the contrary to the reductionist approach – defined as monitoring separately specific soil properties and on that basis concluding on the soil condition. The same authors highlighted that soils of good quality and health have the capacity to function as a living system. Doran and Zeiss, (2000) concluded that healthy soil supports biological activity and promote environmental quality at the same time increases the potential for improved crop yields and reduced nutrient loss. Andriuzzia *et al.* (2015) suggested that improved soil health is vital for resilience and adaptability which in turn is essential for future production particularly in the face of climate change (Congreves *et al.,* 2015). A wide range of indicators of soil quality and health have been considered but there is a consensus that they must include biological components (Edwards, 2004) as soil is a live and dynamic habitat (Blair *et al.,* 1997). Nevertheless, it is generally impractical to collect data for all present organisms to assess quality of soil biology. For such a broad approach very complex expertise and research methodologies would be required since the soil biota consists of a wide range of different taxonomic groups (Rodgers *et al.,* 2018). This problem has been overcome by a focus on a chosen taxon which would play a role of an 'indicator' with the hypothesis that they will indicate on the quality of the remaining biota (Rodgers *et al.* 2018). Until recently it was unfeasible to use microbial indicators of soil quality because of a lack of simple methodologies to be used in the field (Edwards, 2004). The same applied to soil arthropods which requires more specific knowledge and equipment (Edwards, 2004). Therefore, earthworms as relatively large soil organism, have gained the greatest attention and already Aristotle concluded on their positive role in turning up soil. After centuries when no much was written on their role, Darwin (1881) again highlighted the positive role of earthworms in soil processes and plant growth and since then many scientists suggested their population as an indicator of soil health (Edwards, 2004; Karaca, 2011; Blouin *et al.,* 2013; Betrand *et al.,* 2015).

The research, here presented, assessed a limited number of soil biological indicators that could be related alongside soil physical properties as an overall assessment of soil health. The indicators of soil biology that were examined were: earthworms, the abundance of Collembola (springtails), soil microbial carbon (fungi and bacteria), soil organic matter and the feeding activity of soil organisms (using a bait lamina score).

2.6.1 Earthworms as soil health indicator

Earthworms belong to the order Oligochaeta, however there is some controversy on their systematics (Edwards, 2004). Stroud and Bennet (2018) in their guidelines for farmers to investigate earthworms' abundance suggested to use well-developed classification and account the earthworms to one of the three eco-groups: epigeic, endogeic and anecic, or to classify as juvenile. Each ecological grouping is based on certain feeding and burrowing characteristics (Dominguez, 2004) moreover, they can be easily identified due to their different physiognomy. The epigeic are the litter-dwelling earthworms, which live near the soil surface (Karaca, 2011, Stroud and Bennet, 2018). They have dark red head and their length does not exceed 8cm, they are also reported to be fast-moving (Stroud and Bennet 2018). The epigeic earthworms play a great role in mineralization of plant residues from the soil surface. The endogeic earthworms inhabit the top-soil (0-20 cm), where they build a net of tunnels both vertical and horizontal (Karaca, 2011). They are of pale green colour, small to medium size (Bennet and Stroud 2018). The same authors reported that they often curl up when handled. They feed on the soil surface. They also contribute to the mineralization of organic matter from plant residues hence facilitate nutrient uptake by the plants. The anecic earthworms have the greatest size, typically reaching 20 to 25 cm in length when extended in the temperate climate in most areas of Europe (Edwards, 2004). They build their permanent vertical burrows to 1 m down the soil profile through which they transport the decomposition products to lower soil layers (Karaca, 2011). This eco-group governs transport of soil organic matter down the soil profile and contributes to both nutrient cycling and soil formation (Crittenden *et al.,* 2015).

There are scientists who suggest that earthworms are the best available indicator of soil quality (Doube and Schmidt, 1997, Edwards, 2004). Edwards (2004) highlighted the importance of earthworms in formation of water-stable soil aggregates. The aggregate stability is a very important characteristic of well-structured soil. The soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. The space between the aggregates provide pore space for retention and exchange of air and water. Those water-stable soil aggregates are resistant to degradation from external forces such as rainfall and wind. On the other hand, aggregates that break down easily, release individual soil particles that can seal the soil surface and block pores or are susceptible to wind erosion hence do not retain nutrients in the soil (Papadopoulos, 2011). Zhang and Schrader (1993) in their study on the effects of earthworms on physical and chemical properties of soil aggregates found out that earthworms' indigestion at first destroy existing bonds in soil aggregates, and creates reformed stable aggregates: the sand fraction is reduced whereas the organic C content is increased by 21.2–43.0% and 4.1–21.0% for casts and burrow-wall material respectively. They also reported on a significant increase in polysaccharides by 35–87% for casts and by 33–46% for the burrow-wall material of all earthworm species. Edwards (2004) also reported that the feeding activity of earthworms also promotes microbial activity, which play a great role in efficient nutrient cycling as microorganisms process plant litter and residues increasing the nitrogen and carbon pool in soil, on which plant growth and development rely (Chen *et al.*, 2003). Edwards and Lofty (1977) observed that the earthworms activity increases soil porosity. The same authors in their further study (Edwards and Lofty 1978, 1982) concluded, that deep burrowing earthworms (*Lumbricus terrestris* L.) improved soil drainage and increased soil infiltration because they create deep, vertical permanent burrows. Those deep burrows are suggested also to improve soil aeration and decrease anaerobic conditions (Kretzschmar 1978, Edwards 2004). Blouin *et al.* (2013) concluded that thanks to the burrows created by earthworms, the soil structure and soil aeration improves, water drainage is enhanced and root growth facilitated, which in turn decrease the risk of soil erosion by up to 50%. The same authors also reported on a positive correlation of soil organic matter with increased earthworm abundance. Through the decomposition of plant residues and the subsequent production of casts, earthworms achieve a number of processes which are of benefit to soil ecosystems (Blouin *et al.,* 2013). The invertebrates aid soil mixing and formation through the breakdown and incorporation of organic matter, enhancing soil stability and controlling humification rates. Stork and Eggleton (1992) and Blouin *et al.* (2013) observed that the increased earthworm cast production assisted improved root growth and crop yields.

Crittenden *et al.* (2015) suggested that the population of earthworms is greatly influenced by key environmental factors such as pH, soil aeration, salinity, and in particular soil temperature and water content. They are mostly present in pH range of 5.0- 7.4 and in more acidic environment (pH 3.5-4.5) their growth is substantially limited whereas pH below 3.5 creates an environment where they cannot live (Satchell, 1983). Chan (2001) highlighted the reliance on soil temperature – particularly for the hatching process with certain species only tolerating small deviations in temperature range. The same author also underlined the importance of water content for earthworm development because this group of invertebrates depends on the water potential in the surrounding soil media, as they lose moisture through their cuticles. Earthworms feed on organic matter that is why their increase is highly correlated with an increased soil organic matter (Araujo and Lopez-Hernandez, 1999).

The effects of farming practices, particularly tillage on the populations of earthworms were investigated by many researchers. Pelosi *et al.* (2014) in his study into the effects of three main cultivations types; ploughing (250-300 mm), reduced tillage (80 mm), and zero tillage (0 mm) on earthworm populations concluded that the tillage intensity did not affect the number of observed species nor abundance however different cultivation techniques effected the functional traits, (e.g. body length, body mass/length ratio, cocoon diameter, vertical distribution). That experiment however contained inconsistent crops on the experimental plots, namely sugar beet, wheat, and flax which may have had an effect on the results. Crittenden *et al.* (2015), in a two-year experiment found that non-inversion tillage significantly increased total earthworm density by 34% and total earthworm biomass by 15% compared with inversion tillage. The same authors also reported that anecic earthworm particularly suffered from deep tillage which resulted in very low numbers of these organisms. Similarly, Smith (2016), who investigated the effects of three traffic and three tillage treatments on earthworm density found that only tillage had significant effect and zero tillage featured significantly increased earthworm number than deep tillage, whereas shallow tillage was not significantly different from either zero or deep tillage in autumn, whereas in the repeated analysis in winter, the earthworm population was significantly lower under shallow tillage than under zero. No significant effects were found for the alternative traffic systems or interactions between traffic and tillage.

Despite the overall coherent pictures from many studies on the negative effect of tillage on earthworm population, there is a contradictory picture on the effect of time since the last tillage took place. Marinissen (1992) reported on a quick recovery after a few months whereas other researchers (e.g. Barley, 1959; Low, 1972) suggested that the decreased number of earthworms was observed even 25–30 years after the ploughing was applied. The inconsistencies between those observations might result from other factors besides tillage, for example by having legumes as a catch crop as suggested by Bostrom (1995) or the application of manures (Marinissen, 1992). Roarty & Schmidt (2013) suggested that in case of usage very small experimental plots surrounded by large field margins with high number of earthworms, the earthworms might recolonize quickly those affected areas hence the negative effect of ploughing might vanish after a short period of time.

Soil tillage might not only affect the number of earthworms and their biomass but also some authors reported it might change the species richness. Curry *et al.* (2002) reported a decline in species richness from 9 to 1 species after intensive destoning and tillage before potatoes planting. On the other hand, some authors have not observed any significant effect of cultivation practices on species richness (e.g. Gerard, 1979; Reddy *et al.,* 1997). Another study which investigated the effect of five tillage systems on the abundance of earthworms by Ernst and Emmerling (2009) reported only a decrease in the number of anecic earthworms under deep tillage, whereas unlike anecic earthworms, the endogeic earthworms significantly increased in numbers under deep inversion tillage. The same researchers concluded that that phenomenon might have resulted from redistribution of organic matter to deeper soil layers making it more available to endogeic species as suggested by Chan (2001). The same authors also suggested that these earthworms are smaller in size than the anecic species hence are less affected by mechanical damage associated with inversion tillage. Nevertheless, a relatively recent meta-analysis of the effects of cultivation on the abundance and biomass of earthworms and their community structure performed by Briones and Schmidt (2017) based on 165 publications from the period 1950–2016 concluded that conservation tillage (zero-till and minimum-tillage) significantly increases earthworm abundance (mean increase of 137% and 127%, respectively) and biomass (196% and 101%, respectively) in comparison to the conventional tillage system based on soil inversion or vertical loosening of soil below 15 cm. The same authors also found out that particularly in warm climatic conditions a constant no-till practice for longer than 10 years brought significantly better effects than shorter time under that tillage system. They also concluded that endogeic earthworms are less sensitive to conventional tillage than the surface epigeic and the deep burrowing anecic ones. The same meta-analysis reported that the susceptibility to tillage of anecic earthworms depends on species and *Lumbricus terrestris* is particularly sensitive to tillage and benefitted most from the reduced tillage, whereas other deep burrowing species, e.g. *Aporrectodea longa and A. trapezoides* benefited to a smaller extent from NT system.

2.6.2 Collembola (springtails)

It has been suggested that soil accommodates a significant share (at least 25% of described living species) of the global biodiversity (Bardgett and Wardle, 2010). It is also widely acknowledged that decomposers are key determinants of soil fertility and nutrient uptake by plants since they are responsible for organic matter turnover and nutrient cycling (Bradford *et al.,* 2002; Coleman *et al.,* 2004; Wardle *et al.,* 2004; Bardgett and Wardle, 2010). Nevertheless, as it was mentioned before for many years it was only earthworms which gained the main attention in the studies of soil biology. Yet, there are studies which highlight the importance of variation in decomposer groups which can have a synergistic influence on plant and herbivore performance (Heemsbergen *et al.* 2004; Eisenhauer *et al.* 2010). Bardgett *et al.* (1993) suggested that Collembola (the English name for the group is springtails) are among the most abundant microarthropods in soil and their number might reach up to 60,000 ind. m^{-2} in grasslands (Gange and Bower, 1997). Hopkin (1997) suggested that these soil microarthropods by feeding on soil microorganisms and dead organic matter significantly influence soil nutrient cycling, microbial ecology and soil fertility. On the other hand, Collembola communities also respond to changes in soil chemistry, and agricultural practices (Hopkin, 1997), hence might be a good indicator of soil quality. One of the main limitations in studying Collembola is the lack of available taxonomists (Filho *et al.,* 2016). An alternative approach which facilitates taking into ecological study this taxonomic group is to accept a simplified classification to eco-morphological groups (EM) introduced by Parisi (2001). In that concept, each species according to its degree of adaptation to the particular soil conditions at certain horizon and litter layer can be ranked to a specific EM groups which are edaphic, hemiedaphic, and epigeic. This method is based on morphological characteristics (traits) that are connected to adaptation of each species to the environment. The traits used are: presence of ocelli (simple eye), antenna length, development of furca (tail-like appendage used for jumping to avoid predators), presence or absence of body hairs/scales, and pigmentation; and each traits gives certain score which at the end is summed. The total score ranges from 0 to 20 points. The sum of points in the range 14-20 indicates adaptations to the deeper soil conditions hence edaphic EM group, in the range 8-12 points lies hemiedaphic EM group, and in the range 0-6 – epigeic EM which is the group associated with the soil surface habitat (Filho *et al.*, 2016). The same authors evaluated the EM method and concluded that Collembola EM groups were better predictors of the ecosystem functioning than the density.

Springtails are suggested to be sensitive to different soil use practices (Bandyopadhyaya *et al.,* 2002; Parisi *et al.,* 2005; Sousa *et al.,* 2006; Chang *et al.,* 2013), so there were studies investigating the effects of different agricultural practices on the springtails' abundance. The effects of two deep tillage systems on the Collembola communities were investigated by Petersen (2002), who reported that in the uppermost 4 cm stratum conventional ploughing reduced their population more than the non-inverting deep tillage, while in the deepest stratum (28-32 cm) the immediate effect was opposite. Rodgers *et al.* (2018) in their study on the effect of CTF and on the soil arthropod abundance reported that CTF significantly increased the collembolan abundance comparing to the random traffic system, with highly significant differences in the spring.

2.6.3 Soil organisms feeding activity (Bait lamina test)

Another potential indicator which might be used to assess the soil biological activity and more generally soil health is the Bait lamina test (Terra Protecta GmBH, Berlin, Germany). It is an easy and rapid method to investigate soil invertebrates feeding activity. The test uses rigid PVC stick (120 mm x 6 mm x 1 mm) with 16 holes in 5 mm distance (Kratz, 1998). The diameter of each hole is 1.5 mm. The holes are filled with bait which is primarily eaten by Collembola, mites, nematodes, millipedes, and earthworms. The microbial activity is suggested to play much lower role in bait loss (Hamel *et al.,* 2007, Gardi *et al.,* 2009). Siebert *et al.* (2019) who investigated responses of soil invertebrate activity to drought and fertilization established the method of calculating the feeding activity where each of the 16 holes on one stick gave 1 point in case of an empty hole (entirely eaten bait), half a point when the bait was partly eaten (on one side) and when it was fully filled it gave zero points. Consequently, the total score of a single stick could range from 0 to 16 points. This test gives an overall index of the feeding activity; however, it does not indicate any particular ecological group responsible for the consumption of the bait.

2.6.4 Fungi and bacteria – soil microbial carbon

Another group of organisms which play important roles in nutrient cycling and ecosystem functioning and which responses to agricultural practices is critical to better understand soil processes are fungi and bacteria (de Menezes *et al.,* 2017). The same authors suggested that soil is inhabited by extremely diverse bacterial communities on earth, whereas fungi are often considered to dominate soil microbial biomass, especially under low disturbance or conditions low in nutrients. The disturbances to vegetation and soils might impact microbial communities and in turn the ecosystems functions and services might be threatened (Bender and van der Heijden, 2015). In agreement Joergensen and Emmerling (2006) in their review on methods for evaluating human impact on soil microorganisms suggested that soil microorganisms are sensitive to farm management practices. Morales *et al.* (2015) suggested that changes in soil moisture and nutrient availability resulting from soil compaction can influence microbial diversity and in turn ecosystem services delivered by soil, for instance C sequestration might be affected. Hu *et al.* (2014) reported that the soil microbial biomass is determined by soil organic carbon, which is influenced by plant inputs. However, there are no coherent conclusions on the effects of farming traffic or tillage on microbial populations. Some studies show that tillage negatively affects the size of microbial populations (Sun *et al.,* 2016; Wright *et al.,* 2008), others reported on little effect of tillage on microbial biomass (Calderón *et al.,* 2000; Jackson *et al.,* 2003). Kaiser *et al.* (2014) suggested that those inconsistencies might derive from different soil physical properties across different studies as well as from varying tillage intensities. There are some studies that report on changes between microbial taxa with total biomass not changed. Campbell *et al.* (1991), who investigated crop rotation and influence of fertilizers on soil microbial biomass suggested that fungal community takes advantage in case of decrease in bacterial community and vice versa. In agreement, Sun *et al.* (2018) found that susceptibility to tillage intensity vary across different microbial communities and reduced tillage had a greater effect on fungal communities while bacterial communities were more affected by mouldboard ploughing. Thompson *et al.* (2020) in a study of the effects of wheeled traffic on soil microbial communities in grassland found that direct wheeled traffic had no significant effect on the abundance, diversity, or community structure of either the bacterial or archaeal communities (primitive, single-celled procaryote organisms). In contrast, traffic wheeling increased fungal communities in the loamy soil in comparison to unwheeled soil.

2.7 EFFECTS OF TRAFFIC AND TILLAGE ON PLANT ESTABLISHMENT AND ROOT DEVELOPMENT

Roots play a vital role in the plant growth as the above-ground parts of plants are dependent on the water and soil nutrients acquisition from the soil (Klimek-Kopyra et al., 2018). The rooting depth and root distribution are key features upon which water and nutrients uptake depend, particularly in semi-arid climate (Manschadi et al., 1998). During period with water insufficiency, the capacity of water uptake is related to the depths and the uniformity of roots system (Dardanelli et al., 1997). To avoid water stress in dry soil it is the roots density that plays a vital role (Tron et al., 2015). Boone and Veen (1994) reported that deficit of at least one factor, i.e., water, oxygen and nutrients results in restricted crop growth. In over- compacted soil, insufficient supply of oxygen is a result of limited water infiltration and water logging, which in turn diminishes the availability of oxygen through the slaked surface or when the water accumulates at the bottom of seedbed. Millington et al. (2016) suggested that because of reduced pores size and consequently anaerobic conditions, plant establishment and the root dry mass of winter barley in compacted areas was reduced. The effect of soil compaction on root growth was also investigated by Taylor and Gardner (1963) who concluded that the most critical factor for root penetration in the sandy soils of the Southern Great Plains was soil strength, not soil bulk density. They also concluded that the resistance larger than 2.96 MPa is a limiting value for root penetration, regardless of whether the soil strength was caused by a decrease in the soil moisture or by an increase in bulk density. Later, Logsdon and Karlen (2004) suggested that for silt and silt loam soils, the thresholds of soil bulk density at which roots experience restrictions to growth is at 1.55 Mg m-3, whereas for sandy and sandy loam soils this critical threshold is increased to 1.6 Mg m-3 (Huber *et al*., 2008).

Soil compaction affects the root structure. Głąb (2008) found that soil compaction deriving from tractor traffic resulted in shortening of roots of lucerne (Madicago sativa), as well as in increasing root biomass. In agreement, Chen *et al*. (2014) observed that the root system of narrow-leafed lupin under compacted soil in Australia was characterised by a short and thickened taproot. Materechera *et al*. (1991) found that in strong soil the elongation of roots is reduced, and the diameter increased. Hettiaratchi (1990) suggested that thickening of roots in strong soil is a result of a mechanism of overcoming limiting axial stress by loosening the soil at the root tip. Muñoz-Romero *et al*. (2011) concluded that the length and diameter of faba bean roots under no-till were significantly greater than under conventional ploughing.

2.8 EFFECTS OF TRAFFIC AND TILLAGE ON CROP YIELDS

Arshad and Martin (2002) defined the soil quality index as “the ability of soil to enhance crop production”. The effects of farming traffic and different axis loads and tillage on the crop growth and yields have been studied for many years now. Raghavan *et al.* (1979) reported on the effect of contact pressure on maize yield and concluded that in clay soil in a dry year, a moderate amount of trafficking increases water availability and in turn maize crop yield by up to 19%. Similarly, Arvidsson and Håkansson (2014) investigated the effect of traffic-induced compaction on crop yields in an experiment across 13 sites in Sweden. They concluded that with moderate compaction (one pass with low tyre inflation pressures), wheat showed relative yield increases of up to 12% compared to untrafficked and previously loosened soil. The crop response however relates to the species and the traffic intensities and a further increase in traffic intensity (to three passes with high tyre inflation pressures leading to bulk densities of 1.40-1.45 Mg m^{-3}) caused crop yields decrease in the range of 1% to 21.3% for winter wheat (T*riticum aestivum*) and faba bean (*Vicia faba*) respectively. The same authors did not find an answer to the phenomenon of the increase in the crop yield under slightly trafficked soil, as it contradicts findings by other scientist who suggest that heavy traffic results in inhibited root extension and consequently crop growth and yields (Czyz, 2004; Głąb, 2008; Kaczorowska-Dolowy *et al.*, 2018). Seehusen *et al.* (2014) who studied the effects of load and wheeling intensities of two different farming vehicles combinations at a total load of 16 Mg and 36 Mg, concluded that a single pass at 36 Mg and 16 Mg resulted in a 28% and 23% and yield reduction respectively. The same authors also observed that 10 passes at 36 Mg resulted in total crop loss. There are many studies that report on crop yield increase in uncompacted soil. Chamen *et al.* (1992) reported that yields of potatoes sugar beet, onions and ryegrass increased under controlled traffic farming between 4-14%. The improvements in yield of wheat and barley varied in the range of -9-21%. The variation in data in this research might have resulted from complexity of that study e.g. range of soil textures and types together with climatic conditions. Later work by Chamen (2011) reported a 16% decrease in winter wheat yield under trafficked soil in comparison to untrafficked. In agreement, Dickson and Ritchie (1996) reported that winter wheat, winter barley and oilseed rape yields increased by 19% in uncompacted soil when compared to low ground pressure and random traffic. In Australia, Li *et al.* (2007) reported that with no traffic the winter wheat yields increased by 9% in comparison to soil exposed to one pass of a tractor, whereas Gamace (2013) reported yield increase of as much as 9% and 30% for winter barley and winter wheat respectively under CTF in comparison to random traffic. In agreement, Demmel *et al.* (2015), observed higher wheat and rye yields from untrafficked zones in a study in Germany. Galambošová *et al.,* 2014 in a study in Slovakia reported that the crop yield from the permanent wheelways was 13-17% lower than from untrafficked parts of the field. In agreement, Godwin *et al.,* (2015) in their review of on traffic systems concluded that CTF can increase the overall yield in the range of 15-19% (for shallow tillage with CTF 30% and CTF15% trafficked area respectively) over random traffic with deep tillage. The same authors concluded that CTF management can also improve water infiltration rates and reduce energy consumption. In a further study, Godwin *et al.,* 2017 reported that CTF with 30% trafficked area showed improved yields of winter wheat and spring oats than random traffic with standard tyres pressures. From an experiment in Scotland, UK on the effect of soil compaction on crop performance and soil conditions Ball and Ritchie (1999) concluded that significant differences in crop growth and yield can be observed only in wet conditions, when the yields decreased by 24% under trafficked compared to untrafficked soil.

The effect of the low tyres pressures on crop yields however are not very coherent. Chamen *et al.* (1990) between 1982-1986 investigated the effects of tyres pressures on winter wheat and found no significant differences between treatments. In agreement, Kaczorowska-Dolowy et. al, (2020) reported lack of significant effects of tyres inflation pressures on crop yields. On the other hand, Shaheb (2019) in his study on the effects of tyres pressures and tillage systems on soil properties and crop yield of corn and soya bean in Illinois, USA, observed that the low tyres pressures resulted in an increase by 3.55% of the 2-year mean yield of corn (Zea mays). However, the effect the tyres inflation pressures on the yield of soya beans depended on the year and in 2017 there was no effect, while in 2018 the soybean yield was 3.70% higher from LTP than from STP.

Similarly to the effect of tyres pressures on crop yields, results of many studies on the effect of reduced tillage (zero and shallow) on crop yields do not provide coherent conclusions. Clutterbuck and Hodgson (1984) reported 16% lower yields from direct drilling compared to ploughing. However, they observed the greatest yield decrease in the first growing year and the average difference in yield between ploughing and zero tillage was 4% from the three-year study, with yield penalties from zero tillage observed only in the first two years. Rusu (2005) reported on an increase of the crop yields from ploughing systems with a maximum difference of 14%. Alvares and Steinbach (2009) in their meta-analysis of the effects of mouldboard ploughing, chisel ploughing, and zero tillage on Argentinian yields of soybean, wheat and maize reported that wheat and maize experienced yields decrease by 10% when chisel ploughing or zero tillage were applied in comparison to mouldboard ploughing. Nevertheless, the studies investigated within that review differed in the duration and ranged from 0.5 to 20 years, and not all data were available from all investigated sites. Rieger *et al.* (2008) from a study in Switzerland between 1995-1999 reported only 0.9% and 2.9% yield increase of winter wheat under mouldboard plough comparing to a chisel plough and zero tillage respectively. Those results however presented an average difference in yields across the four-year period of the experiment, however details on the change over time are lacking. And the time is suggested to play a key role in the success of zero tillage: studies by Chamen (2011) as well as by Jemai *et al.* (2013) suggested that zero tillage requires time to recover from cultivation and soil properties gradually improve overtime resulting in good crop development and yield. This is in agreement with Kaczorowska-Dolowy (2020) who reported on the long-term effects of traffic and tillage on crop yields and found out that the crop yield penalties were observed for five years after which the yield from zero tillage equalled or exceeded that from deep and shallow tillage.

There are however some studies that reported on increased crop yields under zero tillage systems, even within the first few years following its adoption. Logsdon and Karlen (2004) reported on lack of negative effect of no-till on crop yields in their experiment on soils classified as Haplic Phaeozems, Cumulic-Haplic Phaeozems, and Calcaric Regosols. However, those could have resulted in the experiment layout where the crop rotation was changed from continuous corn to a two or six-year rotation. This in turn could have resulted in improved crop yields and could have mitigated potential negative effects of implementing a no-till system. Another study which reported on a significant increase (by up to 80%) of winter durum wheat yields under zero tillage in comparison to conventional tillage was conducted by De Vita *et al.* (2007) in southern Italy. The same authors observed such an increase on one of two analysed sites and concluded that no-tillage increases yields in case of limited precipitation, suggesting that this system might be beneficial particularly in the Mediterranean areas with rainwater deficits.

Godwin (2015) indicated that not all soils are suitable for zero tillage. He concluded that chalk limestone soils and well-drained loamy soils might provide yields of both: autumn and spring cereals similar to those from conventionally cultivated crops. The second group of soil types include calcareous clays and clayey or loamy soils over clay which had been improved by drainage. Yield of winter cereal crops on those types of soils are likely to be similar to those from conventionally cultivated soil, however spring crops yields are likely to be lower. And the third group of soil – least suitable for zero tillage, with a substantial risk of lower yields – are sandy soils with low organic matter content, silty soils, wet alluvial soils and poorly drained clayey soils.

2.9 IDENTIFIED RESEARCH GAP

The research on the effect of farming practices on soil properties have identified that the activities aiming at improvement in the agricultural productivity led to soil degradation resulting from soil compaction and from intensive tillage which in turn led to reductions in crop yield. There are few studies into the long-term effect of traffic and tillage interactions on soil properties and crop yield. The so-far studies on this trial reported increased yields from CTF and RLTP agricultural traffic systems compared to RSTP system. There is however no data on how the traffic and tillage treatments affect soil biology and their interactions with soil physico-chemical properties. It has also not been possible to assess the time as a factor which affects the response of soil and of crops to the long-term application of traffic and tillage treatments and their interactions. The increased number of observations expressed as years gives also additional data on the effect of interactions between treatments and the fluctuating weather on crop yields. So far, two three-year studies have been completed within the experimental site and the thesis here presented, reports on the third three-year period of detailed investigation on the effects of traffic and tillage and their interactions on soil properties and crop growth and yield. Smith (2017) investigated crop growth and soil physical properties such as soil bulk density, penetration resistance and soil water infiltration under tracks, as well as low and standard inflation pressure tyres. Millington (2019) apart from crop growth and yield included in his research soil porosity analysis, root development and its relationship to biomass in response to the traffic and tillage treatments.

This work expands on work previously conducted at the site (Smith, 2017; Millington, 2019) as well as comprises novel dataset, which includes extensive investigation of soil physico-chemical and biological properties and their effects on crop growth and yields. This thesis additionally embraces agronomic and environmental implications of farming practices and provides practical guidelines for managing agricultural traffic and tillage.

CHAPTER 3 OVERVIEW OF THE LONG-TERM EXPERIMENT

3.1 LOCATION

The field is located within the Harper Adams University campus, United Kingdom (52°46'58.0"N 2°25'43.9"W). The total area of the experimental site is 3.12 ha, which includes the area of the experimental plots as well as the surrounding headlands. Figure 3.2 shows that the predominant soil series is Claverley, with small areas of Ollerton and Salwick at the edges of the site. All these series produced in the top soil (0-250mm) a very slightly stony sandy loam, however in the deeper soil layer (250-400mm) under Claverley – there is a very slightly stony sandy loam, under the Ollerton series very slightly stony loamy sand, whereas under Salwick – slightly stony clay loam or sandy clay loam (Beard, 1988). The same author reported that the particle size of these soils is in the range of 0.06-0.002 mm. This variability of soil series did not influence the investigated soil parameters. According to Beard (1988) the soil texture was the same (sandy loam), and across the whole Large Marsh, had the same profile of available water and was classified as “slightly susceptible to compaction”. The field lies at about 63 m AMSL.

Before the experiment was established, the field had been maintained in a conventional way of farming, with a cropping history of barley in 2008 and 2009 and grass in 2010.

In 2011, this field was dedicated to this experiment, and drained and subsoiled to a depth of 0.45–0.5m. Then 4-m wide plots were established with an 8–furrow mouldboard plough and drilled with a rotary harrow/drill combination. Crop fertilizing and spraying takes place at 90 degrees to plots at 24m spacing, which creates permanent tramlines. Since 2011, the plots have been treated in the same way (Smith, 2017, Millington, 2019) – the description of treatments can be found in Chapter 3.6.

The uniformity across the experimental site was confirmed by examining electro conductivity, penetration resistance, bulk density, surface and sub-surface soil moisture as well as crop yields in 2011/12 (Smith, 2017), and the analysis of the effects of three different traffic systems subject to three tillage depths started only in the season 2012/13.

Figure 3.1 Location of the experimental site on the map of UK. (Source: adapted from Google Maps) and the plot plan.

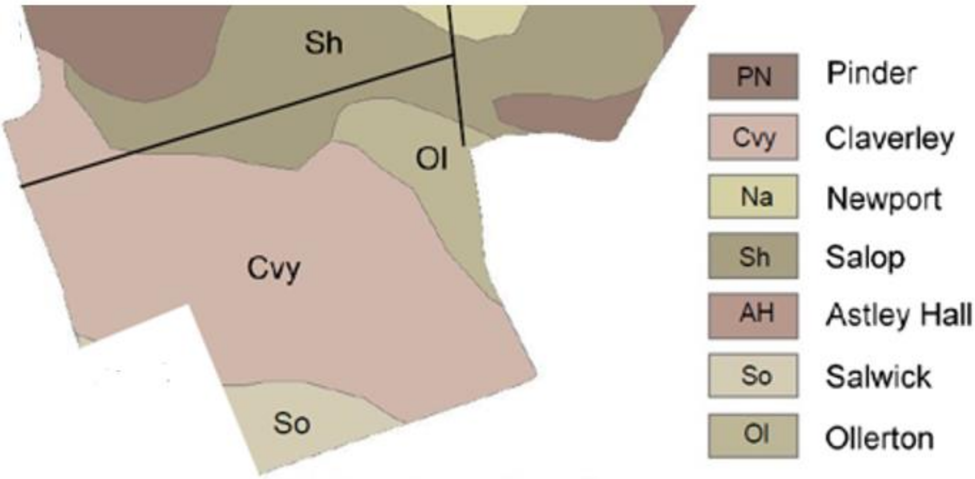


Figure 3.2 Soil series on the Large Marsh field. Adapted from Kristof et al. (2012)

3.2 WEATHER DATA

This chapter presents the weather data from the time of the experiment on the background of the average from 20 years to indicate potential changes of the weather patterns.

The average annual rainfall for years 2000-2020 was 712.9 mm and the yearly average air temperature for 20 years is 10°C, which ranged from 8.8°C (in 2010) and 11°C (in 2011). On average the coolest month is January (5°C) and the warmest is July (17°C). Over the 20-year, the daily minimum observed temperature was -13°C (29 January 2000) and maximum +30.2°C (26 July 2018) (Harper Adams, Weather data).

Figure 3.3 shows monthly average temperatures and total monthly precipitation during the experiment. To reflect weather condition during farming operations (compaction, tillage, drilling) as well as reflect the potential of available soil moisture for growing crops, they are on a seasonal, not yearly basis, i.e. from September until August. The sum of precipitation in season 2017/18 was 590mm, in 2018/19 (winter wheat) was 725mm, and in 2019/20 it was 892mm.

The charts in Figure 3.4 present the temperature and sum of monthly rainfall in each year since the start of the experiment started (i.e., the season 2012/2013). This data is contrasted with the long-term average monthly rainfall and temperature from years 2000-2020.

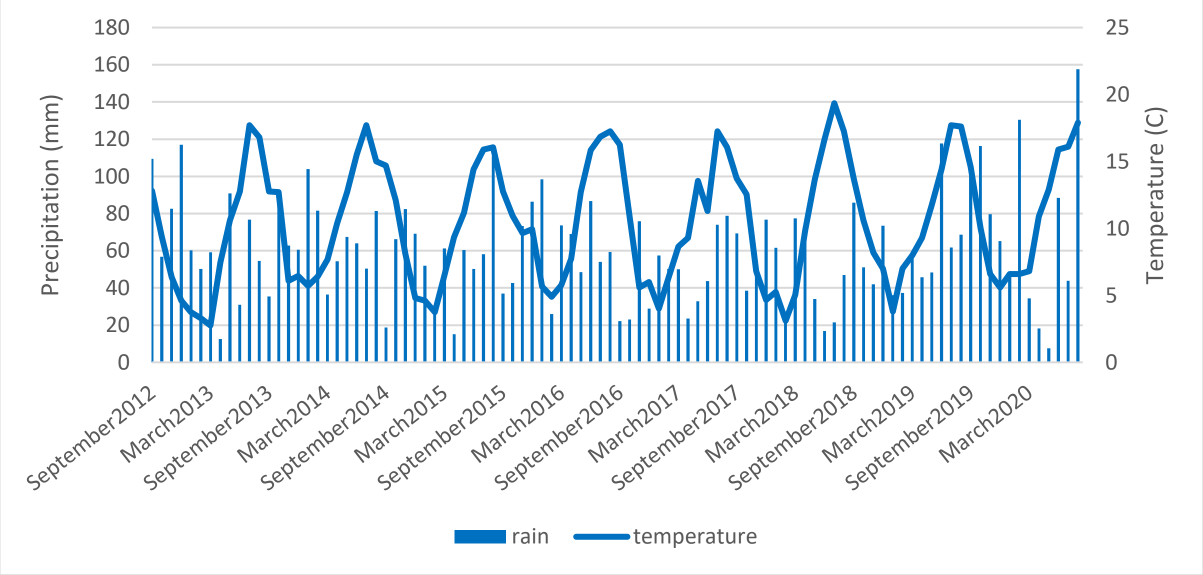
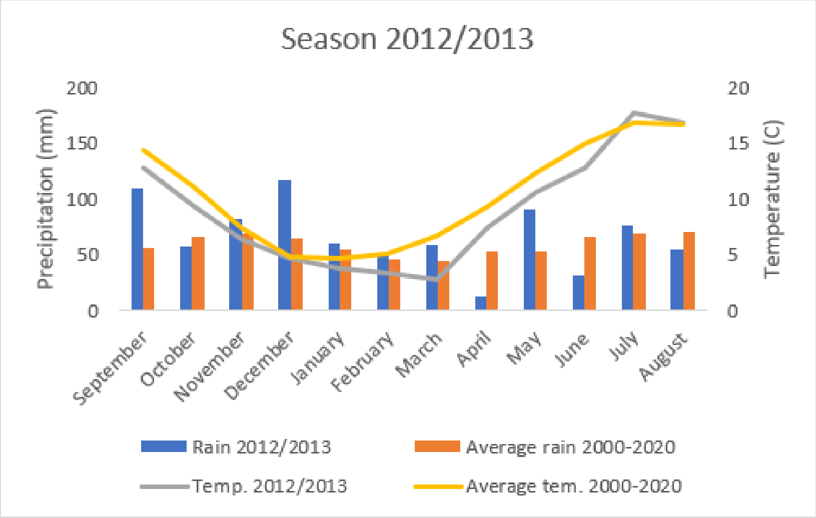


Figure 3.3 Sum of monthly precipitation and mean monthly temperature over the 8-year-study


Season 2012/2013
Precipitation (mm)
Temperature (C)
200
150
100
50
0
20
15
10
5
0
September
October
November
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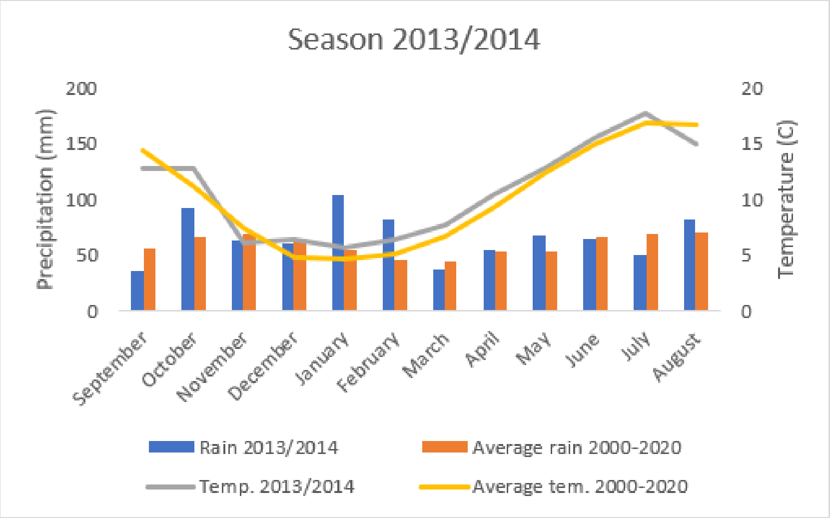
January
February
March
April
May
June
July
August
Rain 2012/2013
Average rain 2000-2020
Temp. 2012/2013
Average tem. 2000-2020


Season 2013/2014
Precipitation (mm)
Temperature (C)
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150
100
50
0
20
15
10
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July
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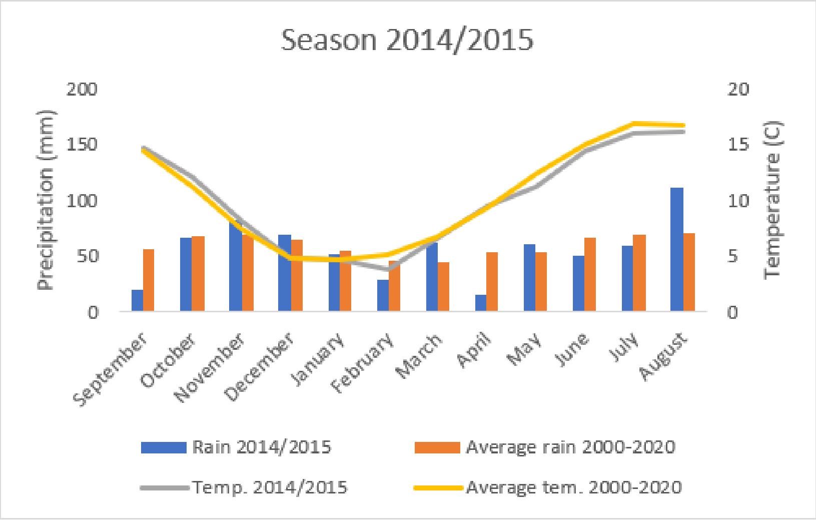
Rain 2013/2014
Average rain 2000-2020
Temp. 2013/2014
Average tem. 2000-2020


Season 2014/2015
Precipitation (mm)
Temperature (C)
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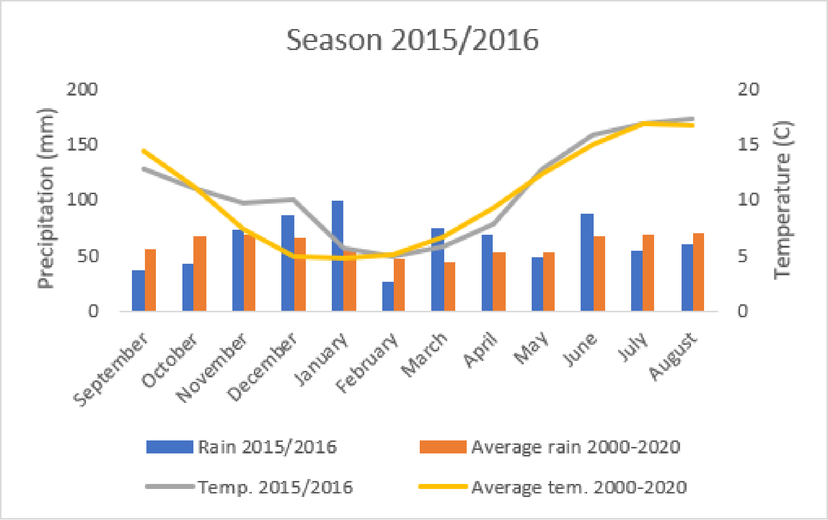
Rain 2014/2015
Average rain 2000-2020
Temp. 2014/2015
Average tem. 2000-2020


Season 2015/2016
Precipitation (mm)
Temperature (C)
200
150
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September
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Rain 2015/2016
Average rain 2000-2020
Temp. 2015/2016
Average tem. 2000-2020

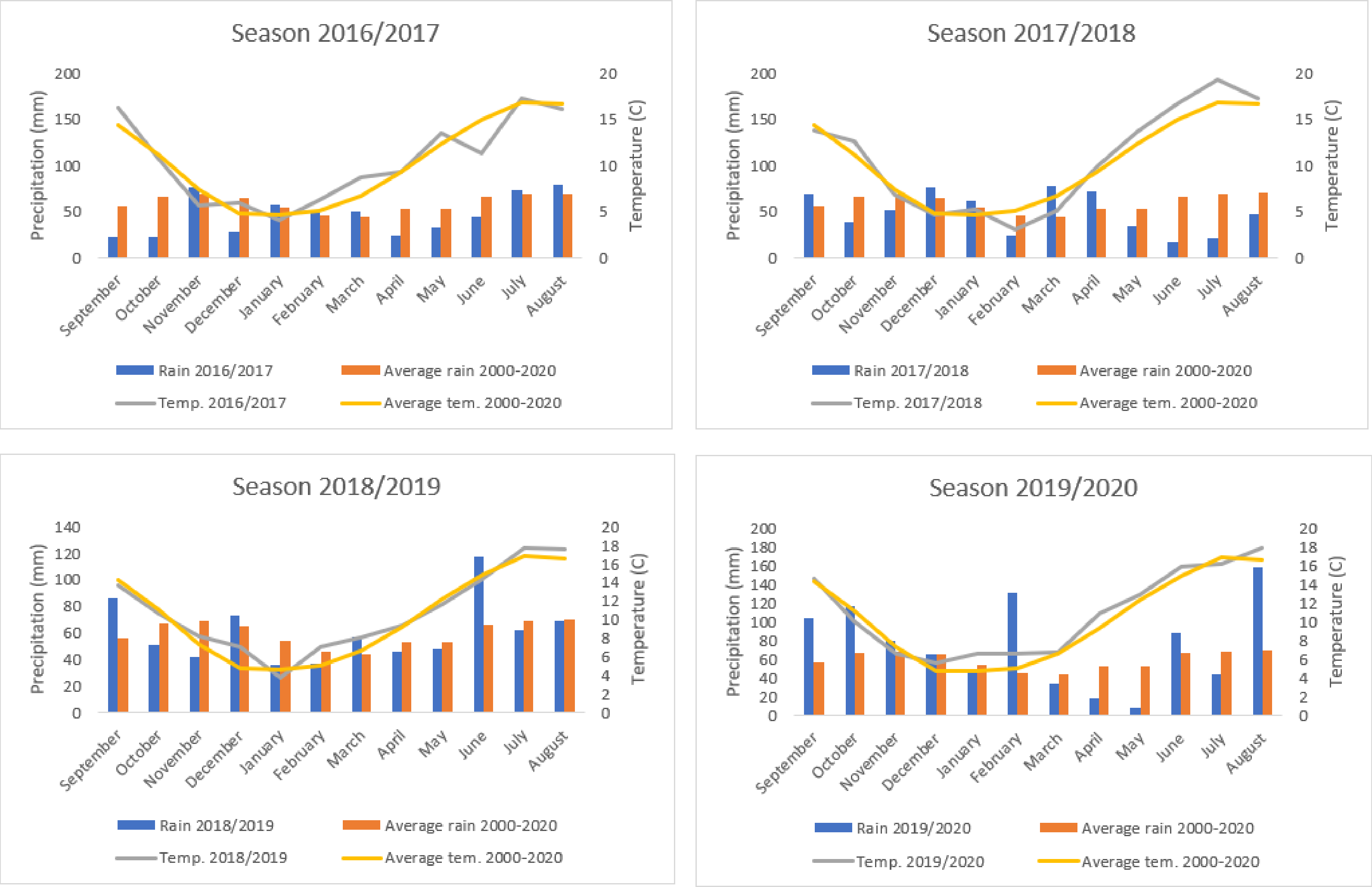


Figure 3.4 Monthly sum of rain and average monthly temperatures in each season of the experiment compared to the average monthly rain ad temperature from the period 2000-2020

The weather conditions from a more crop-related perspective, which is from the time of drilling in the autumn and over the time of intensive growth, in spring to early summer, thus omitting August and September are presented in Figure 3.5. The horizontal straight lines show 20-year-average sum of rain in those two analysed periods. Over the 8 years of the experiment the sum of rain from October till July was greater than the long-term average on four occasions: this related to the crops harvested in 2013, 2014, 2016 and 2020. The sum of rain in those years was respectively 109%, 115%, 113% and 108% of the 20-year average for the same period of time. In seasons related to the crops harvested in the remaining years, i.e., 2015, 2017,2018 and 2019, the sum of rain in those above-mentioned months was lower than average, 93%, 79%, 81%, and 98% respectively. Nevertheless, the average sum of rain from October till July during the 8-year-experiment was very close (99.5%) to the 20-year average for the same period.

The sum of rain over the spring and early-summer months (April-July) was above the long-term average only twice (2016 and 2019, 107% and 114% respectively). The rest of years it was below the 20-year-average and accounted for 88%, 98%, 76%, 72%, 60% and 66% for 2013, 2014, 2015, 2017, 2018 and 2020 respectively. These data show that the 8-year experiment experienced a significant decrease of the sum of rain in the spring and early summer months which on average accounted for 85.1% of the 20-year-average for the same months.

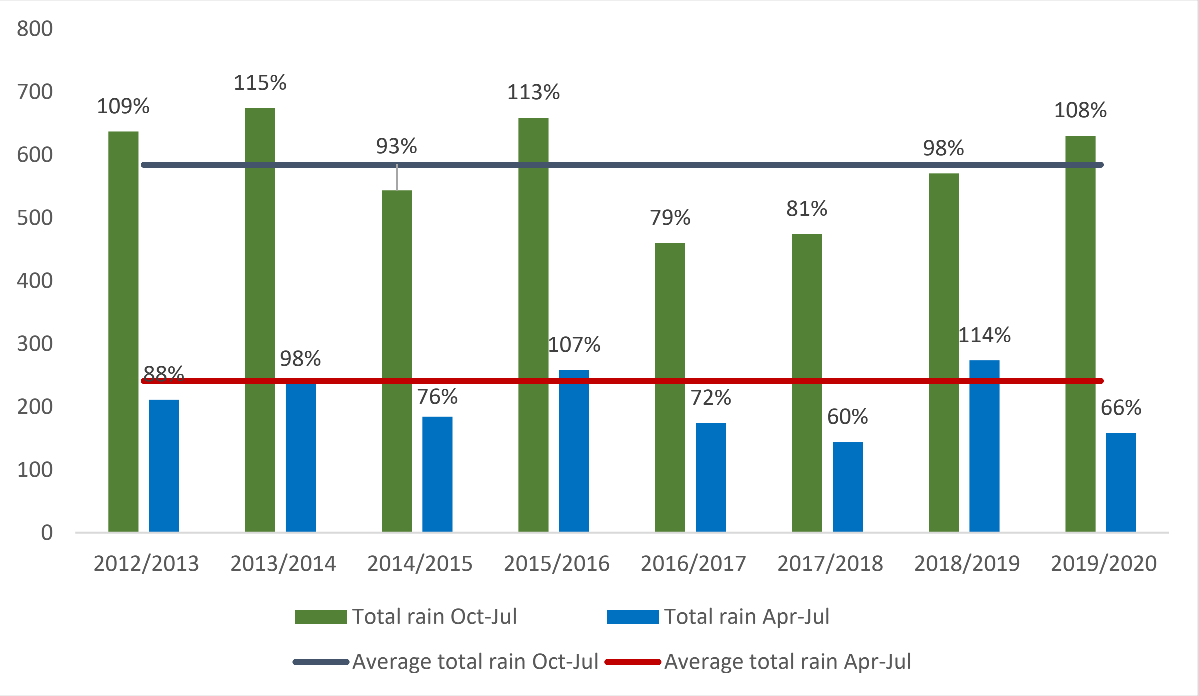


Figure 3.5 Sum of precipitation in each year of the experiment divided into two periods: October- July and April-July in comparison to the average precipitation from years 2000-2020 for the same two periods. The percentage values above the bars indicate the percentage value of the 2000-2020 average for the same periods of time.

3.3 FARM EQUIPMENT AND TYRES

Over the first three years of the experiment (2012-2014), the tillage and crop drilling operations were carried out with a Cat Challenger MT765C tracked tractor (Smith, 2017), whereas a Massey 8480 (290 hp tractor) was used for compaction treatment only (described in more details in Chapter 3.4). An investigation by Smith (2017) found that the Cat Challenger MT765C applied consistently lower ground pressures compared to using MachXBib and AxioBib tyres and concluded that that the wheelways (area under the vehicle's tyre) on all plots regardless the traffic system (CTF, LTP and STP) had benefitted from low ground pressure running gear (Smith *et al.*, 2014).

In 2015 the Cat Challenger was replaced by Massey Ferguson 8480 which since then served for all farming operations, namely tillage and drilling the crops, as well as applying compaction. This change allowed to adjust the tyres pressure accordingly and increase it for STP to better represent the random traffic farming system. Since CTF focuses on minimising the compaction of soil (Gasso *et al.*, 2014) it was decided to apply low tyres pressures for CTF treatments. The current plot layout does not allow the CTF plots to have both low inflation tyre pressure and standard tyre inflation pressure treatments which is recommended for future studies.

The Massey Fergusson 8480 had a total vehicle mass of 12.55 Mg. The mass distribution was 5.55 tonnes on the front axle and and 7.00 tonnes on the rear axle. The track width was 2.1 metres. The tractor was fitted with increased flexion tyres (Michelin AxioBib IF 600/70 R30 159D TL on the front and IF 650/85 R38 179D TL on the rear axle). Prior to 2015, the tyres used were Michelin MachXbib tyres (600/70 R28 front and 650/85 R38 rear) with the same tyre pressures as used with the AxioBib tyres (Smith *et al.*, 2014).

The tyre pressures for STP reflected the common farming practice for this type of tyres applied in farming. The tyre pressure for CTF and LTP plots was adjusted to be the lowest tyre inflation pressure possible whilst maintaining traction and protecting tyre performance (*Michelin,* 2018). The tyre pressures used are shown in Table 3.1 were checked using a calibrated Newbow Ltd © tyre pressure gauge (NB604).

Table 3.1 Tyre pressures (kPa) and tractor loads (kg) depending on task and traffic

	Compaction		Tillage and drilling	
	Front axle	Rear axle	Front axle	Rear axle
CTF	80	80	70	80
LTP	80	80	70	80
STP	110	90	100	100
Additional tractor load	540 - front ballast, 1400 - rear ballast		1400 - front weight	

Both the shallow and deep tillage operations were conducted with a multipurpose Vaderstad Top-Down cultivator. There was no tillage applied on the zero tillage plots.

In 2012 a Vaderstad Rapid drill was used for crop establishment in all treatments. It was replaced by a Vaderstad Spirit in 2013 and used for all subsequent crop seasons. The drill performs levelling, seedbed preparation, reconsolidation, seeding and pressing in one pass (Vaderstad, 2018). For zero tillage plots the discs were lifted to avoid additional soil disturbance.

Harvesting was conducted with a Claas Dominator 85 combine harvester with a 4-m header, matching the plot size (after Smith, 2017 and Millington, 2018). Due to the Claas combine failure, harvest in 2020 was conducted by a New Holland Claydon 8060 combine with the same header width.

To determine the grain weight/plot, an external hopper was hung on a 1-Mg load cell (Novatech Engineering) lifted by a JCB telehandler.

3.4 PLOT PLAN AND COMPACTION TREATMENTS

The four replication blocks were arranged as shown in Figure 3.1. Block 4 had to be offset from blocks 1-3 to avoid the surface inlet of a drain. The three traffic systems were subject to three tillage depths: deep (250mm), shallow (100mm) and zero (no-tillage). These nine treatments were randomly allocated. The final plots layout is shown in Figure 3.6.

Plots were numbered from right to left with a spare plot between blocks. These three spare plots were used to set the tillage and drilling machinery and to check drilling depths prior to applying the treatments to the trial plots.

Plot width is 4 m. Nominally, the plots in block 1-3 are 84 m long and in block 4 – 82 m long, however for operational reasons, the last plot in block 4 (plot 36) is only 78.2 m long (see Figure 3.1).

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

Figure 3.6 Plot layout.

This experiment was designed to reflect trafficked areas reported by Kroulik *et al.* (2009), who determined the percentage of total wheeled area depending on tillage practice. Those authors reported that in an experiment in Czech Republic, which also reflected the typical farming practices in UK, under deep tillage 85.4% of a field is trafficked by at least one wheel-pass within one cropping season. For shallow and zero tillage this is reduced to 64.6% and 42.3% respectively.

To replicate these values, additional traffic was precisely applied on each plot using a Massey Ferguson 8480 tractor with Trimble RTK satellite navigation system. Smith (2017) established the compaction protocol, which was then amended by Millington (2019) who split the compaction treatment to 3 sequences, which allowed to achieve the trafficked area close to the figures suggested by Kroulik. The front and rear tractor tyre from one side of the tractor created additional compaction pass on non-CTF plots, as presented in Figure 3.7. The tyres pressures were adjusted accordingly (described in Chapter 3.3). This way, three different farming traffic system were represented: controlled traffic farming (CTF) which restricts the vehicular traffic to permanent wheelways, random traffic with standard tyre inflation pressure (RSTP) and random traffic with low tyre inflation pressure (RLTP). However, as a result of comparatively narrow plots, constant wheeling width, as well as limitations for driving offsets, the total area covered by wheel passes under RSTP and RLTP was slightly lower than suggested by Kroulik (2009). On CTF plots the permanent wheelways covered 30% of the plot. It is expected that a farm using a CTF system would aim at a lower percentage of wheeled area: Chamen (2015) reported that the usual maximum width for CTF systems is 12 metres, restricting soil wheeled area to 13%. Figure 3.7 presents the layout of the traffic system, depicting the area of the field affected by traffic depending on the combinations of traffic and tillage systems.

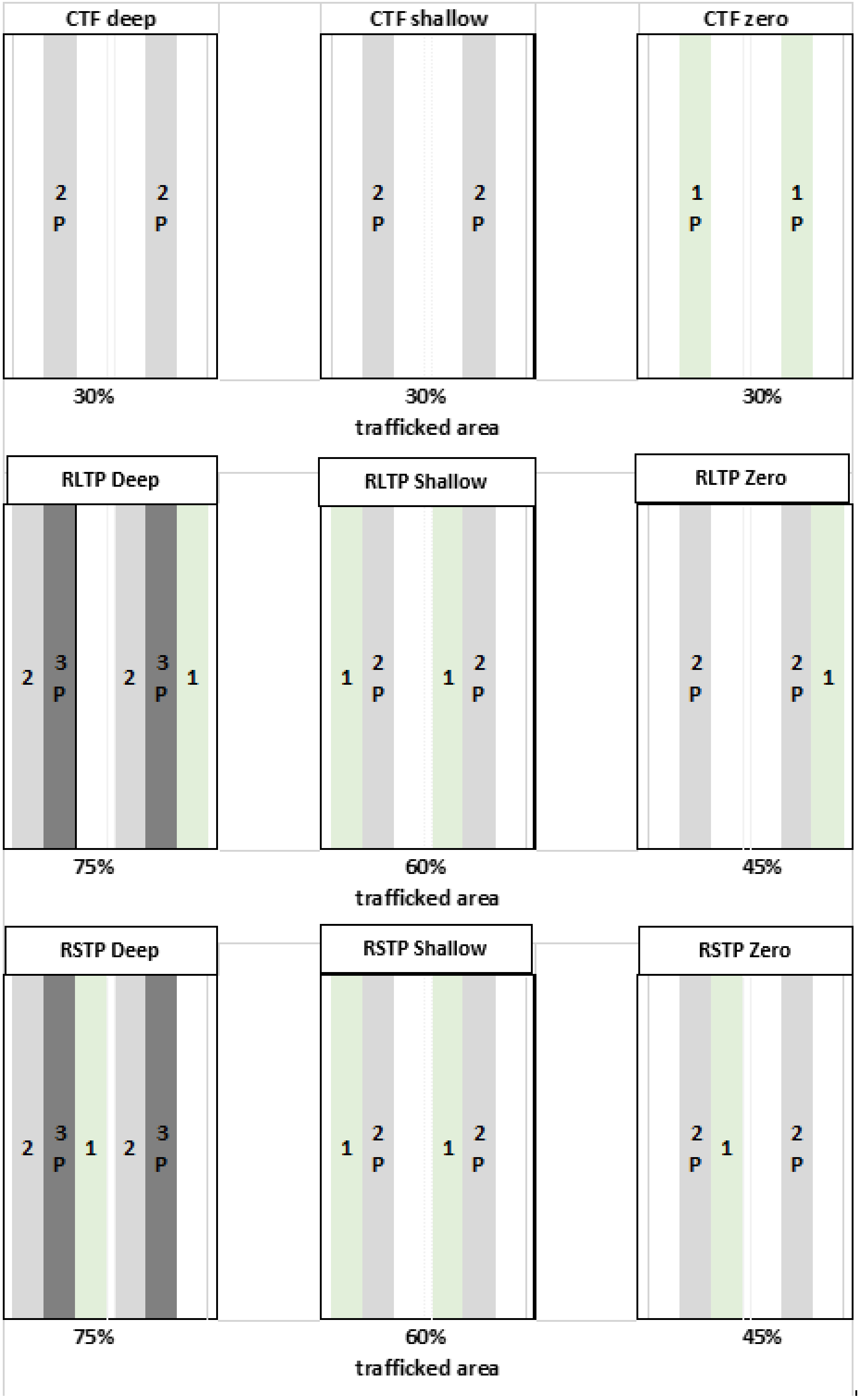


Figure 3.7 Diagram of the traffic system layout depicting the area of the field affected by traffic for the nine combinations of treatments. Coloured strips represent traffic wheel passes. The central numbers show number of passes. Letter P indicates primary wheelways, i.e. tractor passes for tillage (where applicable), drilling and combine harvester. CTF represents controlled traffic farming system, RLTP- random traffic with low inflation pressure tyres and RSTP – random traffic with standard inflation pressure tyres.

The experimental layout allowed for a twofold analysis. On the one hand, CTF plots remained uncompacted in the centres, and so samples from the CTF plot centres allowed to investigate effects of no-traffic (CTFut) on soil and crop characteristics, whereas the wheeled soil on the permanent wheelways on the RSTP and RLTP plots was investigated to quantify the effects of traffic with standard and low inflation pressure tyres (STP and LTP respectively). This approach allowed for further quantification of the overall effects of traffic systems on soil properties and crop growth and yield, as the CTF system retains most of the field unwheeled (Chamen, 2011), whereas under RSTP and RLTP most of the field area is covered with wheel passes (Kroulik *et al*., 2009). Furthermore, as a result of additional compaction treatment on RSTP and RLTP plots described above, the experiment allowed to investigate the overall effects of common traffic systems, namely CTF and RSTP and RLTP on the combine harvested yields, because combine harvester could only collect the crop from the whole plot and could not differentiate between the compacted and the uncompacted parts of the plots.

3.5 TILLAGE AND DRILLING TREATMENTS

Table 3.2 presents the weather and soil conditions on the day of compaction, tillage and drilling, over the 3-year study. It also includes the sum of rain during the 10 days preceding the operation. It shows that whilst preparing the seedbed for winter barley the soil was significantly wetter than in 2018, when the field was being prepared for winter wheat. In 2020 there was no soil moisture analysis done after tillage and drilling due to restricted access to the labs due to covid.

Table 3.2 Weather and soil conditions on the day of compaction, tillage and drilling, as well as sum of rain during the 10 days preceding the operation. GWC stands for gravimetric water content.

Date of operation	Treatment	GWC	Sum of rain
12-Sep-18	Compaction	16%	20.5
03-Oct-18	Tillage	16%	4.0
04-Oct-18	Drilling	16%	4.0
30-Sep-19	Compaction	26%	61.5
10-Oct-19	Tillage	24%	35.9
23-Oct-19	Drilling	27%	20.7
11-Sep-20	Compaction	22%	10.6
26-Oct-20	Tillage	N/A	11.6
27-Oct-20	Drilling	N/A	12.8

3.5.1 Tillage

Tillage was applied with the Vaderstad Topdown 400, which is presented in Figure 3.8. The implement was set for 250 mm for deep and 100 mm for shallow tillage plots. The tillage depth was checked with a wooden ruler inserted in the tine slot. Implement depths were set using packers on the hydraulic rams and depth markers (Figure 3.10). The 14 standard tines had 270 mm spacing and the front discs were set to 50 mm depth. There was no secondary tillage operation on the deep tillage plots.

Figure 3.8 The Top Down 400 implement used for tillage on the Large Marsh experiment.

3.5.2 Drilling

Drilling crops was performed by Vaderstad Spirit 400S which performs levelling, seedbed preparation, reconsolidation, seeding and pressing in one pass (Vaderstad, 2018). For zero tillage plots the front discs were lifted to avoid additional soil disturbance. To enhance combine navigation and to prevent harvesting crop from adjacent plots, the 2 outermost coulters of the 24-coulter drill were blocked to ensure easy identification of gaps between the plots. Wheel mark eradicator tines were lifted on zero tillage plots, while on the remaining plots, they were in use.

Figure 3.9 Layout of the Vaderstad Spirit – seed drill used at the Large Marsh experiment. Reproduced from Vaderstad website (2022).

3.5.3 Crops and varieties

The crop rotation in this study was chosen to reflect typical arable farming in UK with cereals as the main crop. Table 3.3 presents the crop rotation since the first harvest in 2012. This study monitored (year indicates the harvest year): 2018 winter bean (*Vicia faba cv. Tundra*), 2019 winter wheat (*Triticum aestivum cv. Graham*), 2020 winter barley (*Hordeum vulgare cv. Orwell*). In October 2020 another winter barley (*cv. Belfry*) was established to maintain a continuation of the experiment.

A detailed crop husbandry is presented in Appendix.

Table 3.3 Crops target seed rate, dates of drilling and combine harvest since the beginning of the experiment, after Smith, (2017) and Millington, (2019). Crops not highlighted in grey were monitored within this study and their development and yields are presented in this thesis in details.

Crop	Variety	Date of drilling	Target seed rate m^{-2}	Target seed rate m^{-2} on zero tillage plots	Date of combine harvest
Winter wheat	Duxford	09.11.2012	325	325	31.08.-01.09. 2013
Winter barley	Cassia	26.09.2013	No data	No data	22.09.2014
Winter barley	Cassia	20.10.2014	No data	No data	27.08.2015
Cover crop *TerraLife-N-Fixx*	*n/a*	*03.09.2015*	*n/a*	*n/a*	*n/a*
Spring oats	Aspen	25.04.2016	350	450	7-8.09.2016
Spring wheat	Mulika	04.04.2017	400	520	29.08.2017
Winter bean	Tundra	10.11.2017	22	28	10.08.2018
Winter wheat	Graham	05.10.1018	325	417	27.08.2019
Winter barley	Orwell	23.10.2019	400	500	29.07.2020

3.6 DESIGN REPLICATIONS, STATISTICS AND GENERAL APPROACH TO SAMPLING

The experimental design is a 3x3 factorial in 4 complete randomized blocks (3 traffic x 3 tillage systems).

Statistical analysis was conducted using Genstat 18th Edition software. Analysis of variance (ANOVA) was used to determine any significant differences between traffic and tillage systems data as well as interactions. For multiple measurements, mixed effects models were applied and run in R. Post-hoc test for significant differences of means was carried out with Tukey’s test. The significant differences were accepted with 95% confidence, unless otherwise stated.

The measurements of soil and roots attributes were conducted from non-wheeled soil – CTFut and the comparisons were made with soil wheeled with different tyres inflation pressures (low – LTP and standard- STP). Therefore, the performance of soil characteristics under the widely used CTF system was estimated based on the results of the non-wheeled soil which represent the majority of the field in the CTF system.

In agreement, the results from wheeled areas represent the non-controlled (random) traffic systems (RSTP and RLTP) as suggested by Kroulik (2009). Additionally, the condition of the wheeled soil served to predict the performance of soil under permanent wheelways in the CTF system and quantify impacts of absence of traffic vs traffic and estimate the overall benefits of CTF (Chamen, 2011).

CHAPTER 4 SOIL PHYSICO-CHEMICAL PROPERTIES

4.1 OBJECTIVES OF THE CHAPTER, HYPOTHESIS

The objectives of this chapter is to quantify the effects of three different traffic approaches (non-traffic, i.e. CTFut, traffic with low tyre inflation pressure, i.e. LTP and traffic with standard tyre inflation pressure, i.e. STP) and three different tillage depths (deep - 250 mm, shallow - 100 mm and zero tillage) and their interactions on soil physico-chemical properties, namely: bulk density, porosity, penetration resistance, soil volumetric moisture content, soil field saturated hydraulic conductivity and infiltration rate; and on soil chemical properties, i.e.: soil microbial carbon (SMC), soil organic matter (SOM) and pH.

The hypotheses for this chapter are:

1. Agricultural traffic has a negative effect on soil physico-chemical properties; therefore, absence of traffic (CTFut) improves soil health in comparison to trafficked soil (LTP and STP). Additionally, LTP improves soil biological properties in comparison to STP.

2. Reduced tillage (shallow and zero tillage) improves soil physico-chemical properties in comparison to deep tillage.

3. There are no significant effects of interactions between agricultural traffic and tillage depths on soil physico-chemical properties. Hence, the effects of traffic on soil physico-chemical properties are equal for the whole range of analysed tillage depths

4.2 METHODOLOGY

4.2.1 Soil sampling locations

Soil sampling for soil physico-chemical properties followed the same general approach: samples representing untrafficked soil (CTFut) were collected from the centre of each CTF plot, namely between crop row 11 and 12, to represent the soil conditions on the majority of the CTF system. To quantify the effects of traffic with standard and low tyre inflation pressures STP and LTP respectively, soil samples were collected from the primary wheelways of RSTP and RLTP plots respectively, i.e., between crop row 4 and 5, to represent the majority of the random traffic farming with standard and low tyre pressures, as suggested by Kroulik (2009).

4.2.2 Soil bulk density (BD)

Samples for BD were collected on 29-30 March 2019. Undisturbed soil cores were collected with a 50 mm diameter, 300 mm long auger (Eijelkamp, Netherlands), fitted with a plastic liner. One sample was collected from each plot. To avoid potential soil compaction inside the liner, the samples were not completely filled, with the analysis restricted to 250 mm.

The soil sampling reflected the general sampling approach – from CTF, the samples were collected from the unwheeled centre of the plot - further referred to as CTFut - to represent the soil conditions on the majority of the plot, whereas on LTP and STP – from the permanent wheelway to capture the effect of trafficking with different tyre inflation pressures.

The soil core in the liner was put in a bespoke device (jig) made of a section of a wastepipe of an internal diameter matching the external diameter of the core liner. The jig had a slot which allowed a saw to precisely cut the samples vertically into 50-mm slices (Figure 4.1 and Figure 4.2), after Millington (2019). The BD was calculated from the mass of oven-dried soil (ms) to the bulk volume of the soil (Vs), where *BD=ms/Vs* (Blake and Hartge, 1986). The BD was calculated for each 50mm increment and then analysed statistically with mixed effect model.

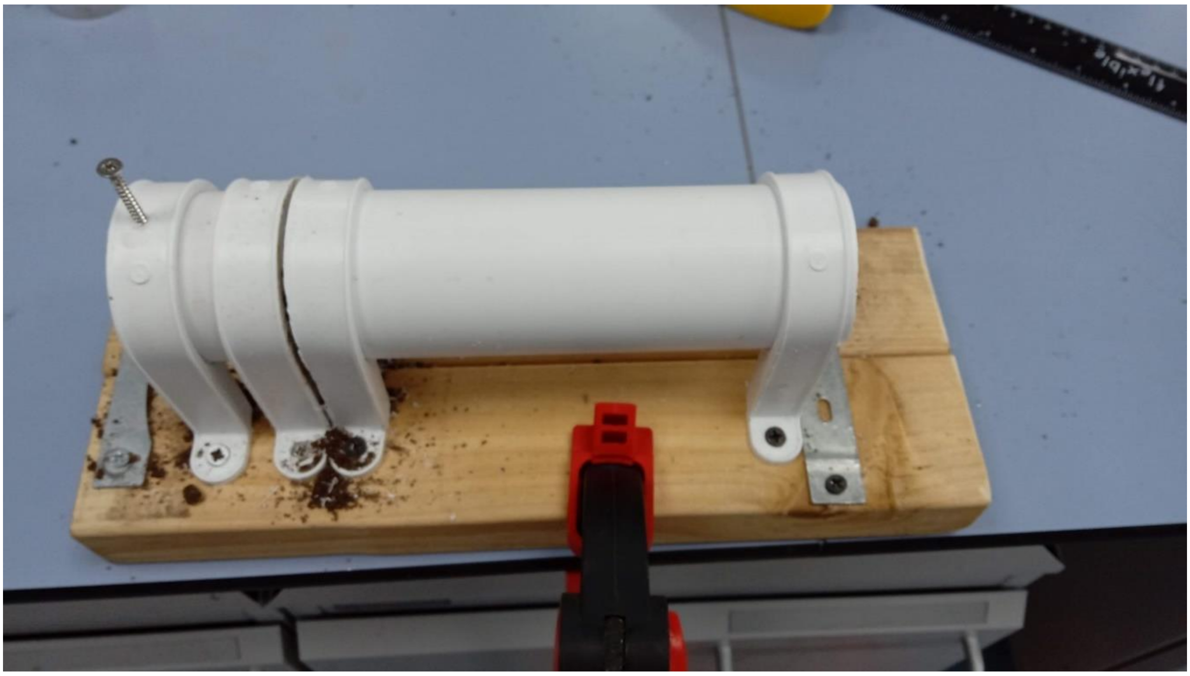


Figure 4.1 Jig used to section cores into 50 mm long samples

Figure 4.2 50-mm long slice of soil after cutting to measure soil bulk density

4.2.3 Penetration resistance (PR)

Soil penetration resistance was assessed with an Eijkelkamp 06.15.31 manual Penetrologger set, with the 1 cm^2 base area cone (30º top angle) following the guidance provided in Eijkelkamp (2000) (Figure 4.3). Five repetitions from each plot were averaged to obtain a single result. The sampling points were spaced several meters apart to account for spatial variability. A great emphasis was put to maintain an equal speed of insertion of the rode down the soil profile. The PR data were collected on 23 October 2020 – after compaction but before tillage to observe the main effect of traffic on penetration resistance, as well as potential long-term effects of tillage. The observation of the draining outlet to the nearby brook, confirmed the field was around field capacity (c. 23% on this site, which was confirmed during the soil moisture analysis, see Chapter 4.3.10), which is suggested to be the right time for PR analysis (Miller *et al.* 2001). It was not feasible to assess the soil water content simultaneously as suggested by Ayers and Perumpral (1982) due to lack of equipment.

The readings were limited to the 0-0.45 m soil horizon as the deeper soil zone resulted in many missed readings due to both high soil resistance and the presence of stones. The reading from the first centimetre was discarded as there was no penetration resistance. The results were analysed with mixed effects models ANOVA with R on the square-rooted results to ensure homoscedasticity, using *lmer4* package. The pair-wise comparisons between means were calculated with *emmeans* package.

Figure 4.3 Eijkelkamp 06.15.31 Penetrologger set (Source adapted from Eijelkamp, 2021).

4.2.4 Soil porosity

Soil porosity was investigated with X-Ray computed tomography (X-Ray CT). Scans were conducted using undisturbed soil cores collected on 17 June 2019 with an Eijkelkamp soil core sampler fitted with plastic liner of ø48 mm x 300 mm length in accordance with Eijkelkamp manual (not dated). This size of a soil core was confirmed to be suitable for the X-ray CT studies of porosity (Rab *et al.* 2014, Millington, 2019). One sample was collected from each plot.

The soil sampling reflected the general sampling approach. The soil cores were sealed with selo-tape to avoid drying and scanned during the next few days using a Phoenix v|tome|x m X-ray microfocus CT system at Hounsfield Facility at The University of Nottingham in UK (Figure 4.4). Samples awaiting scanning were stored in a dark room with temperature set to 4^{o}C to avoid drying out and reduce microbial activity.

The X-ray scanning was conducted by staff of the Hounsfield Facility, Nottingham University, UK following a typical X-ray Computed Tomography cone-beam configuration setup (Wildenschild and Sheppard, 2013), in which the X-rays are emitted from the source and pass through the sample which rotates incrementally through 360°; and subsequently the attenuated X-rays are collected by a detector.

The CT scanning parameters were: 0.075 mm resolution, 160 KV, 150 mA, 250 ms detector time. In order to cover the full length of the core, two scans were required, 0-125 mm, 125-250 mm. Scan files were exported as raw volume files (.raw) which were merged maintaining the same contrast using VG Studio MAX 2.0 software. The resultant 2-dimension X-ray maps were exported as cross-sectional view (top view) files in .tiff format (Figure 4.5).

The Stacked images were then analysed using ImageJ version 1.50i (Abramoff, 2004). To avoid the effect of beam hardening which is the phenomenon when a selective attenuation of lower energy photons from the X-ray beam occurs, effectively increasing brightness of the outer edges of the object's image (Brooks *et al.* 1976), an area of interest 400-pixel x 400 pixel (30mmx30mm) in the centre of the images was selected and the exterior of the images discarded. Then the pictures were converted to 16-bit-images and the soil pore space was selected using the Li thresholding algorithm based on Li and Tam (1998) (Figure 4.6 and Figure 4.7). Values below the threshold were identified as pore space.

The porosity analysis for all of the stacked images was analysed with the ImageJ 'Analyse Particles' function and results were saved in a spreadsheet containing the calculated total number of pores, total porosity area (the percentage of areas highlighted in red during the thresholding representing pores vs the total analysed region of interest), mean pore size, mean pore diameter and mean pore circularity. The perimeter is the length of the outside boundary of the selection of a pore. Pore circularity is a measure of how circular the pores are, with a value range from 0 to 1. When the circularity value approaches 0.0 it indicates an increasingly elongated polygon (Ferreira & Rasband, 2012), whereas a circularity value of 1 indicates a perfect circle (Kim *et al.*, 2010a). Circularity C is measured according to the Equation 4-1, where S is the surface area of the pore, and P is its perimeter:

Equation 4-1

$$C= 4\pi * S * P^{-2}$$

All above mentioned parameters were calculated for each of 1705 slices, namely every 0.130mm of each sample. The ultimate length of the soil core was 221.65 mm.

The coefficient of uniformity (CU) often called uniformity index (UI) was calculated based on the histogram of pore size distribution as the ratio of the size at which 60% of the sum of pores size are smaller to the size at which 10% of the pores are smaller, similarly to the particle size analysis (Craig, 2004). The higher the value of the CU, the larger the range of particle sizes in the soil. This was the only analysis conducted on the raw data which is included the description of each pore. The remaining analyses (number of pores, size, porosity, circularity) were conducted on the summary file which provided averaged information about pores characteristics averaged per image slice (30mmx30mmx0.13mm depth).

The statistical analysis of pores characteristics was conducted in R (2021) with mixed effects model, accepting traffic, tillage and soil layer (horizon at 50mm increments) as fixed effects and plot nested in block as a random effect. To ensure homoscedasticity (homogeneity of variance of the variables), some analysis required data transformation: pore count and porosity percentage analysis was conducted on square-rooted data, whereas pores perimeter and size on log-normal-transformed data. The results presented in Chapter 4.3 show the actual results, so the reader does not need to do back-transformation.

Figure 4.4 Phoenix v|tome|x m X-ray microfocus CT system

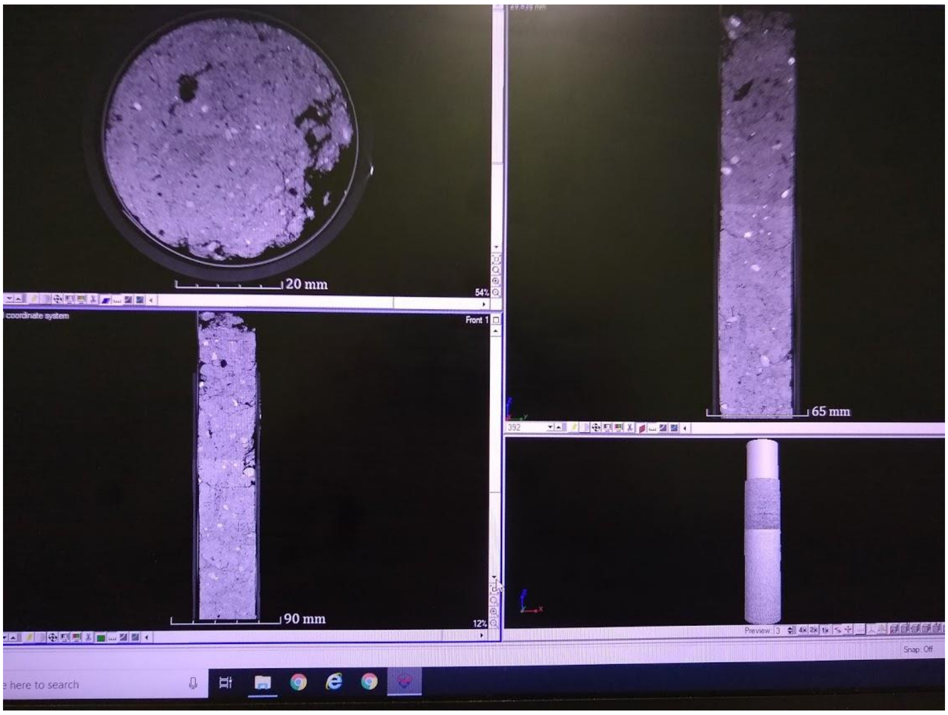


Figure 4.5 Top view (upper left) and side view (bottom left and top right) of combined X-ray CT scans in VG Studio

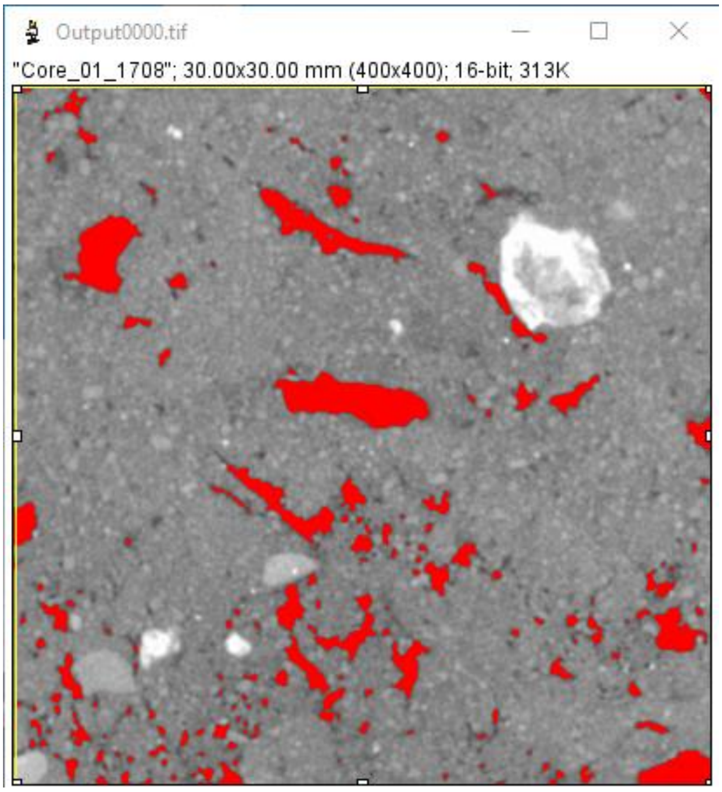
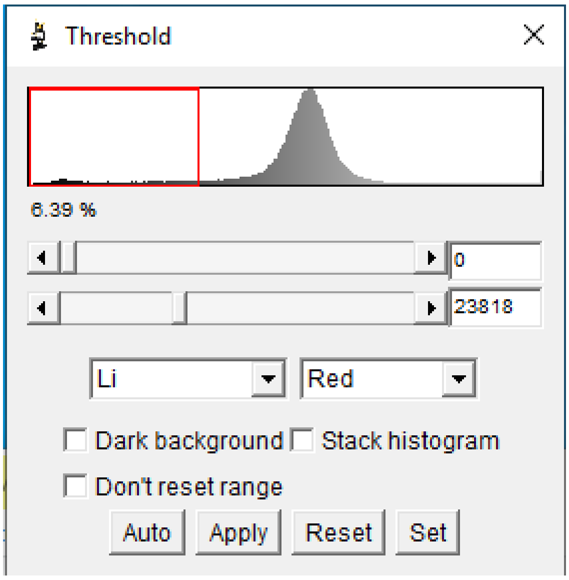


Figure 4.6 Soil pore space selection on a cropped 16-bit image (red) using thresholding



6.39 %

0

23818

Li

Red

☐ Dark background ☐ Stack histogram

☐ Don't reset range

Figure 4.7 Segmenting using the Li thresholding algorithm. Histogram portion in red box represents pore space.

4.2.5 Soil moisture content

Soil samples were collected annually, on the day of the compaction treatments, for soil moisture content analysis using the gravimetric method. Two samples per plot were collected from 0-100 mm layer of soil and mixed, weighted, then oven-dried at 105ºC for 48 h as suggested by Reynolds (1970). The gravimetric soil moisture was calculated as a weight of water (the difference between weight of moist soil and dry soil) divided by the weight of dry soil (Reynolds, 1970).

Additionally, during the 2019 season, the volumetric soil moisture was analysed with the Trime-Pico-IPH by Eijelkamp moisture probe (Figure 4.8), on the dates provided later in this chapter. This is a time-domain reflectometer (TDR) sensor which collects a depth profile of the soil moisture content. A series of 1-m long access tubes were installed at the beginning of the season (in February 2019) and kept in the field until just before the crop harvest in August 2019, following the general approach for sampling (uncompacted centre of plot for CTFut and primary wheelway for LTP and STP). The access tubes were kept closed (lids on) between the consecutive measurements and opened only before the measurement. All condensate water was wiped away with a clean cloth on a 1.5 m long stick before each reading.

It is suggested that the TDR probe features most effective penetration at a distance of about 150 mm with the highest sensitivity in the immediate vicinity of the access tube and decreases exponentially with distance (Trime Eijalkamp manual 2021). To maintain coherence across all plots as well across consecutive measurements, the sensor was always inserted in the access tube in the same direction.

Figure 4.8 Trime-Pico-IPH by Eijkelkamp moisture probe. Adapted from the TRIME-IKO-IPH manual, Eijkelkamp 2021.

The original intention was to record the soil moisture contents with the TRIME TDR probe at three depths 0-200 mm, and 300-500mm and 500-700 mm, it was found, however that the 500-700mm soil depth was unachievable as the permanent tube on one plot could not reach that depth. A series of attempts to find a location where the tube would reach the desired depth were unsuccessful, and as a result the 500-700mm deep readings were not analysed. The two remaining depth 0-200mm and 300-500mm were analysed on eight dates (2019.02.22, 2019.02.26, 2019.04.10, 2019.04.18, 2019.05.24, 2019.06.09, 2019.07.16, 2019.08.06). However, from 18 April, additional two sampling depths were included: 04-24cm and 15-35 cm, which resulted in four readings of full range of depths. It was not possible to select a finer resolution of soil depth as the vertical resolution of the sensor is restricted to 20cm. Hence, the depths were chosen to represent the soil zones affected by the tillage depths, whilst at the same time to making it feasible technically. To ensure the sensor reached the required depth, a colour label was placed on the sensor's cable so that it was visible through the transparent plastic tube. Figures representing average soil moisture depending on traffic, tillage and depths were calculated based on results as from 18 April to ensure balanced design.

The statistical analysis was undertaken using R (2021) with repeated measures (mixed effect) models as suggested by Zuur (2009). The model applied to this analysis included plot nested in block and date as a random effect, whereas traffic, tillage and depth as the fixed effect. The packages used for this analysis included *lme4*, *visreg*, *lmerTest*, and *emmeans*.

4.2.6 Field-saturated hydraulic conductivity and instant water infiltration rate

To determine the field-saturated hydraulic conductivity (Kfs), the simplified falling head technique (SFH) was used, as suggested by Bagarello *et al.* (2004), and Bagarello *et al.* (2007). The SFH technique requires applying quickly a small volume of water, V, on the soil surface confined by a ring inserted to the soil and in measuring the time (t) from the application of water to the moment at which the surface is no longer covered by water. This method is much less time consuming in comparison to the double-ring infiltrometer method, at the same time provides with trustworthy results (Bagarello, 2004).

The Kfs was calculated using the Equation 4-2 (after Bagarello *et al.*, 2004), where Kfs is field saturated hydraulic conductivity, ΔΘ is the difference between the final (after water application) and the initial volumetric soil water content, D represented the height of water corresponding to the volume of water V, (calculated by dividing the volume of water by the surface area of the cross section of the ring), and the value for α was accepted at 12 m^{-1} representing structured soils, medium and fine sands (Elrick and Reynolds, 1992). The Kfs results were then averaged per each plot. The results were then transformed using a square root transformation to achieve Gaussian distribution of residuals and analysed using ANOVA in Genstat 19th Edition.

Equation 4-2

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

The test was conducted in two sampling points approximately 2 m and 5 m into the plots from the third tramline for two sampling points respectively. The data was collected during three days from 7 to 9 October 2020 and on each day a whole block or two were sampled to mitigate potential changes in soil conditions resulting from weather changes. These dates were chosen to investigate the effects of soil compaction and potential long-term effects of tillage on the soil hydraulic properties: the compaction treatment was done four weeks before the analysis (11.09.2020), whereas the last tillage was delivered a year before (10.10.2019).

For this test, metal rings of internal diameter of 153 mm were used. The rings were gently inserted to the soil with a wooden plank and mallet at a depth of 0.12m as suggested by Bagarello *et al.* (2007). Bagarello *et al.* (2004) suggested that to ensure one-dimensional flow of water, the volume of water needs to be small so it does not exceed the volume of voids within the soil volume confined by the ring. To assess the required amount of water, before the test, a trial on plot 1 at around 2 m to 4 m from the first tramline was conducted. It showed that 500 ml and 300ml failed to infiltrate after 2 hours. The high results of volumetric soil moisture indicated that 100ml of water would be adequate for this analysis. To calculate the difference of soil moisture, required by the Equation 4-2 for Kfs, volumetric soil moisture was measured with a Theta Probe (FieldScout TDR100) equipped with rods of 75mm length. It was measured in three points outside the ring which were averaged to represent the initial soil moisture. After the water infiltrated in the ring, the soil moisture measurement was conducted in 2-3 points inside the ring and again the readings were averaged to calculate the final soil moisture.

The results from this analysis were also used to calculate the instant infiltration rate, by dividing the amount of water by infiltration time taking into account the area of soil confined by the ring (USDA, 1999). The instant infiltration results were transformed using a natural-logarithmic-transformation to ensure homoscedasticity (equal variance of the samples).

4.2.7 Soil microbial carbon (SMC), soil organic matter (SOM) and pH

Samples for the analysis of soil microbial carbon, soil organic matter and pH were collected on 27 September 2019, i.e., after harvest, but before compaction and tillage. From each plot soil samples were collected from three points to account for field heterogeneity. The soil sampling reflected the sampling approach – from CTF, the samples were collected from the unwheeled centre of the plot - further referred to as CTFut - to represent the soil conditions on most of the plot area, whereas on LTP and STP – from the permanent wheelway to capture the effect of trafficking with different tyre inflation pressures.

The sampling points were at a distance of around 7 m one from another. At each point, four soil samples were collected at a distance 200-500mm, with an auger (Ejelkamp, 40 mm diameter) and separated to two depths: 0-100mm 100-200mm. On the same day the soil samples were pressed through a 0.475 mm sieve and divided into subsamples for further analyses, i.e., moisture, soil microbial carbon (SMC), soil organic matter (SOM), and pH. Soil subsamples for moisture were immediately put to the oven set for 105ºC for 48 hrs. Samples for SMC were processed the next day with 0.5 M K_2SO_4 as described by Vance *et al.* (1987). The chloroform-fumigated samples were kept in the chloroform atmosphere for 7 days. Samples were processed with TOC (Analytik Jena, Germany). The sample digestion method for TOC was the high-temperature combustion at 800ºC. Calculation of SMC was done using the *Equation 4-3*.

Equation 4-3

$$SMC=Fc/Kc$$

where Fc is the difference between TOC from chloroform fumigated and non-fumigated sample, accounting for moisture and weight of sample, while coefficient Kc=0.45 was accepted after Jenkinson and Powlson (1976).

Samples for SOM were air dried in 30ºC for 3 weeks and just before the analysis, oven dried in 105ºC for 24 hrs to reduce water content, next ashed in 400ºC for 16 hours (Nelson *et al.*, 1996). SOM was calculated as %OM = [(W105-W400)*100]/W105 where W105 is weight of oven dry soil and W400 is the weight of soil ashed in 400ºC (Nelson *et al.*, 1996).

The soil pH was analysed on air-dried samples (30ºC for 3 weeks); mixed with distilled water in the volumetric proportion 1:2.5, and analysed with Jenway 3510 pH meter as suggested by Carter and Gregorich, (2008), see Figure 4.9.

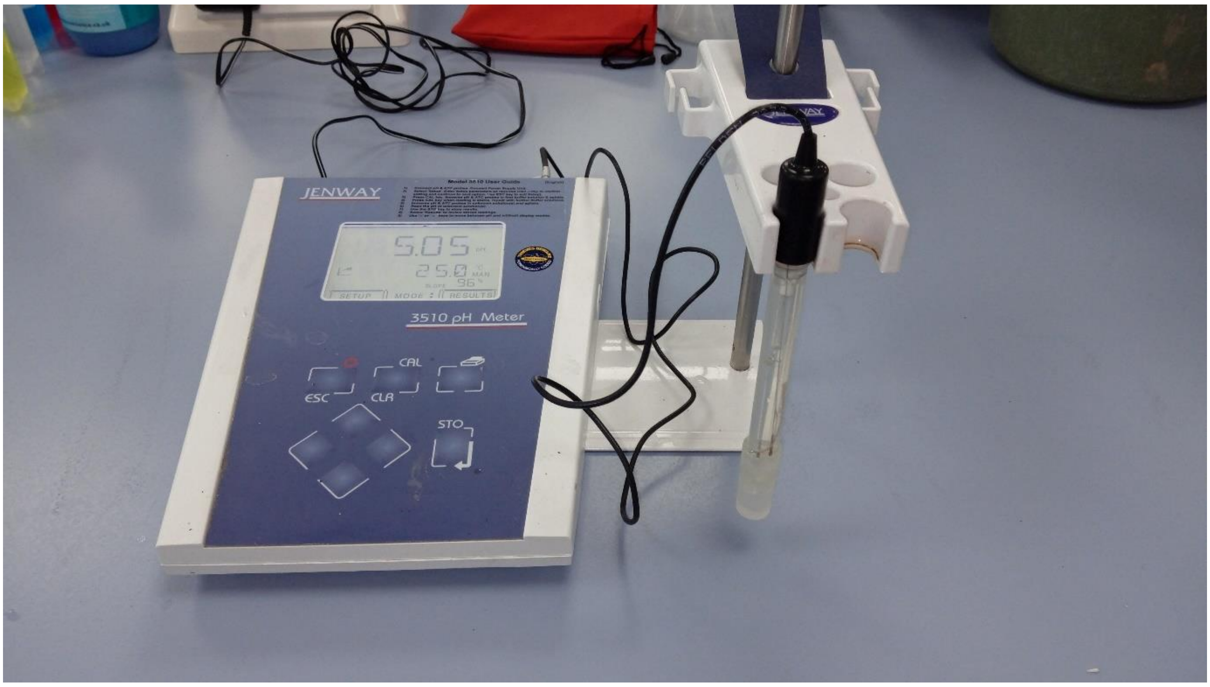


Figure 4.9 The pH meter (Jenway 3510).

4.3 RESULTS

4.3.1 Soil bulk density (BD)

The main effect of traffic and depth were significant on soil bulk density (BD) ($p<0.001$ for both factors). The main effect of tillage was not significant (p=0.758), similarly interactions between tillage and traffic (p=0.159), depth and tillage (p=0.224), depth and traffic (p=0.422) as well as depth and tillage and traffic (p=0.586) were not significant (cv=6.2%). For the three analysed traffic systems the averaged soil BD down the 0-250mm soil profile was 1.31, 1.42 and 1.45 Mg m^{-3} for CTFut, LTP and STP respectively and for tillage 1.40, 1.39 and 1.40 Mg m^{-3} for deep, shallow and zero tillage respectively.

Figure 4.10 presents the BD for three traffic systems across 0-250mm soil horizon in 50-mm increments and shows that the untrafficked soil CTFut featured significantly lower BD than remaining two traffic systems down to 200mm soil depth. At each soil horizon there was no significant difference between LTP and STP. The BD increased down the soil profile: on CTFut from 1.15 g cm^{-3} to 1.42 g cm^{-3}, on LTP from 1.29 g cm^{-3} to 1.50 g cm^{-3} and on STP from 1.34 g cm^{-3} to 1.48 g cm^{-3} from the top soil stratum to the deepest. Under STP the maximum BD was reached already at 100-150mm soil horizon, whereas on CTFut it decreased with each soil stratum. At 200-250mm depth there was no significant difference between traffic systems.

Figure 4.11 shows the BD depending on tillage systems down the soil profile and reveals that the main effect of tillage was not significant. Only separate ANOVA for each depth shows significant difference between tillage systems at only one soil horizon (100-150mm) where deep tillage featured significantly lower BD than zero tillage, whereas shallow tillage did not differ significantly from the remaining tillage systems (1.37 g cm^{-3}, 1,43 g cm^{-3} and 1.40 g cm^{-3} respectively).

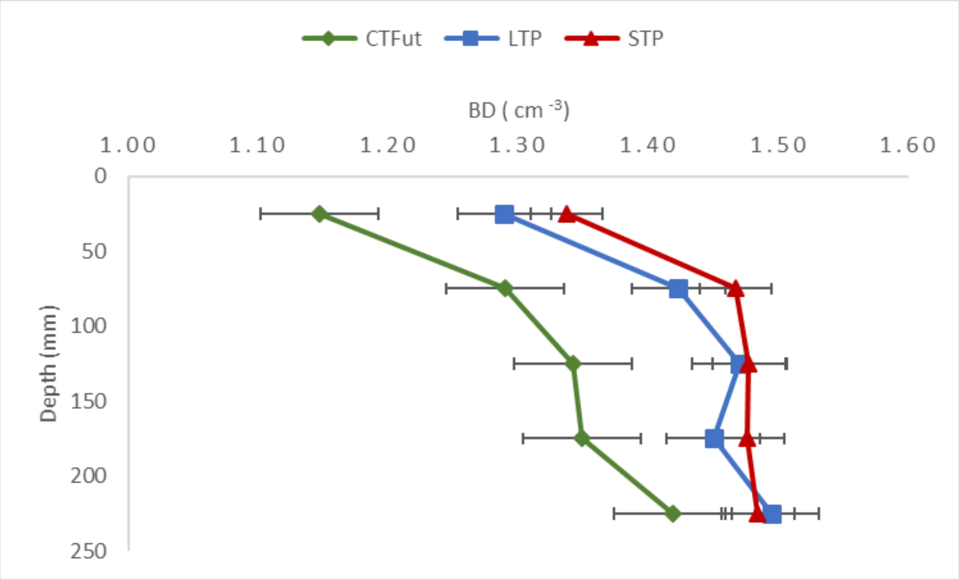


Figure 4.10 Soil bulk density (BD) across five soil horizons in 50-mm increments depending on three traffic systems: CTFut – non-trafficked soil, LTP –soil trafficked with low inflation pressure tyres, STP –soil trafficked with standard tyres pressure. Horizontal lines represent the standard error.

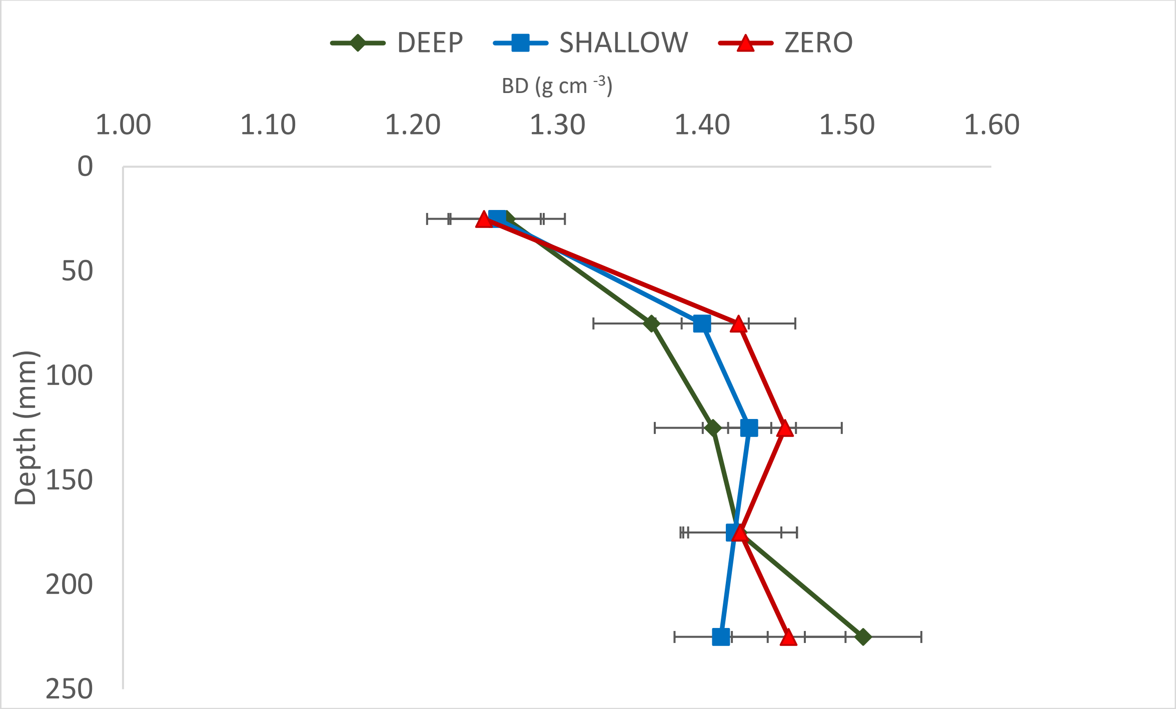


Figure 4.11 Soil bulk density (BD) across five soil horizons in 50-mm increments depending on tillage system: Deep – 250 mm, Shallow – 100mm, ZERO – no tillage. Horizontal lines represent standard error.

4.3.2 Penetration resistance (PR)

The main effects of traffic and depth on the penetration resistance were significant ($p<0.001$). Interactions between traffic and depth as well as tillage and depth were also significant ($p<0.001$). The main effect of tillage was not significant ($p=0.1204$). There was no significant effect of interactions between traffic and tillage ($p=0.397$, cv=8.7%).

Figure 4.12 presents the main effect of traffic on the PR down the soil profile and shows that across the analysed soil horizon, the unwheeled soil under CTFut featured significantly lower PR than LTP and STP (on average across all depths 1.65 MPa, 2.27 MPa and 2.32 MPa respectively). The PR under the LTP did not differ significantly from STP. The PR thresholds of 2MPa which is suggested to restrict root growth (Hamza and Anderson, 2005) was exceeded at 0.30 m, 0.15 m and 0.12 m under CTFut, LTP and STP respectively. The highest observed PR values were: 2.99 MPa under CTFut, 3.30 MPa under LTP and 3.25 MPa under STP at the respective depths of 47 cm, 40 cm and 37cm.

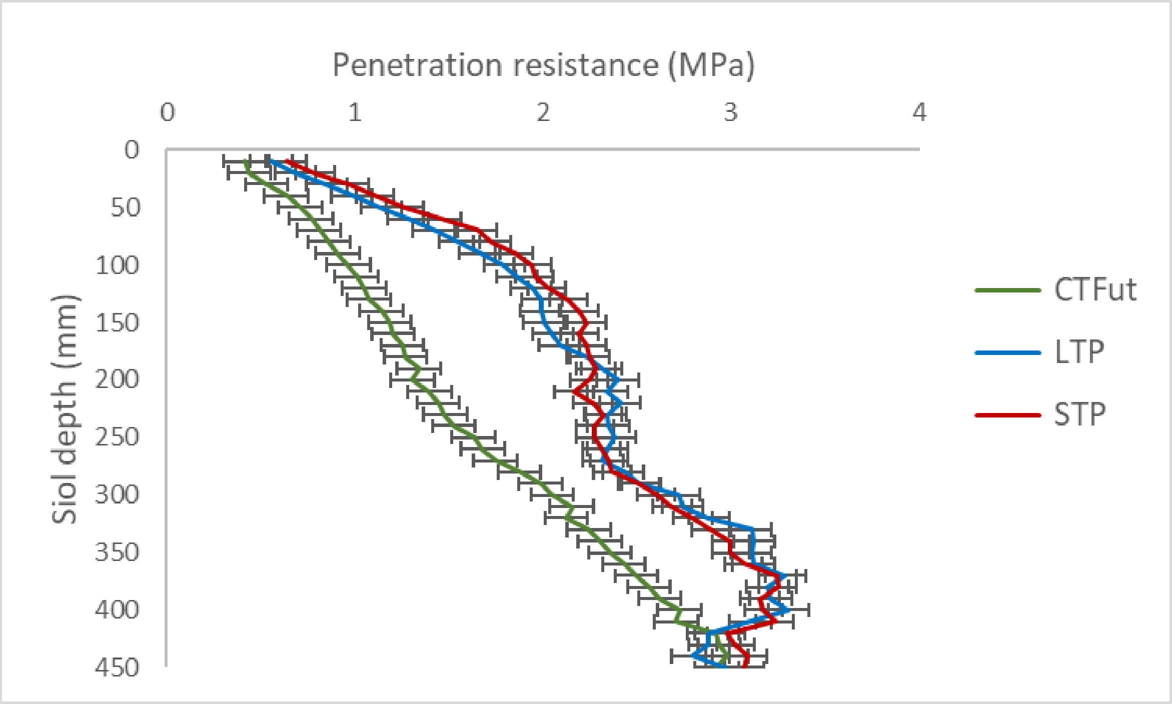


Figure 4.12 Penetration resistance (MPa), down the soil profile depending on three traffic systems. CTFut stands for untrafficked soil, LTP- soil trafficked with low tyre inflation pressure, STP- soil trafficked with standard tyre inflation pressure. Results presented with standard errors. Data from October 2020.

The effect of tillage on PR down the soil profile is presented in the Figure 4.13, which shows that there were no significant differences (*p=0.1204*) between analysed tillage systems (1.98 MPa, 2.10 MPa and 2.15 MPa on average for deep, shallow and zero tillage respectively). The 2 MPa resistance threshold was exceeded at the depth of 0.23m, 0.13m and 0.22m for deep, shallow and zero tillage respectively.

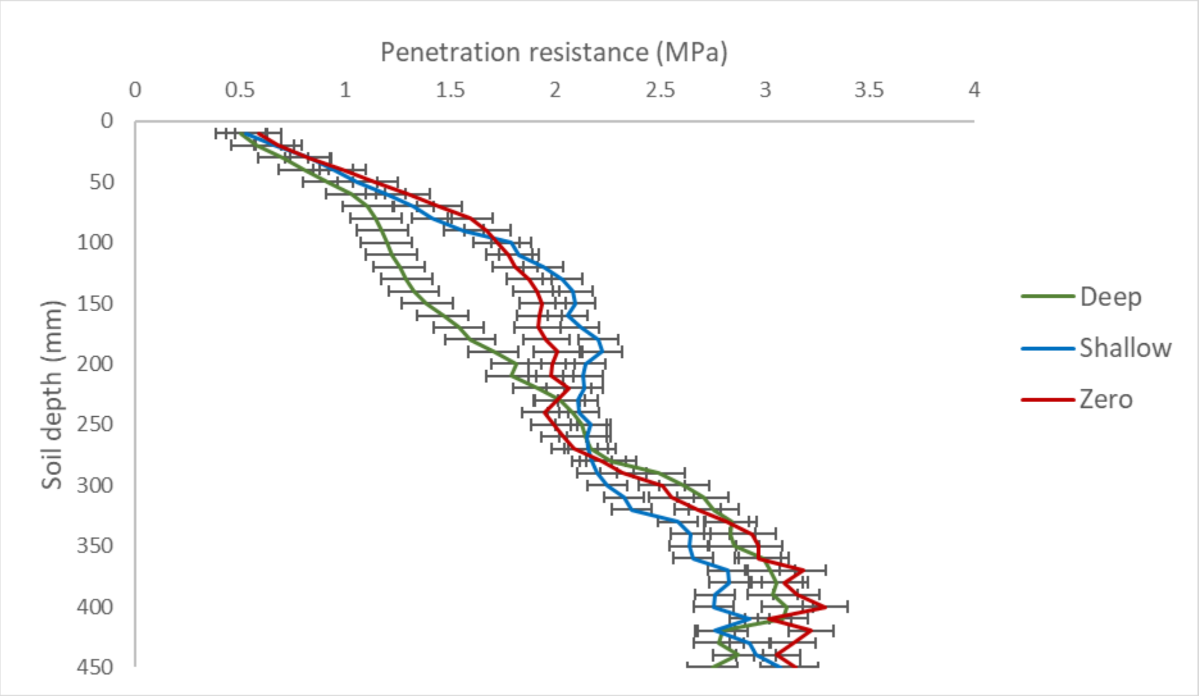


Figure 4.13 Penetration resistance (MPa), down the soil profile depending on three tillage systems: Deep – tillage at 250mm, Shallow – 100mm, Zero – zero tillage. Results presented with standard errors. Data from October 2020.

The detailed results of PR in 50-mm soil layers are presented in Table 4.1 which shows that the main effect of traffic was significant in the first seven analysed soil horizons, i.e., down to 350 mm and the PR under CTFut was significantly lower than under STP and LTP. Below 350 mm soil depth there was no significant difference in PR between those three traffic systems. At every soil horizon the effect of tyres pressures was not significant and there were no significant differences between LTP and STP.

Table 4.1 Penetration resistance (MPa) for 50-mm soil horizons depending on three traffic systems. Significant differences between means at each soil horizon are represented by different letters.

Soil depth (mm)	Layer	CTFut	LTP	STP
0-50	1	0.55 a	0.84 b	0.96 b
60-100	2	0.86 a	1.55 b	1.73 b
110-150	3	1.09 a	1.96 b	2.11 b
160-200	4	1.28 a	2.22 b	2.24 b
210-250	5	1.50 a	2.37 b	2.26 b
260-300	6	1.87 a	2.46 b	2.43 b
310-350	7	2.24 a	2.99 b	2.87 b
360-400	8	2.57 a	3.21 a	3.18 a
410-450	9	2.89 a	2.89 a	3.08 a

The results of PR at each 50-mm soil horizon depending on tillage system are presented in Table 4.2, which shows that only in the 3rd soil horizon (110-150mm) there was a significant difference in PR between analysed tillage systems and the PR under deep tillage was significantly lower than under zero and shallow tillage (1.3 MPa, 2.0 MPa and 1.86 MPa respectively). In the remaining soil horizons, there were no significant differences between tillage systems.

Table 4.2 Penetration resistance (MPa) for 50-mm soil horizons depending on three tillage systems. Significant differences between means at each soil horizon are represented by different letters.

Depth (mm)	Layer	Deep	Shallow	Zero
0-50	1	0.70 a	0.80 a	0.84 a
60-100	2	1.13 a	1.46 a	1.55 a
110-150	3	1.30 a	2.00 b	1.86b
160-200	4	1.62 a	2.15 a	1.96 a
210-250	5	1.99 a	2.13 a	2.00 a
260-300	6	2.34 a	2.19 a	2.24 a
310-350	7	2.80 a	2.51 a	2.79 a
360-400	8	3.05 a	2.77 a	3.14 a
410-450	9	2.86 a	2.93 a	3.08 a

The effect of interactions between traffic, tillage and depth on the PR is presented in Figure 4.14. The PR analysis across nine soil horizons in 50-mm increments revealed that in the 0-50 mm there were no significant differences between tillage systems under each traffic system (0.45 MPa, 0.55 MPa and 0.65 MPa for CTFut with deep, shallow and zero tillage respectively, 0.81 MPa, 0.86 MPa and 0.86 MPa for LTP with deep, shallow and zero tillage respectively and 0.84 MPa, 1.00 MPa and 1.03MPa for STP with deep, shallow and zero tillage respectively). The PR a under deep tillage with CTFut was significantly lower than under LTP and STP (0.45 MPa, 0.81 MPa and 0.84 MPa respectively) and there was no difference between LTP and STP. Shallow tillage with CTFut had significantly lower PR than STP and LTP did not differ significantly from both CTFut and STP (0.55MPa, 0.86 MPa and 1.00MPa for CTF, LTP and STP respectively). Zero tillage with CTFut had significantly lower PR than with STP, whereas LTP with zero tillage did not differ significantly from remaining two traffic systems (0.65MPa, 0.86MPa and 1.03MPa for CTFut, LTP and STP respectively). The effect of tyres pressures did not have a significant effect, as there were no significant differences between LTP and STP with deep tillage, similarly between LTP and STP with shallow tillage and between LTP and STP with zero tillage.

Similarly, in the 60mm-100mm soil layer there were no significant differences in PR between tillage systems under CTFut (0.59MPa, 0.93MPa and 1.08 MPa for deep, shallow and zero tillage respectively). Interactions between traffic and tillage were significant and the PR under deep tillage with CTFut was significantly lower than with LTP and STP (0.59MPa, 1.33MPa, and 1.48MPa respectively) and LTP did not differ significantly from STP. Under shallow tillage the PR was also significantly lower under CTFut than under LTP and STP (0.93MPa, 1.70MPa and 1.75MPa respectively) and LTP did not differ significantly from STP. Under zero tillage with CTFut the PR was significantly lower than under STP. LTP did not differ significantly from STP and CTFut (1.08MPa, 1.61MPa and 1.96MPa for CTFut, LTP and STP respectively). The effect of tyres pressures did not have a significant effect, as there were no significant differences between LTP and STP with deep tillage, similarly between LTP and STP with shallow tillage and between LTP and STP with zero tillage.

In the 110mm-150mm soil horizon the PR under CTFut was significantly lower than under LTP and STP for all tillage systems. There was no significant effect of tyres pressure. CTFut with deep tillage was significantly lower than CTFut with zero tillage whereas CTFut shallow did not differ significantly from deep and zero tillage under CTFut (0.75 MPa, 1.2 MPa, 1.33 MPa for deep, shallow and zero tillage under CTFut respectively). The PR was significantly lower under LTP with deep tillage than with shallow tillage whereas LTP with zero tillage did not differ significantly from the remaining tillage systems (1.43MPa, 2.41 MPa 2.04 MPa respectively). LTP with deep tillage did not differ significantly from CTFut with shallow and CTFut with zero tillage. For STP there were no significant differences between tillage systems (1.71MPa, 2.38 MPa, 2.23 MPa for deep shallow and zero tillage respectively).

In the next soil horizon (160mm-200mm) there were no significant differences between tillage systems under CTFut (1.09 MPa, 1.26MPa and 1.48 MPa for deep, shallow and zero tillage respectively). Under LTP with deep tillage the PR was significantly lower than under LTP with shallow tillage whereas zero tillage did not differ significantly from deep and shallow tillage (1.72 MPa, 1.64 MPa and 2.29 MPa for deep, zero and shallow tillage under LTP respectively). There were no significant differences between tillage systems under STP (2.06 MPa, 2.55 MPa, 2.11 MPa for deep, shallow and zero tillage with STP respectively). The effect of tyre pressures did not have a significant effect, as there were no significant differences between LTP and STP with deep tillage, similarly between LTP and STP with shallow tillage and between LTP and STP with zero tillage.

In the 210mm-250mm soil horizon, under CTFut there were no significant differences between three tillage systems (1.46 MPa, 1.43 MPa and 1.61 MPa for deep, shallow and zero tillage respectively). For LTP there were no significant differences between tillage systems (2.68 MPa, 2.19 MPa, 2.23 MPa respectively). For STP there were no differences between tillage systems (2.32 MPa, 2.30 MPa and 2.16 MPa for deep, shallow and zero tillage respectively). The effect of tyre pressures did not have a significant effect, as there were no significant differences between LTP and STP with shallow tillage; similarly, between LTP and STP with deep tillage; or between LTP and STP with zero tillage.

In the 260mm-300mm soil horizon there were no significant differences between tillage systems under CTFut (1.86 MPa, 1.83 MPa and 1.91 MPa for deep, shallow and zero tillage respectively), similarly under LTP (2.51MPa, 2.48 MPa, 2.41 MPa for deep, shallow and zero tillage respectively) and STP (2.64 MPa, 2.25 MPa and 2.40 MPa for deep, shallow and zero tillage respectively) no significant differences between tillage systems were observed. STP with deep tillage had significantly greater PR than CTFut with shallow and CTFut with deep tillage. The effect of tyre pressures did not have a significant effect, as there were no significant differences between LTP and STP with shallow tillage; similarly, between LTP and STP with deep tillage; or between LTP and STP with zero tillage.

In the 310mm-350 mm soil horizon there were no significant differences between CTFut with deep, shallow and zero tillage (2.30 MPa, 2.03 MPa, 2.38 MPa respectively). There were no significant differences between three tillage systems under LTP (2.86 MPa, 2.90 MPa and 3.22 MPa for deep, shallow and zero tillage respectively). Similarly, there were no significant differences between tillage systems under STP (3.23 MPa, 2.61 MPa and 2.78 MPa, for deep, shallow and zero tillage respectively). The effect of tyre pressures was not significant and there were no significant differences between deep tillage with LTP and STP, similarly between shallow tillage with LTP and STP; and zero tillage with LTP and STP. CTFut with shallow had significantly lower PR than LTP with zero tillage and STP with deep tillage.

In the 360mm-400 mm soil horizon there were no significant differences between traffic and tillage systems (2.66 MPa, 2.19 MPa and 2.86 MPa for deep, shallow and zero tillage under CTFut respectively; 2.82 MPa, 3.18 MPa and 3.62MPa under LTP respectively and 3.65 MPa, 2.93 MPa and 2.95MPa under STP). The difference between LTP with deep tillage and with shallow and zero tillage was not significant. Under STP with deep tillage the PR was significantly greater than with shallow tillage (3.65 MPa and 2.93 MPa respectively) and it was not significantly different from zero tillage (2.95 MPa). Shallow and zero tillage did not differ significantly under STP. The effect of tyre pressures on the PR was observed only for deep tillage which subject to LTP had significantly lower PR than under STP (2.82 MPa and 3.65 MPa respectively).

In the deepest analysed soil horizon (410mm-450 mm) there were no significant differences between traffic and tillage interactions: under CTFut the PR was 3.05 MPa, 2.47 MPa and 3.16 MPa for deep, shallow and zero tillage respectively, under LTP 2.53, MPa, 3.07 MPa and 3.08 MPa and under STP it was 2.99 MPa, 3.25 MPa and 2.99 MPa for deep, shallow and zero tillage respectively).

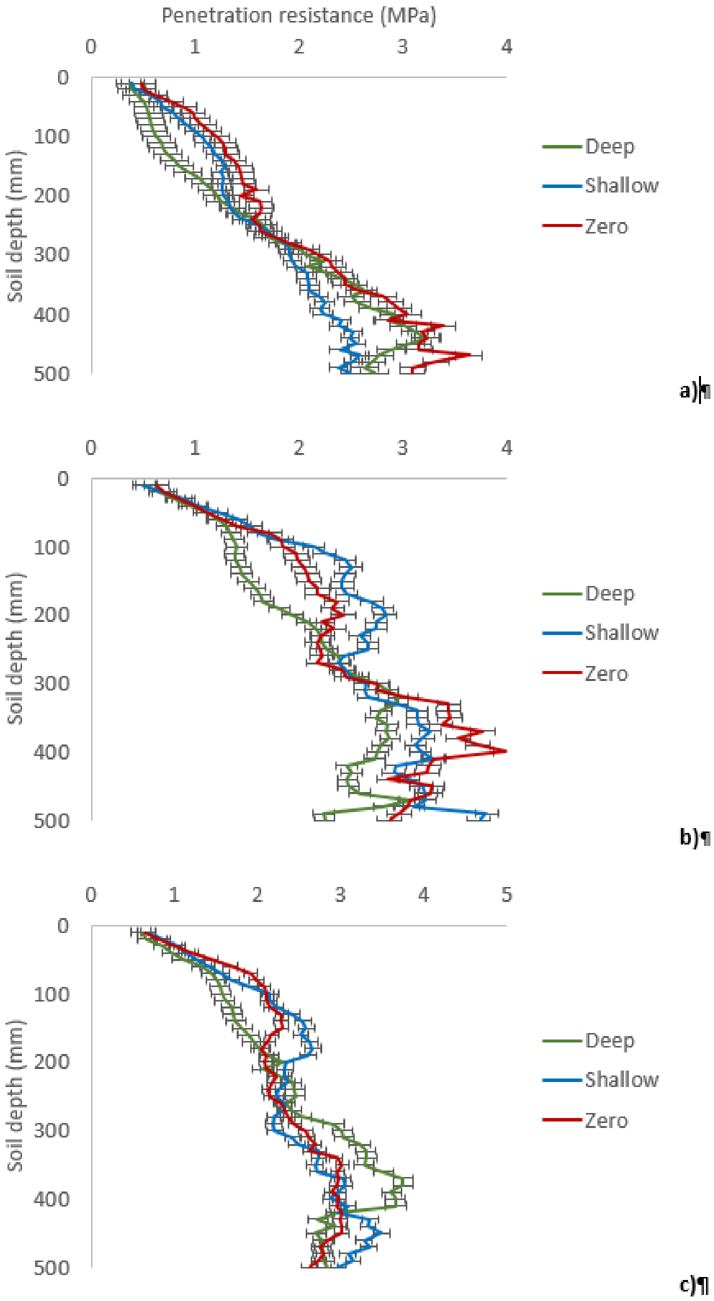


Figure 4.14 Penetration resistance down the soil profile for: a) CTF ut - untrafficked soil, b) soil trafficked with low tyre inflation pressure (LTP) and c) soil trafficked with standard inflation pressure tyres (STP), subject to three tillage depths: Deep – deep tillage (250mm), Shallow – shallow tillage (100mm), Zero – zero tillage. Results presented with standard errors. Data collected in October 2020.

4.3.3 Soil porosity

This chapter in the subsequent sub-chapters presents result of the soil roporosity analysis, namely:

- Pore count (number of pores per image slice),
- Pore circularity,
- Pore uniformity index,
- Average size of pore and pore size distribution,
- Pore perimeter,
- Total porosity.

4.3.4 Pore count

The main effect of traffic and depth (soil horizon) were significant for the pore count ($p<0.001$ for both factors). The main effect of tillage was not significant similarly interactions between traffic and tillage were not significant ($p=0.362$ and $p=0.936$, respectively, cv= 16.8%). Interactions between traffic and depth, tillage and depth were significant ($p<0.001$ in both cases). The pore count ranged from 2 to 1677 pores per image slice (area of 900mm^2).

Figure 4.15 shows that across all analysed five soil horizons the untrafficked soil - CTFut featured significantly greater number of pores than LTP and STP (average across all depths 491, 243 and 221 pores/ slice of 900 mm^2 respectively). The number of pores under CTFut at first significantly increased from 508 to 523 pores/ slice and then it significantly decreased with each soil increment down the soil profile resulting in the average number of pores of 501, 460 pores and 427 per image slice in the three deepest soil horizons respectively. At each soil horizon there was no significant difference between STP and LPT. For both LTP and STP number of pores significantly changed with each soil horizon, however under LTP the number of pores decreased significantly down to 200 mm (from 285 in the top stratum via 252, 235 to 207 pores per image slice) and then it significantly increased in the deepest soil horizon to 230 pores per image slice. Under STP however, number of pores significantly decreased with depth down to 100mm (from 235 to 175) and from there it increased with each soil horizon obtaining 206, 248 and 272 in the three deepest soil horizons respectively.

Figure 4.16 presents the number of pores per image slice as a result of interactions between tillage and the soil depth and reveals that under deep tillage the number of pores increased significantly down to 150mm and then it significantly decreased between 100mm-150 mm and 151mm-200mm soil horizon. Between the soil layers of 151-200mm and 201-222mm there were no significant differences. Under shallow and zero tillage the number of pores significantly decreased down the soil profile to 150mm and it again increased in the 150-200mm. Under shallow tillage the increase continued to the 201-222mm soil layer, whereas under zero tillage the difference between the 150-200mm and 201-222mm soil depths was not significant.

Interestingly, at any soil horizons there were no significant differences in number of pores between the tillage systems, although at first three soil layers (down to 150mm) the number of pores was much greater under deep tillage than under shallow and zero tillage.

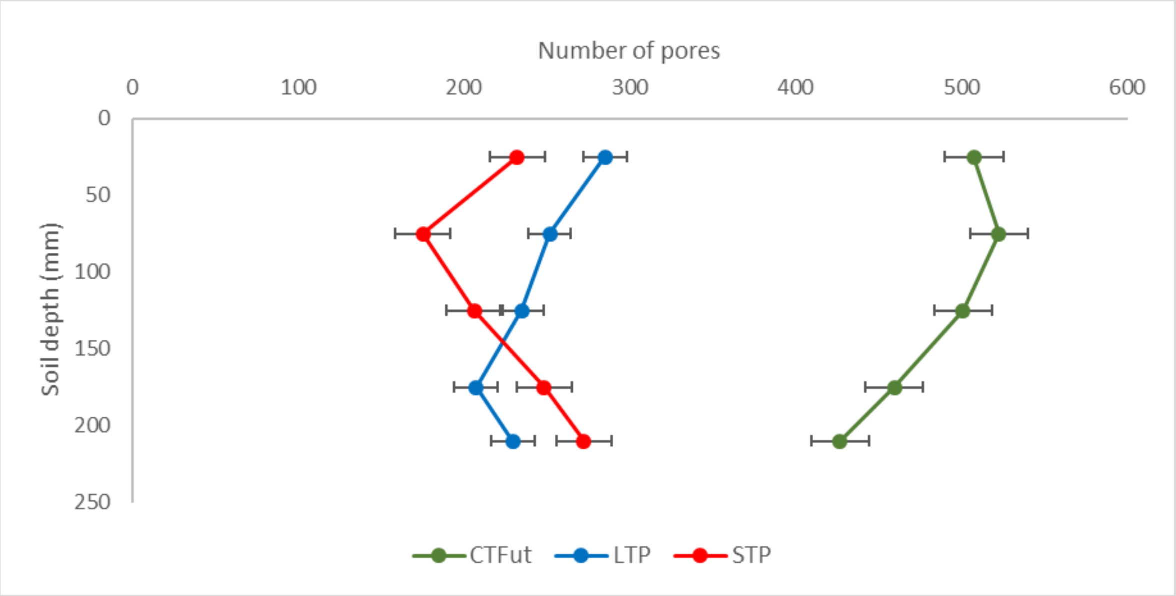


Figure 4.15 Number of pores per image slice of 900mm^2 down the soil profile depending on three traffic approaches: CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal lines represent standard errors.

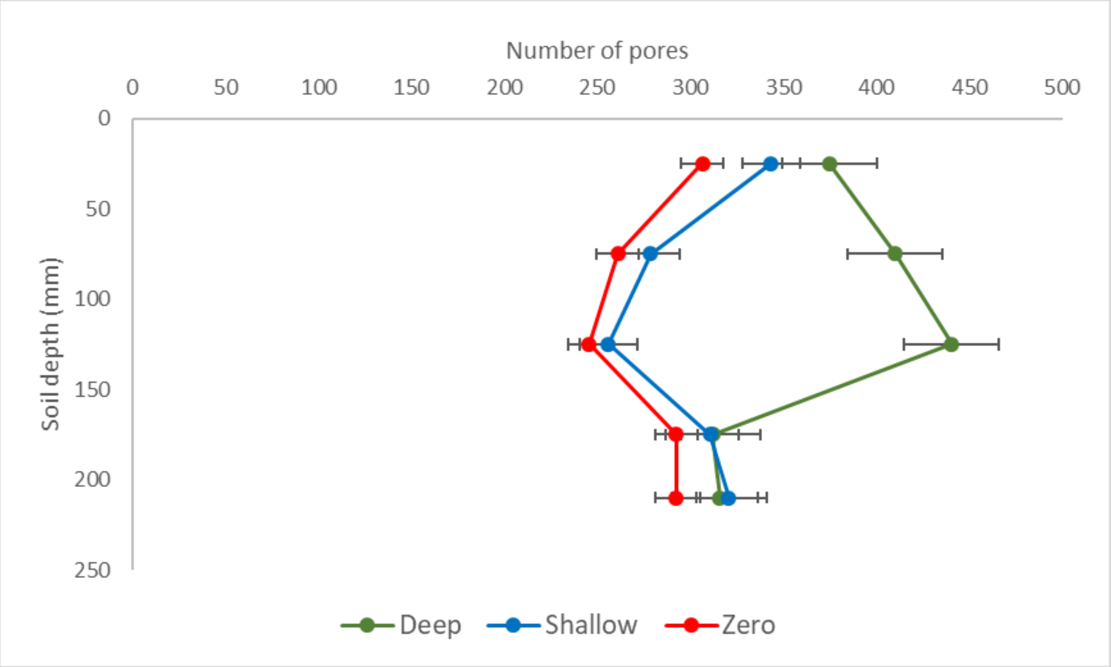


Figure 4.16 Number of pores per image slice of 900mm ^{2} down the soil profile for three tillage depths: Deep = 250mm, Shallow = 100mm and Zero = zero tillage. Horizontal lines represent standard errors.

4.3.5 Pore circularity

The circularity index ranged from 0.555 to 0.979, and its averaged results across all analysed depth are presented in Table 4.3.

Table 4.3 Pores circularity depending on traffic and tillage system, averaged across analysed soil depth of 222 mm (1705 image slices). CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep- tillage to 250mm, Shallow – 100mm, Zero- zero tillage.

	Deep	Shallow	Zero	Average
CTFut	0.843	0.851	0.853	0.849
LTP	0.849	0.850	0.845	0.848
STP	0.849	0.855	0.851	0.852
Average	0.847	0.852	0.850	0.850

The statistical analysis found that the main effect of traffic and tillage was not significant and their interactions were not significant either (*p=0.515, p=0.978, p=0.894* respectively, cv=31.6%). The effect of soil depth expressed as soil horizon was significant (*p<0.001*) and the Tukey's test revealed that with each soil layer the circularity slightly but significantly increased and it equalled: 0.831, 0.843, 0.854, 0.862 and 0.866 for consecutive five consecutive soil horizons respectively at every 50mm. The interactions between soil depth and traffic as well as soil layer and tillage were also significant (*p<0.001* for both interactions).

The pores circularity depending on traffic and soil depth is presented in Figure 4.17 which shows that there were no significant differences between analysed traffic systems at every soil horizon down to 200mm. Only in the deepest soil horizon (201-222mm) the circularity under STP was significantly greater than under remaining traffic systems.

Under CTF the circularity significantly increased down 150 mm, then it slightly decreased and there was no significant difference between the fourth and the fifth soil layer. Under LTP the circularity significantly increased down to 200mm and there was no significant difference between the last two soil horizons. Under STP the circularity steadily and significantly increased with each soil horizon, and at the deepest soil layer it was significantly greater than under LTP and under CTF (0.882, 0855 and 0.861 respectively).

The pores circularity depending on tillage and soil depth is presented in Figure 4.18 which reveals that there were no significant differences in the first soil layer between tillage systems. Under deep tillage the circularity significantly decreased between the first and the second soil horizon (from 0.832 to 0.829), and as from 50-100mm soil layer the pore circularity significantly increased with each soil increment. Under shallow tillage the circularity significantly increased with every soil horizon reaching its highest value of 0.865 at the 200-222 mm. Under zero tillage the significant increase was observed only down to 150-200 mm (circularity value of 0.859) and then it significantly decreased in the deepest soil layer to 0.852.

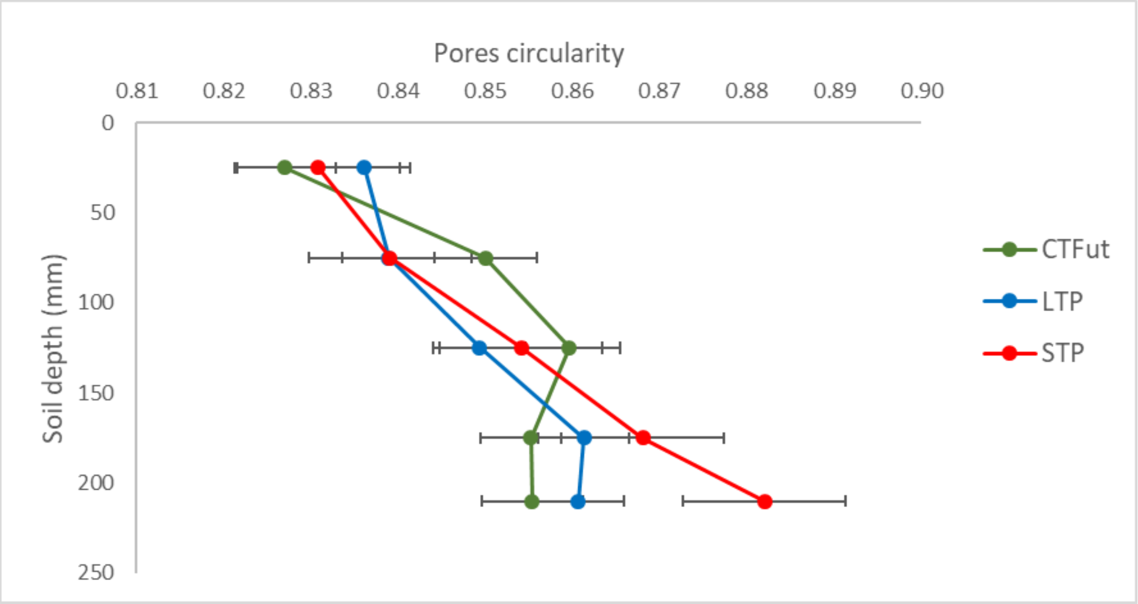


Figure 4.17 Pore circularity depending on traffic and soil depth. CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal lines represent standard errors.

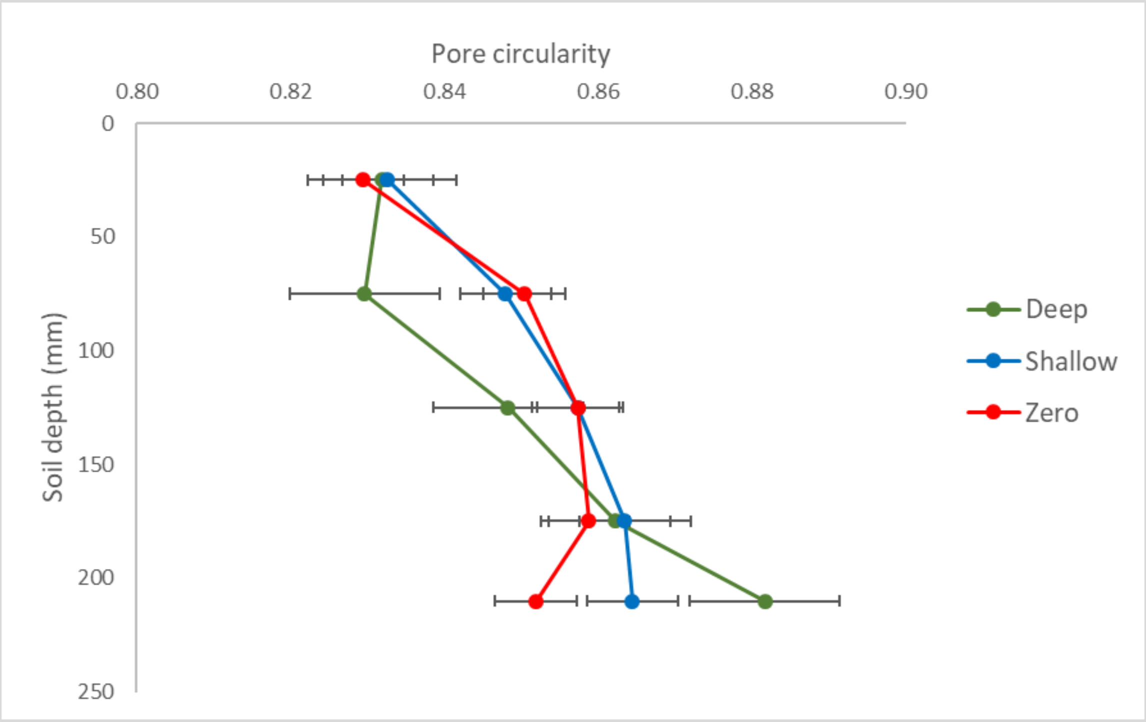


Figure 4.18 Pore circularity down the soil profile for three tillage depths: Deep - 250mm, Shallow - 100mm and Zero - zero tillage. Horizontal lines represent standard errors.

4.3.6 Pore uniformity index (UI)

The effect of traffic, tillage and their interactions had no significant effects on the pores' uniformity index (*p=0.392, p=0.696, p=0.914* respectively, *CV= 27.4%*). The effect of soil horizon and the interactions between soil horizon with traffic and tillage were not significant either (*p=0.244, p=0.996* and *p=0.473* respectively). The value of UI varied from 6 to 680. Although in the two deepest soil horizons (151mm-200mm and 201mm-222 mm) on average the UI under CTFut and LTP was greater than under STP (Figure 4.19), the variation of the results resulted in the overall lack of significant differences. Figure 4.20 presents the UI depending on tillage and shows that there were no significant differences between tillage systems down the soil profile.

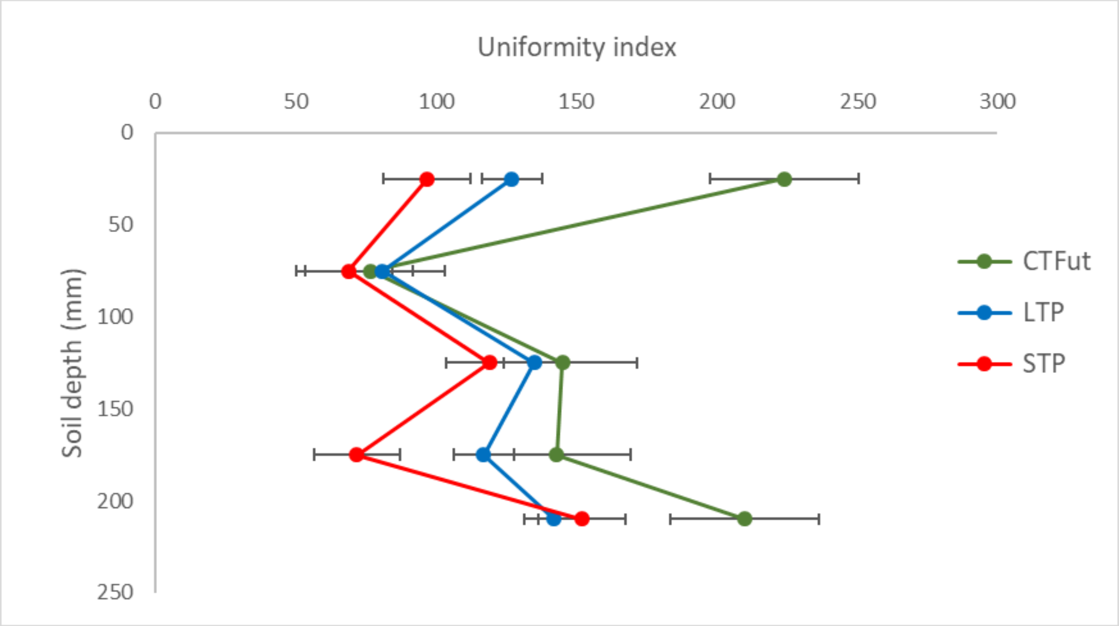


Figure 4.19 Pore uniformity index (UI) depending on three traffic systems down the soil profile. CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal lines represent standard errors.

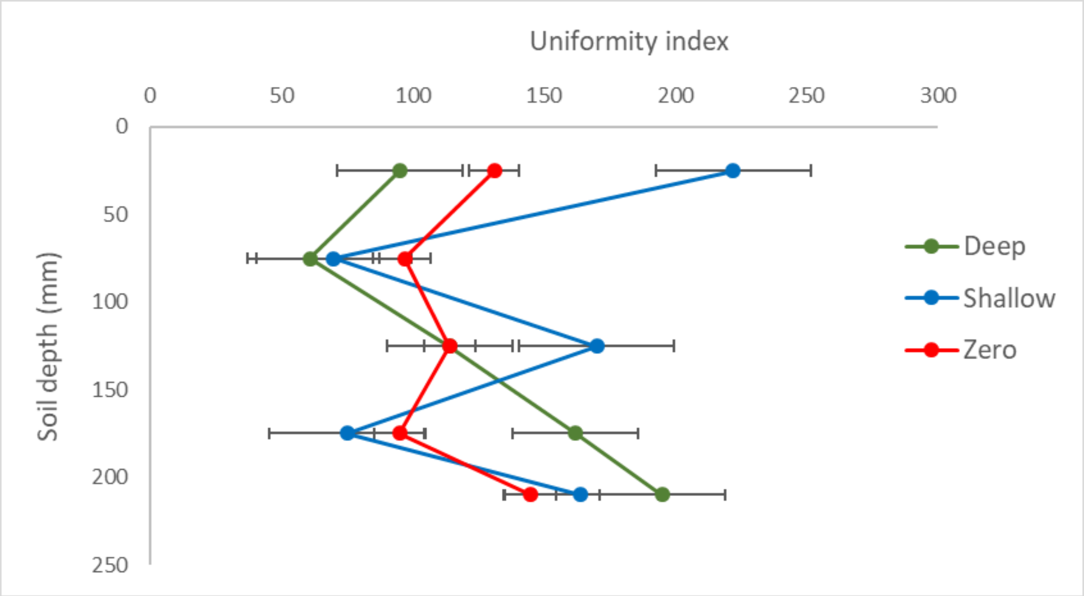


Figure 4.20 Pore uniformity index (UI) down the soil profile for three tillage depths: Deep - 250mm, Shallow - 100mm and Zero - zero tillage. Horizontal lines represent standard errors.

4.3.7 Average size of pore and pore size distribution

The pore size distribution down the soil profile is presented Figure 4.21 and Figure 4.22 for traffic and tillage respectively. Those two figures show that there were cracks resulting in big pores sizes under STP at the depth 20-30mm and under CTFut at the depth of 200-202mm. Under zero tillage the big pores were observed at around 25-28mm whereas under deep tillage the cracks were observed at the depth around 200-203mm. The mixed effects model ANOVA for five soil horizons showed that the main effect of traffic, tillage and their interaction did not have significant effect on the sizes of pores (*p=0.3939, p=0.7157, p=0.9903, cv =44.9%*). The depth was significant, similarly the interactions between tillage and depth as well as traffic and depth ($p<0.001$ for both interactions). The average pore size was greatest in the shallowest soil layer (0.48 mm^2), then it decreased down to the third soil horizon (0.289 mm^2 at 100-150 mm soil horizon) and it again increased below 150mm soil layer (0.305 $mm^2$and 0.398 mm^2 in the deepest two soil layers respectively). Figure 4.23 presents the pore size down the soil horizons and reveals that it did not differ significantly between traffic systems down to 200mm soil depth. Only in the deepest 200-222 mm soil layer there was a significant difference (p=*0.01672*) in the pore size and under STP it was significantly smaller than under CTFut and LTP (0.18 mm^2, 0.32 mm^2 and 0.69mm^2 respectively). LTP did not differ significantly from CTFut.

Figure 4.24 presents the pore sizes depending on tillage and soil horizons and shows that at each soil horizon there was no significant difference in the pore sizes between analysed tillage systems ($p= 0.9165$). There was however a significant effect of the soil depth ($p<0.001$), and under deep and zero tillage there was a significant decrease in the pore size down to 150mm (the third soil layer) whereas under shallow tillage the significant decrease was observed only to the second soil horizon (100mm) and there were no significant differences between second and third soil layer. Below the 150mm soil horizon, the pore sizes under shallow tillage kept decreasing with soil depth, whereas under deep and zero tillage the sizes increased significantly.

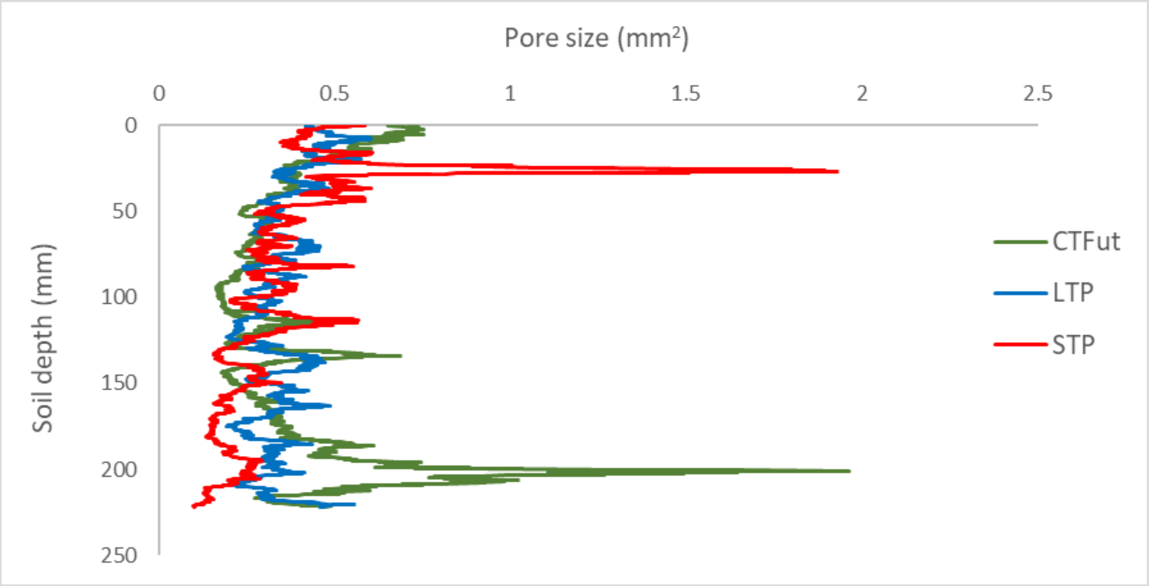


Figure 4.21 Pore size distribution down the soil profile depending on traffic: CTFut – untrafficked soi, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres.

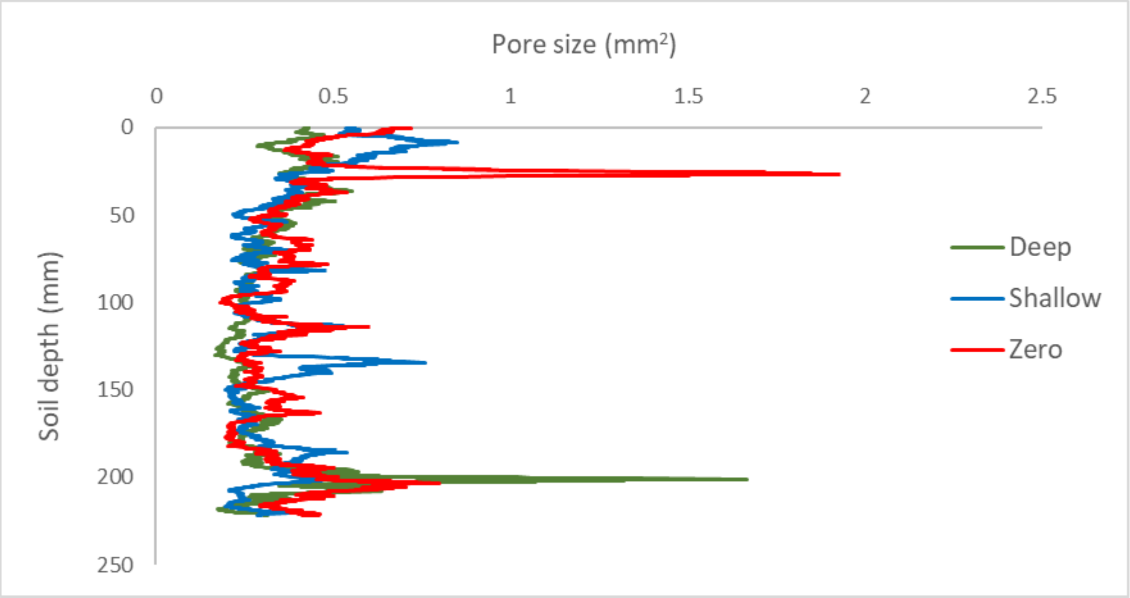


Figure 4.22 Pore size distribution down the soil profile for three tillage: Deep - 250mm, Shallow - 100mm, Zero - zero tillage.

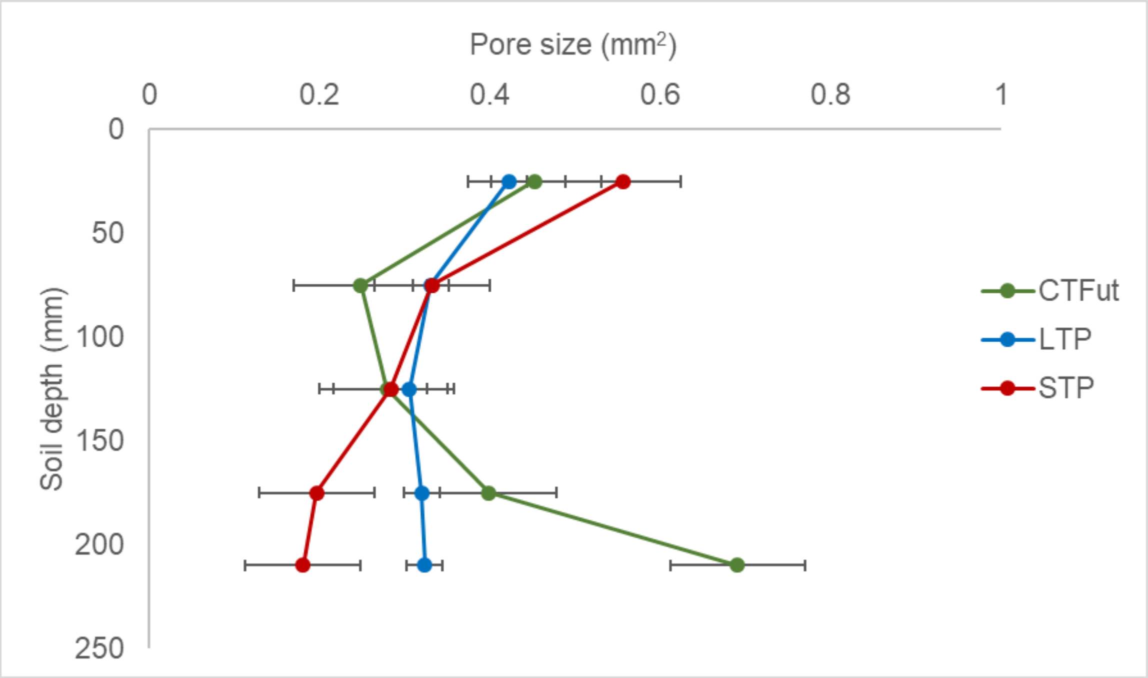


Figure 4.23 Average pore size depending on traffic and soil depth. Horizontal lines represent standard errors. CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres.

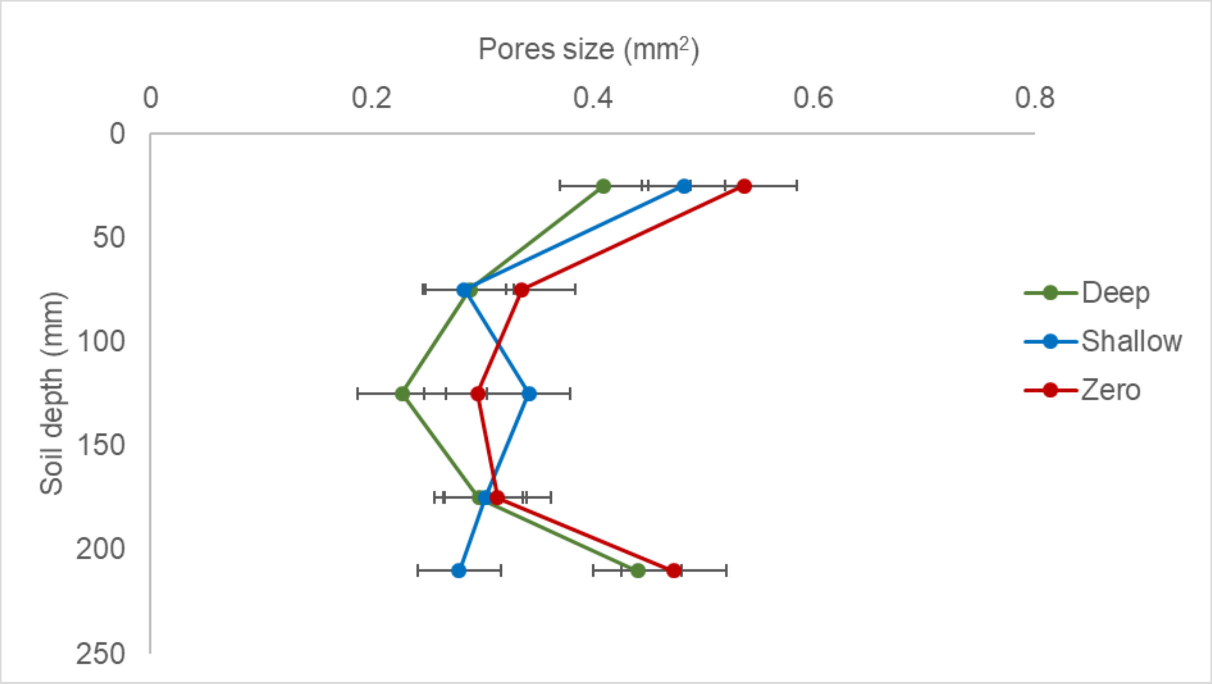


Figure 4.24 Average pore size down the soil profile for three tillage depths: Deep - 250mm, Shallow - 100mm and Zero - zero tillage. Horizontal lines represent standard errors.

4.3.8 Pore perimeter

The average perimeter of a pore ranged from 0.56mm 14.60mm, with the mean of 1.69mm. The main effect of traffic, tillage and interactions between traffic and tillage were not significant (*p=0.81*, *p=0.951* and *p=0.882* respectively). The effect of depth and the interactions between soil depth and tillage as well as soil depth and traffic were significant (*p<0.001* for all those factors, *cv=62%, SEM = 0.00279*).

Figure 4.25 shows how the pore perimeter changed down the soil profile depending on traffic and reveals that in the four top soil layers there was no significant difference between three traffic systems, however in the deepest soil layer (201-222mm) the pore perimeter under STP was significantly lower (*p=0.013*) than under CTFut (1.27mm and 1.90 mm respectively) and LTP did not differ significantly from CTFut and STP (1.65mm). Under STP the pore perimeter decreased significantly with each soil horizon from 2.07 mm to 1.27mm in the top and deepest soil layer respectively). Under LTP there was a significant decrease in pore perimeter down to 4th soil layer (from 1.93 to 1.57mm) and in the deepest soil horizon the pore perimeter increased to 1.65mm. Under CTFut the decrease in pore perimeter was observed only down to the third soil layer (from 2.14 mm in the top layer to 1.43mm) from where it increased with depth and in the deepest soil horizon it was 1.90mm.

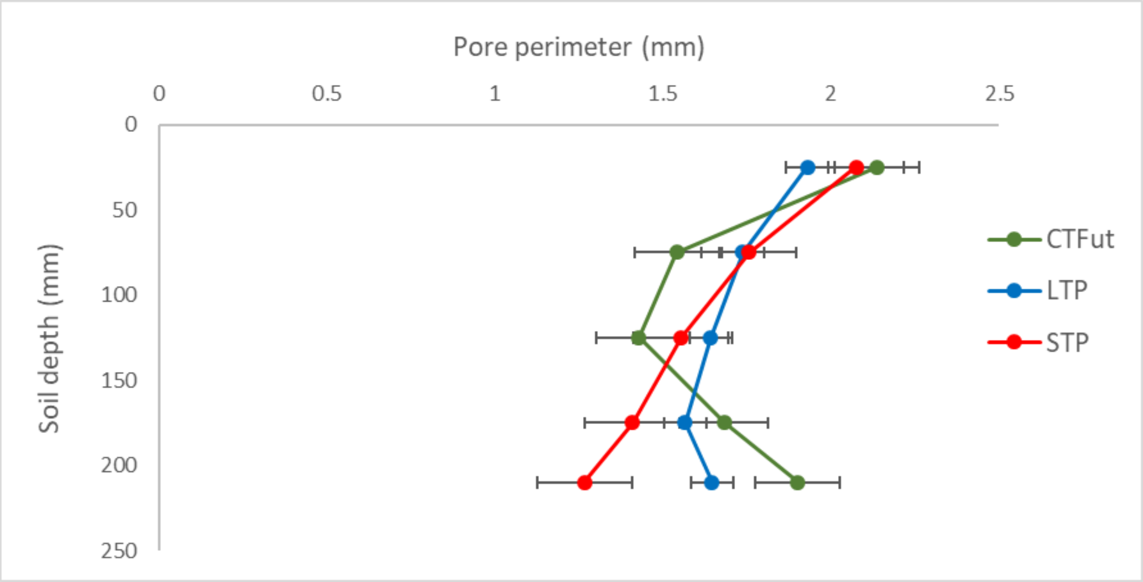


Figure 4.25 Pore perimeter depending on three traffic systems: CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal lines represent standard errors.

Figure 4.26 shows that at each soil horizon there was no significant difference between analysed tillage systems. Only the effect of depth was different for each tillage depth, and under deep tillage the pore perimeter decreased significantly with most soil horizons down the soil profile from 1.90 in the top 50mm to 1.42 mm in the 201-222mm soil layer, however the difference between layer 3 and layer 4 was no significant. Under shallow tillage the decrease in pore perimeter decreased with each soil horizon only down to 200mm soil layer and there was no significant difference between two deepest soil layers. The average perimeter under shallow decreased from 2.08mm in the top 0-50m soil layer to 1.49 in the deepest soil layer. A different pattern of the pore perimeter change with the soil depth was observed under zero tillage, as it decreased significantly only down to 3rd soil layer (150mm), then there was a slight but not significant increase in the perimeter and the pore perimeter significantly increased between two deepest soil layers (151-200 mm and 201-222mm).

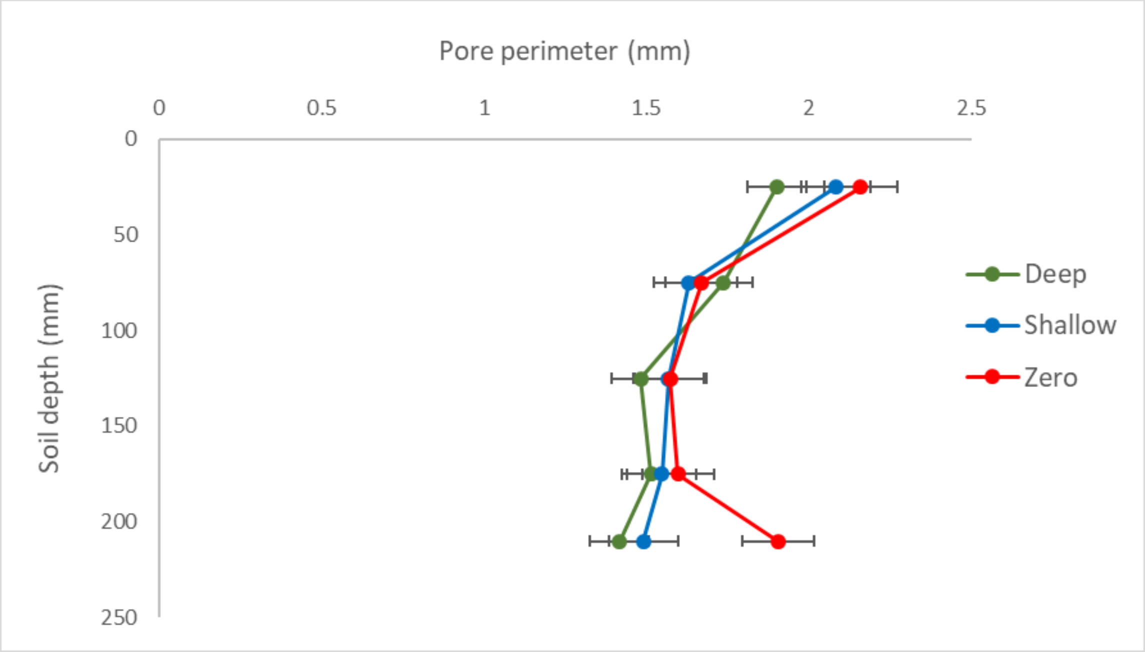


Figure 4.26 Pore perimeter depending on three tillage depths: Deep- 250mm, Shallow – 100mm and Zero – zero tillage. Horizontal lines represent standard error

4.3.9 Total porosity

The average porosity under untrafficked area (CTFut) was significantly greater than under trafficked area ($p<0.001$) and the effect of tyres pressures was not significant. The total porosity equalled 13.7%, 8.4% and 6.8% under CTFut, LTP and STP respectively. The average soil porosity did not differ significantly between tillage system (p=0.7842) and was

9.9%, 9.8% and 9.2% for deep, shallow and zero tillage respectively. Interactions between traffic and tillage were not significant (*p=0.847* respectively, cv=31.9%).

Interactions between traffic and soil depth were significant (*p<0.001*) and are presented in Figure 4.27 which reveals that the greatest porosity was observed in the 0-50mm soil layer under untrafficked area (CTFut): 20.6%, and it significantly decreased down the soil profile reaching its minimum of 10% at the third soil horizon (101-150mm), then it significantly increased in the fourth soil layer to 12.5% and did not change significantly down the soil profile, with the result of 12.6% porosity at the 200mm-222mm soil layer. Under the LTP the soil porosity decreased significantly with soil depth achieving its minimum at 4th soil layer (6.8%) and then it significantly increased to 7.6% at the deepest soil horizon (200-222mm). Under STP there was a significant decrease in soil porosity between the two shallowest soil horizons (from 10.9% to 5.9% respectively) then there was no significant difference between soil 2nd and 3rd soil layer (5.9% and 5.8% respectively) then the percentage porosity again significantly decreased to 5.4% at 4th soil horizon (151mm-200mm) and did not change significantly between layer 4th and 5th achieving the lowest porosity of 5.1% at the deepest soil horizon (200-222mm). At each soil horizon the tyre pressures had no significant effect on the soil porosity.

Interactions between tillage and soil depth were also significant (*p<0.001*) and are presented in Figure 4.28 which reveals that in the shallowest soil horizon the soil porosity was significantly greater then in deeper soil strata, but there was no significant difference between the three tillage systems (13.4%, 16.3% and 14.1% for deep, shallow and zero tillage respectively). Under deep tillage the soil porosity significantly decreased with each soil horizon down the soil profile, achieving its minimum at the deepest soil stratum (6.7%). Under shallow tillage the porosity in the 1st soil horizon was significantly greater than at any deeper horizon, there was no significant difference between 2nd and 3rd soil layer (7.0% and 7.5% respectively) then the porosity significantly increased from 3rd to 4th soil horizon (from 7.5% to 9.0%) and slightly but not significantly decreased to 8.2% in the deepest soil horizon. Under zero tillage the soil porosity significantly decreased with soil depth down to the third soil horizon (150mm) where it achieved its minimum (6.3%) and from there it significantly increased down the soil profile (7.7% and 10.4% at 4th and 5th soil horizon respectively). Significant differences in soil porosity between different tillage systems were observed in the 2nd (51mm-100mm) soil stratum where under deep tillage it was significantly greater than under shallow tillage (10.6% and 7.0% respectively), in the 3rd soil horizon (101mm-150mm) where it was significantly greater under deep then under zero tillage (9.1% and 6.3% respectively) and in the 5th (200-222mm) soil horizon where under zero tillage the porosity was significantly greater than under deep tillage (10.4% and 6.7% respectively).

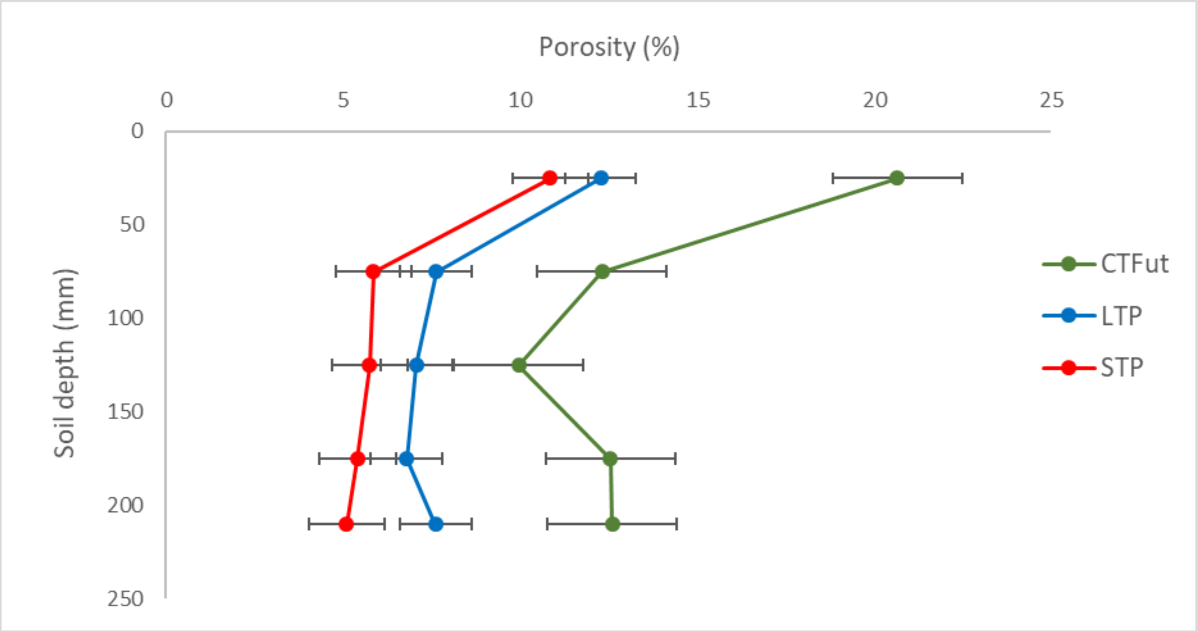


Figure 4.27 Soil porosity percentage depending on three traffic systems and soil depth. CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal lines represent standard errors.

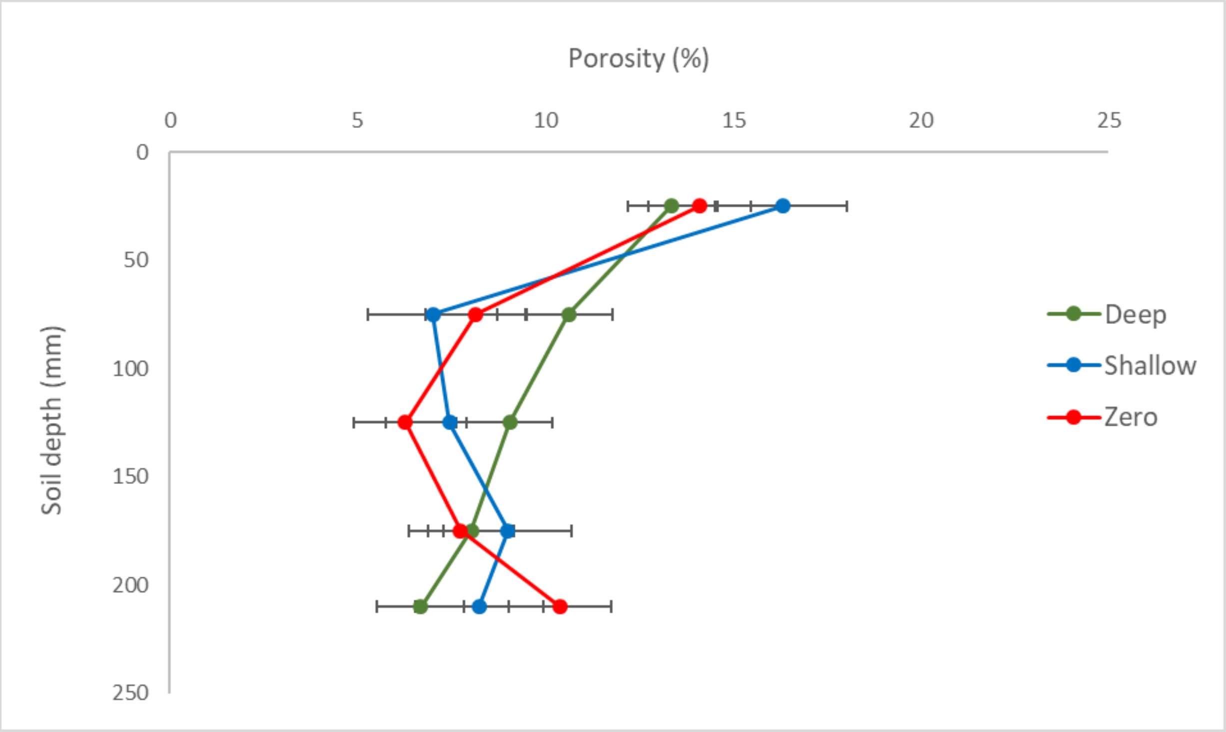


Figure 4.28 Soil porosity percentage depending across soil profile for three tillage depths: Deep= 250mm, Shallow = 100mm, Zero = zero tillage. Horizontal lines represent standard errors.

4.3.10 Soil moisture content

The main effect of traffic, tillage as well as the interactions between traffic and tillage did not have a significant effect on soil moisture (*p=0.298, p=0.4396* and *p=0.3507* respectively). Only depth had significant effect and interactions between tillage and depth ($p<0.001$ and $p= 0.0102$ respectively). Interactions between traffic and depth were not significant ($p= 0.7231$, CV = 15.1%).

Figure 4.29 and Figure 4.30 show how soil moisture changed across the 8 measuring dates depending on traffic and tillage respectively. The day zero stands for the first reading, i.e., 22 February 2019. The two reading from 22 and 26 February show the same results (average on each day 23.0%) suggesting the field capacity on this soil is around 23%. The lowest observed soil moisture was on 16 July (average 14.9%, the minimum readings on untrafficked soil CTFut with deep tillage – 10.2% in the 0-20 cm soil horizon) which might have resulted from low sum of rain (15.7mm) in the 30-day period preceding the reading. There was observed an increase in soil moisture on the 6 August (28.2%, 29.9%, 25.6% and 20.5 for 0-20cm, 4-24cm, 15-35cm and 30-50cm soil stratum respectively) which resulted from the rain during the last five days of July (sum 38.6 mm) followed by five days of interim showers at the beginning of August delivering additional precipitation of 1mm for those 5 days.

Figure 4.31 shows how soil moisture changed down the soil profile depending on traffic. Although under untrafficked soil - CTFut the soil moisture was lower than under STP and LTP, the difference was not significant ($p=0.298$) (average 18.8%, 20.2% and 20.2% respectively). There was an increase in soil moisture observed between the first soil profile (0-200mm) and the second (40mm-240mm), below which the soil moisture decreased with each depth for all analysed traffic systems.

Figure 4.32 shows how soil moisture changed down the soil profile depending on tillage and reveals that under deep tillage soil moisture at the 0-20cm horizon was significantly lower than at the 4-24cm (by 1.8%) and under shallow and zero tillage the difference was not significant (0.9% and 1.4% respectively). Then, from the 4-24cm soil horizon, moisture slightly decreased to the 15-35cm soil horizon (from 20.5%, 20.7% and 22.1% to 20.3%, 19.6% and 20.9% for deep, shallow and zero tillage respectively) and then it significantly decreased down the soil profile so at 30-50cm soil stratum the soil moisture was significantly lower than at all the above soil horizons for shallow and zero tillage systems (16.9% and 18.0% respectively), and for deep tillage the soil moisture at the 30-50cm soil depth (18.4%) was significantly lower than at 04-24cm and 15-35cm soil layer, but it was not significantly different to the 0-20cm soil layer. On average the soil moisture under zero tillage was slightly greater than under shallow and deep tillage (20.4%, 19.2% and 19.5%

respectively), and at every soil horizon there was no significant effect of tillage system on the soil moisture.

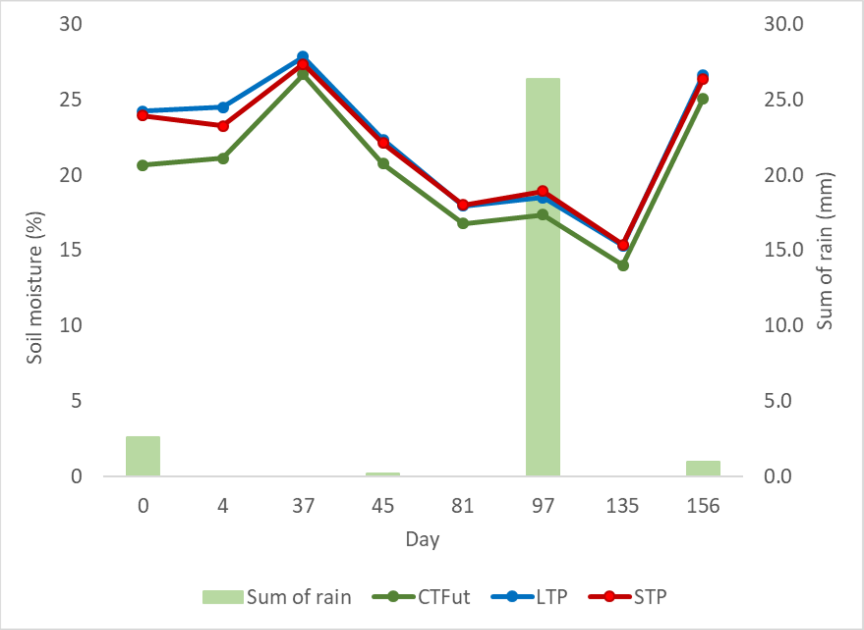


Figure 4.29 Volumetric soil moisture (%) depending on three traffic systems traffic and date. Days counted as from the first measurement on 22 Feb. 2019. Traffic systems: CTFut – untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Vertical bars show sum of rain (mm) from 5-day period preceding the moisture reading.

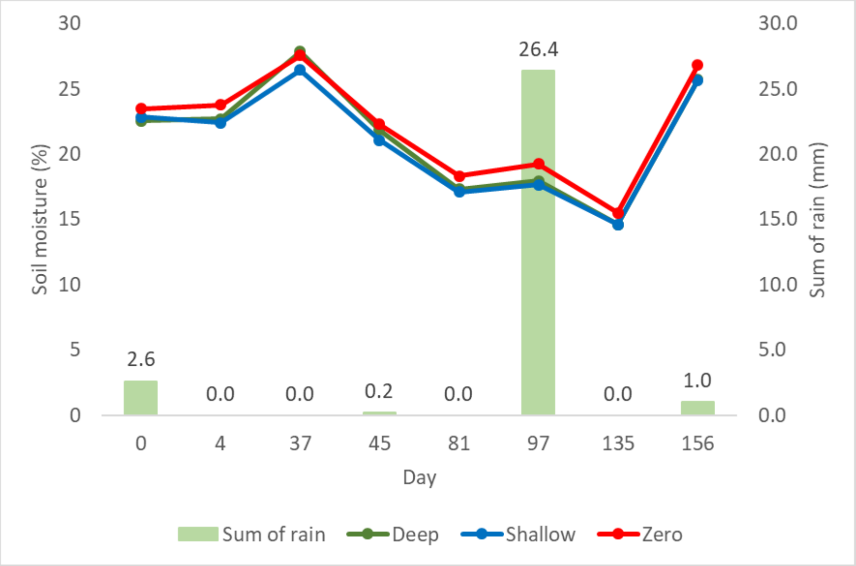


Figure 4.30 Volumetric soil moisture (%) depending on tillage and date. Days counted as from the first measurement on 22 Feb. 2019. Vertical bars show sum of rain (mm) from 5-day period preceding the moisture reading.

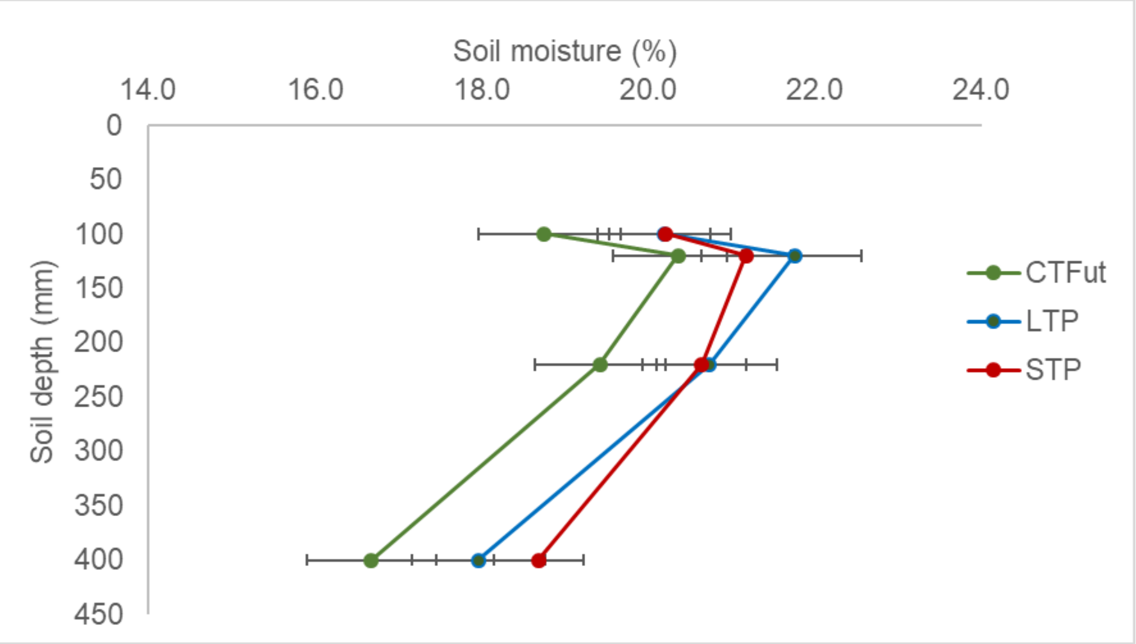


Figure 4.31 Volumetric soil moisture (%) depending on three traffic systems down the soil profile. CTFut-untrafficked soil, LPT – soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres. Horizontal lines represent standard error.

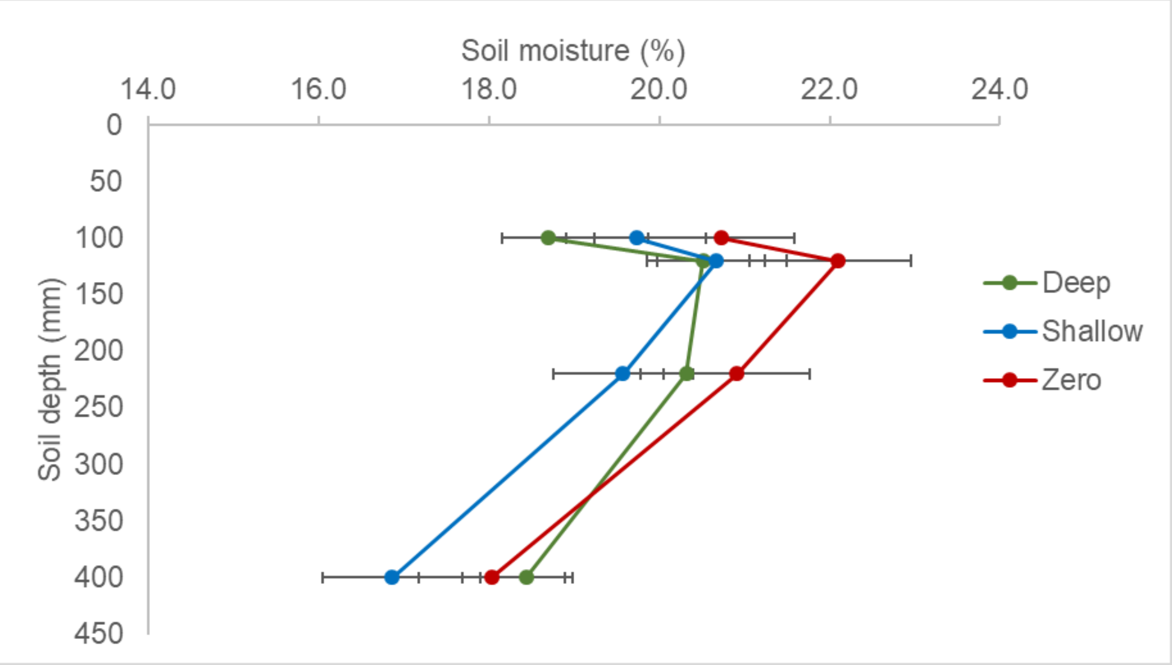


Figure 4.32 Volumetric soil moisture depending down the soil profile depending on three tillage depths: Deep = 250mm, Shallow = 100mm, Zero = zero tillage. Horizontal lines represent standard error.

4.3.11 Field-saturated hydraulic conductivity (Kfs) and instant infiltration rate

The main effect of traffic was significant (*p<0.001*) whereas the main effect of tillage or the interactions between traffic and tillage had not significant effect on field-saturated hydraulic conductivity (*p=0.22, p=0.105* respectively, CV = 42.6%). Figure 4.33 presents the Kfs (cm h^{-1}) depending on traffic and tillage and shows that the average value on CTFut (unwheeled) was almost 6 and 8 times greater than under LTP and STP respectively (0.56 m h^{-1}, 0.10 m $h^{-1}$and 0.07 m h^{-1} respectively). The average saturated hydraulic conductivity (Kfs) for tillage systems was greater under deep tillage than under shallow and zero tillage (0.32 m h^{-1}, 0.24 m h^{-1} and 0.16 m h^{-1} respectively) however the differences were not found statistically significant.

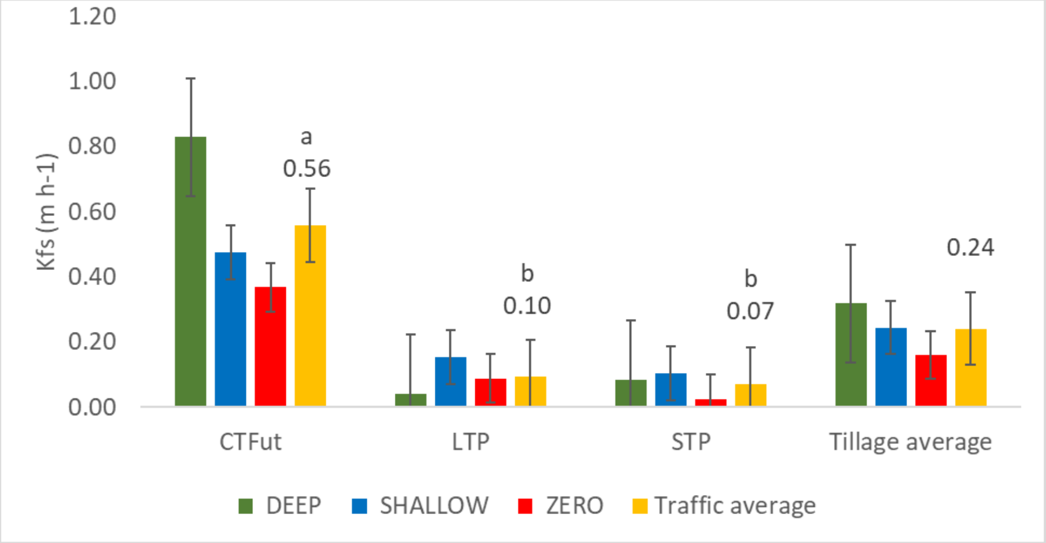


Figure 4.33 Field-saturated hydraulic conductivity (Kfs) m h^{-1} depending on traffic and tillage. Significant differences between means are represented by different letters. Whiskers on the bars represent standard error.

Similarly, the instant water infiltration rate significantly differed between the traffic systems (*p<0.001*), whereas the effect of tillage and interactions between traffic and tillage were not significant (*p=0.085* and *p=0.258* respectively, CV=89.8%). The instant infiltration rate under CTFut was 8-times greater than STP and almost 6.5-times greater than under LTP (1.86, 0.23 and 0.30 m h^{-1} respectively). Despite over twofold higher value of infiltration under deep and by 85% greater under shallow than zero tillage (1.03, 0.87 and 0.47 m h^{-1} respectively), the differences were not significant (*p=0.085*).

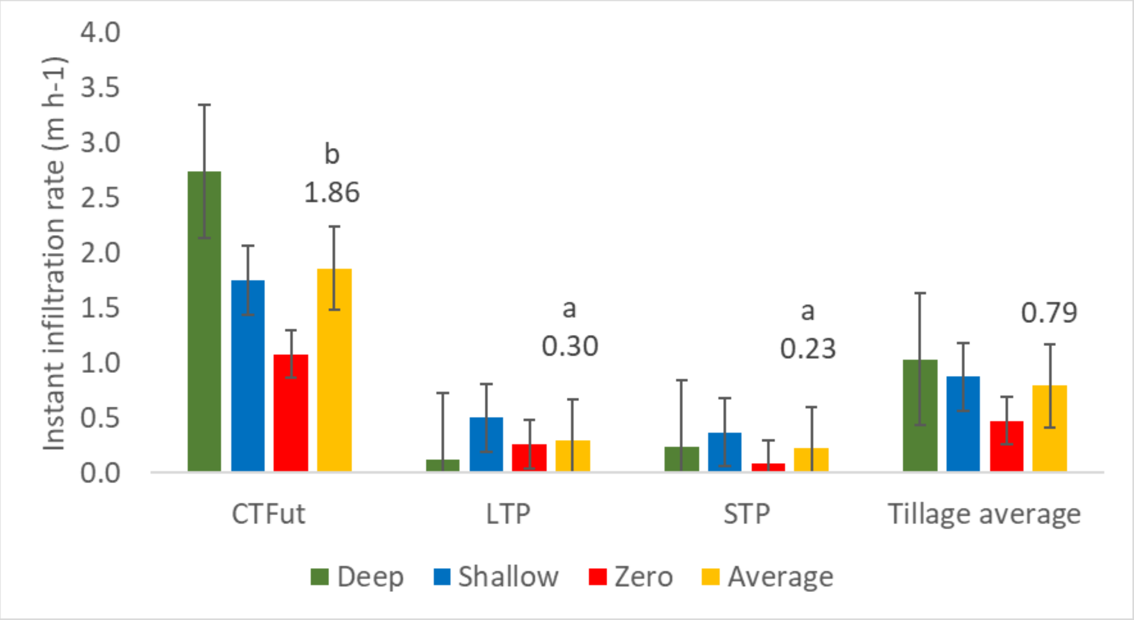


Figure 4.34 Instant infiltration rate (m h^{-1}) depending on traffic and tillage. Significant differences between means are represented by different letters. Whiskers on the bars represent standard error.

4.3.12 Soil microbial carbon, soil organic matter (SOM), and pH

Soil microbial biomass carbon (MBC) was not found significantly different between contrasting traffic and tillage or their interactions in the 0-100mm soil stratum (*p=0.294, p=0.206 and p=0.688 respectively, cv=13.4%*). The results of MBC varied in the range of 0.191 – 0.428 mg C g^{-1} soil.

Analysis of soil pH did not show significant differences between contrasting traffic and tillage systems or their interactions (p=0.602, p=0.111 and p=0.357 respectively, CV=3.5%). The average pH was 5.8.

SOM was analysed in two soil depths: 0-100mm, 101-200mm. Significant differences in SOM were observed only in the shallow soil stratum (0-100mm) and only for tillage (*p=0.002*). Traffic and interactions between traffic and tillage were not significant (*p=0.748* and *p=0.743* respectively, *CV=5%*). In the deeper soil horizon traffic, tillage and their interactions were not significant (*p=0.41, p=0.521, p=0.774* respectively, *CV=6.1%).*

Figure 4.35 shows that the SOM in the 0-100mm soil stratum was significantly greater under zero and shallow tillage in comparison to deep tillage (4.44%, 4.35% and 4.11% respectively). The average SOM content was 4.30%.

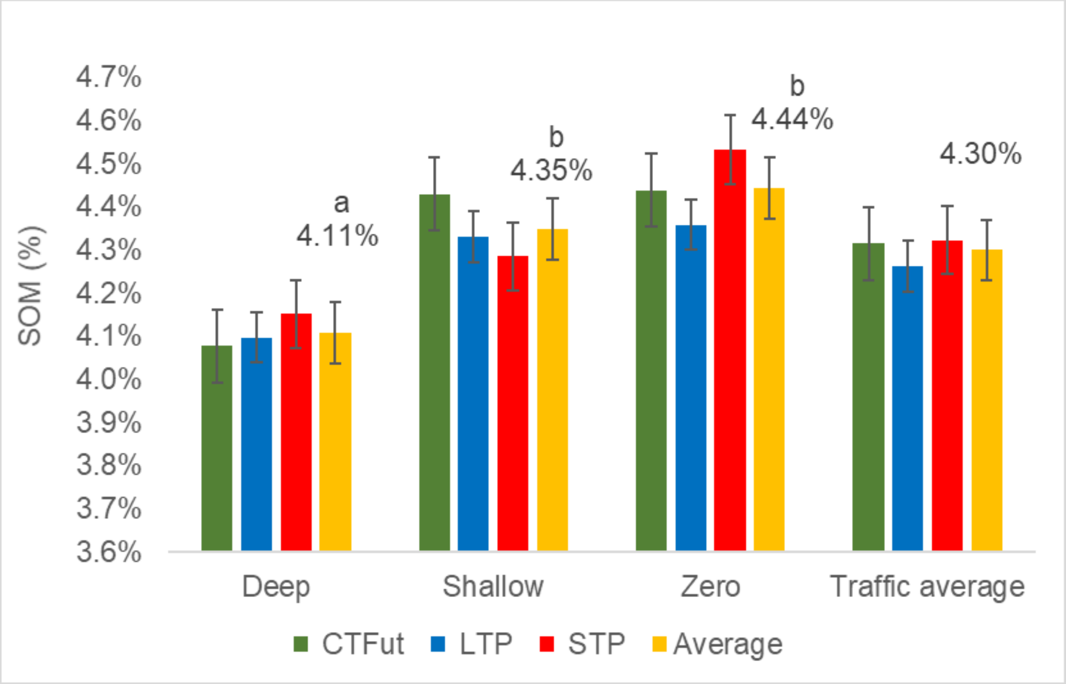


Figure 4.35 Soil organic matter (SOM) content in the 0-100mm soil stratum depending on three traffic systems and three tillage depths. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

Down the soil profile the SOM content decreased to average 3.64%, and there was no significant difference between traffic systems and tillage depths.

4.4 DISCUSSION

4.4.1 Soil bulk density (BD)

The significantly lower bulk density (BD) under untrafficked areas (CTFut) in comparison to LTP and STP (1.31, 1.42 and 1.45 Mg m^{-3} average in the 250mm soil profile) is in agreement with previous studies (Millington, 2019; Shaheb, 2019; Smith, 2017; Lipiec *et al.*, 2003). The analysis from 2019 presented in this thesis, similarly to the analysis by Millington (2019) on the same site done in 2018 found out that there was no significant difference between LTP and STP. However, Smith (2017) reported on differences in the BD between STP and LTP, but the differences were not of high magnitude (1.62 g cm^{-3} and 1.59 g cm^{-3} respectively). The study within here-presented-thesis found that under STP the greatest increase was observed between 0-50mm and 51-100mm soil depths –

from 1.34 g cm^{-3} to 1.47 g cm^{-3} with very little increase further down the soil profile (1.48 g cm^{-3} at remaining soil horizons). This might suggest that at the depth of 100mm under STP soil achieved already enough density to bear the load without further increase in BD, as suggested by Antille *et al.* (2013) and Stranks (2006) who suggested that the increase in soil bulk density decreases progressively as the initial soil bulk density increased. The lack of significant differences between STP and LTP contradicts findings of Antille *et al.* (2013) who reported lower values of soil bulk density under lower inflation pressure tyres with a larger contact area. That study however investigated three different sizes of combine tyres at three inflation pressures. The experiment described in this thesis investigated the effect of the same tyres under two different inflation pressures with only c.30% decrease in tyres pressures from STP to LTP. The lack of differences in BD between STP and LTP might suggest that the difference of tyre inflation pressure is not enough to significantly increase the contact area, which in turn would lead to decrease in soil compaction. Another study which investigated the effects of tyres pressures on the contact pressure distribution and contact area by Shaheb *et al.* (2021) also found that there was no significant difference in the contact pressure under tyres inflation pressure in the range of 30/30 psi (0.21/0.21 MPa), 20/16 psi (0.14/0.11 MPa) and 15/12 psi (0.10/0.08 MPa) on the front and rear tyre respectively, despite significant increase in contact area associated with the decrease in tyre inflation pressures presented above. Only the dual tyres with 12/12 psi (0.08/0.08 MPa) resulted in significantly lower contact pressure in comparison to the previously mentioned three tyres inflation pressures.

Smith (2017) reported that the values of soil BD depending on traffic decreased by 6% between the first and the second year while under STP it increased from 1.52 to 1.68 Mg m^{-3}). The values of BD reported in this thesis however did not change much since the 5th year of study – under CTFut Millington (2019) reported 1.32 Mg m^{-3} – very similar value as presented in this thesis (1.31 Mg m^{-3}) which represented year nine, whereas under both STP and LTP the same author reported 1.44 g cm^{-3} while in year nine the values were 1.45 g cm^{-3} and 1.42 g cm^{-3} respectively.

The comparison of the cultivated soil with zero tillage, in the ninth year of experiment, (2019) showed no significant differences in BD between those three tillage systems. Franzluebbers *et al.* (1995) observed reduced soil BD shortly after tillage, but with the growing season the differences between tiled and no-tilled soil decreased regardless the crop. The presented in this thesis analysis of BD was done around 7 months after tillage. The lack of significant differences between tillage systems was already reported by Millington (2019) from the analysis done in the fifth year of experiment, as well as with Burch *et al.*, (1986); Taboada *et al.*, (1998); Logsdon and Cambardella, (2000). Also, Jabro *et al.* 2016; as well as Martínez *et al.* (2008).

4.4.2 Penetrometer resistance (PR)

In agreement to the results of BD, penetration resistance (PR) was significantly lower on untrafficked than trafficked soil and the effect of tyres pressures was not significant at any depth. These findings are in agreement with previously done PR analysis on the same site by Millington (2019) and Smith (2017) who also reported lack of significant differences between LTP and STP and significantly lower PR under CTFut. Similarly, Arvidsson *et al.* (2001) reported a significant increase of PR two to four years after the traffic was applied in comparison to untrafficked soil. Lack of the effect of tyres pressures contradicts other studies which suggested that low tyre pressures are potential mitigation measures for soil compaction. Schjønning *et al.* (2016) found that lower tyre pressures produced lower stresses in the upper soil profile resulting in lower penetration resistance but for deeper layers penetration resistance was correlated to vehicle load. That study however investigated the effect of tyres pressures which differed by up to 100% (e.g. 150-300kPa). The experiment described in this thesis investigates the effects of tyres pressures in the range of 80 kPa to 110 kPa and 70-100 kPa on the front axis for compaction and tillage/drilling operation on LTP and STP respectively. The differences on the rear axis was even smaller (80 kPa vs 90 kPa and 80 kPa vs 100 kPa for compaction and tillage/drilling operation respectively). These findings suggest that the potential benefits of low tyres pressures might be observed in case of a greater difference in tyres inflation pressures.

The lack of significant effect of tillage on PR systems was in agreement with Millington (2019) and Smith (2017) who also did the analysis after harvest but before tillage. This might suggest that the effect of tillage on PR is not long-lasting and the whole season under the growing crop decreases the effects of tillage on penetration resistance, as suggested by Villarreal (2020).

The PR thresholds of 2MPa which is suggested to restrict root growth (Hamza and Anderson, 2005) was exceeded at 0.30 m, 0.15 m and 0.12 m under CTFut, LTP and STP respectively. The highest observed PR values were: 2.99 MPa under CTFut, 3.30 MPa under LTP and 3.25 MPa under STP at the respective depths of 47 cm, 40 cm and 37cm.These results suggest that the untrafficked soil provides much better soil condition for roots growth as suggested by Hamza and Anderson, (2005) and Kaczorowska-Dolowy (2019) and might have a significant effect on the ultimate crop growth and yield.

4.4.3 Porosity

The total porosity reported in this thesis (average 9.6%) shows much lower results than suggested by literature: Nimmo (2004) suggested that the value of porosity in soil falls in the range of 30-70% and hardly ever is lower than 26%. The X-ray CT method has limited resolution, and consequently it underestimates the total porosity of soil which has been confirmed by Marcelino *et al.* (2007), Millington (2019) and Shaheb (2019). The porosity results in this study are in the same order of magnitude to previously done analysis with the same X-ray CT method: Shaheb (2019) in his study on silty clay loam and clay loam soils reported average porosity of 5.1% and Millington (2019) on sandy loam observed average porosity of 13.5%.

The significantly greater total porosity in uncompacted CTFut soil in comparison to LTP and STP (13.7%, 8.4% and 6.8% respectively) are in agreement with Millington (2019) who reported 17.1%, 11.7% and 11.7% for CTFut, LTP and STP respectively and Shaheb (2019) who observed 6.4% and 3.8% on untrafficked and trafficked soil respectively. The lack of significant effect of tyres pressures on total porosity was also reported by Millington (2019), but contradicts findings of Shaheb (2019) who reported significant decrease in porosity under STP in comparison to LTP (4.4% and 5.8% respectively). Here presented results showed that the significant differences between total porosity under three traffic systems derived mainly from the significant increase in the number of pores under CTFut in comparison to LTP and STP (by 102 and 122% respectively), as the main effect of traffic, tillage or their interactions on pores circularity and pore sizes was not significant. Similarly, Millington (2019) and Shaheb (2019) did not find significant differences in those two aspects between traffic, tillage and their interactions. On circularity, depth had significant effect and its interactions with traffic. The analysis of pore circularity and its changes down the soil profile revealed that under STP in the deepest soil horizon (200-222mm) the pores were significantly more circular than under LTP and CTFut (0.882, 0855 and 0.861 respectively), which suggest that the soil under STP at that stratum was densified and homogenised as suggested by Schjønning and Thomsen (2013). Similarly, the pore size was significantly affected by depth and interactions between depth and traffic as well as tillage and depth: the significant difference between traffic systems in the pore sizes was observed only in the deepest 200-222 mm soil layer where under CTFut the pores were significantly greater than under STP and LTP (0.69mm^2, 0.18 mm^2, 0.32 mm^2 respectively), which might have resulted from cracks under CTFut in soil at that depth, already visible in the soil profiles. The cracks might have resulted from some issues during transport, however all means have been undertaken to reduce the potential effect of transport – samples were carried vertically and carefully. Other potential reason for those cracks might be the effect of weather conditions, particularly wetting-drying and freezing-thawing cycles, as suggested by Rajaram (1998), Hussein and Adey (1998). The smaller pore sizes down the soil profile under STP confirm that the soil compaction under STP reaches deeper in the soil profile, as suggested by Lamandé and Schjønning (2011) who reported that the depth to which higher stresses extended in the soil profile increased under the narrower tyres. It is also in agreement with findings from a laboratory-based study completed by Antille *et al.* (2013) who investigated vertical soil displacement and changes in soil bulk density following a single pass of three sizes of combine harvester tyres at a fixed vertical load of 10.5 t. That research concluded that the narrower tyres, which also had the highest tyre inflation pressure, resulted in the greatest soil displacement.

The cracks were also observed under zero tillage in the shallow layers. The development of horizontal cracks near the soil surface has often been observed during the transition to reduced tillage. Alvarez and Steinbach (2009) and Sasal *et al.* (2006) reported a common platy structure in the soil in the Argentinean Pampas under zero-tillage systems.

The effect of interactions between tillage and depth shows that under shallow tillage the pore sizes kept decreasing below 150 mm. This might have resulted from reduced bearing capacity below the depth of the tillage (100mm), as suggested by Soane *et al.* (1986) and Yavuzcan *et al.* (2002) who found that soil that had been tilled had reduced bearing capacity and was easily recompacted which is illustrated by the reduction in porosity with depth. Under deep and zero tillage the pore sizes increased significantly below 150mm, however due to limited depth to 222mm of the analysis, there was no opportunity to investigate the effect of traffic and tillage below the depth to which the tines reached on deep tillage (250mm). The increase of pore sizes under zero tillage with depth might suggest that zero tillage is more resilient to traffic in comparison to cultivated soil as suggested by Soane *et al.* (1986).

The greater porosity in the shallow soil layers was also observed by Millington (2019) and Shaheb (2018) and possibly resulted from more intensive weather and microbial action in the surface layer than deeper in the soil profile as suggested by Kay and VandenBygaart (2002).

4.4.4 Soil moisture

Soil moisture analysis conducted twice on February 2019 showed 23% which indicates that this is the value of soil moisture content at field capacity (FC), defined as the soil water content at the soil matric potential of -0.03 MPa (Kirkham, 2005), or as the amount of water held in a draining soil 48 hours after being saturated (Ward and Robinson, 2000). This is in agreement with that value reported by Millington (2019), however is slightly lower that that indicated by Godwin and Dresser (2003) who suggested the FC on a sandy loam at around 27%. The decrease in soil water content below the 40-240 mm soil layer was observed under all traffic and tillage systems. This phenomenon of a decrease of soil moisture with an increase with depth was also observed by Gruber *at al.* (2011) who investigated the effects of different tillage systems in a long-term experiment in Germany. There are many studies which report on contradictory effects of tillage on soil water content. The experiment being subject to this thesis found no significant differences in soil moisture between different tillage systems, which is in agreement with Oorts *et al.* (2007) who reported on a study in Northern France, featuring a similar climatic condition to that of the current experiment. Similarly, Smith (2017) did not find any significant differences in gravimetric soil moisture between contrasting tillage and traffic treatments. Contradictory findings however were reported by Wuest *et al.* (2010) who found out that in U.S. Pacific Northwest, tillage to depths of 10 and 15 cm preserved up to 0.01 kg kg^{-1} greater water content than zero-tillage or shallow tillage (5cm). Slawinski *et al.* (2012) reported higher soil moisture under zero-tillage than conventionally- ploughed, nevertheless the differences were not always significant, and the differences varied across season and years and depth, with some observations of higher MC in 300mm under ploughed-based soil. On the other hand, Triplett and Dick, (2008) in their review study, Alvarez and Steinbach, (2009) for Argentine Pampas, Gruber *et al.* (2011) in Germany, Rasmussen (1999) for Scandinavia and Fuentes *et al.* (2003) for no-till in North America drylands observed an increase in soil moisture under no-tillage in comparison to cultivated soil. Gruber *et al.* (2011) indicated that the differences were slight but were found significant (by 0.4–1.2 percentage points). The study being subject of this thesis found slightly greater differences between tillage systems with an increase in soil moisture under zero tillage (average 1.4 percentage point) as Gruber *et al.* (2011), however the differences were not found significant. It has been reported that it is often difficult to discern significant differences between treatments because of high variability across time points (Wuest, 2010).

The location of the field trial in a temperate climate with an annual precipitation of >650 mm in each year being subject to this study means that it did not suffer from water scarcity based on yearly means, however in comparison to a long-term average (2000-2020), two out of three seasons observed (2017/2018 and 2019/2020) experienced significantly lower rainfall in the growing season April-July (60% and 66% of the 20-year average those months) which means that retaining more moisture in the soil might be crucial for the crop growth and yield.

The lack of significant effect of tillage on the volumetric soil moisture content is in line with total porosity results and field-saturated hydraulic conductivity, which might suggest that the loosening effect of tillage is short-term as suggested by Villarreal *et al.* (2020) and after a few months since cultivation soil regained its structure which derive from texture.

4.4.5 Field saturated hydraulic conductivity and instant infiltration rates

Soil field saturated hydraulic conductivity is suggested to be dependent on soil structure and texture, thus it can vary significantly across both - field and region scale (Bagarello *et al.*, 2004). It also depends on organic matter content and population of earthworms which build the vertical holes facilitating water movement down the soil profile (Unger 1996). Kirkham (2014) reported that the value of Kfs varies significantly depending on the soil texture from 30 m/ day on silty clay to 0.05m/ day on silty clay loam. The results obtained in this study are very similar to Abel's (pers. communication) who in July 2016 did the hydraulic conductivity analysis according to the same protocol on the same site and found that CTFut had significantly greater Kfs than STP whereas LTP did not differ significantly from the remaining systems (0.31, 0.07 and 0.19 m h^{-1} respectively). Those values were of the same order of magnitude to the values obtained in 2020, however the values for CTFut increased since 2016 by 81%, whereas under LTP in 2020 Kfs was 2-fold lower than in 2016, that might be the reason in 2020 there was no significant difference between STP and LTP. Chamen (2011) also reported significant increase in infiltration and field saturated hydraulic conductivity on CTF which in one site exceeded 2.5 mm s^{-1} (9 m h^{-1}). In contradiction to the 2016 results by Abel, in 2020 there was no significant difference between tillage systems. Abel in his saturated connectivity analysis in July 2016 found that tillage was also significant and deep tillage had significantly greater Kfs than zero tillage (0.29, 0.20 and 0.08 m h^{-1} for deep shallow and zero tillage respectively). In comparison to his results, the Kfs results in 2020 increased under zero tillage twofold thus no significant differences were observed. Villarreal *et al.* (2020) reported that tillage can increase temporally the values of total macroporosity, while the biological activity during the growing period increases the connectivity of soil macropores, improving water transport during the growing period increases the connectivity of soil macropores, improving water transport. Millington (2019) however in an analysis of soil properties on the same site, reported that traffic and tillage did not have a significant effect on the pore connectivity ($p=0.09$ and $p=0.584$ respectively). The significantly lower infiltration rate expressed as instant infiltration and field saturate hydraulic conductivity (Kfs) under STP than CTFut is in agreement with Smith (2017). This may be related to a significantly reduced number of pores under STP and LTP in comparison to CTFut (by a factor of 2.2 and 2 respectively) which in turn might lead to water logging and reduced soil aeration in the wet periods, and ultimately anaerobic soil condition adding to the detrimental effects of field traffic on the crop growth and yields on STP and LTP (Fageria, 1992, Czyz, 2004).

The simplified falling head method (SFH) in comparison to constant-head (CH) techniques like double ring is suggested to increase the value of Kfs by factor of around 1.8 (Bagarello 2004). However, practically many authors have suggested that an error of the estimate of K_{fs} by a factor of two or three can be considered acceptable for many practical purposes (Elrick and Reynolds, 1992, Reynolds, 1996). Moreover, Bagarello (2004) revealed that the correlation between the values of Kfs obtained with the two techniques was statistically significant (P = 0.05, coefficient of determination, $r^2 = 0.65$). The relatively coherent results of Kfs with the SFH method between 2016 (Abel) and in 2020 suggest that the SFH method is reliable and can be applied widely in the field trials.

The lack of significant differences in Kfs and infiltration rates between tillage systems are in agreement with Villarreal *et al.* (2020) who reported that the effect of tillage on total porosity is temporal, however as a result of improved soil biological activity under zero tillage water transport under zero tillage is improved. This is confirmed in agreement with the findings on increased earthworm population under zero tillage in comparison to deep tillage (Chapter 5.3.3).

4.4.6 SMC, SOM and pH

Concentration of MBC was not found significantly different for contrasting: traffic, tillage or interactions. Sun *et al.* (2018) suggested that different tillage practices affect different microbial communities and reduced tillage had a greater effect on fungal communities while bacterial communities were more affected by mouldboard ploughing. This effect might explain lack of significant difference in MBC. In agreement, Campbell *et al.* (1991) who investigated crop rotation and influence of fertilizers on soil microbial biomass suggested that the “influence of treatments on soil microbial biomass C (MBC) was less pronounced than on microbial biomass N” and fungal community takes advantage in case of decrease in microbial community and vice versa.

This study confirms that soil organic matter concentration is greater on reduced tillage (zero and shallow tillage) in comparison to deep tillage, but the differences found were restricted to the 0-100 mm soil stratum, with traffic or interactions between tillage and traffic not significant. Many studies suggest that reduced tillage increases SOM (West and Post, 2002, West *et al.*, 2004; Syswerda *et al.*, 2011). Lack of significant difference in soil organic carbon in the deeper soil horizon was reported by Syswerda *et al.* (2011) who found out that soil C was more spatially variable with depth and concluded that the lack of significant differences results from lower concentration and greater variability with increased depth of soil horizon.

4.5 CONCLUSIONS

1. The results of soil physico-chemical properties proved that the agricultural traffic has a negative effect on soil physico-chemical properties. Forasmuch, the absence of traffic (CTFut) improved soil health aspects and featured:
    a. significantly lower soil bulk density and penetration resistance than LTP and STP;
    b. significantly greater total porosity and number of pores than LTP and STP;
    c. significantly greater field saturated hydraulic conductivity and instant infiltration than LTP and STP.
2. The hypothesised improvements in soil physico-chemical properties under reduced tillage were limited only to the increased SOM in the topsoil (0-10cm) in comparison to deep tillage. Tillage had no significant effects on the remaining soil physico-chemical properties.
3. The interactions between traffic and tillage were limited. The number of pores in the 200-222mm soil stratum (200-222mm) under STP tyres acting on the deep tilled soil produced significantly smaller pores than LTP and CTFut. Additionally, the penetration resistance under deep tillage with STP in the 360mm - 400 mm soil horizon, was significantly greater than for the LTP.

CHAPTER 5 SOIL BIOLOGY

5.1 OBJECTIVES OF THE CHAPTER, HYPOTHESIS

The objective of this chapter is to quantify the effects of three different traffic approaches (non-traffic, i.e., CTFut, traffic with low tyre inflation pressure, i.e., LTP and traffic with standard tyre inflation pressure, i.e., STP) and three different tillage depths (deep - 250 mm, shallow - 100 mm and zero tillage) and their interactions on soil biological properties, namely on:

- soil fauna feeding activity (Bait lamina score);
- springtails (Collembola) population;
- earthworm population.

The hypotheses of this chapter are:

1. Agricultural traffic has a negative effect on soil biological properties. Therefore, absence of traffic (CTFut) improves soil health in comparison to trafficked soil (LTP and STP). Additionally, LTP improves soil biological properties in comparison to STP.

2. Deep tillage deteriorates soil biological properties in comparison to reduced tillage (shallow and zero tillage).

3. There are no significant interactions between traffic and tillage systems. Hence, the effects of traffic on soil biological properties are equal for the whole range of analysed tillage depths.

5.2 METHODOLOGY

5.2.1 Soil sampling locations

Soil sampling for soil physico-chemical properties followed the same general approach: samples representing untrafficked soil (CTFut) were collected from the centre of each CTF plot, namely between crop row 11 and 12, to represent the soil conditions on the majority of the CTF system. To quantify the effects of traffic with standard and low tyre inflation pressures STP and LTP respectively, soil samples were collected from the primary wheelways of RSTP and RLTP plots respectively, i.e., between crop row 4 and 5, to represent the majority of the random traffic farming with standard and low tyre pressures, as suggested by Kroulik (2009).

5.2.2 Soil invertebrates feeding activity (bait lamina score)

To investigate soil invertebrates feeding activity, a Bait lamina test was used (Terra Protecta GmBH, Berlin, Germany). The test uses PVC stick (120 mm x 6 mm x 1 mm) with 16 holes in 5 mm distance (Kratz, 1998), i.e., reaching 80 mm deep in the soil. The diameter of each hole is 1.5 mm. The holes were filled with original bait by Terra Protecta. The bait substrate is primarily eaten by Collembolans, mites, nematodes, millipedes, and earthworms; the bait loss accounts much less as a result of microbial activity *(*Hamel *et al.*, 2007, Gardi *et al.*, 2009).

The soil fauna feeding activity was conducted twice – in September 2019 and September 2020 in both cases after compaction and before the tillage. In 2019 three strips were used per plot, and in 2020 it was increased to five to increase the statistical power of the test. Prior to inserting the bait lamina stick to the soil, a narrow steel knife was used to make a slot in the soil. The bait lamina sticks were inserted vertically to the soil with the top hole just below the soil surface. In 2019 the sticks were kept in the soil for 8 days. In 2020 the bait lamina sticks were kept in soil for 10 days, because of adverse weather conditions on the 8th day of the analysis. The distance between the sticks on a plot was around 10 m.

The method of calculating the feeding activity followed the protocol given by Siebert *et al.* (2019). Each of the 16 holes on one stick gave 1 point in case it was empty (entirely eaten bait), half a point when the bait was partly eaten (on one side) and when it was fully filled it gave zero points. The results were averaged per each depth (hole) from all sticks on each plot before further statistical analysis. Figure 5.1 shows a bait lamina stick just after collection from the soil. The red flag-like piece of Sellotape was stuck to the top of each bait lamina stick to increase its visibility in the field and ensure each one was collected at the end of the experiment.

To investigate the effects of the plant residues on the soil surface on the Bait lamina score, an additional experiment on zero tillage plots was set up. For this purpose, before inserting the bait lamina stick, an area of around 2.25m^2 (1.5m x 1.5 m) was gently cleared from plant residues. For this analysis additional five Bait lamina sticks were used per plot, each in between of those already used for the standard procedure, resulting in around 5-m distance between the sticks on zero tillage plots.

Figure 5.1 Bait lamina stick after collection from the soil

Gravimetric soil moisture analysis was also conducted on the start day of the test as well as on the last day of the test. Two samples per plot were collected from 0-100 mm layer of soil and mixed, weighted, then oven-dried at 105ºC for 48 h as suggested by Reynolds (1970). The gravimetric soil moisture was calculated as a weight of water (the difference between weight of moist soil and dry soil) divided by the weight of dry soil (Reynolds, 1970).

5.2.3 Springtails (Collembola) abundance

Soil samples for springtails abundance analysis were collected from 10 points per plot at a distance of about 5 m, with a 40 mm x 100 mm corer. The dates of collections were 6 June 2019 from block one and two and 8 June 2019 from block three and four. Soil sampling followed the general sampling protocol.

Tullgren Funnels presented in Figure 5.2 were used to extract soil fauna, including springtails from the soil samples. Tullgren funnel works by creating a desiccation and temperature gradient over the sample by using bulbs (40W) above the samples which makes the mobile organisms move away and fall into a collecting vessel, filled with 70% industrialized methylene spirit. The samples remained in the funnels for 10 days.

Figure 5.2 Tullgren funnels used for extracting springtails

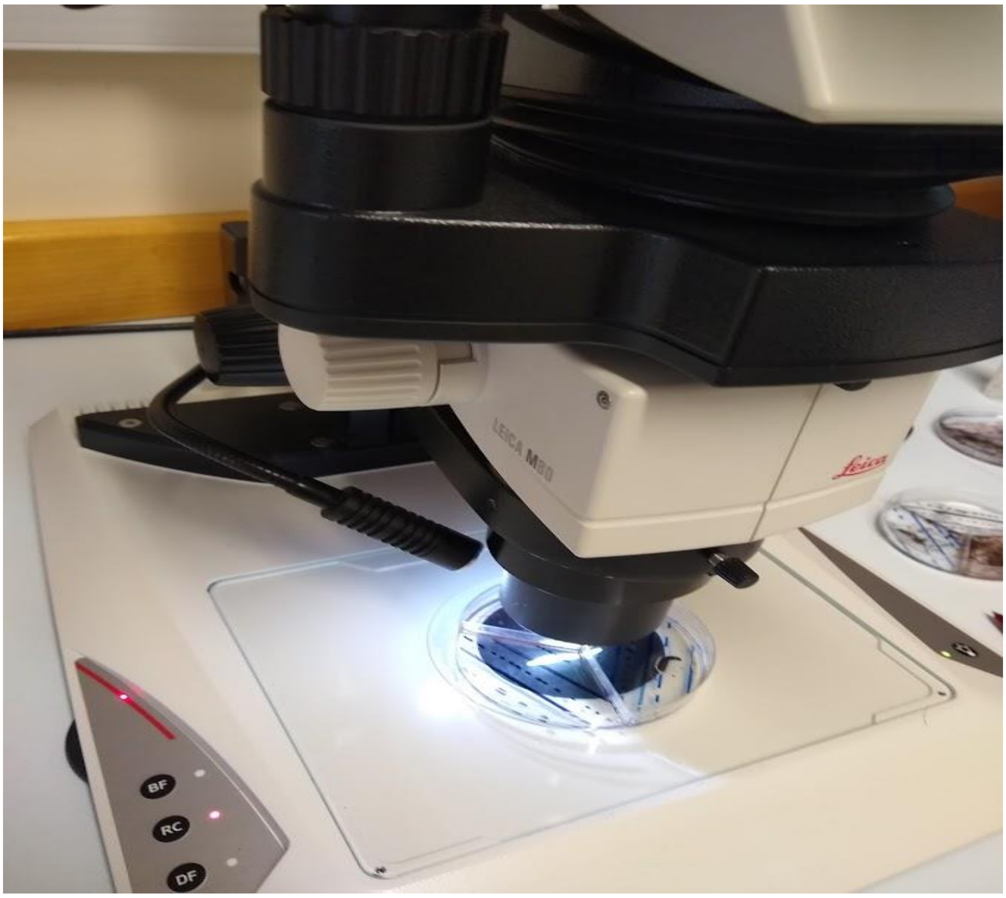


Figure 5.3 Leica M30 stereomicroscope used for identifying springtails.

The evaluation of microarthropods was restricted to Collembola, categorized into eco-morphological (EM) groups (edaphic, hemiedaphic, and epigeic) as suggested by Filho *et al.* (2016). This method is based on morphological characteristics (traits) that are connected to adaptation of each collembolan species to the soil environment. Since springtails are microscopic organisms, they were identified using Leica M30 stereomicroscopes shown in Figure 5.3. The traits used are: presence of ocelli, antenna length, development of furca (tail-like appendage), presence or absence of body hairs/scales, and pigmentation with each trait giving a score which at the end is summed. The total score ranges from 0 (epigeic forms with adaptations to the surface) to 20 (adaptations to soil habitat indicating edaphic forms). The method thresholds the scores accordingly: epigeic forms get a final EM score in the range of 0-6, hemiedaphic 8-12, and edaphic 14-20. Lack of total score of 7 and 13 derives from the way the points are assigned, since each trait can obtain even number of points only, with potential scores for hair and scales of 0 or 4 points and for the antenna, furca and pigmentation there are 3 levels of scores, 0, 2, 4 (Filho *et al.* 2014). The abundance of the springtails was recalculated from the number of organisms representing each EM group, obtained from the soil volume to number per m $^{-2}$ which reflected the 0-100mm soil stratum.

Volumetric soil moisture was conducted on 9 June 2019, i.e. the next day after collecting soil samples for Collembola analysis from block 3 and 4. The moisture was analysed with a TDR soil moisture probe (Spectrum Field Scout TDR 100) from the 0-75mm soil horizon.

5.2.4 Earthworms abundance

The earthworm count was done in two sampling points on each plot: on 29 September 2020, and on 2 October 2020, i.e. after compaction (done on 11 September 2020) and before next tillage and drilling. The earthworms were extracted with an expellant made of 4 g mustard powder (by Colemans) per 1 l water since the concentration of 3-4.5 g l $^{-1}$ was suggested to be optimal for the earthworm numbers (Chan and Munro, 2001; Karaca, 2011). Prior to the analysis, 10 g of mustard powder was weighed out to small containers so it was suitable for 2.5 l of water – the exact volume of the available bottles. On the day of the field experiment, prior to the field work, the containers with mustard powder were filled with around 100 ml of water and shaken to start the extraction of the allyl isothiacyde (AITC) – the active ingredient of the mustard seeds that is suggested to irritate the earthworms (Karaca, 2011), see Figure 5.4.

Figure 5.4 Water solution of mustard powder

The balance of water was added in the field to make up to the final volume of the 2.5 l. The experiment started with a trial on the headland and then on plot 1 (different sampling place than for the proper analysis) to ensure that the accepted volume of solution is capable to infiltrate within reasonable time (below 40 minutes), so that the analysis might have been completed during one day to ensure similar soil moisture condition between plots. The accepted volume of mustard solution was 700 ml split into 500 ml at the beginning followed by another 200ml after 10 minutes. Rings of 225 mm diameter were gently pressed to c. 5 cm down the soil profile with a mallet and a plank to ensure vertical flow of the solution. The rings used for earthworm extraction are presented in Figure 5.5, and the rings layout in the field is presented in Figure 5.6.

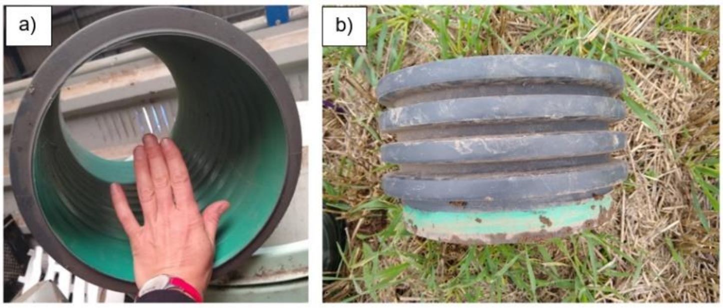


Figure 5.5 A ring used for earthworm extraction – a) view from above; b) a side view.

Figure 5.6 Rings layout in the fields for earthworm extraction

The soil touching the ring was gently pressed to avoid any voids which could potentially limit the area treated with mustard solution (similarly to the method suggested for simplified soil water infiltration by Bagarello *et al.*, 2011). The analysis was conducted in 9 plots at the same time (one block). In each ring at first 500 ml of the solution was used. After the solution was poured into a ring, a stop watch was started to ensure similar time of observation between the rings. After 10 min, another 200 ml was poured into each ring. Total time of monitoring was 40 min. Monitoring of emerging earthworms was conducted constantly. Each earthworm which emerged was picked up with a pair of tweezers and put to a labelled container for further count and body mass analysis.

Prior to putting the samples into the fridge each sample was gently rinsed with water to help the earthworms remove the irritating substances, and the next day the earthworms were counted, weighed on a balance with accuracy to 0.001g and assigned to one of three eco-types (anecic, endogeic and epigeic) or classified as juvenile, following the procedure suggested by Stroud and Bennet (2018). The epigeic are the litter-dwelling earthworms, which live near the soil surface (Karaca, 2011, Stroud and Bennet, 2018). They have dark red head and their length does not exceed 80mm, they are also reported to be fast-moving (Stroud and Bennet 2018). The endogeic earthworms inhabit the top-soil, where they build a net of tunnels both vertical and horizontal (Karaca, 2011). They are of pale green colour, small to medium size. Bennet and Stroud (2018) reported that they often curl up when handled. The anecic earthworms have the greatest size, typically reaching 20 to 25 cm in length when extended in the temperate climate in most areas of Europe (Edwards, 2004). They build their permanent vertical burrows to 1 m down the soil profile through which they transport the decomposition products to lower soil layers (Karaca, 2011).

Soil moisture was analysed with a TDR Field Scout probe with 75 mm-long rods, in three places outside of the ring ensuring the sampling point represent the same position on the plot. Results from those three sampling points were averaged before further analysis.

5.3 RESULTS

5.3.1 Soil fauna feeding activity (FA) – bait lamina score

The Bait lamina score indicates soil fauna feeding activity (FA) where higher score indicates higher feeding activity and therefore higher invertebrate population. Detailed statistics are presented in the Appendix 11.3.

The analysis of FA in two years (2019 and 2020) revealed that that the main effect of traffic, tillage and depth was significant in both years, whereas the interactions between depth and traffic were significant in 2020 only.

Figure 5.7 shows the Bait lamina score in 2019 across the soil profile depending on traffic and reveals that it was significantly greater (*p=0.005*) on untrafficked soil - CTFut than on LTP and STP (average 0.57, 0.48 and 0.41 respectively); on LTP it was significantly greater than STP, but lower than on CTFut.

The FA in 2019 depending on tillage and depth is presented in Figure 5.8, which shows that it was significantly greater (*p=0.015*) under shallow and deep tillage than under zero tillage (average 0.53, 0.52 and 0.40 respectively) and deep tillage did not differ significantly from shallow tillage.

The effect of depth on the FA in 2019 is presented in Figure 5.9, which reveals that it was highest at the shallow soil stratum (0-10mm) and decreased significantly down the soil profile until 25 mm, since when no significant differences between consecutive depths were observed.

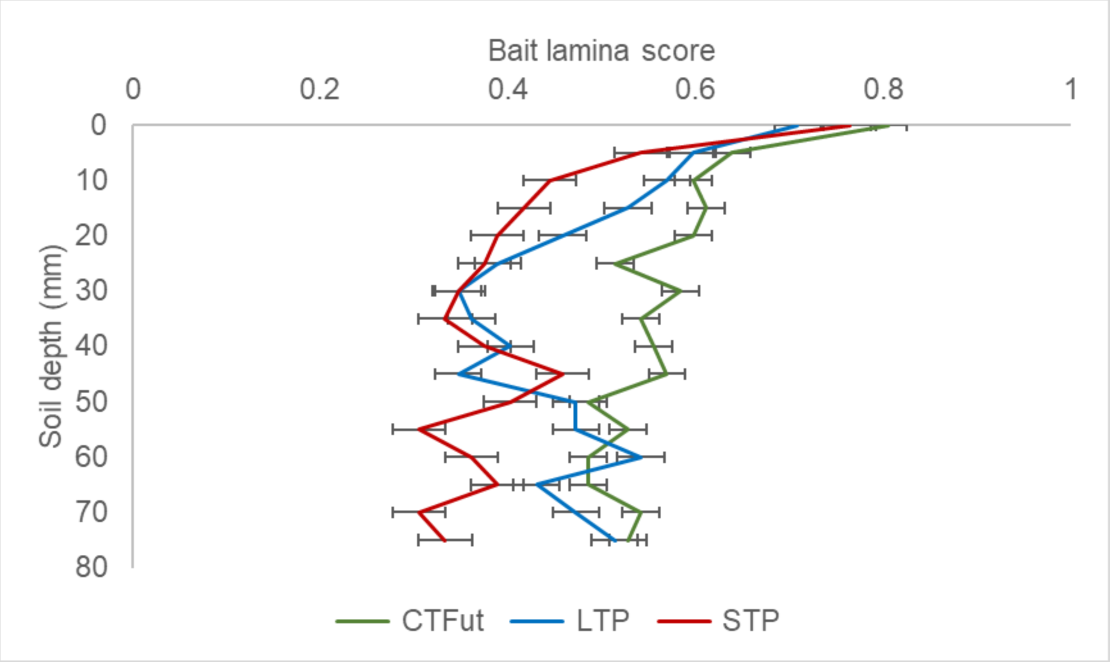


Figure 5.7 Soil fauna feeding activity (Bait lamina score) in 2019 down the soil profile depending on three traffic systems: CTFut – untrafficked soil, LTP – soil trafficked with tyres with low inflation pressures, STP – soil trafficked with standard inflation pressures tyres. Horizontal whiskers represent standard error.

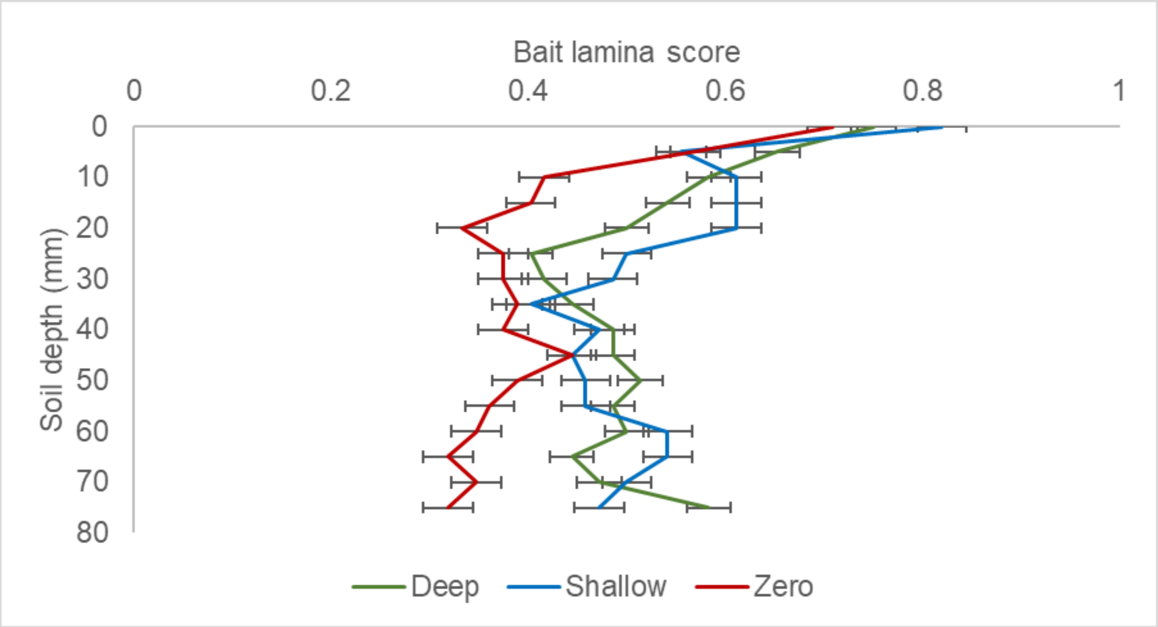


Figure 5.8 Soil fauna feeding activity (Bait lamina score) in 2019 down the soil profile depending on three tillage systems: Deep = 250mm, Shallow = 100mm, Zero = zero tillage. Horizontal whiskers represent standard errors.

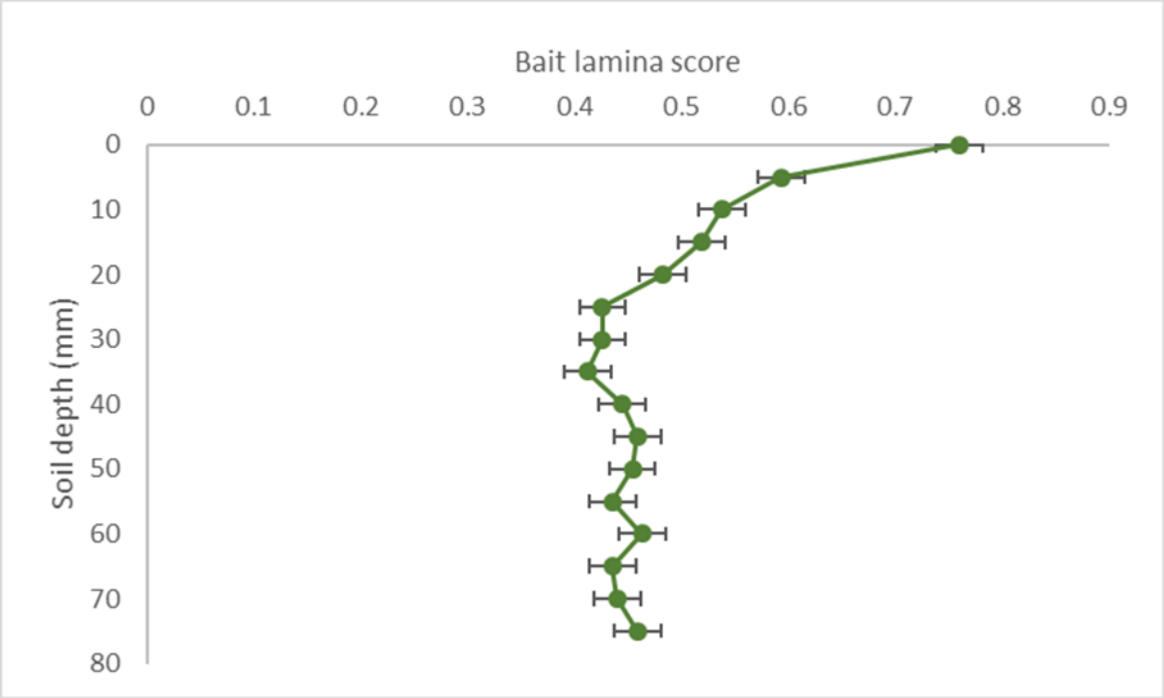


Figure 5.9 Soil fauna feeding activity (Bait lamina score) in 2019 depending on soil depth. Horizontal whiskers represent standard errors.

Figure 5.10 which presents the FA in 2020 depending on traffic and depth shows that it was significantly greater (*p<0.001*) on untrafficked soil - CTFut than on LTP and STP (0.35, 0.21 and 0.14 respectively) and on LTP it was also significantly greater than on

STP, but lower than on CTFut. Interactions between depth and traffic were also significant: the FA under CTFut was significantly greater (*p=0.039*) than under STP across all depths, whereas the FA under CTFut in comparison to LTP was significantly greater on most of the analysed depth, apart from 10 mm, 55 mm and 60 mm, where there was no significant difference between those two traffic systems. The FA was significantly greater on LTP than on STP only in the 0-50 mm soil zone, while below the 50 mm there was no significant difference between LTP and STP.

Figure 5.11 shows the FA in 2020 depending on tillage and depth and reveals that tillage was significant (*p=0.014*) and the FA under shallow and zero tillage was significantly greater on than under deep tillage (0.28, 0.26 and 0.16 respectively). Interactions between tillage and depth were not significant (*p=0.059*).

The average Bait lamina score in 2020 across the soil profile is presented in Figure 5.12, which reveals that the greatest feeding activity was observed in the top soil with the very first hole in the stick featuring the highest score (0.61), and the score decreased significantly with each increment down to 15mm (result 0.25), then the FA decrease down the soil profile however the differences between consecutive increments were not significant between the following depths: 15mm-20mm-25 mm and 55mm-60mm. The FA at 70mm where reached the lowest result (0.13), which was the same at 75 mm.

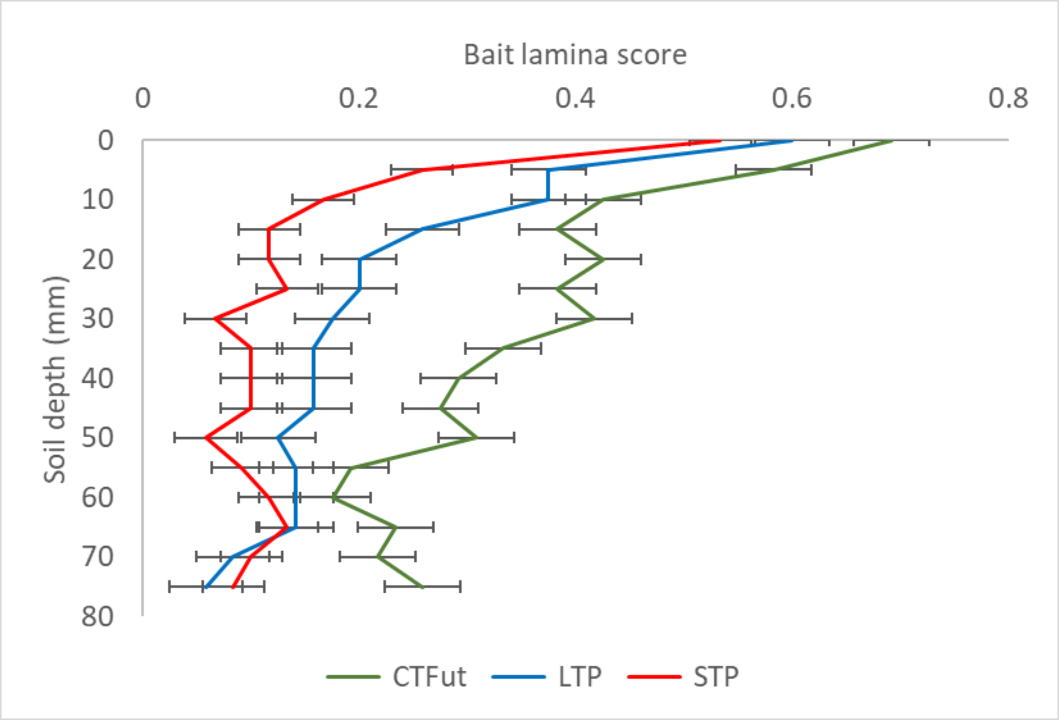


Figure 5.10 Soil fauna feeding activity (Bait lamina score) in 2020 down the soil profile depending on three traffic systems: CTFut – unwheeled soil, LTP – soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal whiskers represent standard errors.

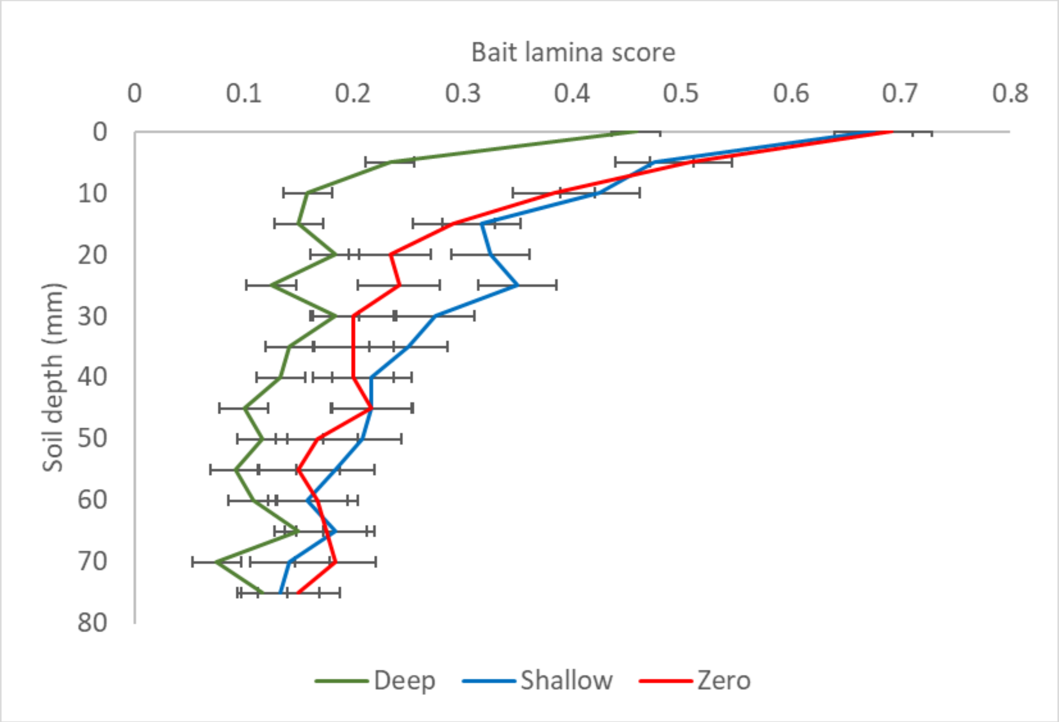


Figure 5.11 Soil fauna feeding activity (Bait lamina score) in 2020 down the soil profile depending on three tillage depths: Deep = 250mm, Shallow = 100mm, Zero = zero tillage. Horizontal whiskers represent standard errors.

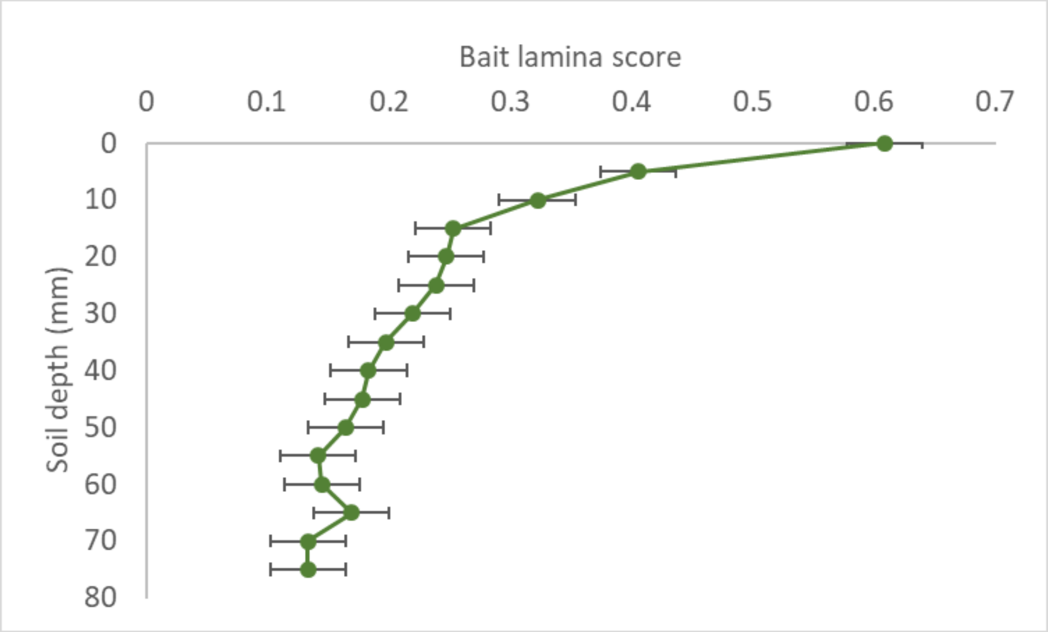


Figure 5.12 Average soil fauna feeding activity (Bait lamina score) in 2020 down the soil profile. Horizontal whiskers represent standard errors.

Table 5.1 presents the gravimetric soil moisture on the first and last day of the Bait lamina experiment in both years (2019 and 2020) and reveals that in 2019 at the beginning as well as at the end of the experiment, tillage had significant effect on soil moisture (*p=0.008* and *p=0.031* respectively) and under zero tillage it was significantly greater than under deep tillage (23.0% vs 21.4% and 23.8% vs. 22.7% respectively). Shallow tillage did not differ significantly from zero and deep tillage on any date. Traffic and interactions between traffic and tillage were not significant on any day. In 2019 the soil moisture was much greater than in 2020 (average 22.2% and 23.3% on the first and last day in 2019 vs 17.5% and 19.3% in 2020 respectively).

Table 5.1 Gravimetric soil moisture on the first and last day of the Bait lamina experiment in 2019 and 2020, depending on three traffic systems and three tillage depths. Significantly different means are represented by different letters.

2019								
	Start day				**Last day**			
Traffic/ tillage	Deep	Shallow	Zero	Average	Deep	Shallow	Zero	Average
CTFut	20.5%	22.2%	22.8%	21.5% a	22.2%	22.9%	23.9%	23.0% a
LTP	22.3%	21.8%	23.3%	22.4% a	22.9%	23.2%	23.9%	23.3% a
STP	21.5%	22.2%	23.0%	22.2% a	22.9%	23.6%	23.7%	23.4% a
Average	21.4% a	22.1% ab	23.0% b	22.2%	22.7% a	23.2% ab	23.8% b	23.3%
2020								
	Start day				**Last day**			
Traffic/ tillage	Deep	Shallow	Zero	Average	Deep	Shallow	Zero	Average
CTFut	16.8%	17.3%	19.1%	17.7% a	20.7%	19.3%	21.5%	20.5% a
LTP	17.4%	16.0%	17.8%	17.1% a	19.0%	17.9%	19.1%	18.7% a
STP	17.6%	17.3%	18.2%	17.7% a	18.8%	17.3%	20.2%	18.8% a
Average	17.3% a	16.9% a	18.4% a	17.5%	19.52% a	18.19% a	20.28% a	19.3%

Figure 5.13 shows the soil fauna feeding activity on zero tillage plots depending on the presence of plant residues (trash) and reveals that despite the Bait lamina score on the areas without trash was greater than on the areas with trash (0.33 and 0.26 respectively), the difference was not significant. Only traffic was significant and CTFut featured 227% and 214% greater feeding activity than LTP and STP respectively; LTP did not differ significantly from STP.

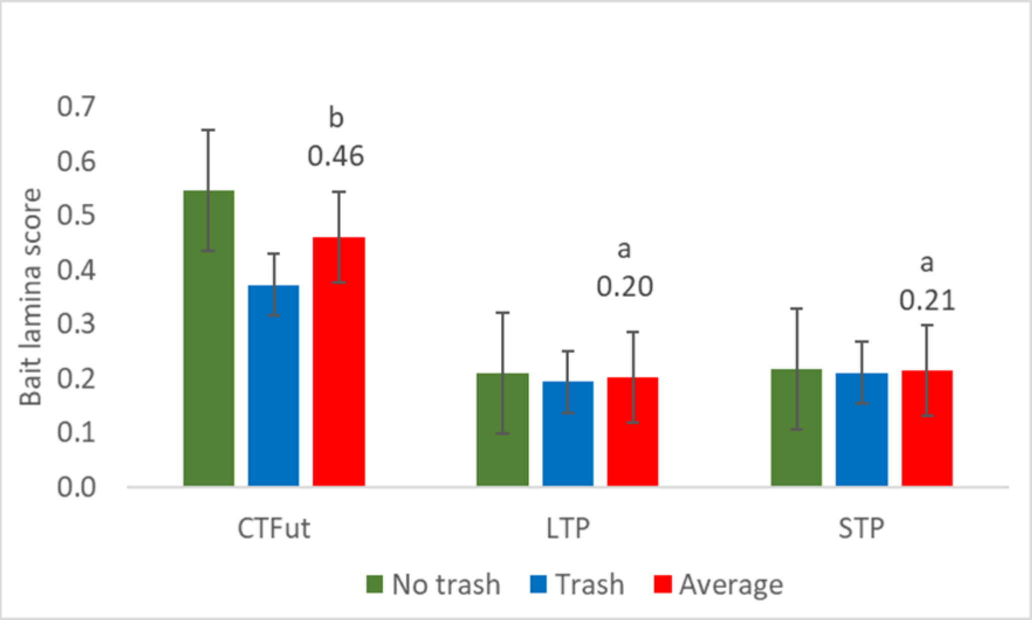


Figure 5.13 Soil fauna feeding activity on zero tillage plots depending on traffic and the presence of plant residues (trash vs no trash). Significantly different means are represented by different letters. Whiskers on the bars represent standard errors.

Figure 5.14 presents the Bait lamina score depending on traffic across the soil profile on zero tillage plots and shows that in the very shallow soil stratum (0 mm) there was no significant difference between STP and CTFut, and as from 5 mm down the soil profile, CTFut featured significantly greater (p=0.019) soil fauna feeding activity than LTP and STP. In the first three measuring points (0mm, 5mm and 10 mm) and at the last point (75mm depth) the bait lamina score was significantly greater on STP than on LTP. At the depths of 30mm, 35mm, 40mm and 50mm the Bait lamina score was significantly greater on LTP than on STP.

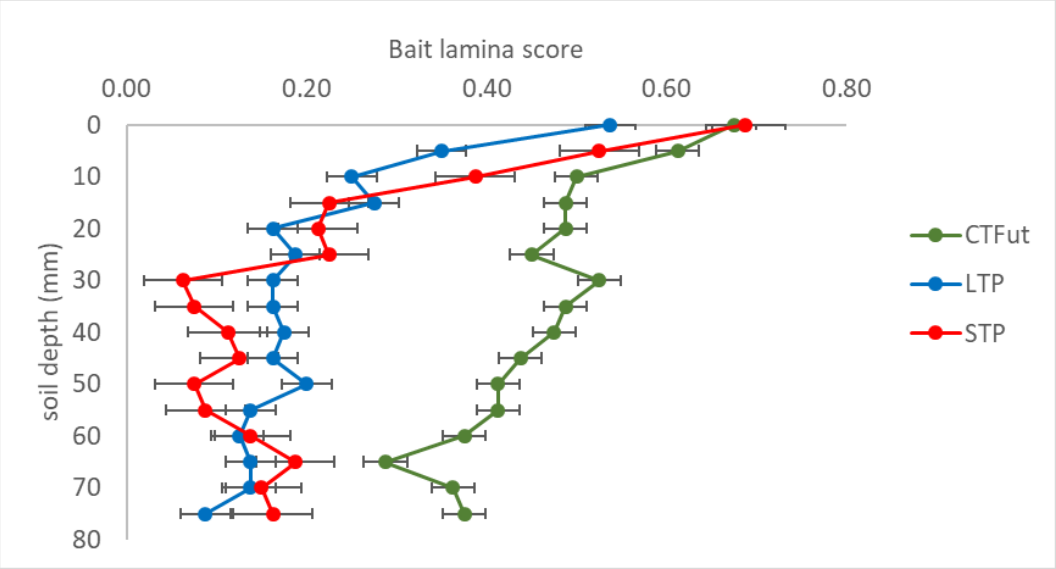


Figure 5.14 Soil fauna feeding activity (Bait lamina score) down the soil profile under zero tillage, averaged from the trash and no trash treatments for three traffic approaches: CTFut- untrafficked soil, LTP – soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Horizontal whiskers represent standard errors.

5.3.2 Collembola (springtails)

The total number of springtails counted was 1514 which gives the average density of 3336 individuals m^{-2} in the 0-100mm soil zone. The percentage of each EM group is presented in Figure 5.15, which shows that the epigeic group had the greatest percentage, followed by hemiedaphic and edaphic (58%, 26% and 16% respectively).

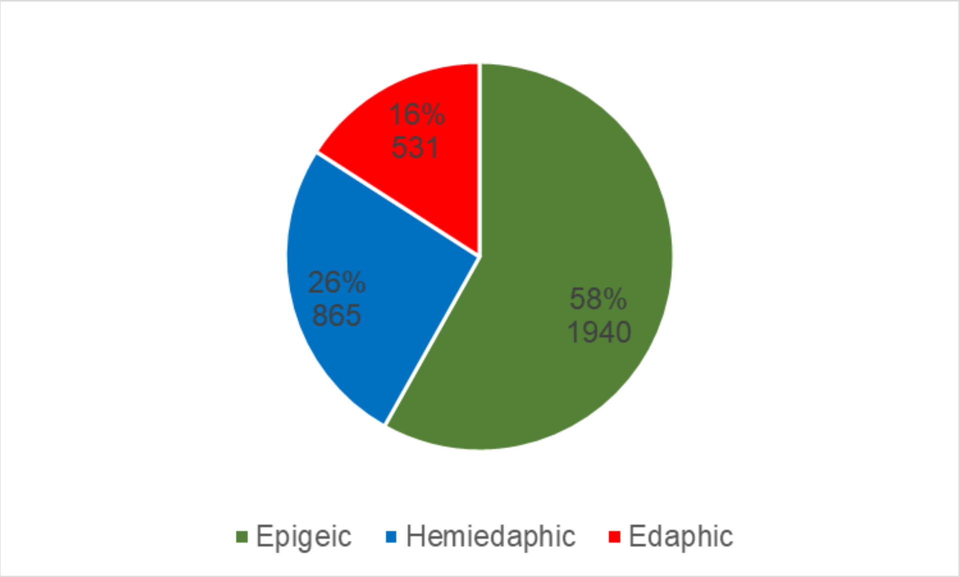


Figure 5.15 Percentage of each ecomorphological group found in the study and their density (number m^{-2}) in the 0-100mm soil layer.

Figure 5.16 shows the total density of springtails (number of organisms m^{-2} in the 0-100mm soil zone) for different traffic and tillage systems, and reveals it was significantly (*p<0.001*) greater on CTFut than on STP (148%) and LTP did not differ significantly from either traffic system. Tillage was also significant and the total Collembola density on shallow tillage was significantly (*p=0.004*) greater than on zero (159%) and deep tillage did not differ significantly from remaining two tillage depths.

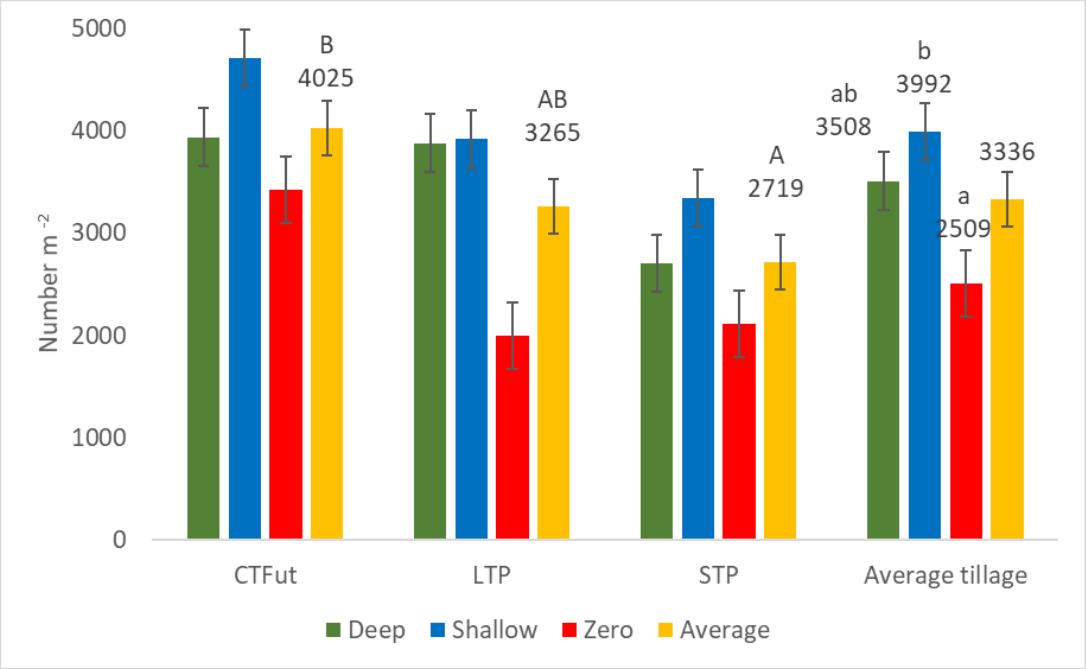


Figure 5.16 Total density of springtails (number m-2) in the 0-100mm soil stratum, depending on traffic and tillage system. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

The density of springtails from epigeic EM group - which inhabits the most surface soil zone – is presented in Figure 5.17, which shows that only tillage was significant (p=0.045) and on deep tillage it was significantly greater than on zero tillage whereas shallow tillage did not differ significantly from the remaining two traffic systems (2281, 1351 and 2188 ind. m^{-2} respectively).

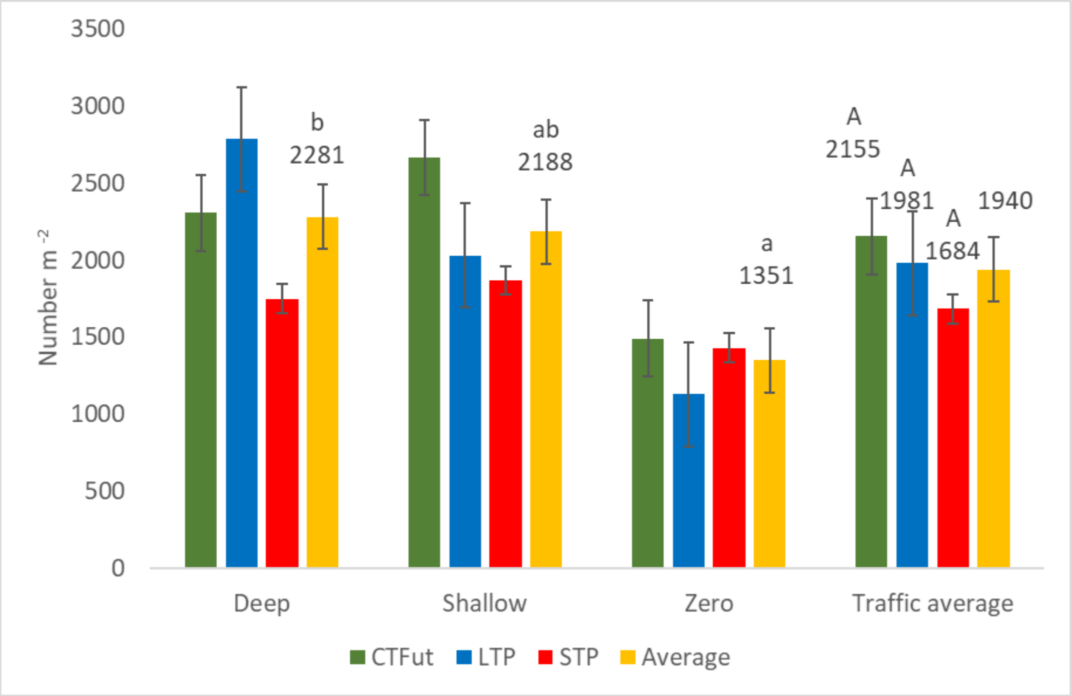


Figure 5.17 Density of epigeic springtails (number m-2) in the 0-100mm soil stratum depending on traffic and tillage. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

The population of hemiedaphic EM group of springtails is presented in Figure 5.18, which shows that on shallow tillage it was significantly (*p=0.009*) greater than on zero tillage whereas deep tillage did not differ significantly from the remaining two tillage depts (1068, 605 and 922 ind. m^{-2} respectively). Traffic was not significant (*p= 0.117*).

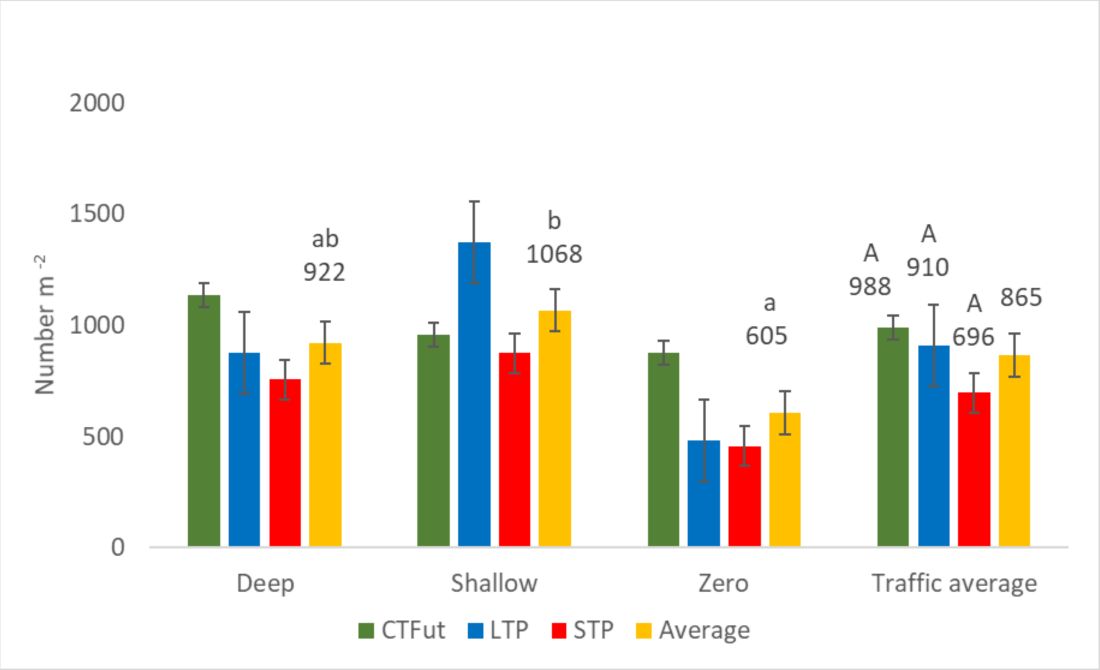


Figure 5.18 Density of hemiedaphic springtails (ind. m-2 in the 0-100mm soil stratum) depending on traffic and tillage. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

The edaphic group of springtails was the least abundant (16% of total number). Both factors: tillage and traffic had significant effect on their number (*p=0.038 and p=0.003 respectively*).

Figure 5.19 shows that on shallow tillage it was significantly greater than on deep tillage whereas zero tillage did not differ significantly from the remaining two tillage depths (736, 305 and 552 ind. m^{-2} respectively). This EM group was also significantly affected by traffic and its population in untrafficked soil - CTFut was significantly greater than on STP and LTP (882, 338 and 373 ind. m^{-2} respectively).

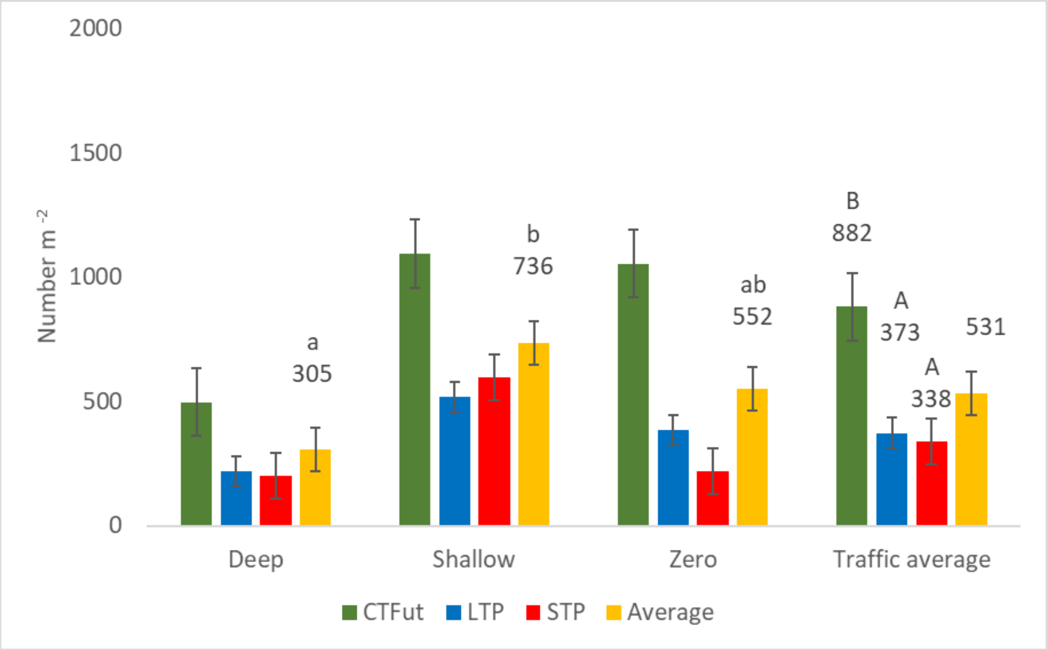


Figure 5.19 Density of edaphic springtails (number m-2) in the 0-100mm soil stratum depending on traffic and tillage. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

The detailed results of the total number of springtails in the 0-100 mm soil stratum and for each EM group separately are presented in Table 11.7 (in Appendix).

Table 5.2 presents the values of volumetric soil moisture (VSM) depending on traffic and tillage and reveals that VSM was significantly lower (p=0.033) on CTFut than on STP and LTP and did not differ significantly from the remaining two traffic systems (19.7% and 22.5% and 21.0% respectively). Deep tillage featured significantly lower (p=0.048) VSM than zero whereas shallow did not differ significantly from the remaining two tillage systems (19.7%, 21.1% and 20.8% respectively).

Table 5.2 Volumetric soil moisture (%) on the next day after soil samples collection for Collembola analysis. Significant differences are represented by different letters in red font.

Tillage	CTFut	LTP	STP	Average
DEEP	16.1	21.4	21.6	19.7 a
SHALLOW	20.6	20.4	21.5	20.8 ab
ZERO	22.4	21.1	24.3	22.6 b
Average	19.7 a	21.0 ab	22.5 b	21.1

5.3.3 Earthworms

In total, from the two sampling points per each plot 381 earthworms were collected, which gives on average 5.2 organism collected per ring which is equivalent to 131 earthworms m^{-2}.

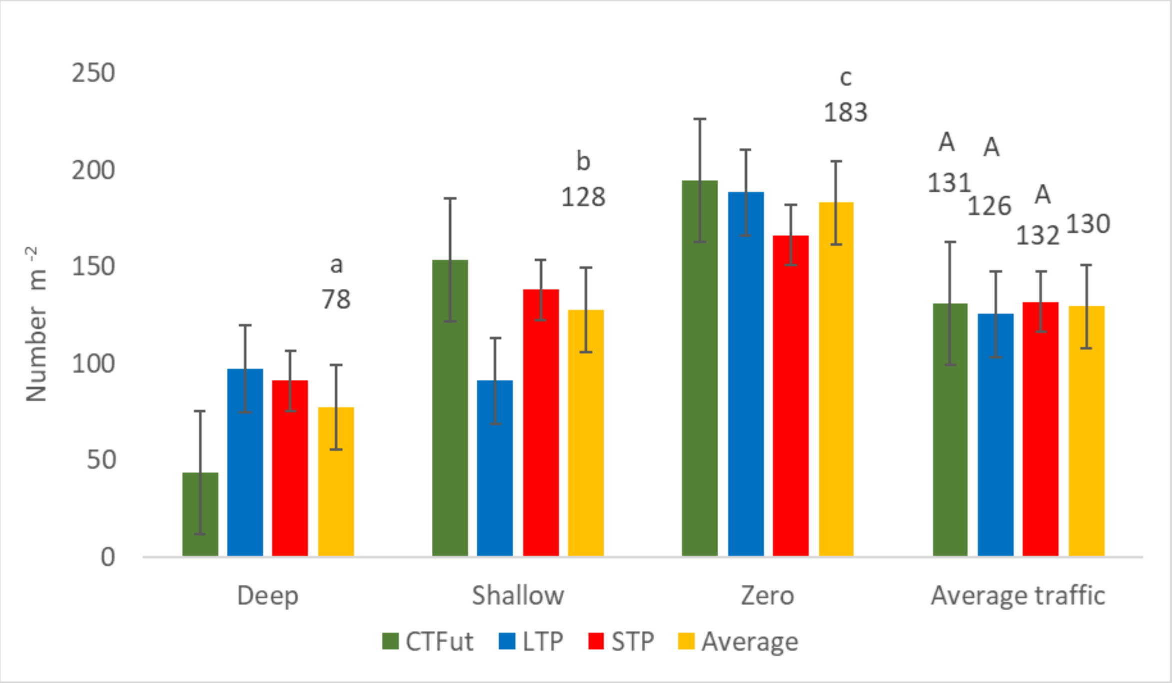


Figure 5.20 Density of earthworms (number m-2) depending on traffic and tillage: CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

Figure 5.20 shows he density of earthworms (total number m^{-2}) depending on tillage and traffic and reveals that it increased with the reduction of tillage depths and was significantly greater (*p<0.001*) under zero tillage than under deep and shallow tillage (230% and 142% respectively). Also, the shallow tillage featured significantly greater population of earthworms than deep tillage (162%). The main effect of tillage was also significant on the population of epigeic and juvenile earthworms (p=0.03 and p=0.005 respectively). Traffic and interactions between traffic and tillage were not significant on each analysed EM group of earthworms as well as on the total number. Detailed statistics are presented in Appendix 11.3.

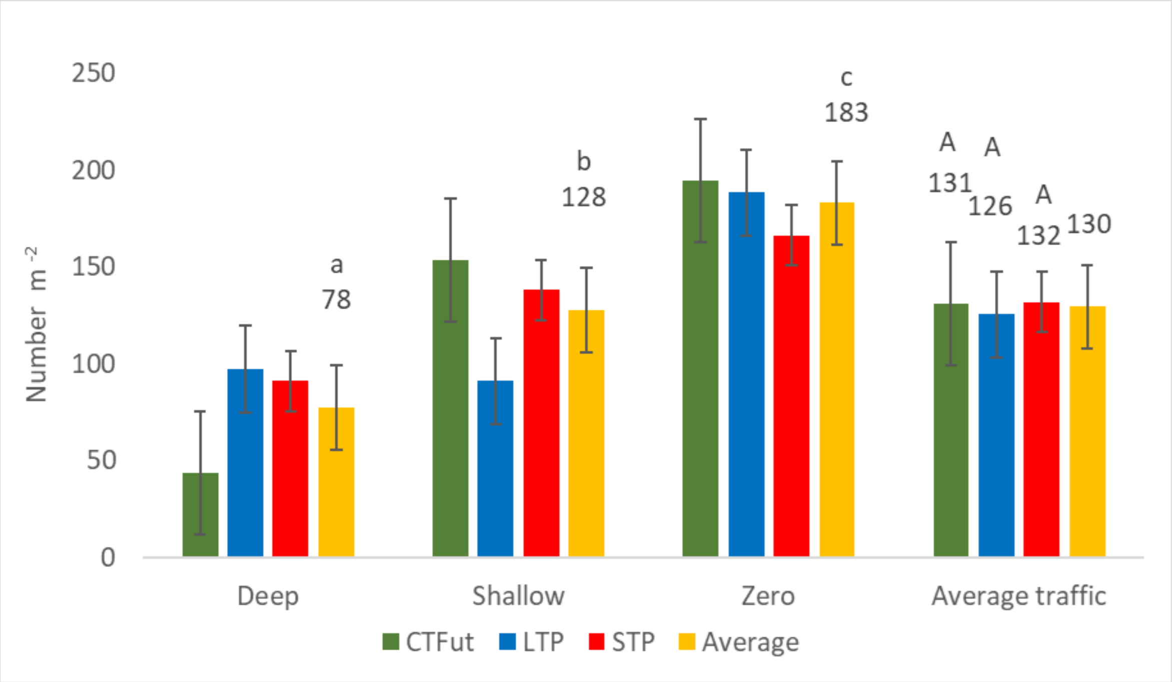


Figure 5.20 Density of earthworms (number m^{-2}) depending on traffic and tillage: CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

The percentage of each earthworm eco-group is presented in Figure 5.21, which shows that endogeic earthworms were most abundant (40%), and epigeic, juvenile and anecic constituted of 26%, 23% and 11% respectively.

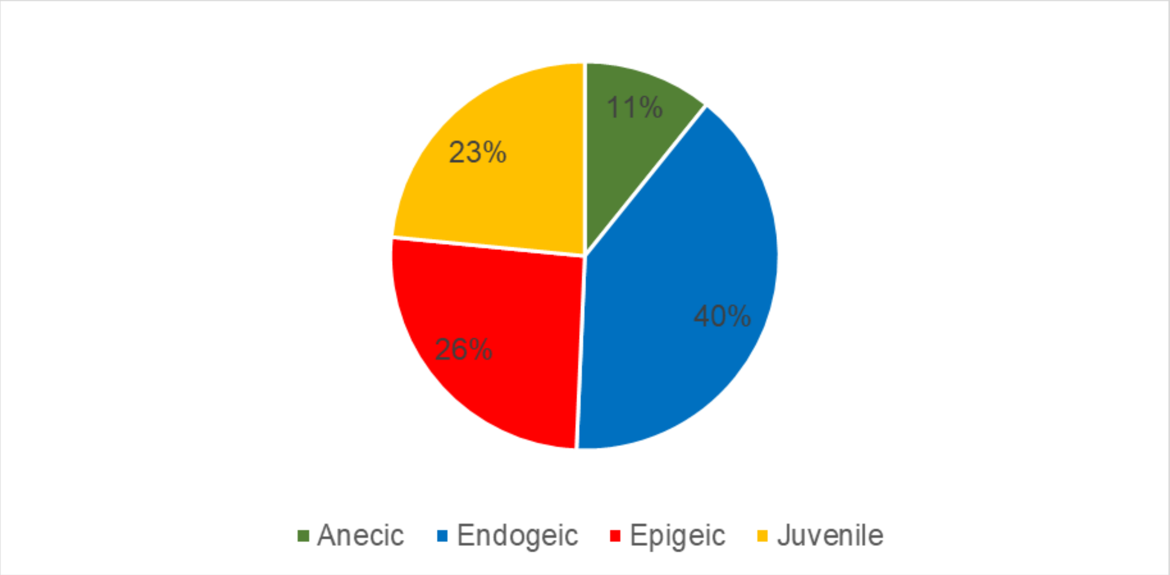


Figure 5.21 Percentage of earthworm eco-groups found in the study.

A comparison of the earthworm density (number of organisms m^{-2}) of each eco-group separately (anecic, endogeic and epigeic) showed that only epigeic and juvenile groups significantly differed between tillage systems (*p=0.03, p=0.005* respectively). Traffic and interactions between traffic and tillage did not have significant effects on those EM groups of earthworms. The remaining EM groups, namely anecic and endogeic did not differ significantly under different traffic and tillage systems and their interactions.

Figure 5.22 shows that the density of epigeic earthworms m^{-2} was significantly greater on zero tillage in comparison to deep tillage (255%), and under shallow tillage it did not differ significantly from zero and deep tillage (34, 48 and 19 respectively). Traffic and interactions between traffic and tillage were not significant (*p=0.355* and *p=0.489* respectively).

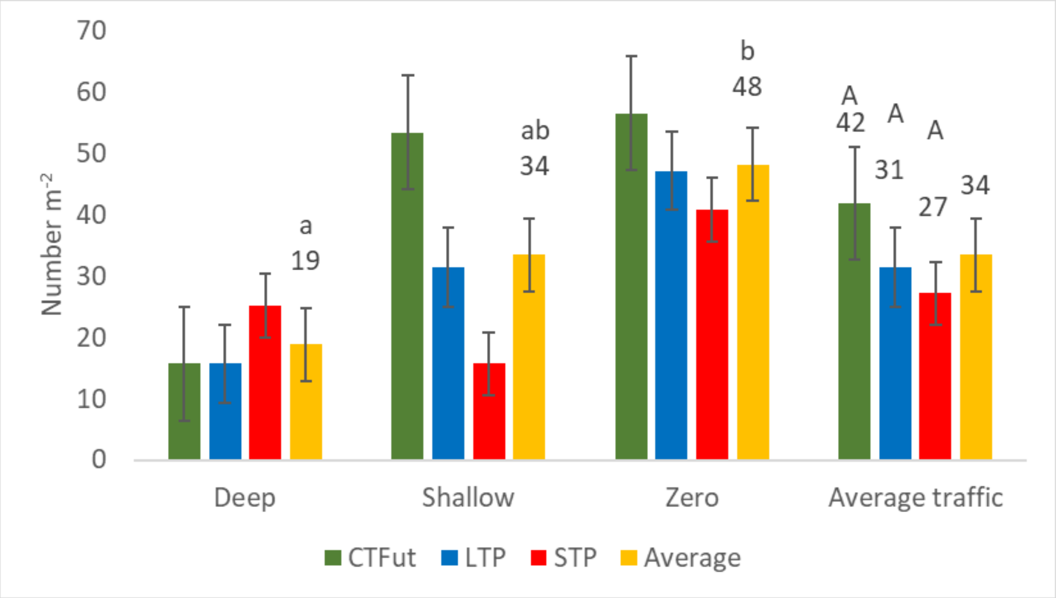


Figure 5.22 Density of epigeic earthworms (number m-2) depending on traffic and tillage systems. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

Figure 5.23 presents density of juvenile earthworms m^{-2} and reveals that on zero tillage it was again significantly greater than on shallow and deep tillage (51, 25 and 15 respectively). Traffic and interactions between traffic and tillage were not significant (p=0.721 and p=0.644 respectively).

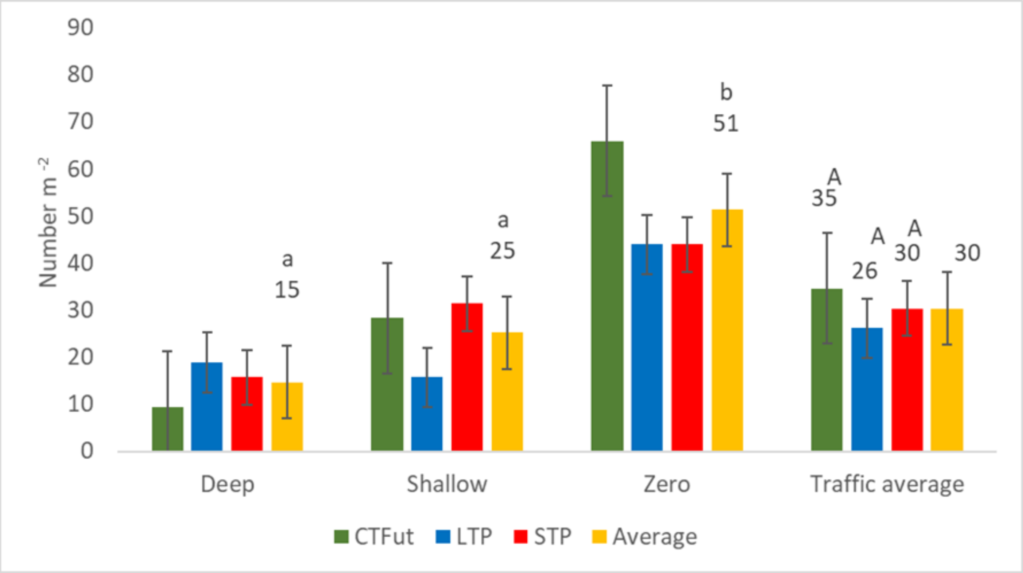


Figure 5.23 Density of juvenile earthworms (number m-2) depending on three traffic systems and three tillage depths. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on the bars represent standard error.

Figure 4.24 presents the biomass of earthworms (g m^{-2}) and shows that it was significantly greater (*p=0.004*) on zero tillage in comparison to deep tillage (236%), while shallow tillage did not differ significantly from zero tillage and deep tillage (40.4, 51.7 and 21.9 g m^{-2}). Traffic and interactions were not significant (p=0.804 and p=0.098 respectively).

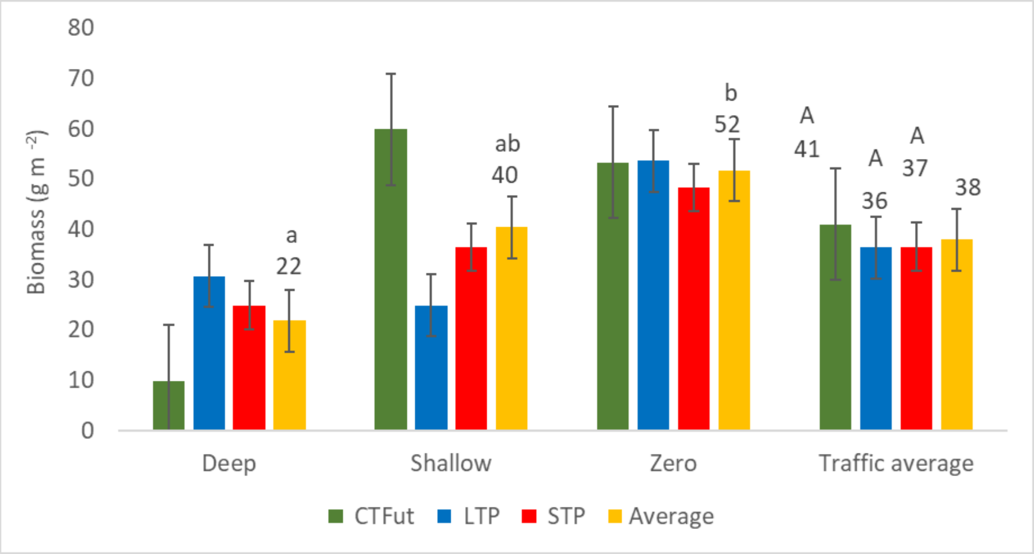


Figure 5.24 Total biomass of earthworms (g m-2) depending on three traffic and three tillage systems. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Different letters represent significant difference between means. Whiskers on top of the bars represent standard errors.

The biomass of juvenile earthworms (g m-2) is presented in Figure 5.25 which shows that it was significantly greater on zero tillage than on deep tillage (2.5 g and 0.9 g respectively) while shallow tillage did not differ significantly from remaining tillage depths (1.9 g). The biomass of remaining EM group analysed separately did not differ between traffic and tillage systems and their interactions.

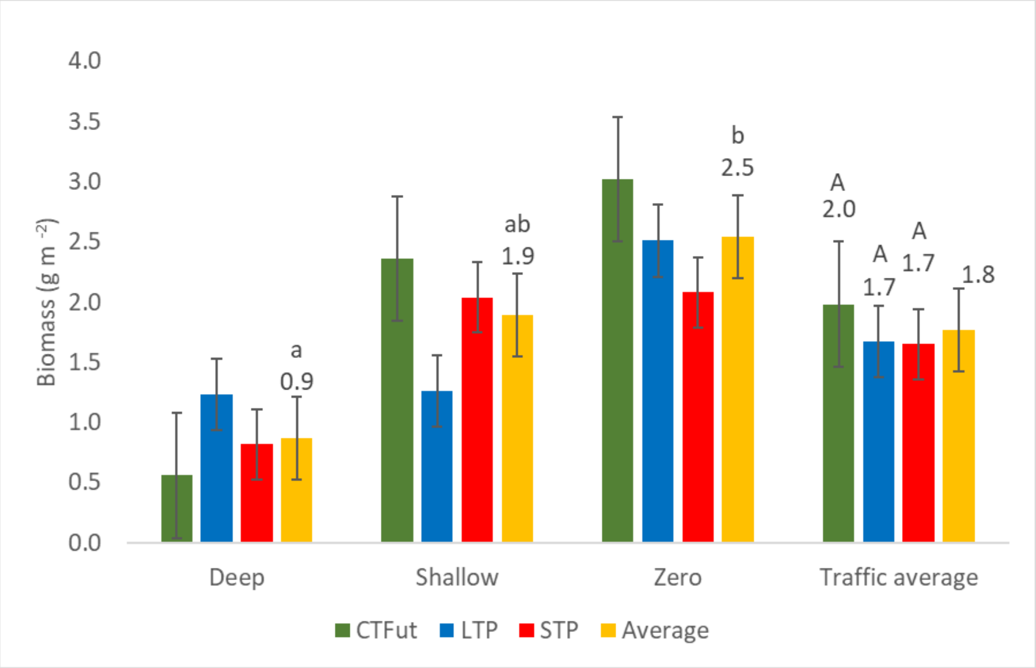


Figure 5.25 Biomass of juvenile earthworms m-2 depending on three traffic systems and three tillage depths. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significant differences between means are represented by different letters. Whiskers on top of the bars represent standard errors.

Figure 5.26 shows the soil moisture on the day of earthworm extraction and reveals that it was significantly lower (*$p<0.001$*) on untrafficked soil, i.e. CTFut than on LTP and STP (26%, 28% and 30% respectively). Soil moisture for interactions between traffic and tillage is presented in Figure 5.27, which reveals that on CTFut with deep tillage it was significantly lower ($p=0.003$) than under remaining traffic and tillage interactions apart from LTP with shallow tillage which was not significantly different from all the remaining systems. Tillage was not significant (*$p=0.235$*).

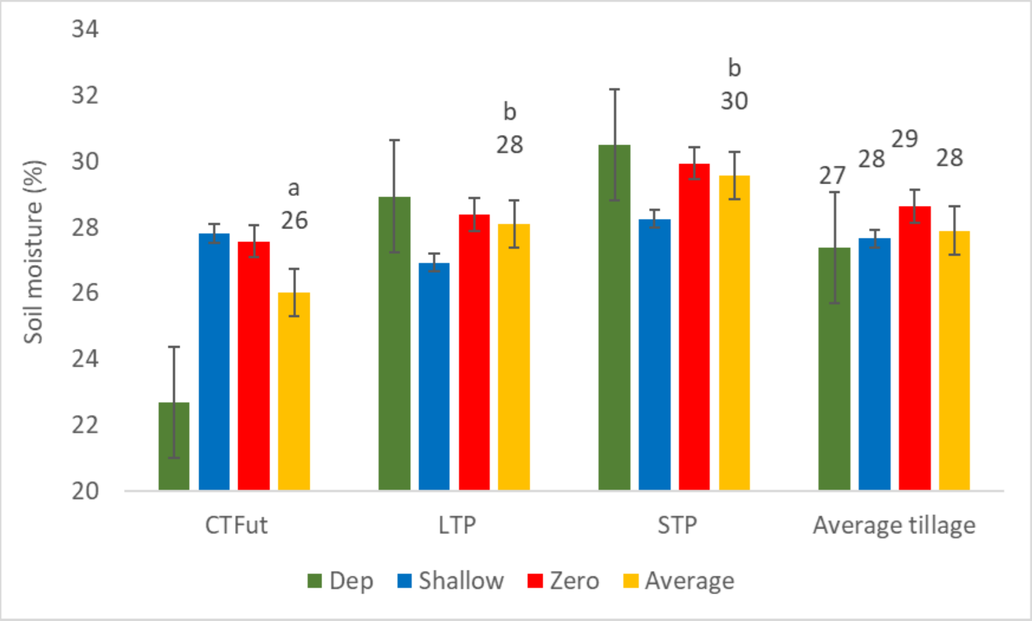


Figure 5.26 Soil moisture on the day of earthworm extraction for three traffic and three tillage systems. CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significant differences between means are represented by different letters. Whiskers on top of the bars represent standard errors. For reader's convenience the Y axis starts at 20% to visually magnify the differences.

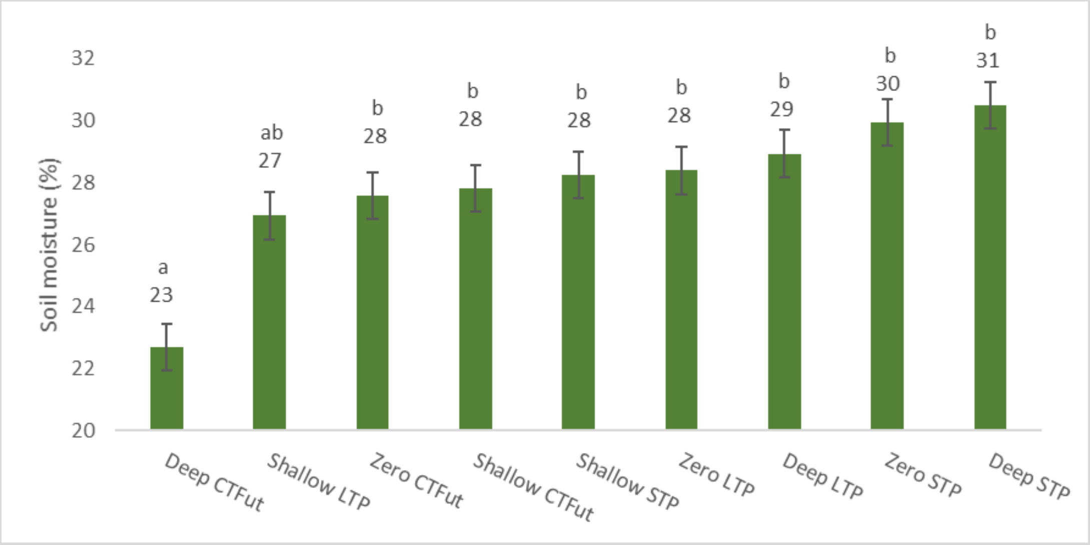


Figure 5.27 Soil moisture on the day of earthworm extraction for interactions between three traffic and three tillage systems: CTFut represents untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres, Deep- tillage at 250mm, Shallow – tillage at 100mm, Zero – zero tillage. Significantly different means are represented by different letters. Whiskers on top of the bars represent standard errors. For reader's convenience the Y axis starts at 20% to visually magnify the differences.

5.4 DISCUSSION

The soil invertebrates feeding activity expressed as the Bait lamina score was significantly greater on untrafficked soil - CTFut in comparison to STP and LTP in both 2019 and 2020. Also, in both years the FA under LTP was significantly greater than under STP. The total density of springtail was also significantly greater on CTFut than on STP with LTP not significantly different from the remaining two traffic systems (4025, 2719 and 3265 ind. m^{-2} respectively). Since soil compaction affects soil porosity (Millington, *et al.*, 2016) and bulk density (Soane and van Ouwerkerk, 1994), uncompacted soil is likely to create a better habitat for invertebrate communities (Pangnakorn, 2002). Tillage did not have a consistent effect over the two – year study on the soil fauna feeding activity: in 2019 (after wheat) the FA score was significantly lower on zero tillage than on shallow and deep (0.40, 0.53 and 0.52 respectively). In 2020 (after barley), zero and shallow tillage featured significantly greater Bait lamina score than deep tillage (0.26, 0.28 and 0.16 respectively). The significantly lower results of Bait lamina score in 2019 under zero tillage in comparison to the shallow and deep tillage might have been caused by oxygen deficiency resulting from significantly greater soil moisture in 2019 on zero tillage than on deep and shallow tillage. Taking into account the soil bulk density, recalculation of the gravimetric to volumetric soil moisture (VSM) shows the VSM on zero tillage was 31% in comparison to 29% and 28% on shallow and deep tillage respectively at the start of the experiment and at the end of the experiment VSM was 32%, 31% and 30% on zero, shallow and deep tillage respectively. This suggests that during the whole 8-day experiment in 2019 the VMC was above the field capacity which on sandy loam is around 27% (Godwin, and Dresser, 2003). In 2020 the VMC was not significantly different between tillage or traffic systems and it was much lower than in 2019 (average 23% and 26% at the beginning and end of the experiment) which potentially did not restrict the soil fauna feeding activity (Karaca, 2011). The significantly greater feeding activity on the reduced tillage plots in 2020 (zero and shallow) in comparison to deep tillage might result from significantly greater abundance of earthworms. It is in agreement to Chan (2001), Crittenden *et al.* (2014) and Smith (2016) who suggested that lower soil disturbance in the zero tillage treatments provides better habitat for earthworms, which are highly involved in the process of feeding off the bait lamina. In 2019, the high soil moisture might have affected the earthworm activity which is suggested to decline with an increase of soil moisture above the field capacity (Edwards *et al.* 2004). Also, the decline of the FA with soil depth is in line with the increase of BD.

The springtails abundance (average 3336 ind. m^{-2}) was slightly lower to that reported by a German researcher who investigated the effects of soil compaction and tillage on Collembola and straw decomposition (Dittmer and Shrader, 2000) who reported in June

8000 ind. m^{-2} and 4000 ind. m^{-2} for conservation tillage (power harrow to 150mm) and conventional tillage with mouldboard plough (down to 250mm) respectively. An experiment in Brazil reported Collembola abundance of around 7000 ind. m^{-2} (Filho *et al.*, 2016).

Filho *et al.* (2016) reported that the density of springtails did not differ significantly between the two investigated farming practices (no-till and integrated crop-livestock), however the community structure based on the EM groups varied between the sites. In the integrated crop-livestock site they observed a predominance of edaphic springtails whereas under no-till, there was more even distribution among groups. Xin *et al.* (2018) reported than on a sandy loam in China, the tillage practice influenced the distribution and abundance of soil arthropods, however it was mainly Acari group (mites) that were mostly negatively affected by zero-tillage, and the differences were significant in autumn and spring. The same author also reported greater number of Collembola on conventional (deep) tillage than zero-tillage however these differences were not significant. The significantly lower Collembola abundance on zero tillage plots in comparison to shallow and deep tillage (2509, 3999 and 3508 ind. m $^{-2}$) might have resulted from increased and more efficient uptake of soil nutrients on zero tillage ultimately leading to significantly greater yield. In June when the crop was at its maximal growth phase this might have decreased the pool of available nutrients for microorganisms and microarthropod as suggested by Dittmer and Shrader (2000).

The density of earthworms found in this study (average 131 m^{-2}) was similar to others in north-western Europe (De Oliveira *et al.*, 2012, Critterden *et al.*, 2014 who reported ranges from 104 in the autumn 2010 on non-inversion deep tillage up to 560 in the autumn of 2011 on zero-tillage). The endogeics in this study accounted for 40% of all earthworms, which is in agreement with other studies (De Oliveira *et al.*, (2012), Critterden *et al.*, (2014)

The biomass of earthworms observed in this study (average 38 g m^{-2}) was in the range of that reported by Critterden *et al.* (2014) who over four-year monitoring in the Netherlands reported average biomass from autumn count in the range of 25-77 g m^{-2} for non-inversion tillage and 15-56 g m^{-2} on min-till depending on the year of observation.

There are studies that suggest that earthworms are very sensitive to soil compaction and their density (number m^{-2}) decreases in compacted areas in comparison to non-compacted (Althoff *et al.* 2009, Capowiez, *et al.* 2012). Capowiez *et al.* 2012 reported a significant decrease of 40% in the abundance of adults and 70% in the total biomass in the first phase after compaction (one week, one and 2 months after), suggesting that this phenomenon might derives from direct death of animals by crushing (as observed during our first sampling) and then the lateral escape of the surviving earthworms towards more favourable conditions. This study however did not confirm those findings and traffic or interaction between traffic and tillage were not significant for either earthworm density or biomass for all eco-groups and total.

Findings from this study are in agreement with many other studies that suggest that reduced tillage increases earthworm population in comparison to conventional tillage systems (e.g., Gerard and Hay, 1979; Lal, 1982; Edwards and Lofty, 1982; Bohlen *et al.*, 1995, Karaca, 2011). The observed in this study increase of the earthworm density on zero tillage in comparison to deep and shallow tillage (230% and 142% respectively) is in agreement to Chan (2001) who in his overview of some tillage impacts on earthworm population abundance and diversity reported that total earthworm populations under no-tillage can be 2–9 times greater than that found under conventional tillage. The intensity of tillage is also suggested to have significant effect on the earthworm population and deep tine tillage was suggested to have detrimental effect on earthworm abundance since tines tend to shatter the soil, and potentially damaging many earthworms in deeper layers (Gerard and Hay 1979, Edwards, 2004, Karaca, 2011). This might explain why shallow tillage also featured significantly greater earthworm density in comparison to deep tillage (161%) however it was still significantly lower than on zero tillage.

Gerard and Hay (1979) suggested that the observed increase in earthworm density on zero-tillage derive from reduced mechanical damage during ploughing and harrowing as well as higher soil water content and litter layer in the spring due to the lack of soil disturbance and consequently longer periods of feeding and cocoon production. Nevertheless, the soil moisture analysis at the time of earthworm count showed lack of significant differences for tillage, only for traffic ($p<0.001$), with STP having significantly greater soil moisture than CTFut (29.9% and 27.6% VWC respectively), both being close to field capacity (around 26%).

There are studies that suggest that the negative effect of tillage is short-term and is limited to a few months after the operation. Wyss *et al.* (1992) found that for a silty sandy loam on the Swiss Plateau, endogeic species, were more abundant in the conventionally tilled soil than under no-till and suggested that both – the density and biomass of endogeic earthworms returned to pre-tillage levels in the following months. Similarly, De Oliveira *et al.* (2012) who investigated the effects of ploughing in France suggested that endogeic earthworms may adapt to the disturbance caused by tillage, at the same time suggesting that the vulnerability to soil disturbances is species dependent and *Aporrectodea caliginosa* is more susceptible to ploughing than *A. rosea* (both endogenic species). Edwards (1983) in his classification of lumbricidae in the cultivated soils of Britain reported *A. Caliginosa* to be “dominant”, whereas *A. rosea* was described as “common”. Since both those species belong to the same eco-group they share the same habitat and compete for the same resources. This might suggest that the effect of tillage on one species which is more sensitive to tillage might increase the abundance of the other. The results from this experiment showed lack of significant differences in endogeic density and biomass which might result from quick recovery of endogeic population after tillage.

The eco-groups that were affected by tillage in the long-term perspective (12 months since last cultivation) was epigeic and juvenile. The epigeic density on zero tillage was 2.5-fold greater than on deep tillage and on zero tillage did not differ significantly from remaining tillage depths (48 and 19, and 35 earthworms m^{-2} respectively). In agreement, Crittenden *et al.* (2014) reported that the reduced tillage in conventional farming significantly increased the epigeic species from 0.1 m^{-2} in mouldboard ploughing to 9 m^{-2}.

Ernst and Emmerling (2009) suggested that on conventionally tilled soils lower bulk density as well an increased transport of organic matter down the soil profile might result in an increase of endogeic earthworms. In this study, bulk density did not differ significantly between the different tillage treatments, only between traffic, but this was not reflected in a significant increase of earthworm population on CTFut. The increased SOM in the 0-100 mm soil stratum on zero and shallow tillage might be the main reason of the greater abundance of epigeic earthworms on zero tillage.

The results of the soil health aspects investigated in this study are summarised in Figure 5.28 and in Figure 5.29 in the form of spider diagrams. The diagrams additionally include aggregate stability analysed by Abel (2016), as this aspect is suggested to be an important indicator of soil health (Barthes and Roose, 2002). The aggregate stability was analysed in the same field according to the same protocol as the remainder of the soil health aspects. For each characteristic, the highest result obtained from each traffic or tillage system represents 100% and so the results from the remaining two systems are represented by a percentage of the highest value. Not all aspects were significant (on the diagrams the stars indicate the level of significant differences), nevertheless the results could still be plotted.

Figure 5.28 shows that for those soil health aspects, where significant results were observed, CTFut featured the highest results, which are desired for a good soil health. There was not a single soil health aspect which would benefit from any form of vehicular traffic. Figure 5.29 shows, that there was not a single soil health aspect which would significantly benefit from deep tillage. Only soil hydraulic conductivity was higher under deep than shallow and zero tillage, however the results were not significant.

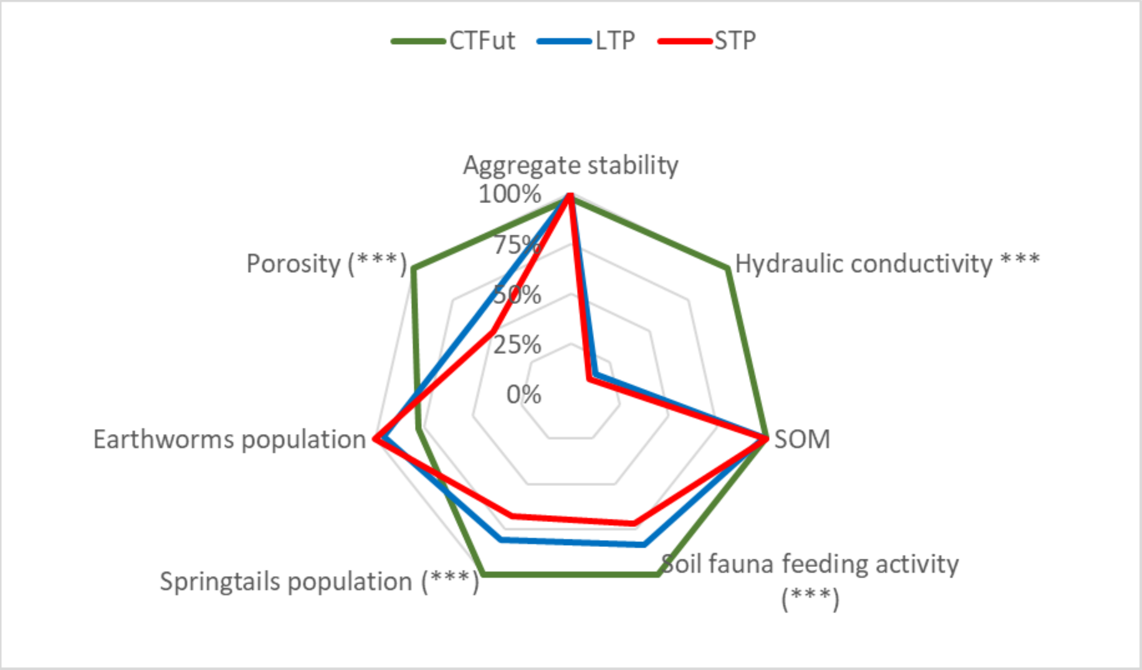


*Figure 5.28 Traffic effects on soil health aspects. CTFut stands for untrafficked soil, LTP – soil trafficked with low inflation pressure tyres, STP – soil trafficked with standard inflation pressure tyres. Stars in brackets represent significant differences with p values <0.05 for *, p<0.005 ** and p<0.001 for ***. Aggregate stability after Abel (2016).*

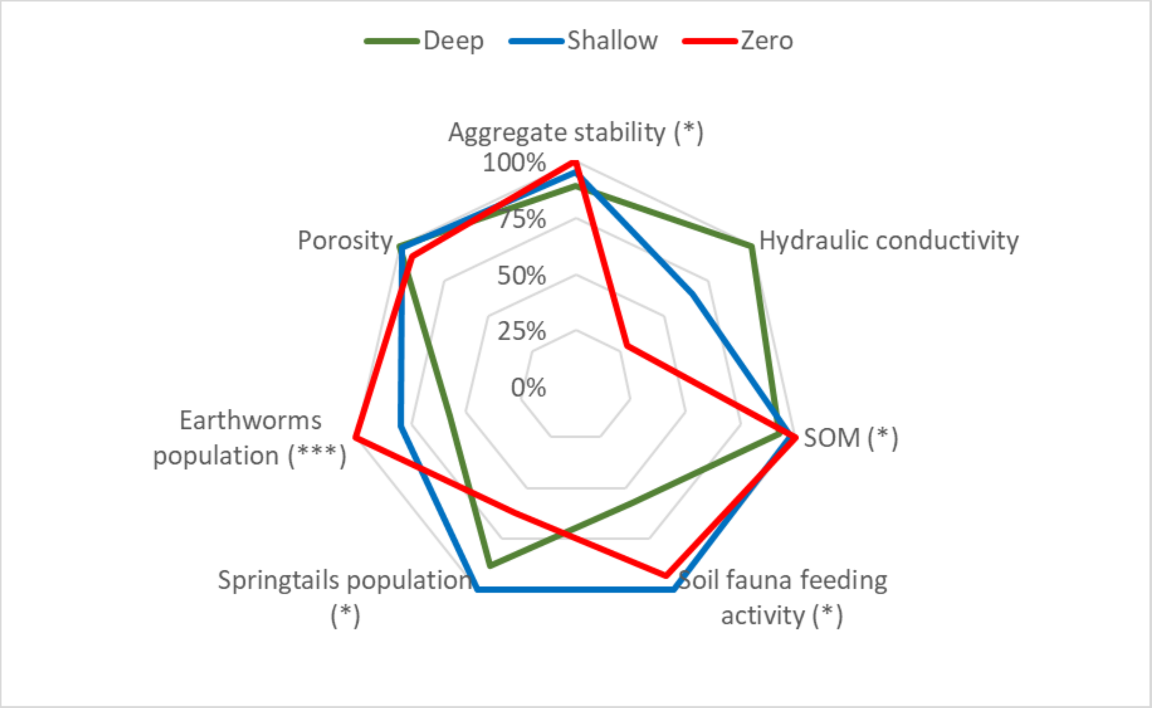


*Figure 5.29 Tillage effects on soil health aspects. Deep = tillage at 250mm, Shallow = tillage at 100mm, Zero = zero tillage. Stars in brackets represent significant differences with p values <0.05 for *, p<0.005 ** and p<0.001 for ***. Aggregate stability after Abel (2016).*

5.5 CONCLUSIONS

1. Agricultural traffic had a negative effect on some soil biological properties. Consequently, absence of traffic (CTFut) improved soil biology, namely soil fauna feeding activity (Bait lamina score) and total springtail density in comparison to STP. However, traffic had no significant effect on earthworm population. In addition, LTP resulted in improved some soil biological properties, as soil fauna expressed as the Bait lamina score under LTP was significantly greater than under STP in both analysed years.
2. The hypothesis that deep tillage has negative effects soil biological properties in comparison to reduced tillage system (shallow and zero) cannot be accepted. Although deep tillage had negative effects on the majority of analysed soil biological properties, the Bait lamina score in 2019 on zero tillage was significantly lower than on remaining tilled treatments, similarly the Collembola density was significantly lower on zero tillage in comparison to shallow tillage, whereas deep tillage did not differ significantly from the remaining tillage. In 2020 both reduced tillage treatments (zero and shallow tillage) featured significantly greater Bait lamina scores than deep tillage. Additionally, under reduced tillage (zero and shallow) total earthworm density was significantly increased in comparison to deep tillage. Nevertheless, there was no single aspect of soil biology which would indicate that deep tillage resulted in improved soil biology than shallow tillage. This might suggest that deep tillage is not a recommended practice to improve soil biology on sandy loam in the West Midlands.
3. There were no significant interactions between traffic and tillage systems, and the effects of traffic on soil biological properties were equal for the whole range of analysed tillage depths.

CHAPTER 6 CROP GROWTH AND YIELD

6.1 OBJECTIVES OF THE CHAPTER, HYPOTHESIS

The objective of this chapter is to quantify the effects of: absence of vehicular traffic (CTFut), presence of traffic with low inflation pressure tyres (LTP) and presence of traffic with standard inflation pressure tyres (STP) on plant establishment, root growth and crop yield (hand harvested) for typical arable rotation.

Additionally, this chapter aims to determine the effects of common agricultural traffic systems: CTF with 30% wheeled area, and two non-controlled (random) traffic systems with standard and low tyre inflation pressure (RSTP and RLTP respectively) subject to three different tillage depths (deep - 250 mm, shallow - 100 mm and zero tillage) and their interactions on combine harvested crop yield for a typical arable crop rotation.

The hypotheses of this chapter are:

1. Agricultural traffic has a negative effect on plant establishment, root development and crop yields. Therefore, absence of traffic (CTFut) improves growth of roots, and plant establishment, as well as increases crop yields in comparison to trafficked soil (LTP and STP). In addition, agricultural traffic with standard tyre inflation pressure (STP) has negative effects on root growth, plant establishment, and crop yield in comparison to low inflation pressure tyres (LTP).
2. Reduced tillage (shallow and zero tillage) enhances plant establishment, root growth and consequently improves crop yields in comparison to deep tillage.
3. There are no significant interactions between traffic and tillage, hence, the effects of traffic on plant establishment, root growth and crop yields are equal for the whole range of analysed tillage depths.

6.2 METHODOLOGY

6.2.1 Plant establishment

The plant establishment was calculated based on plant count conducted on a transect across all plots, at a distance about 0.5 m from the spraying tramline. The width of the transect for winter bean was 5 m wide, whereas next crops, i.e. winter wheat and winter barley were analysed based on a 0.5 m wide transect. Number of plants was counted for each plant row separately within the whole width of the transect.

Winter bean plant count was conducted on 26 March 2018, with the crop at a growth stage with visible true leaves (BBCH stage 12). For each plot several high-resolution (9.6 Megapixels) photographs were taken, from above the centreline to the right, and to the left, always keeping the centreline label as well as the corner labels visible. To determine the transect area, a pole was placed at a distance of 5 m from the starting point (the label). The plant count was then undertaken for each row separately, using the photographs. The average distance between consecutive plants was approximately 300 mm, ensuring sufficient resolution.

The plant count of winter wheat was done on 05-06 December 2018 and 27 February and 02 March 2020 for winter barley. At the time of plant count, both crops were at the growth stage 2.0/2.1 beginning of tillering. A stick of exactly 0.5 m length was placed along the rows to determine the width of the transect.

Number of plants m^{-2} was calculated directly from the plant count, given the area of one row per 5m-transect equals 0.8350 m^2 (for winter bean) and 0.5 m-transect (for winter wheat and winter barley) equals 0.0835 m^2, since the row spacing was 0.167 m. To avoid any edge effects, the outermost rows (number 1 and 22) were not taken into the calculations. Plant establishment percentage was calculated considering the seed rate, noting there was an increase of seed rate on zero tillage plots by 25%. The overall analysis per row, across all plots was calculated versus grand mean seed rate taking into account 24/36 plots with standard seed rate and 12/36 with the increased seed rate.

The analysis of establishment percentage on wheeled and unwheeled areas was conducted on CTF plots only, since those plots were not subjected to additional compaction and no offset was ever applied, hence it was feasible to compare trafficked vs untrafficked areas. For trafficked area, the calculations based on establishment percentage on rows under permanent wheelways (rows 4,5, 18 and 19) whereas for the untrafficked areas the results from four middle rows were taken into the account (rows 10,11,12 and 13). The statistical analysis to compare those results was conducted with repeated measures ANOVA with Crop as time points.

The analysis of yield per plant (g $plant^{-1}$) took into account the average number of plants m^{-2} from the plant count and the average crop yield from hand harvest data (g m^{-2}) per plot. For winter bean and winter wheat the data derived from all rows apart from the outermost (1 and 22) to avoid the edge effect.

6.2.2 Root growth

Root analysis was conducted for the first two crops only: winter bean and winter wheat. The third crop's root analysis was impossible due to Covid-19 restriction. The roots were excavated with different method depending on the crop which is described below, however in both cases the roots were washed, then analysed (visual analysis in case of bean and Image analysis of roots scans in case of winter wheat). Both crops' roots were also dried at 70^{o}C for 48 hours (Jones, 2001) to record the total dry biomass. For measuring the biomass, a Precisa XT1220XM balance was used with accuracy d=0.001g.

The sampling protocol followed the general sampling approach described in Chapter 3.6.

6.2.2.1 Winter bean root analysis (2018)

The bean roots were excavated from the ground using a spade and a fork on 29 May 2018, when the crop was at the beginning of flowering growth stage. One whole plant (sample) was collected from each plot at a distance of approximately 1 m to the north from the first sprayer line. A great emphasis was put to ensure that a whole plant with its roots was excavated.

The roots extraction was conducted by two people: one was responsible for root excavation, the other for carrying the plant to a water tank on the edge of the field and immersing the plants in water (for around 3hrs) and first root washing. Once the roots were washed, all the samples were taken to the laboratory and placed in a cool air-conditioned room and left for further analysis. The roots were analysed in terms of tap root diameter, length, biomass, and for lateral roots – number and biomass. Where applicable the roots were scrutinised in 2 depths: 0-50 mm and > 50 mm, while tap root diameter was also measured at the soil surface and the depth of 100 mm. The diameter was measured with electronic callipers, whereas length of tap root was measured with a ruler. The number of lateral roots was counted by cutting them off (from a given depth of tap root) with nail scissors.

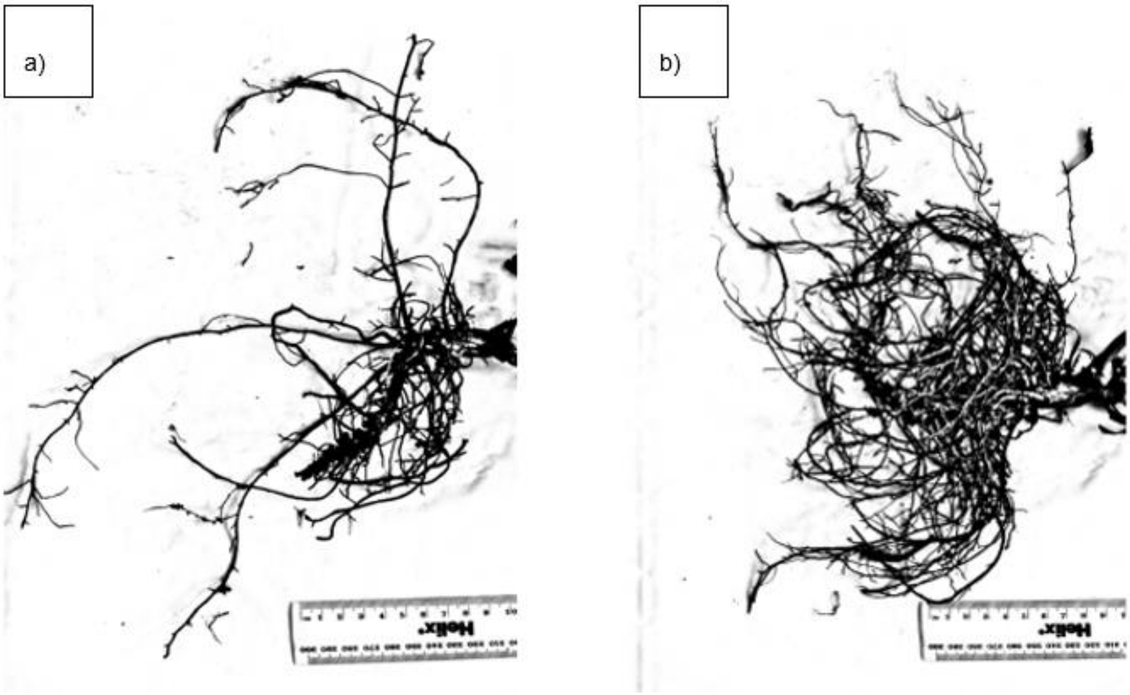


Figure 6.1 Examples of winter bean roots from: a) wheelways trafficked with standard inflation pressure tyres (STP) subject to shallow tillage (100mm); and b) from untrafficked soil (CTFut) subject to deep tillage (250mm)

6.2.2.2 Winter wheat root analysis (2019)

Collection of roots of winter wheat for root volume and biomass took place on 5-6 June 2019 with the wheat at GS 55 where half of the ear had emerged above flag leaf ligule (Haun, 1973). A representative self-standing plant was chosen at a distance of around 7 m from the first spraying line, the above ground part of the biomass was cut off and discarded. An undisturbed soil core (50 mm diameter x 300 mm length) enclosing the plant roots was taken from each plot with a soil corer (Eijelkamp, Netherlands), fitted with a plastic liner. The samples were stored in a dark, cold room (4ºC) until processed. The soil samples were immersed separately in water over night and the next day the roots were washed, with the use of fine sieves 0.5mm as described in Bohm (1979). The washed roots were air dried, to remove surface water, and scanned on a flat scanner with 600 dpi resolution and saved as in a TIFF format. The roots were covered with a blank white A3 format sheet of paper with a line indicating the reference length of 10 cm to adjust the pixel numbers to the actual size. To avoid overlapping of the roots, each sample – when necessary - was split into a few scans depending on the root volume. The scans were then analysed with Fiji - an image processing package to a free software ImageJ, that features many plugins which facilitate scientific image analysis (ImageJ Instruction, 2020). Before the analysis, the colour pictures were changed into an 8-bit grayscale image and the root surface area measurement was taken after applying the Otsu thresholding, shown in Figure 6.2. In this method the algorithm separate pixels into two classes, foreground and background as a result of a single intensity threshold. This threshold is determined by minimizing intra-class intensity variance (Otsu, 1979). The area of the roots was obtained by the “Measure” function in ImageJ limited to the thresholded area.

Figure 6.2 View of roots scan on the left and the same picture after applying Otsu thresholding in Image J Fiji processing on the right.

The roots length was not recorded as many of the roots snapped while being washed and cleared of the mineral debris.

The calculations of root volume took into account the volume of roots obtained from the image processing and the volume of the soil core of 589cm^3.

6.2.3 Crop yields

The crop yields data were collected from two sets of data, described in two consecutive sub-chapters:

- hand harvest done on a transect across all plots, with detailed information on the yield from separate rows;
- from a combine harvester which collected the yield data from each plot.

6.2.3.1 Hand harvested yield

For the analysis of crop yields separately from trafficked and untrafficked areas, a hand harvest was performed every year from one transect across all plots. The width of the transect for winter bean was 5 m, whereas for the next two consecutive cereals it was 0.5m. The crop was cut at ground level using hand secateurs or shears. Each row was cut and processed separately. In 2020 due to the Covid-19 restrictions and limited access to helpers for the field work as well as access to the lab for the following processing, the hand harvest was limited to the permanent wheelways (rows 4, 5, 18, 19) and centre of the plots (rows 10, 11, 12, 13).

The bean samples had to be manually husked in first instance before being threshed, as the thresher could not cope with the amount of biomass. Once husked, the samples were threshed at Rothamsted Research. The samples did not require any prior oven drying as the weather over a few weeks preceding the hand harvest was very dry and hot: on only three days over the July 2018 the maximum daily temperature dropped below 25°C and the maximum temperature in the month was noted on 26.07.2018 and equalled 30.2°C.

The following cereal crops (winter wheat and winter barley) were oven-dried at 70°C for 72 hrs to facilitate threshing, and then threshed on a laboratory thresher F. Walter and H. Wintersteiger KG at Harper Adams University. Once threshed, the beans and grain were oven dried at 70°C for 48 hours and weighed with the accuracy to two decimal places.

The yield from each row was calculated accepting that each row represented 0.167 m width (seed drill row spacing) and length equalled the size of a transect (5 m and 0.5 m for bean and cereal crops respectively). However, to avoid edge effect, the mean yield per plot from hand harvest was calculated from rows 2 to 21, i.e. omitting the first and the last. The grain weight was then re-calculated to Mg ha^{-1}.

As the CTF plots were not subjected to additional offset traffic, it facilitated the comparison between trafficked areas and untrafficked areas. The trafficked area was represented by rows from the permanent wheelways: 4-7,16-19 while the rows from the middle of the plots, i.e. rows 2-3, 8-15, 20-21 represented untrafficked areas. The yield data from each of the above-mentioned row were averaged accordingly to represent the trafficked and untrafficked area and an ANOVA for two traffic systems subjected to three tillage depths was conducted. In 2020 due to covid restrictions, the protocol was restricted to limited number of rows hence the trafficked areas were represented by rows 4-5 and 18-19, whereas untrafficked – by rows 10-13. The grain weight was adjusted for moisture for each sample.

6.2.3.2 Combine harvested yield

Combine harvesting was conducted with a Claas Dominator combine with 4-m header, to match the plots widths. The combine harvester operated in the same direction for all plots and the grain from each plot was separately weighed in a hopper hung on a telehandler with a 1-tonne loadcell (Figure 6.3); subsequently a sample for hectolitre weight was taken. A second sample was also taken from each plot and placed in airtight containers for further moisture content analysis, which took place on the same day. Grain moisture from the combine harvest was measured with the Grainmaster protimeter (Figure 6.4) to enable the crop yield to be corrected to x% mc. The bean samples were ground using a coffee grinder before the moisture reading could be made. The results were then adjusted to the standard moisture in the yield 14% which was calculated from the Equation 6-1:

Equation 6-1

$$Y = [(1 - M)/0.86] * Ym$$

where:

Y – grain weight at 14% moisture
Ym – grain weight at current moisture level
M – current moisture level (expressed as decimal)

Figure 6.3 JCB telehandler with an external hopper and a loadcell for weighing the yields

Figure 6.4 Grainmaster protimeter for assessing grain moisture during harvest

6.3 RESULTS

6.3.1 Plant establishment

The next three consecutive sub-chapters presents the results of number of plants per square meter, plant establishment percentage as well as show the effects of the position on the plot which is related to traffic intensities on the plant establishment percentage.

6.3.1.1 Plant number

The effect of traffic and tillage on the plant number m^{-2} varied between crops. For winter bean, tillage and interactions between traffic and tillage were significant ($p<0.001$ and $p=0.025$ respectively, cv=6.4%, whereas for winter barley only traffic was significant ($p=0.005$, cv=23.1%), and for winter wheat there was no significant effect of traffic, tillage and their interactions.

Table 6.1 Shows that for winter bean, on zero tillage the average number of plants was significantly greater than on deep and shallow tillage (22.0, 18.5 and 18.8 plants m^{-2} respectively). Number of plans m^{-2} of winter wheat did not differ significantly between traffic or tillage, however the number of plants of winter barley was significantly greater on CTF compared to RSTP system (149.5 and 105.7 respectively), and RLTP (129.3) was not significantly different to CTF or RSTP.

Table 6.1 Average number of plants for three crops and three traffic and tillage systems, where CTF – Controlled traffic farming, RLTP- random traffic with low tyre inflation pressure, RSTP- random traffic with low tyre inflation pressure; Deep- tillage at 250mm, Shallow – at 100mm and Zero – zero tillage. Significantly different means are represented by different letters

Crop	Traffic/tillage	DEEP	SHALLOW	ZERO	Average
Winter bean	CTF	19.9	18.4	22.8	20.4 a
	RLTP	17.6	18.7	22.8	19.7 a
	RSTP	18.1	19.2	20.3	19.2 a
	Average	18.5 a	18.8 a	22.0 b	19.8
Winter wheat	CTF	310.4	293.9	341.9	315.4 a
	RLTP	293.7	300.3	343.9	312.6 a
	RSTP	321.1	317.2	322.9	320.4 a
	Average	308.4 a	303.8 a	336.2 a	316.1
Winter barley	CTF	156.1	154.6	137.6	149.5 a
	RLTP	126.8	130.8	130.2	129.3 ab
	RSTP	81.6	95.4	140.3	105.7 b
	Average	121.5 a	126.9 a	136.0 a	128.2

Table 6.2 presents the number of plants m^{-2} for interactions between tillage and traffic systems for winter bean and reveals that shallow tillage regardless traffic, as well as deep tillage with RSTP and RLTP featured significantly lower results than Zero tillage with RLTP and with CTF.

Table 6.2 Average number of plants m $^{-2}$ of winter bean depending on interactions between traffic and tillage, where CTF – Controlled traffic farming, RLTP- random traffic with low tyre inflation pressure, RSTP- random traffic with low tyre inflation pressure; Deep- tillage at 250mm, Shallow – at 100mm and Zero – zero tillage. Significant differences between means are represented by different letters

Tillage and traffic system	Mean	
DEEP RLTP	17.6	a
DEEP RSTP	18.1	a
SHALLOW CTF	18.4	a
SHALLOW RLTP	18.7	a
SHALLOW RSTP	19.2	a
DEEP CTF	19.9	ab
ZERO RSTP	20.3	ab
ZERO RLTP	22.8	b
ZERO CTF	22.8	b

6.3.1.2 Plant establishment percentage

The main effect of tillage and interactions between tillage and traffic system on plant establishment percentage was significant for winter bean (*p=0.037* and *p=0.024* respectively, cv=6.2%), whereas for winter wheat only main effect of tillage was significant, p=0.009, cv=12.7%), while for winter barley only traffic had significant effect (p=0.003, cv=23.7%).

Table 6.3 presents the plant establishment percentage depending on crop and shows that for winter bean zero tillage featured significantly lower establishment percentage in comparison to shallow tillage whereas deep tillage did not differ significantly from zero or shallow (0.79, 0.84 and 0.83 respectively). The results of establishment percentage for winter bean for traffic x tillage interactions, revealed that RSTP with zero tillage had lower result in comparison to RSTP with shallow tillage and CTF with deep tillage (0.73, 0.86 and 0.90 respectively). For winter wheat zero tillage featured significantly lower result than shallow and deep tillage (0.81, 0.93 and 0.95 respectively), whereas for winter barley the plant establishment percentage under CTF was significantly greater than under RSTP, while RLTP did not significantly differ from the remaining two traffic systems.

Table 6.3 Average plant establishment percentage depending on crop, tillage and traffic system, where CTF – Controlled traffic farming, RLTP- random traffic with low tyre inflation pressure, RSTP- random traffic with low tyre inflation pressure; Deep- tillage at 250mm, Shallow – at 100mm and Zero – zero tillage. Significant differences between means are represented by different letters.

Crop	Traffic/tillage	DEEP	SHALLOW	ZERO	Average
Winter bean	CTF	0.90	0.83	0.82	0.85 a
	RLTP	0.79	0.84	0.82	0.82 a
	RSTP	0.81	0.86	0.73	0.80 a
	Average	0.83 ab	0.84 a	0.79 a	0.82
Winter wheat	CTF	0.96	0.90	0.82	0.89 a
	RLTP	0.90	0.92	0.83	0.88 a
	RSTP	0.99	0.98	0.77	0.91 a
	Average	0.95 b	0.93 b	0.81 a	0.90
Winter barley	CTF	0.39	0.39	0.28	0.35 a
	RLTP	0.32	0.33	0.26	0.30 ab
	RSTP	0.20	0.24	0.28	0.24 b
	Average	0.30 a	0.32 a	0.27 a	0.30

6.3.1.3 Plant establishment and the position on the plot

Figure 6.5 shows an average establishment percentage for 3 analysed crops (winter bean, winter wheat and winter barley) and reveals that it was affected by the position on the plot: the permanent wheelways had lower establishment than remaining plot area.

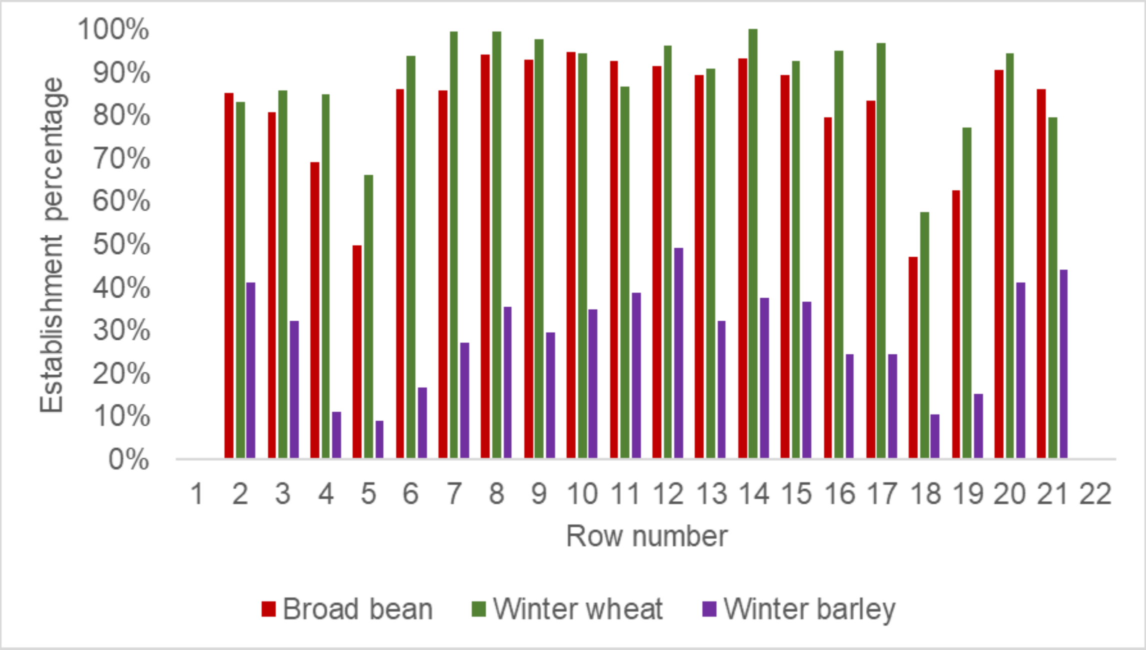


Figure 6.5 Plant establishment percentage for 3 analysed crops depending on the position on the plot

The analysis of plant establishment depending on the position (permanent wheelways vs untrafficked areas) on CTF plots revealed that the position, tillage and crop were significant (p=0.004, p<0.001 and p<0.001 respectively, cv=19.3%), but interactions were not significant (p=0.357).

Table 6.4 presents establishment percentage for all analysed crops, two positions (centres and wheelways) and three tillage depths, on CTF plots. It shows that winter barley (2020 crop) featured significantly lower establishment percentage (0.29%) in comparison to winter bean and winter wheat (on average 79% and 82% respectively). Average establishment percentage on permanent wheelways was significantly lower than in the unwheeled area (51% and 75% respectively) over the three-year analysis. The establishment percentage on zero tillage plot was significantly lower in comparison to shallow and deep tillage (57%, 65% and 68% respectively).

Table 6.4 Plant establishment percentage depending on tillage, position and crop on CTF plots, where Deep- tillage at 250mm, Shallow – at 100mm and Zero – zero tillage.

	Position	Winter bean	Winter wheat	Winter barley	Average
Deep	Centre	100%	94%	49%	81% a
	Wheeled	62%	85%	14%	54% b
Shallow	Centre	88%	94%	46%	76% a
	Wheeled	65%	74%	21%	53% b
Zero	Centre	87%	83%	35%	68% a
	Wheeled	67%	60%	11%	46% b
Average	Centre	92%	90%	43%	75% a
	Wheeled	65%	73%	16%	51% b
Average total		79% a	82% a	29% b	

6.3.2 Root growth

The results of the analysis of root growth are presented in the next two sub-chapters which reflect two separate analysis for two consecutive crops: winter bean (2018) and winter wheat (2019). Detailed statistics (p-values, standard error of means and coefficient of variations) are presented in Appendix.

6.3.2.1 Winter bean roots

Most of the winter bean roots characteristics were analysed in two different soil strata: 0-50mm and >50mm, i.e.: biomass of tap root, biomass of lateral roots, total biomass of roots, number of lateral roots. The tap root diameter was measured at the soil surface as well as at 50mm and 100mm of length, whereas tap root length was measured from the soil surface to the end of the root tip.

The significant effects of traffic and tillage and their interactions on winter bean root were mainly observed in the soil horizon >50mm where the main effect of traffic was significant ($p<0.05$) on all analysed root characteristics, whereas tillage was not significant. Interactions between traffic and tillage had significant effect only on the number of lateral roots ($p=0.027$). In the shallow soil horizon there was no significant effect of traffic, tillage and their interaction on any root characteristics apart from tap root biomass on which the interactions between traffic and tillage was significant ($p=0.015$). Detailed statistics are presented in the Appendix.

Table 6.5 presents results of all root characteristics in the >50mm soil stratum depending on traffic and reveals that in uncompacted soil (CTFut) biomass of tap and lateral roots, total root biomass, the number of lateral roots and the tap root length were much greater than under STP (289%, 226%, 255%, 153%, 140% respectively). LTP did not differ significantly from CTFut and STP for biomass of tap root, total roots biomass and the number of lateral roots, however the biomass of lateral roots and the tap root length under LTP was significantly lower than under CTFut (60% and 74% respectively) and not significantly different than under STP.

Table 6.5 Winter bean roots characteristics depending on three traffic approaches at the soil stratum >50mm. CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Significant differences between means are represented by different letters.

	STP	LTP	CTFut
Biomass of tap root (g)	0.19 a	0.39 ab	0.55 b
Biomass of lateral roots (g)	0.23 a	0.31 a	0.52 b
Total biomass of roots (g) (tap root + lateral)	0.42 a	0.71 ab	1.07 b
Number of lateral roots	26.3 a	32.6 ab	40.3 b
Tap root length (mm)	12.6 a	13.1 a	17.7 b

In the >50mm soil horizon interactions between traffic and tillage were also significant on the number of lateral roots and under CTFut with deep tillage the number of lateral roots was over 250% greater than under STP with zero tillage, while the remaining interactions did not differ significantly one from another.

Table 6.6 Average number of lateral roots of winter bean at the depth >50mm for interactions between three traffic approaches and three tillage depths: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences between means are represented by different letters.

Interactions traffic x tillage	Number of lateral roots	
STP Zero	19.5	a
LTP Deep	23.3	ab
STP Deep	24.5	ab
CTFut Shallow	29.0	ab
LTP Zero	33.3	ab
STP Shallow	34.8	ab
LTP Shallow	41.3	ab
CTFut Zero	42.8	ab
CTFut Deep	49.0	b

In the shallow stratum (0–50 mm) interactions between traffic and tillage had significant effect on tap root biomass and STP with zero tillage delivered almost 100% greater result than CTF subject to shallow tillage and STP with shallow tillage, Table 6.7.

Table 6.7 Tap root biomass (g) of winter bean at 0–50 mm stratum for interactions between 3 traffic approaches and 3 tillage depths: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences between means are represented by different letters

Interactions traffic x tillage	Tap root biomass (g)	
CTFut Shallow	0.72	a
STP Shallow	0.73	a
STP Deep	0.98	ab
LTP Deep	0.99	ab
CTFut Zero	1.01	ab
LTP Zero	1.04	ab
CTFut Deep	1.20	ab
LTP Shallow	1.24	ab
STP Zero	1.43	b

Across both analysed depths there were no significant effect of traffic, tillage and their interactions on most of the analysed roots characteristics apart from tap root biomass, for which interactions between traffic and tillage were significant and CTFut with deep tillage featured significantly greater (over twice) results than STP with shallow tillage, Table 6.8.

Table 6.8 Total tap root biomass (g) of winter bean across both depths: 0–50mm and >50 mm for interactions between 3 traffic approaches and 3 tillage depths: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences between means are represented by different letters.

Interactions traffic x tillage	Tap root biomass (g)	
STP Shallow	0.89	a
CTFut Shallow	1.10	ab
STP Deep	1.13	ab
LTP Deep	1.20	ab
LTP Zero	1.49	ab
CTFut Zero	1.61	ab
STP Zero	1.71	ab
LTP Shallow	1.76	ab
CTFut Deep	1.86	b

Another analysed roots characteristic was tap root diameter, which was measured at the surface, at the depth of 50mm and at 100mm. Significant differences were observed only at the depth of 100mm where the main effect of traffic was significant and under CTFut it was twofold greater than under LTP and over 240% greater than under STP. LTP and

STP did not differ significantly one from another (Table 6.9). Tillage and interactions between traffic and tillage were not significant at any depth.

Table 6.9 Mean tap root diameter (mm) of winter bean at 100 mm depth for contrasting three traffic approaches: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Significant differences between means are represented by different letters.

	Diameter of tap root (mm)	
STP	1.4	a
LTP	1.7	a
CTFut	3.4	b

The tap root length differed significantly only between traffic systems while tillage or interactions were not significant. CTFut featured significantly longer tap root than STP and LTP (over 40% and 35% respectively). LTP and STP did not differ significantly from one another, see Table 6.10.

Table 6.10 Tap root length (mm) of winter bean for contrasting three traffic approaches: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Significant differences between means are represented by different letters.

	Tap root length (mm)	
STP	12.6	a
LTP	13.1	a
CTFut	17.7	b

6.3.2.2 Winter wheat roots

The main effect of traffic and interactions between traffic and tillage systems had significant effect on winter wheat root density expressed as a root area per volume of soil ($p=0.007$, $p=0.02$ respectively). The effect of tillage was not significant ($p=0.943$). Table 6.11 shows the root density of winter wheat and reveals that it was 133% greater from CTFut than from STP and almost 109% greater than from LTP.

Table 6.12 presents the results of root area density for interactions between traffic and tillage and reveals that CTFut with deep tillage featured significantly greater root area density in comparison to STP with deep (168%) and shallow tillage (173%) as well as LTP with deep tillage (176%). The remaining interactions did not differ significantly.

Table 6.11 Roots area density of winter wheat (cm^2 cm$^-$3) for thre traffic approaches: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage Significant differences between means are represented by different letters.

Traffic	Root area density (cm cm^{-3})	
STP	0.114	a
LTP	0.124	ab
CTFut	0.152	b

Table 6.12 Roots area density of winter wheat (cm^2 cm$^-$3) for interactions between three traffic approaches subjected to three tillage depths: CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences between means are represented by different letters

Treatment	Root area density (cm cm^{-3})	
LTP Deep	0.104	a
STP Shallow	0.106	a
STP Deep	0.109	a
LTP Zero	0.120	ab
STP Zero	0.127	ab
CTFut Shallow	0.132	ab
CTFut Zero	0.141	ab
LTP Shallow	0.148	ab
CTFut Deep	0.184	b

There were significant for interactions between traffic and tillage (*p=0.046*) for biomass of winter wheat roots, and CTFut with deep tillage featured significantly greater roots biomass (over 250%) than STP with shallow tillage. The remaining interactions were not significantly different from each other (Table 6.13). Traffic, was significant only with decreased confidence (*p=0.087*), and CTFut featured significantly greater biomass of winter wheat roots biomass which accounted for 140% of that from STP (Table 6.14). The main effect of tillage was not significant (0.734).

Table 6.13 Total root biomass (g) of winter wheat cv Graham depending on interactions between traffic and tillage. CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences are indicated with different letters.

Treatment	Root biomass (g)	
STP shallow	0.648	a
STP deep	0.943	ab
LTP deep	0.947	ab
LTP zero	1.018	ab
CTFut zero	1.052	ab

CTFut shallow	1.132	ab
STP zero	1.135	ab
LTP shallow	1.415	ab
CTFut deep	1.634	b

Table 6.14 Total roots biomass (g) of winter wheat cv. Graham depending on three traffic approaches: : CTFut- untrafficked soil, LTP- soil trafficked with low inflation pressure tyres, STP- soil trafficked with standard inflation pressure tyres. Significant differences are indicated with different letters.

Traffic	Biomass (g)	
STP	0.909	a
LTP	1.127	ab
CTFut	1.273	b

6.3.3 Crop yields

This chapter in the next three sub-chapters presents the results of a) hand- harvested and b) combine-harvested yields from the three-year study as well as c) the long-term analysis of the yields from combine harvester since the beginning of the experiment.

6.3.3.1 Hand harvested yield data

The main effect of tillage was significant on the hand-harvested yields for winter wheat and winter barley (*p=0.029* and *p=0.012* respectively). The main effect of traffic was significant only on winter barley (*p=0.006*). The interactions between traffic and tillage were not significant in any year. The yields from the hand harvest from the three-year-study are presented in Table 6.15, which shows that for winter wheat (2019) zero tillage delivered significantly greater yield (106%) in comparison to shallow tillage, whereas deep tillage did not differ significantly from either. For winter barley (2020) the yield from zero tillage was significantly greater than from deep tillage (128%) whereas shallow tillage did not differ significantly from either tillage system. For winter barley traffic was also significant and CTF delivered significantly greater yield than STP (131%), while LTP did not differ significantly from either.

Table 6.15 Mean hand harvested yields (Mg ha^{-1}) depending on three traffic systems subjected to three tillage depths across three analysed crops. CTF- controlled traffic farming system with 70% untrafficked soil, RLTP- random traffic with low tyre inflation pressure, STP- random traffic with standard tyre inflation pressure; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences between means are represented by different letters.

Crop	Traffic	Deep	Shallow	Zero	Mean
Winter bean	CTF	4.62	5.32	4.76	4.90 a
	RLTP	5.60	5.03	4.80	5.14 a
	RSTP	4.46	4.58	4.85	4.63 a
	Mean	4.89 a	4.98 a	4.80 a	4.89
Winter wheat	CTF	11.57	10.96	11.62	11.38 a
	RLTP	12.11	11.22	11.60	11.64 a
	STP	11.42	11.28	12.18	11.62 a
	Mean	11.70 ab	11.15 a	11.80 b	11.55
Winter barley	CTF	4.37	5.14	4.91	4.81 b
	RLTP	3.58	4.21	4.65	4.15 ab
	RSTP	3.01	3.58	4.45	3.68 a
	Mean	3.65 a	4.31 ab	4.67 b	4.21

The results of yields from trafficked versus un-trafficked areas on CTF plots only, from each year of study are presented in Table 6.16 which shows that the yield was significantly greater from un-wheeled areas in comparison to wheeled areas for winter bean in 2018 and winter barley in 2020 (141% and 168% respectively, $p<0.001$ in both cases). For winter wheat in 2019 there was no significant difference for traffic systems. Tillage or interactions between tillage and traffic were not significant on any crop.

Table 6.16 Average yield (Mg ha $^{-1}$) from CTF depending on presence of traffic and tillage depths, where Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. across all three years of study. Significantly different means are indicated by different letters

Crop	Tillage	Unwheeled	Wheeled
Winter bean	Deep	5.05	3.96
	Shallow	6.13	4.11
	Zero	5.07	4.30
	Mean	5.42 b	4.12 a
Winter wheat	Deep	11.64	11.46
	Shallow	10.53	11.61
	Zero	11.76	11.41
	Mean	11.31 a	11.49 a
Winter barley	Deep	6.37	2.38
	Shallow	6.29	3.98
	Zero	5.44	4.38
	Mean	6.03 b	3.58 a

6.3.3.2 Combine harvested yield data 2018-2020

Table 6.17 presents average yield from combine harvester and reveals, that for winter bean only traffic was significant ($p=0.005$) and the mean yield on CTF was significantly greater than on RSTP (108%) whereas RLTP did not differ significantly from the remaining two traffic systems (4.02 Mg ha^{-1}). Tillage or interactions between traffic and tillage were not significant ($p=0.873$ and $p=0.356$ respectively). In the next crop, i.e. winter wheat, only tillage was significant ($p<0.001$) and the yield of winter wheat under zero tillage was significantly greater than under deep and shallow tillage (104% and 105% respectively). Traffic and interactions between traffic and tillage were not significant ($p=0.257$ and $p=0.089$ respectively). For winter barley significant effects of traffic and tillage or their interactions on the yield were observed only with decreased confidence ($p=0.077$, $p=0.068$ and $p=0.13$ respectively).

Table 6.17 Average yield Mg ha^{-1} from combine harvester depending on the three traffic and three tillage systems for the crops in 2018-2020 (winter bean, winter wheat and winter barley respectively). CTF- controlled traffic farming system with 70% untrafficked soil, RLTP- random traffic with low tyre inflation pressure, STP-random traffic with standard tyre inflation pressure; Deep = 250mm tillage depth, shallow = 100mm tillage depth and zero – no tillage. Significant differences between means are represented by different letters. For winter barley the significant differences were observed with decreased confidence ($p=0.077$ ad $p=0.068$ for traffic and tillage respectively).

		RSTP	LRTP	CTF	Mean
Winter bean	Deep	3.79	4.17	4.07	4.01 a
	Shallow	3.85	3.87	4.19	3.97 a
	Zero	3.82	4.02	4.13	3.99 a
	Mean	3.82 b	4.02 ab	4.13 a	3.99
Winter wheat	Deep	10.61	10.76	10.88	10.75 a
	Shallow	10.70	10.64	10.68	10.67 a
	Zero	11.07	11.38	11.05	11.17 b
	Mean	10.79	10.93	10.87	10.86
Winter barley	Deep	4.24	4.52	5.16	4.64 a
	Shallow	4.78	4.70	5.57	5.02 ab
	Zero	5.13	5.31	4.95	5.13 b
	Mean	4.72 a	4.84 a	5.23 b	4.93

6.3.3.3 Long-term yield data

An analysis of the effects of traffic, tillage and their interactions on the crop yields since the first harvest in 2013 reveals that tillage was significant five times over the 8-year experiment and traffic was significant once with $p=<0.05$, and three times with decreased confidence ($p<0.1$). Interactions were significant twice but one of those two years with decreased confidence, after Smith (2017) and Millington (2019). Detailed results of crop yield since the beginning of the experiment are presented in Table 6.18. It shows that in all years when traffic was significant (2013, 2016, 2018 and 2020) CTF gave significantly greater crop yields in comparison to STP with at least 90%-confidence. RLTP was not significantly different from either of the traffic systems. In four out of five first years of the experiment (2013, 2015, 2016 and 2017) zero tillage delivered significantly lower crop yields than deep and shallow tillage. Nevertheless in 2018 there were no significant differences between tillage systems and in 2019 the yield of winter wheat under zero tillage was significantly greater in comparison to deep and shallow tillage, and again in 2020 - however with decreased confidence (p=0.077) - the yield under zero tillage was significantly greater in comparison to deep tillage (111%), whereas shallow tillage was not significantly different from the remaining two tillage systems.

Table 6.18 Average crop yields depending on three traffic systems and three tillage depts for all crops since the beginning of the experiment. CTF- controlled traffic farming with 70% area unwheeled area, LTP- random traffic and low inflation pressure tyres systems, STP - random traffic and standard inflation pressure tyres system. Deep – tillage at 250mm, Shallow – tillage at 100mm, Zero – no tillage system. Significant differences within each year are indicated with different letters (data for 2013-2014 after Smith, 2017 and data for 2016-2017 after Millington, 2019).

Harvest year	Crop	*P* value		Tillage	Yield Mg ha^{-1}			
		traffic	tillage		RSTP	RLTP	CTF	Mean
2013	Winter wheat	*P= 0.073*	*P<0.001*	Deep	7.29	7.71	7.93	7.65 b
				Shallow	7.67	7.93	8.39	8.00b
				Zero	6.87	7.02	7.01	6.97 a
				Mean	7.28a	7.55ab	7.78b	7.54
2014	Winter barley	*P=0.68*	*P=0.86*	Deep	8.521	8.543	8.477	8.50 a
				Shallow	8.617	8.236	9.061	8.63 a
				Zero	8.784	8.617	8.369	8.60 a
				Mean	8.64a	8.47a	8.64a	8.58
2015	Winter barley	*P=0.841*	*P<0.001*	Deep	10.67	10.96	11.02	10.88 b
				Shallow	11.02	11.09	10.89	11.00 b
				Zero	9.49	9.54	9.82	9.62 a
				Mean	10.4 a	10.53 a	10.58 a	10.99
2016	Spring oats	*P=0.057*	*P<0.001*	Deep	8.61	8.96	9.12	8.90 b
				Shallow	8.81	8.86	9.06	8.91 b
				Zero	6.7	6.91	7.6	7.07 a
				Mean	8.04 a	8.25 ab	8.60 b	8.29
2017	Spring wheat	*P=0.258*	*P<0.001*	Deep	3.7	3.77	3.72	3.73 b
				Shallow	3.51	3.62	3.78	3.64 b
				Zero	3.68	3.19	3.12	3.33 a
				Mean	3.63 a	3.53 a	3.54 a	3.57
2018	Field beans	*P=0.005*	*P=0.873*	Deep	3.79	4.17	4.07	4.01 a
				Shallow	3.85	3.87	4.19	3.97 a
				Zero	3.82	4.02	4.13	3.99 a
				Mean	3.82 a	4.02 ab	4.13 b	3.99
2019	Winter wheat	*P=0.257*	*P<0.001*	Deep	10.61	10.76	10.88	10.75 a
				Shallow	10.70	10.64	10.68	10.67 a
				Zero	11.07	11.38	11.05	11.17 b
				Mean	10.79 a	10.93 a	10.87 a	10.86
2020	Winter barley	*P=0.068*	*P=0.077*	Deep	4.24	4.52	5.16	4.64 b
				Shallow	4.78	4.70	5.57	5.02 ab
				Zero	5.13	5.31	4.95	5.13 a
				Mean	4.72 b	4.84 ab	5.22 a	4.93

The long-term analysis of standardised crop yields (expressed as a percentage of the grand mean yield yearly) with repeated measures ANOVA reveals that traffic, tillage and interactions between traffic and tillage as well as interactions between tillage and year were significant. The data presented in Figure 6.6 shows that CTF system was consistent over the whole study and on average delivered significantly greater crop yields in comparison to RSTP. There was only one year (2017) when RSTP delivered greater yield than CTF, and in 2014 RSTP and CTF delivered the same crop yield. Over the 8-year analysis CTF on average delivered 104% of the mean RSTP yield and 102% of that from RLTP, whereas RLTP 102% of RSTP.

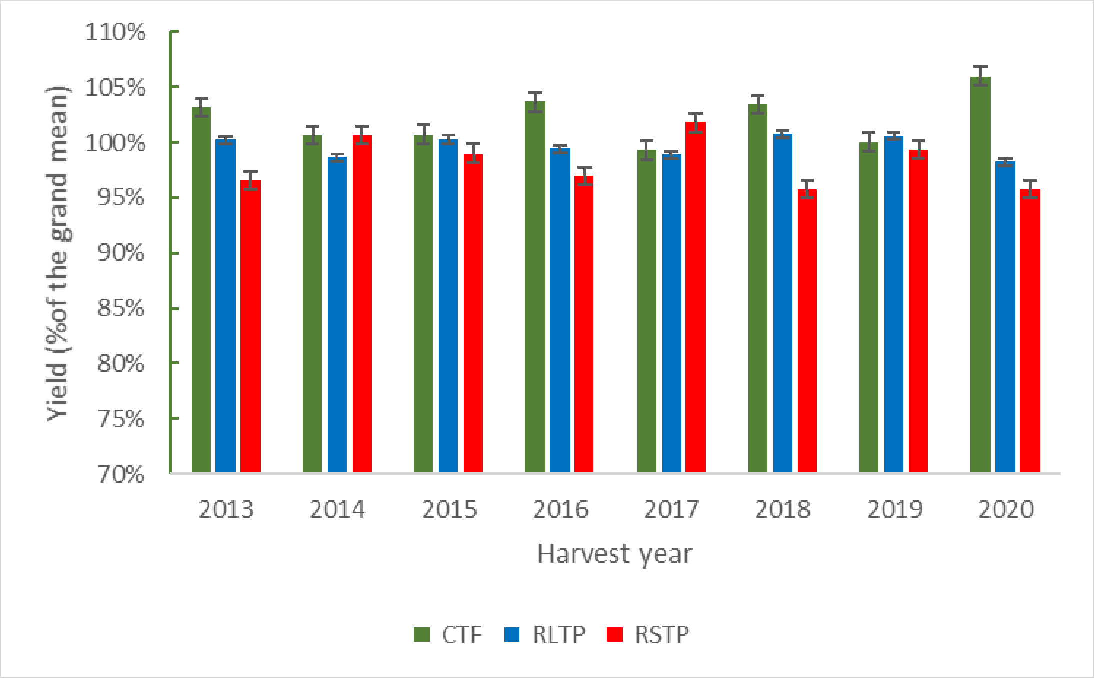


Figure 6.6 Standardised crop yields (percentage of the grand mean) depending on three traffic systems over the 8-year study. CTF- controlled traffic farming system with 70% unwheeled area, LTP- random traffic with low tyre inflation pressure systems, STP – random traffic with standard tyre inflation pressure system. For reader's convenience, the Y axis starts at 70% to magnify the differences. Whiskers on top of each bar represent standard error.

Figure 6.7 shows the standardised crop yields depending on tillage system over the 8-years of the experiment and reveals that that in the first five years there was a yield penalty from zero tillage with an exception in 2014 when there was no significant difference in the yield results from different tillage depths, however in the 6th year of the study there was no significant difference between the tillage systems in the next year (the 7th season) the yield under zero tillage was significantly greater than under shallow and deep tillage, and again in the 8th season – but with decreased confidence (p=0.077) it was significantly greater under zero tillage than under deep tillage, while shallow tillage did not differ significantly from the remaining two depths of tillage.

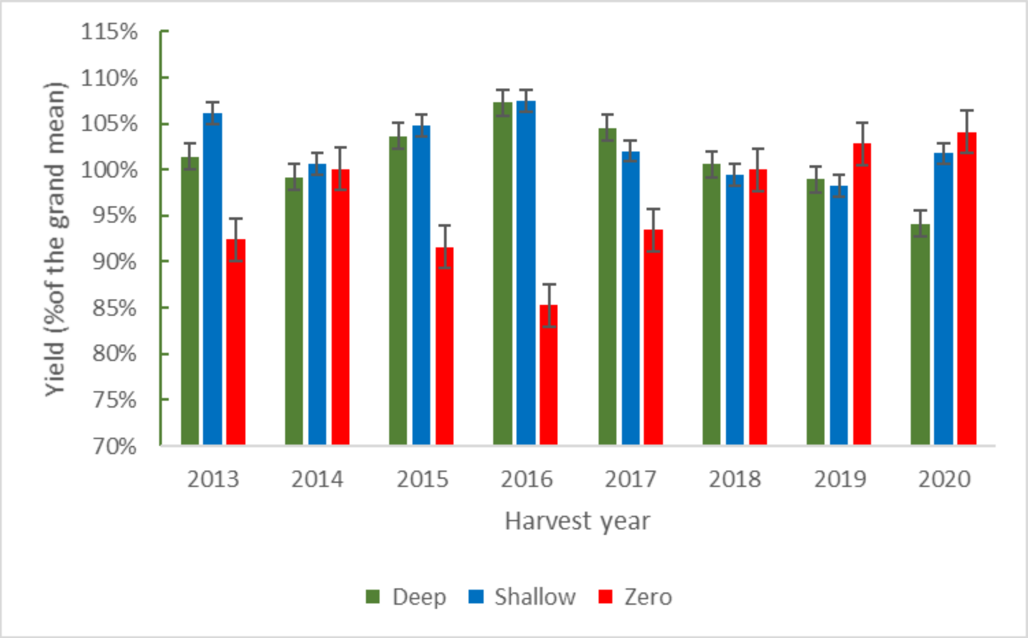


Figure 6.7 Standardised crop yields (percentage of the grand mean for each year) depending on three tillage depths over the 8-year study. Deep – tillage at 250mm, Shallow – tillage at 100mm, Zero – no tillage system. For reader's convenience, the Y axis starts at 70% to magnify the differences. Whiskers on top of each bar represent standard error.

The interaction plot between traffic and tillage from the long-term analysis, presented in Figure 6.8 shows that for deep tillage both CTF and RLTP gave a significantly ($P<0.05$) greater yield than RSTP; for shallow tillage CTF gave a significantly greater yield than both random traffic treatments, with no significant difference between RLTP and RSTP; and for zero tillage there was no significant difference between any of the traffic treatments.

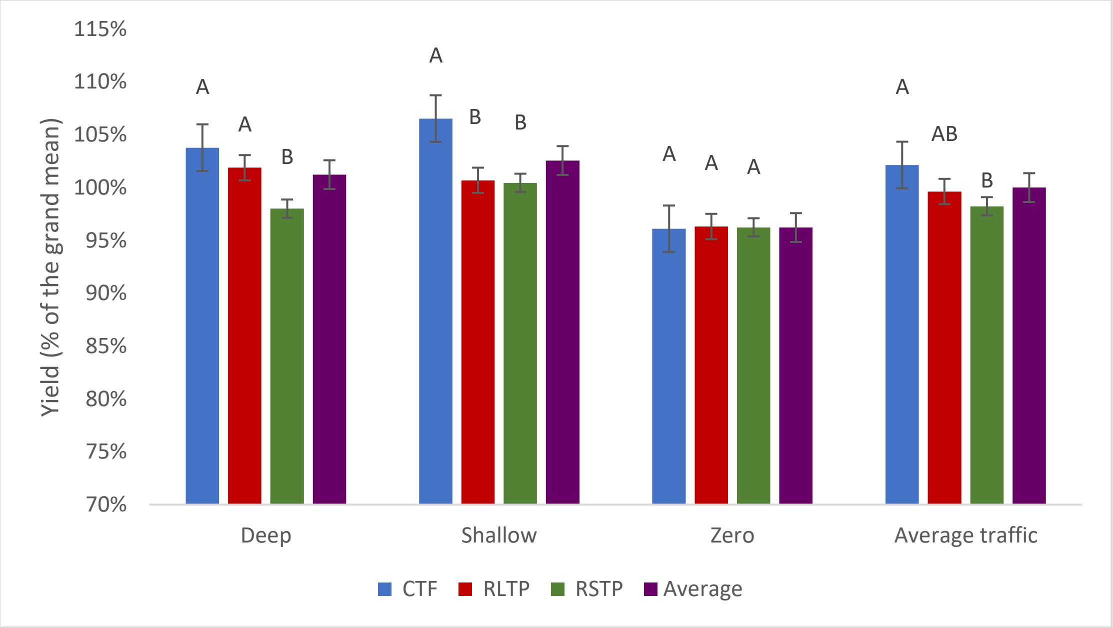


Figure 6.8 Standardised crop yields (percentage of the grand mean for each year) depending on three traffic systems and tillage depths over the 8-year study. CTF- controlled traffic farming system with 70% unwheeled area, RLTP- random traffic with low inflation pressure tyres systems, STP – random traffic with standard inflation pressure tyres system. Deep – tillage at 250mm, Shallow – tillage at 100mm, Zero – no tillage system Significant differences between means of each tillage/ traffic group are represented by different letters. For reader's convenience, the Y axis starts at 70% to magnify the differences. Whiskers on top of each bar represent standard error.

6.4 DISCUSSION

Despite lower establishment percentage on zero tillage plots, an increase in the seed rate by 25% resulted in significantly greater ($p<0.001$) number of plants for winter bean than on shallow and deep tillage (117% and 119% respectively). This greater number of plants however was not reflected in significant boost in yield on zero tillage which featured lower yield per plant in comparison to shallow and deep tillage (19g and 23g and 23 g plant^{-1} respectively). The significantly higher yield per plant was observed on LTP subject to deep tillage in comparison to CTFut and LTP subject to zero tillage as well as CTFut and deep tillage (152%, 149%, 137% respectively) confirming studies by Ishag (1973) as well as Graf and Rowland (1987) who concluded that an increase in plant density of beans leads to diminishing yield response since higher density might lead to a competition between vegetative shoot apex and developing reproductive structures as suggested by Hodgson and Blackman (1957) and Rowland (1984). For winter wheat there was lack of significant differences in the yield per plant which was related to the lack of significant differences in plant density.

For winter barley there was significantly greater number of plants on CTF system, however as a result of very poor establishment (on average 30%) this low density of plants might have resulted in limited competition between plants and greater availability of internal supplies as suggested by Chapman *et al.* (1978) and Duc and Picard and in turn equal yield per plant.

Enormously poor establishment percentage of winter barley in 2020 (30% on average) might have resulted from very wet winter (see weather data in Chapter 3.2). During only seven days after sowing the crop (on 23.10.2019) the sum of rain almost reached the monthly average for the whole October (20-year average) (64.8 mm and 66.7 mm respectively). This was followed by another extremely high rain in February when the sum of rain equalled 284% of the 20-year-average for this period. The field observations revealed water logging, particularly on the permanent wheelways. This is in agreement with water infiltration rates which showed significantly lower results on STP in comparison to CTF (see Chapter 4). Watson *et al.* (1976) suggested that waterlogging reduced growth of roots and their penetration, as well as restricted the production of tillers and fertile head and consequently lead to yield decrease and it might have been a reason for very poor establishment of winter barley.

This study confirms that the root development is affected by soil compaction. In both analysed crops – winter bean and winter wheat, the total biomass of roots was greater on untrafficked soil (CTFut) than on soil trafficked with standard tyre pressures (STP). For both analysed crops it was also significant for interactions and CTFut subject to deep tillage delivered greater tap root biomass of winter bean in comparison to trafficked areas on STP subject to shallow tillage (209%). The root area density was again greater on CTFut with deep tillage in comparison to STP with deep and shallow tillage as well as in comparison to LTP with deep tillage. These findings are in agreement with Głąb (2013) who reported highest root biomass from uncompacted soil. Czyz (2004) suggested that uncompacted soil leads to better root penetration and possibly better oxygen availability. Deep and shallow tilled soil subject to agricultural traffic are subject to additional compaction as reported by Kroulik (2009) which leads to re-compaction of the loosened during the tillage soil, this in turn might affect the roots growth.

The reduction of vehicular traffic as a consequence of implementation of CTF resulted in higher yields in comparison to RSTP (on average by 4 % over a long term mean yield). Soil compaction resulting from vehicular traffic was suggested as the main reason for crop yield penalties by many researchers (Raghavan *et al.,* 1979; Horn *et al.*, 2003; Kroulik *et al.* 2009; Chamen *et al.,* 2011; Chyba, 2012). The yield reduction on trafficked soil may result from restricted root growth as discussed above, and lower access to nutrients as a consequence of increased bulk density and reduced pore size in trafficked areas as suggested by Kaczorowska-Dolowy *et al.* (2018). Other researchers however suggested a greater yield increase on CTF - between 7.3% – 10% (Lamers *et al.*, 1986; Li *et al.*, 2007;

Chamen *et al.*, 2011; Godwin *et al.,* 2015; Godwin *et al.*, 2017). Such a great increase in the crop yield on CTF over RSTP in this experiment was observed only in 2018 (by 8%). 2018 was a year of extreme temperatures (in July 28 days daily maximum temperature was over 25°C) and low precipitation. The comparatively highest increase in yield from CTF in 2018 may have resulted from better developed roots (length, biomass) as suggested by Kaczorowska-Dolowy *et.al* (2018) which allowed the plants to uptake more water in comparatively dry months of filling the pods (May–July 2018). The total precipitation in these 3 months was only 30% (72 mm), compared to a long-term average of 216 mm (Harper Adams University weather data for 2007–2017). *Faba bean* is suggested to be very susceptible to water stress particularly when filling pods which again might have been a reason to particularly low yield on RSTP (Bond *et al.*, 1994). Moreover, winter bean is suggested to be a very vulnerable crop to compaction by Arvidsson *et al.* (2014), who concluded that dicotyledons are more sensitive to compaction than monocotyledons.

The overall greater yields from CTF than RSTP might derive from better developed roots and consequently access to water and nutrients. The analysis of weather patterns, with a special attention to precipitation over the spring/early-summer months (April-July) shows that there has been a decrease in the amount of rain in that crucial for the crop development time, see Chapter 3.2. With lower amount of available water, better developed root might be of a great benefit for the growing crop as suggested by Kjell (2017).

The non-controlled traffic system with low tyre pressures - RLTP resulted in greater crop yield by 2% comparing to RSTP over the 8-year-analysis, albeit the result was not found to be significantly different. The result is in line with the results from previous years from Large Marsh and Illinois experiments, where RLTP delivered higher yields than RSTP. The Large Marsh 2013-2020 results revealed that RLTP gave greater yields than RSTP, however the means of yields have not been found significantly different (with $p<0.05$) from STP or CTF. Another experiment focused on different tyres pressures in Illinois (Shaheb, 2018) revealed significantly greater yield of corn in 2017 by 4.31% ($p=0.005$) and in 2018 by 2.8% ($p=0.019$) and of soybean in 2018 by 3.7% ($p=0.021$) on RLTP comparing to RSTP. The significant interaction between tillage and traffic ($p = 0.018$) showed that for deep tillage both CTF and RLTP gave a significantly ($P<0.05$) greater yield than RSTP. This finding suggests that both systems: controlled traffic farming -CTF and random traffic with low tyre pressures (RLTP) mitigate some of the damage caused by deep tillage followed by re-compaction. The X-ray tomography found that the differences in soil porosity between soil trafficked with LTP and STP were restricted to the tillage layer (Millington, 2018).

Over the eight seasons the main effect of tillage was significant (P <0.001) with both deep and shallow tillage producing a significantly (P <0.05) greater yield than zero tillage. This however should not be treated as a recommendation to dismiss zero tillage, because the interaction between tillage and harvest year was significant (<0.001) showing that the effect of tillage was not consistent across the eight years. The yield penalties on zero tillage were observed in the first five years but the highest in the last two years (Figure 6.7). The lack of interactions between zero tillage and traffic suggests that zero tillage produces soils with greater resilience to trafficking. Observations in the field suggested that a more friable tilth was developing in the surface soil layers of the zero tillage plots, supported by measurement of increased soil organic matter in the top 100 mm and increased earthworm numbers. There was no significant difference between deep and shallow tillage in the long-term analysis, which might suggest that the most important role of tillage is to form a seedbed, a process that can be achieved by biological processes in a zero tillage system, albeit at the cost of yield in the early years. Studies by Chamen, (2011), as well as by Jemai *et al.* (2013) suggested that zero tillage requires time to recover from cultivation and soil properties gradually improve overtime resulting in good crop development and yield. It also needs to be highlighted that the 2019 crop was grown after a winter bean that had delivered fragile, easy to decompose and rich in nitrogen residues as suggested by St Luce *et al.* (2014*)*, and this might also have had an effect on the high yields of following crops on zero tillage. The lack of significant difference between crop yields from deep and shallow tillage indicates that there was no need for deep tillage since in implies additional costs of fuel and time in comparison to shallow tillage. Adopting a shallow tillage depth of 100 mm could reduce the draft force requirement for tillage and lead to corresponding reductions in fuel costs of up to 42.5% as found by Arslan *et al.* (2014).

6.5 CONCLUSIONS

1. The agricultural traffic had negative effect on plant establishment, root growth and crop yields. Under untrafficked soil (CTFut) root growth and plant establishment were significantly improved. This led to significantly increased combine harvested crop yields from the CTF system (with 70% of untrafficked area) in comparison to RLTP and RSTP (on average by 4% in the 8-year observation period). It is calculated that the CTF with further reduction of trafficked area to 15% increases the yield by additional 3.5% (Godwin *et al.* 2021). However, there were no significant effects of tyre pressures on root growth and plant establishment.

2. The hypothesis that both reduced tillage systems (zero and shallow) improve root growth, plant establishment and crop yields needs to be rejected. Tillage depth did not have a significant effect on the root growth. Moreover, the plant establishment percentage for winter bean and winter wheat was significantly lower under the zero tillage treatment than under shallow and deep tillage. However, the combine-harvested crop yields under zero tillage increased with time and after 5 years of yield penalties in the 6th year there were no differences in the crop yields between analysed tillage depths, whereas in the two following years (year 7th and year 8th) the yield from zero tillage was significantly greater than from deep tillage. The lack of significant differences in crop yields between deep and shallow tillage over the 8-year analysis, might suggest that the most important role of tillage is to form a seedbed, a process that can be achieved by natural biological processes in a zero tillage system, albeit at the cost of yield in the early years. It might also suggest, that adopting shallow tillage (100mm) might bring similar yield results as deep tillage, with significantly reduced fuel, equipment and operator costs on sandy loam for cereal and bean crop rotation.
3. There was a significant interaction between traffic and tillage system. For deeply tilled soil, CTF and RLTP might be mitigation measures for compaction since they delivered significantly greater yield than RSTP (by 6% and 4% respectively). Additionally, the lack of significant difference in yields for interactions between zero tillage and any of the traffic treatments might suggest that zero tillage produced soils with greater resilience to trafficking.

CHAPTER 7 DISCUSSION, IMPLICATIONS OF THE STUDY AND RECOMMENDATION FOR POLICY

As it was stated at the beginning of this thesis, the aim of this study was to provide management guidelines for agriculture community on the sustainable approach to managing field traffic for a range of tillage depths. First concerns for farmers are obviously crop yields which ensures the farming business viability, and so this chapter will start with discussion on the effects of farming traffic and tillage on the crop yields. Nevertheless, the aim of this study is to take into consideration the maintenance of soil health and improvements to the carbon footprint of the agricultural activities, so the demand of increased food production can be met without compromising natural habitats. And so, this chapter will discuss these broader effects of traffic and tillage on the sustainability in farming.

7.1 AGRONOMIC AND ENVIRONMENTAL IMPLICATIONS

The results from this study confirmed that vehicular traffic negatively affects the crop yields as reported in previous studies and it suggests that much can be gained by adopting the CTF system (Raghavan *et al.,* 1979; Horn *et al.*, 2003; Kroulik *et al.* 2009; Chamen *et al.,* 2011; Antille *et al.*, 2019). The reduction of vehicular traffic as a consequence of implementation of CTF with 30% of the wheeled area resulted in significantly increased combine-harvested yields by 4% in comparison to RSTP (a long-term mean from 2012-2020). These gains might increase if the wheeled area is further reduced: Godwin *et al.* (2021) estimated that the effect of reducing the trafficked area to 15% would result in a further 3% increase in mean yield with a corresponding total increase in crop value of 7% from CTF15% vs RSTP. These yield improvements might be a result of better plant establishment on unwheeled areas (CTFut) comparing to traffic lanes (STP) (142%, 124% and 279% in 2018, 2019 and 2020 respectively). The poorer plant establishment on traffic lanes might have resulted from much lower water infiltration (13% and 17% under wheelways with STP and LTP respectively in comparison to unwheeled soil CTFut) which potentially led to waterlogging (observed in the field) as well as anaerobic soil conditions as suggested by Fageria (1992) and Czyz (2004). The waterlogging in turn might have resulted in unfavourable conditions for root development and consequently limited access to water and nutrients, which are a key feature for the growing crop as suggested by Kjell (2017). Those disadvantages were potentially enhanced by much higher PR and its distribution across the soil profile because the thresholds of 2MPa which is suggested to restrict root growth (Hamza and Anderson, 2005) was exceeded at much shallower soil stratum of 0.15 m and 0.12 m under LTP and STP respectively in comparison to 0.30 m under CTFut. On average across the whole 0-450mm soil horizon the PR was 141% and 148% higher under STP and LTP than under CTFut respectively. The significantly higher PR under trafficked area was also reflected in increased soil bulk (1.5 Mg m^{-3}, 14 Mg m^{-3} vs 1.3 Mg m^{-3} in the 0-250mm soil horizon for STP, LTP and CTFut respectively). In agreement, vehicular traffic negatively affected number of pores and total porosity which under STP was 50%, whereas under LTP 61% of that under CTFut. This suggests that those changes in soil physical conditions resulting from vehicular traffic created disadvantageous conditions for soil fauna, as the Collembola abundance was significantly lower under STP than under CTFut (59%) (LTP was not significantly different from the remaining two traffic systems, however the number of springtails was only 68% of that under CTFut) and similarly, the soil fauna feeding activity was significantly lower under STP and LTP than under CTFut (60% and 75% respectively on average from two years observation). The increased soil fauna feeding activity under CTFut however was not reflected in an increase of earthworms as there was no significant difference between three traffic systems. This might suggest that the greater porosity under CTFut enhances microbial communities as they are more dependent on soil porosity (Kravchenko 2017) whereas soil macro-fauna, namely earthworms, is less dependent on soil porosity, bulk density and penetration resistance as suggested by Capowiez (2009). The overall results of the soil health aspects investigated in this study and presented in Chapter 4 and 5, show that for those soil health aspects, where significant results were observed, the untrafficked soil (CTFut) featured the highest results and so a great emphasis should be put to reduce trafficked area to ensure soil health.

This study observed beneficial effects of low tyres pressures system (RLTP) on combine harvested yields but only subject to deep tillage (long term increase by 4% in comparison to RSTP). LTP also had beneficial effects on soil fauna feeding activity in comparison to STP. Deeply tilled soil is suggested to be susceptible to re-compaction and so the lower tyres pressures might have resulted in lower stress as suggested by Hamza and Anderson (2005). Nevertheless, this study did not find significant differences between STP and LTP in soil BD, PR, pore count and size, hence the explanation for this yield increase is not clear. Gantzer and Anderson, 2002 suggested that the X-ray CT measured parameters although appear to be useful, they have limited capability to describe the systematic behaviour of soil. The total porosity under LTP was slightly greater (at each soil profile by 1%-2% point) than under STP. The statistical analysis did not find those differences significant. This might have resulted from low number of samples and so increasing the number of samples could potentially increase the statistical power. This hypothesis is confirmed by the fact that the soil fauna feeding activity in both analysed years (2019 and 2020) was significantly greater under LTP than STP (117% and 150% in year 2019 and 2020 respectively). Soil fauna feeding activity is suggested to be related to soil pores as the bait substrate is primarily eaten by Collembolans, mites, nematodes, millipedes, and earthworms (Hamel *et al.,* 2007; Gardi *et al.,* 2009). Nevertheless, those were the only two benefits of LTP over STP of many investigated soil physico-chemical and biological properties. The main effect of tyres pressures did not have significant effect on soil BD, PR and total porosity, similarly on soil moisture, soil infiltration and hydraulic conductivity. The remaining analysed biological properties, namely earthworm and Collembola population, soil organic matter and soil microbial carbon did not differ between STP and LTP either. This might suggest that the range 70-100 kPa and 80-110 kPa in tyre inflation pressures is not enough to observe increased contact area, which in turn would lead to decrease in soil compaction. Similarly, Shaheb *et al.* (2021) reported that that there was no significant difference in the contact pressure under tyres inflation pressure in the range of 210/210 kPa, 140/110 kPa and 100/80 kPa on the front and rear tyre respectively, despite significant increase in contact area associated with the decrease in tyre inflation pressures presented above. Only the dual tyres with 80/80 kPa resulted in significantly lower contact pressure in comparison to the previously mentioned three tyres inflation pressures.

The interactions between traffic and soil depth were significant for number of pores and in the deepest soil stratum (200-222mm) deep tillage with STP featured significantly smaller pores than LTP and CTFut (0.18 mm ^{2}, 0.32 mm ^{2} and 0.69 mm ^{2} respectively). The interactions between soil depth and traffic were significant on penetration resistance only in the 360mm - 400 mm soil horizon, where under deep tillage with STP it was significantly greater than under LTP (2.82 MPa and 3.65 MPa respectively). This is in agreement with Horn *et al.* (1995), who suggested that tilled soil loses its structural strength and so it is susceptible for re-compaction.

The main effect of tillage and the interactions between traffic and tillage were not significant for soil physical characteristics and there were no significant differences observed between deep, shallow and zero tillage in scope of soil bulk density at 50-mm increments soil horizons, number of pores, total porosity, penetration resistance at 50-mm increments soil horizons, field saturated hydraulic conductivity, instant infiltration rate and soil moisture. This is in agreement with Smith (2017) and Millington (2019) who also did not observe significant differences between BD, PR, moisture ad porosity between analysed tillage systems. Reduced tillage however improved soil chemical properties, namely SOM in the topsoil (0-100 mm) in comparison to deep tillage (4.44%, 4.35% and 4.11% for zero, shallow and deep tillage respectively), whereas in the deeper soil horizon

(100-200 mm) there were no significant differences between tillage systems. Additionally, tillage had significant effects on soil biological properties. Nevertheless, the results do not conclusively indicate one tillage depth which could improve soil biology. The soil fauna feeding activity (FA) in 2019 on zero tillage was significantly lower than on remaining tilled treatments (0.40, 0.52 and 0.53 for zero, deep and shallow tillage respectively), similarly the Collembola density (measured in 2019) was significantly lower on zero tillage in comparison to shallow tillage, whereas deep tillage did not differ significantly from the remaining tillage depths (2509, 3992 and 3508 ind. m^{-2} respectively). Nevertheless, in 2020, both reduced tillage treatments (zero and shallow tillage) featured significantly greater FA than deep tillage (0.26, 0.28 and 0.16 for zero, shallow and deep tillage respectively). These differences might have resulted from differences in soil moisture between those two years, as in 2019 the moisture was by around 9%, 5% and 4% greater than in 2020 under zero, shallow and deep tillage respectively which means that particularly under zero tillage it exceeded the field capacity (after Godwin and Dresser, 2003), which might have restricted the feeding activity of soil fauna as suggested by Karaca (2011). The significantly greater feeding activity on the reduced tillage plots in 2020 (zero and shallow) in comparison to deep tillage might have resulted from significantly greater abundance of earthworms. Total earthworm density under zero and shallow tillage was significantly greater than under deep tillage (183 ind. m^{-2}, 128 ind. m^{-2} and 78 ind. m^{-2} respectively). Total earthworm biomass under zero tillage was significantly greater than under deep tillage whereas shallow tillage did not differ significantly from the remaining two systems (52g m^{-2}, 22g m^{-2} and 40g m^{-2} respectively). It is in agreement to Chan, (2001), Crittenden *et al.* (2014) and Smith (2016) who suggested that lower soil disturbance in the zero tillage treatments provides better habitat for earthworms, which are highly involved in the process of feeding the bait lamina. In 2019, the high soil moisture might have affected the earthworm activity which is suggested to decline with an increase of soil moisture above the field capacity (Edwards *et al.*, 2004). Also, the decline of the FA with soil depth is in line with the increase of BD.

There was no single aspect of soil physico-chemical and biological properties, as well as crop growth and yields which would indicate that deep tillage provided better results over shallow tillage, which might suggest that deep tillage is not a recommended practice on sandy loam in West Midlands.

Interactions between tillage and time revealed that with time under zero tillage the crop yields improve and, in the year 7th the yield from zero tillage was significantly greater than from shallow and deep tillage (105% and 103% in 2019) while in year 8th the yield from zero tillage was significantly greater than from deep tillage (112% in 2020), however shallow tillage did not differ significantly from the remaining tillage systems.

7.2 ECONOMIC IMPLICATIONS AND RECOMMENDATION FOR POLICY

Although it has not been an objective of the thesis at the outset, with the changes in the current government agricultural policies it was felt that some attention should be paid to the broader implications of this study. Due to a broad range of time-consuming field and laboratory analyses, there was no time for a major economic study, but key economic thoughts are given below.

Soil is an indispensable resource for crop production: it sustains plant growth, provides anchorage for roots, holds water and supplies the nutrients (Kimble, *et al.,* 2007). In addition, soil is a massive carbon storage - it contains approximately three times more C than the atmosphere (2400 vs. 800 GtC) in the form of organic C in organic matter (OM) (Jobbágy and Jackson 2000). It is also a water storage and plays a great role in water purification and filtration (Bagarello, 2004), and is a source of raw materials. Fundamentally soil is suggested to be “a tool to maintain human life” (Stockdale, *et al.,* 2013). Despite those many crucial functions of soil, this resource is being subject to degradation. The European Commission's Thematic Strategy for Soil Protection (2006) indicated that the main degradation that threaten soil resources are:

- Soil erosion,
- SOM decline (45% of European soil is subject to low SOM content –data from 1995),
- Compaction,
- Salinization,
- Landslides,
- Contamination,
- Soil sealing
- Loss of soil biodiversity.

In agreement, the conclusions of UK DEFRA (2009) Soil Strategy stated that the soil degradation of physical, chemical and biological qualities and functions result in significant economic costs to the whole society now and into the future. And most of the costs of soil degradation are off-site, hence they would need to be subtracted from the yield obtained with non-sustainable land management to evaluate the benefits of a certain land management practice (Gorlach *et al.,* 2004). While some researchers suggest that the crop performance ultimately delivers information on the soil conditions (Gantzer and Anderson, 2002), others suggest that the value of ecosystem services provided by well-maintained soil exceed the value expressed by the yield (Costanza *et al.*, 1997).

The conclusions from this study indicate benefits from reduced traffic and tillage expressed in increased yields. This in turn might be easily expressed in monetary values. Godwin *et al.* (2021) calculated that CTF with 30% trafficked area increases the crop value by £39 ha^{-1} (based on 2019 crop prices from AHDB Cereals and Oilseeds) and further reduction of the trafficked area to 15% provides an extra 3% increase in mean yield with a corresponding total increase in crop value of 7% worth £74ha^{-1} compared to STP systems. The same authors concluded that the CTF system is economically viable already for farm of 100ha with greater gains with increase in the enterprise size. Nevertheless, many additional improvements in ecosystem services and functions resulting from reduced traffic and tillage systems require to be taken into account to obtain the true effects of the land management practices. This is however challenging as many of the negative effects of intensive farming practices are off-site (e.g., contamination of water bodies with increased water runoff, increased risks of floods etc.) and the lack of adequate incentives to take the off-site effects into account is the main reason for undertaking practices leading to soil degradation (Gorlach, 2004).

The attempts to estimate the value of the world’s ecosystem and natural capital services have been undertook by Costanza *et al.* (1997). The same authors defined the stock of capital as a stock of materials or information in a time point, hence the natural capital consists of trees, minerals, ecosystems, the atmosphere etc.; while the ecosystem services definition refers to “flows of materials, energy, and information from natural capital stocks which combine with manufactured and human capital services to produce human welfare”. That valuation of ecological services was based on the total value of the service, regardless of whether they are currently marketed. The authors suggested that the real value of ecosystem services might be understood when it is determined what it would cost to replicate them in an artificial way and concluded that Earth is a very cost-efficient provider of services supporting human life. Since the total value of natural capital to human welfare is infinite, the only way to evaluate it, is through estimation of the changes in the quantity or quality of various types of natural capital and ecosystem services which may have an impact on human welfare. That study estimated that the total annual value of all identified ecosystem services was in the range US$16–54 trillion, with an estimated average of US$33 trillion, which was 1.8 times the current global GNP.

In an updated study by Costanza *et al.* (2014) the annual value of earth ecosystem services was estimated as high as $145 trillion (in 2007 prices). But the study found that the change to the land use had resulted in an annual loss of between $4.3tn and $20.2tn between 1997 and 2011. In agreement, Duffy *et al.* (2017) in a review of more than 500 controlled experiments suggested that biodiversity loss reduces ecosystem productivity, while species richness increases community biomass productivity, and concluded that the role of biodiversity in maintaining productive ecosystems should figure prominently in global change science and policy. The study by Costanza *et al.* (1997) in a summary of average global value of annual ecosystem services identified that on the cropland, the extra value from pollination and from biological control provides 58% and 44% respectively of the value of food production respectively, and so their total value exceeds the value of the crop yield.

Costanza *et al.* (1997) proposed general valuation of all ecosystem services from both marine and terrestrial biomes, which were further split into 4 main categories: regulating, provisioning, cultural and supporting services. Those were divided into 17 ecosystem services and functions. Table 7.1 presents chosen ecosystem services with their functions and examples after Constanza *et al.* (1997), which might be related to the soil properties investigated within this study. It reveals that traffic and tillage have significant effects on many ecological services which potentially can be valued, and then the actual benefits or costs of accepted traffic and tillage system exceeds that from crop yields increases or penalties.

Table 7.1 Ecosystem services, functions and their examples identified by Costanza et al. (1997) in columns 1 - 3, with relevant aspects investigated within this study given in columns 4 and 5.

Ecosystem service	**Ecosystem functions**	**Examples**	**Aspect investigated within the study**	**Significant effect of traffic/ tillage/interactions**
Climate regulation	Regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels.	Greenhouse gas regulation	Soil organic matter and soil carbon	Tillage
Water regulation	Regulation of hydrological flows. Provisioning of water for agricultural (such as irrigation)	Provisioning of water for agricultural (such as irrigation) or industrial (such as milling) processes or transportation	Soil saturated hydraulic conductivity and infiltration by reduction of surface water runoff and increased water retention	Traffic
Water supply	Storage and retention of water.	Provisioning of water by watersheds, reservoirs and aquifers	Soil saturated hydraulic conductivity and infiltration by reduction of surface water runoff and increased water retention	Traffic

Erosion control and sediment retention	Retention of soil within an ecosystem.	Prevention of loss of soil by wind, runoff, or other removal processes, storage of stilt in lakes and wetlands.	Soil saturated hydraulic conductivity, infiltration total porosity by reduction of surface water runoff and increased water retention	Traffic
Soil formation	Soil formation processes.	Weathering of rock and the accumulation of organic material.	Soil organic matter	Tillage
			Earthworm population	Tillage
Nutrient cycling	Storage, internal cycling, processing and acquisition of nutrients.	Nitrogen fixation, N, P and other elemental or nutrient cycles	Roots growth	Traffic
			Earthworms population	Tillage
			Collembola population	Traffic
			Soil fauna feeding activity	Traffic
			Soil microbial carbon	No differences
Biological control	Trophic-dynamic regulations of populations	Keystone predator control of prey species, reduction of herbivory by top predators.	Earthworms population	Tillage
			Collembola population	Traffic, tillage
			Soil fauna feeding activity	Traffic, tillage

The climate regulation function can be related to the increased soil C sequestration under reduced tillage and so brings a forthright conclusion that shallow and zero tillage should be the prevailing tillage systems on a sandy loam in West Midlands, UK.

Significantly greater SOM content in the top 100mm of soil under zero and shallow tillage than under deep soil can be recalculated into monetary value, as this aspect is already marketed. The SOC content in the upper 100mm of soil can be calculated at 2.06%, 2.18% and 2.22% for deep, shallow and zero tillage respectively, accepting the conversion factor of SOM to SOC at 0.5 (Pribyl, 2010). Taking into account the soil BD at 1.31 Mg m^{-3}, 1.33 Mg m^{-3} and 1.34 Mg m^{-3}, the C content in the upper 100mm of soil is 24.23, 26.02 and 26.71 Mg ha^{-1} under deep, shallow and zero tillage respectively. The value of C can be calculated from the benchmark of the UK Allowance (UKA) contract at £45.25 per Mg of CO2 (Twidale, 2021), which can be recalculated to £165/ Mg of C. This in turn gives the value of soil carbon at £3998 ha^{-1}, £4293 ha^{-1} and £4407 ha^{-1} for deep shallow and zero tillage respectively. This calculation shows that the conservation tillage (zero and shallow) provides additional benefits greater by respectively £409 ha^{-1} and £295 ha^{-1} in comparison to deep tillage. To visualize the long-term effects of these practices these gains should be added to the the benefits from labour and fuel inputs savings (Godwin *et al., 2017*) ranging between £28 ha^{-1} to £36.50 ha^{-1} year compared to deep tillage. Moreover, the long-term analysis showed lack of significant differences of crop yields between shallow and deep tillage, hence the increased fuel consumption and labour, required by deep tillage (Godwin *et al.*, 2015, Godwin *et al.*, 2021), makes this system less profitable than shallow tillage. Zero tillage despite initial crop yield penalties in comparison to deep and shallow, with time improved and as from year 6, the yield was similar to or greater than that from deep and shallow tillage.

Other aspects of soil properties however are not so easily recalculated into monetary values, due to lack of comprehensive system and markets of those ecosystem services. Nevertheless, the system approach becomes increasingly popular. “The Economics of Ecosystems and Biodiversity for Agriculture and Food” (TEEBAgriFood) (Müller and Sukhdev, 2018) put a great emphasis on the “systems approach” which looks along the entire food value chains. This approach highlights, that apart from the monetary values of crops, there are also economically invisible stocks (i.e. non-market) which are significant and their flows must also be considered as the eco-agri-food value chain has a significant impact on the success or failure of several sustainable development goal (SDG), namely: climate (SDG13), freshwater (SDG 6), biodiversity and ecosystems (SDGs 14 and 15), human health (SDG 3), social equity (SDGs 5 and 10) and livelihoods (SDGs 1 and 8). The same authors suggested that eco-agri-food systems take part in both – the production and generation of all classes of capitals along their value chains - from production and manufacturing to distribution and consumption. And so, the information on the economic value of different capital stocks is key, because putting the monetary values may help understand the degree of return on investment, which is crucial to maintain ownership and management of assets. The changes to soil properties might be related to massive costs or savings resulting from accepted farming practice. The increased water infiltration and hydraulic conductivity under non-trafficked soil which represents the majority of the CTF system, might potentially decrease the costs of flood prevention and pollution control as the water runoff is less occurring (Bagarello *et al.,* 2004). Moreover, decreased risk of soil erosion prevents loss of soil organic material, which is crucial for carbon sequestration as well as for maintaining soil fertility (Haynes, 2005). Improved root growth under CTFut apart from increasing the crop access to water and nutrient (Manschadi *et al.,* 19984) might also contribute to increased carbon sequestration as suggested by Rasse *et al.* (2005) who calculated that the mean residence time in soils of root-derived C is 2.4 times that of shoot-derived C. The analysis of SOM within the PhD study did not reveal differences in SOM between traffic treatments, nevertheless, if CTF was combined with reduced tillage, this effect might be visible in the future. Absence of traffic also improved soil biology via increased Collembola population and soil fauna feeding activity. These aspects play a great role in nutrient cycling (Wardle *et al.,* 2004; Bardgett and Wardle, 2010) and so the efficiency of fertilizers is not compromised and the turnover of organic matter is increased over random traffic systems with STP. Additionally, improved conditions for soil organisms can be accounted for protecting biodiversity and biological control.

The conclusion from this study is that by reduction of traffic and tillage intensities the soil degradation resulting from farming practices might be significantly mitigated.

The policy makers should consider the economically invisible stocks (i.e. non-market) and their flows to ensure the sustainable development goal is achieved. Hence, it is recommended to include into the political debate the global costs of different farming tillage and traffic systems and promote those which limit the environmental footprint, via implementation of CTF as well as reduced tillage as the changes to soil properties might be related to massive costs or savings resulting from an accepted farming practice.

CHAPTER 8 CONCLUSIONS AND MANAGEMENT GUIDELINES

1. Untrafficked soil (CTFut) features significantly improved physico-chemical and biological properties, leading to improved plant establishment, crop growth and yield. Hence the adoption of the controlled traffic farming systems (CTF), in which the wheeled (and compacted) area is limited, as opposed to random traffic systems (RSTP, RLTP), is recommended. This applies for deep, shallow and zero tillage systems, as there were no interactions between tillage and traffic in the study. The investigated characteristics of wheeled (STP and LTP) and unwheeled (CTFut) soil could be used to predict the agricultural and environmental performance of the adopted traffic systems based on the percentage of the wheeled area.

2. Deep tillage produces less active soil biology without any long-lasting improvements in soil physical properties over shallow and zero tillage. Additionally, it leads to a significant SOM decrease. Unless required to overcome deep compaction, or to control weeds, there are no direct benefits from deep tillage for cereal crop and pulse crop rotations, as shallow tillage (100mm) returned similar crop yields, with the added benefits of reduced fuel, equipment and operator costs on sandy loam soils. As a result, shallow and zero tillage are recommended. Moreover, zero tillage system can produce a seedbed by natural biological processes, albeit at the cost of yield in the early years. Nevertheless, increases in crop yield from zero tillage as from the 6th year – together with potential cost savings from this tillage system – compensate the yield losses in comparison to deep tillage.

3. Should deep tillage be required without CTF, the use of low inflation pressure tyre systems is recommended, as low inflation pressure mitigates soil compaction and improves the crop yield.

4. This leads to a conclusion that the optimal mechanisation system’s approach (the combination of traffic system and tillage depth) likely consists of CTF with shallow or zero tillage. However, the current study does not deliver a definite answer for all soil and climatic conditions.

CHAPTER 9 LIMITATIONS ENCOUNTERED WITHIN THIS STUDY, RECOMMENDATION FOR FURTHER STUDIES AND THE FUTURE SITE MANAGEMENT

Within this study many soil and crop attributes have been investigated, aiming to deliver the knowledge necessary to provide traffic and tillage systems optimisation and guidelines for farming community. Nevertheless, although a great emphasis was put on a thorough scientific approach, this study encountered several limitations which potentially might have affected the robustness of the results.

The available methods of soil sampling and analysis were very laborious and time consuming and this resulted in limited repetition of sampling over time and across the field. Harper Adams University does not have an automatic soil sampler be it for the soil bulk density or penetration resistance. Consequently, soil sampling was conducted manually with a very limited help from casual workers. Similarly, due to the small size of the university and limited number of the members of laboratory staff, further processing of soil samples was conducted solely by the researcher. Likewise, the root analysis due to limited budget of the project, required digging out a plant and then further manual washing and root visual analysis (for the winter bean crop) or scanning (for the winter wheat crop) which was time consuming and required work over-time to process the samples whilst in good condition. Additionally, hand harvest is a crucial part of the long-term experiment as it ensures comparability of the results over time, for each row of crop separately. However, as a consequence, the researcher had to spend a few days collecting the samples, additionally, a few weeks on threshing the grain samples, as the thresher available at Harper Adams University is of small size and low efficiency. Consequently, the samples had to be pre-processed before threshing. Similarly, due to the limited budget of the project only one soil sample from each plot was collected for the porosity analysis.

These factors combined with the amount of time required for organising and supervising basic farming operation to keep the experiment going, caused a limited capacity for the researcher to repeat the analysis of soil properties and roots over the season and over the years of study. Additionally, for over one year of the experiment, the researcher had restricted access to the laboratory as a result of lockdown caused by the covid pandemic.

These limitations might be overcome by improving the technology available, as well as increasing the project’s budget, particularly for soil sampling and analysing. Future investments should be targeted at improving the capability of analytical equipment and field instrumentation e.g., hydraulic soil corer/penetrometer, on-the-go soil moisture sensors, Troxler nuclear moisture density gauges, etc. Modern techniques which are less laborious, will allow for an increase in observations frequency. This in turn will provide the project with very valuable information, helping to understand the observed effects of analysed traffic and tillage systems on soil properties and ultimately on crop growth and yields. Once such technology is available, it is recommended to sample the soil for all investigated soil attributes in multiple locations along the plots and track the positions with GPS. The time intervals over the growing season and the depth of soil sampling should be established and maintained for the years to come to capture potential changes in soil properties over time, at the same time accounting for the spatial variability.

Moreover, a spatial analysis should be undertaken, particularly, in relation to modelling surface and subsurface hydrology and green-house gas emissions, C sequestration, and fertiliser use efficiency.

Additionally, since this experiment aims to become a long-term experiment, it is recommended to develop a data management system for systematic storage and access to data derived from the site, including an electronic logbook to record every activity conducted at the field in a detailed manner. Moreover, an archive for samples collected from the site is highly recommended. These samples might be used in the future to determine the properties not measured at the time of sample collection using novel analytical techniques.

Furthermore, the study proved that as from the sixth year of zero tillage, the crop yields ceased to be lower than under shallow and deep tillage and further improved with another two years of observations, exceeding those from deep tillage. The effects of tillage on some soil biological properties remain unclear (e.g. soil fauna feeding activity) and so it would be beneficial to repeat them as well as to focus on the effects of traffic and tillage on plant available nutrients which could provide information on the reasons for improved crop growth and yields under reduced tillage and CTF.

Infiltration rates and Ksat showed significant differences between treatments, nevertheless these are not reflected in significant differences in soil water content. Hence, it is recommended to increase the frequency of measurements (e.g., weekly/bi-weekly basis) of these aspects, as well as to measure additional crop data (e.g., yield/biomass) which could potentially help explain the soil water data vs infiltration/Ksat. Additionally, a water balance model could be then used to ‘fill in’ the gaps between measurements – this would generate an uninterrupted dataset (made up of measured and modelled data), which would be useful to understand treatment differences in soil water dynamics, and inform crop agronomic performance (both yield and nitrogen use – co-limitation for nitrogen and water).

During the first two years in the study, zero tillage was drilled with increased seed rate by 25% to reflect common farming practice on zero tillage. Nevertheless, in this way another variable is introduced, and might have affected the results. Forasmuch, the crop might respond differently to inputs, importantly water, fertiliser and plant density. That is why it is recommended to ensure that all traffic and tillage treatments have the same seed rate.

Additional investigations could consider what the effects are of cover crops on crop growth and yields under three traffic and tillage systems and if this approach stimulates the biological activity under analysed traffic and tillage systems.

Another aspect that deserves extended investigation is the recognition of the hidden costs of analysed farming practices. This will allow a better-informed assessment of total value and sustainability of alternative farming practices. It is important not to limit the analysis of the effects of contrasting traffic and tillage systems to their on-site costs and benefits expressed as yields, but to take into consideration all ecosystem services and changes in the underlying stocks or capital base of farm production (e.g. soil condition, pollinator diversity, off-farm water quality), both on-site and off-site.

A study of the effects of LTP should be undertaken to determine the potential benefit of this system for root and tuber crops which of necessity are grown using deep tillage practices (Howeler, 1993). Careful planning will be needed in the establishment of such an experiment as many root and tuber crops (e.g. potatoes) are grown in traffic-controlled bed systems (effectively CTF practices). Little work has been undertaken in the UK but some progress has already been made following the redesign of the harvester wheel arrangement to avoid extraneous wheel traffic in Tasmania (McPhee, 2013).

CHAPTER 10 REFERENCES

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CHAPTER 11 APPENDICES

11.1 WEATHER DATA

Table 11.1 Sum of monthly precipitation in the Harper Adams Weather station

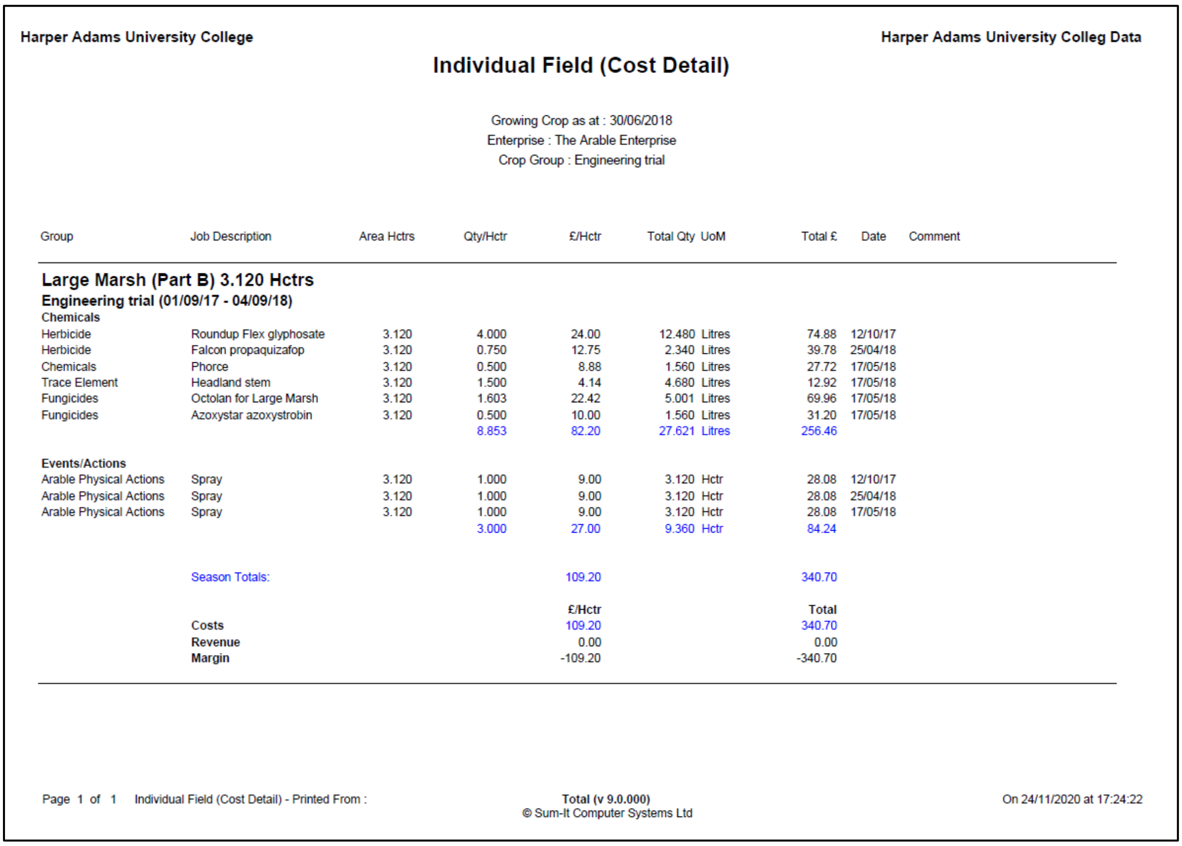
	January	February	March	April	May	June	July	August	September	October	November	December	total
2000	20.0	68.8	17.2	120.6	56.0	49.0	89.2	60.0	118.2	110.6	118.6	87.6	915.8
2001	30.8	53.4	54.2	86.2	62.2	17.8	42.9	96.9	60.8	11.8	39.6	29.4	586.0
2002	33.2	62.9	32.5	33.8	45.8	47.8	57.8	55.4	34.6	85.2	88.5	81.5	659.0
2003	47.0	31.6	23.7	46.1	71.2	49.2	111.1	30.9	35.6	67.0	28.6	79.7	621.7
2004	82.7	31.6	37.2	83.0	28.6	51.0	63.7	131.7	48.3	88.8	77.8	31.8	756.2
2005	22.4	33.6	62.0	64.6	24.4	75.2	54.0	33.6	73.6	80.4	67.4	38.8	630.0
2006	12.8	27.2	54.0	41.2	97.2	16.8	20.2	95.6	72.2	85.2	62.2	97.4	682.0
2007	71.2	72.2	42.0	9.6	107.2	236.8	125.8	20.4	24.6	26.6	56.4	64.6	857.4
2008	84.4	28.2	60.0	69.6	47.5	35.2	94.4	83.6	97.1	102.8	60.8	45.8	809.4
2009	69.6	23.0	26.2	41.0	50.2	92.2	110.6	37.8	20.0	53.4	123.4	49.0	696.4
2010	52.2	27.8	43.0	26.8	27.4	59.4	41.2	46.4	54.8	57.8	39.8	23.8	500.4
2011	44.2	54.4	11.8	2.4	52.6	51.6	55.4	32.1	22.5	47.5	59.3	91.9	525.7
2012	57.6	21.3	19.4	176.9	46.5	114.9	136.7	79.1	109.4	56.8	82.5	117.0	1018.1
2013	60.2	50.2	59.2	12.5	90.9	31.0	76.7	54.6	35.4	92.4	62.8	60.6	686.5
2014	103.9	81.6	36.5	54.4	67.4	64.0	50.4	81.4	18.8	66.2	82.4	69.2	776.2
2015	52.0	28.2	61.3	15.2	60.3	50.3	58.1	110.8	37.0	42.6	73.3	86.3	675.4
2016	98.4	26.0	73.7	69.0	48.5	86.7	54.0	59.3	22.1	23.1	75.9	28.8	665.5
2017	57.5	50.3	50.1	23.5	32.9	43.7	74.0	78.8	69.4	38.6	51.8	76.7	647.3
2018	61.5	24.2	77.4	71.3	34.0	16.8	21.4	47.0	85.8	51.0	43.4	73.4	607.2
2019	36.1	37.3	56.8	45.7	48.4	117.6	61.7	68.6	104.4	116.3	79.6	65.2	
2020	46.1	130.5	34.3	18.3	7.5	88.5	43.8	157.6	32.0	96.0			

Table 11.2 Average monthly temperature

	January	February	March	April	May	June	July	August	September	October	November	December	Mean
2000	5.0	6.2	7.3	Missing	12.0	15.1	15.5	16.5	14.9	10.4	6.8	5.4	10.5
2001	1.7	4.4	5.3	7.6	12.7	14.7	16.9	16.8	13.6	13.3	7.6	3.2	9.8
2002	5.2	7.0	7.5	9.0	12.0	14.3	15.8	16.9	14.2	9.7	8.4	2.0	10.2
2003	4.6	3.8	7.3	9.9	12.1	15.8	17.2	17.7	14.1	8.8	7.9	4.8	10.3
2004	5.2	5.5	6.6	9.7	12.1	15.3	15.6	17.5	14.8	10.6	7.7	5.8	10.5
2005	6.4	4.5	7.5	9.1	11.9	16.1	16.7	16.2	15.3	13.3	5.8	4.5	10.6
2006	4.1	3.8	5.1	8.7	12.6	16.5	20.1	16.2	16.7	12.8	7.9	6.3	10.9
2007	6.9	5.9	7.1	10.9	12.0	15.6	15.4	15.9	13.9	10.8	7.5	5.1	10.6
2008	6.5	5.4	6.1	7.9	13.6	14.1	16.7	16.7	13.6	10.0	7.1	3.3	10.1
2009	2.9	4.6	7.1	10.2	12.4	15.0	16.3	16.7	14.4	11.9	8.5	2.7	10.2
2010	1.2	2.9	6.0	9.0	11.1	15.7	16.8	15.3	14.1	10.1	4.8	-1.9	8.8
2011	3.6	6.8	6.7	11.7	12.5	13.8	15.6	16.0	15.8	13.0	9.5	6.1	10.9
2012	5.4	4.3	8.4	7.2	12.1	14.0	15.8	16.6	12.8	9.4	6.4	4.6	9.7
2013	3.8	3.3	2.8	7.5	10.6	12.8	17.7	16.8	12.8	12.7	6.1	6.5	9.4
2014	5.7	6.4	7.7	10.4	12.7	15.5	17.7	15.0	14.7	12.1	8.1	4.8	10.9
2015	4.6	3.8	6.5	9.4	11.2	14.4	15.9	16.1	12.8	11.0	9.7	10.0	10.4
2016	5.7	4.9	5.8	7.8	12.7	15.9	16.9	17.3	16.3	10.8	5.6	6.0	10.4
2017	4.0	6.3	8.7	9.3	13.6	11.3	17.3	16.1	13.8	12.6	6.8	4.7	10.3
2018	5.3	3.1	5.1	9.9	13.7	16.7	19.4	17.3	13.7	10.6	8.2	7.0	10.8
2019	3.8	7.0	8.0	9.3	11.7	14.4	17.7	17.6	14.6	10.0	6.6	5.6	10.5
2020	6.6	6.6	6.8	10.9	12.9	15.9	16.1	17.9	14.2	10.3			

11.2 CROP HUSBANDRY

11.2.1 Season 2017/2018



Harper Adams University College

Harper Adams University Colleg Data

Individual Field (Cost Detail)

Growing Crop as at : 30/06/2018
Enterprise : The Arable Enterprise
Crop Group : Engineering trial

Group	Job Description	Area Hctrs	Qty/Hctr	£/Hctr	Total Qty	UoM	Total £	Date	Comment
Large Marsh (Part B) 3.120 Hctrs									
Engineering trial (01/09/17 - 04/09/18)									
Chemicals									
Herbicide	Roundup Flex glyphosate	3.120	4.000	24.00	12.480	Litres	74.88	12/10/17	
Herbicide	Falcon propaquizafop	3.120	0.750	12.75	2.340	Litres	39.78	25/04/18	
Chemicals	Phorce	3.120	0.500	8.88	1.560	Litres	27.72	17/05/18	
Trace Element	Headland stem	3.120	1.500	4.14	4.680	Litres	12.92	17/05/18	
Fungicides	Octolan for Large Marsh	3.120	1.603	22.42	5.001	Litres	69.96	17/05/18	
Fungicides	Azoxystar azoxystrobin	3.120	0.500	10.00	1.560	Litres	31.20	17/05/18	
			8.853	82.20	27.621	Litres	256.46		
Events/Actions									
Arable Physical Actions	Spray	3.120	1.000	9.00	3.120	Hctr	28.08	12/10/17	
Arable Physical Actions	Spray	3.120	1.000	9.00	3.120	Hctr	28.08	25/04/18	
Arable Physical Actions	Spray	3.120	1.000	9.00	3.120	Hctr	28.08	17/05/18	
			3.000	27.00	9.360	Hctr	84.24		
	Season Totals:			109.20			340.70		
				£/Hctr			**Total**		
	Costs			109.20			340.70		
	Revenue			0.00			0.00		
	Margin			-109.20			-340.70		

Page 1 of 1 Individual Field (Cost Detail) - Printed From :

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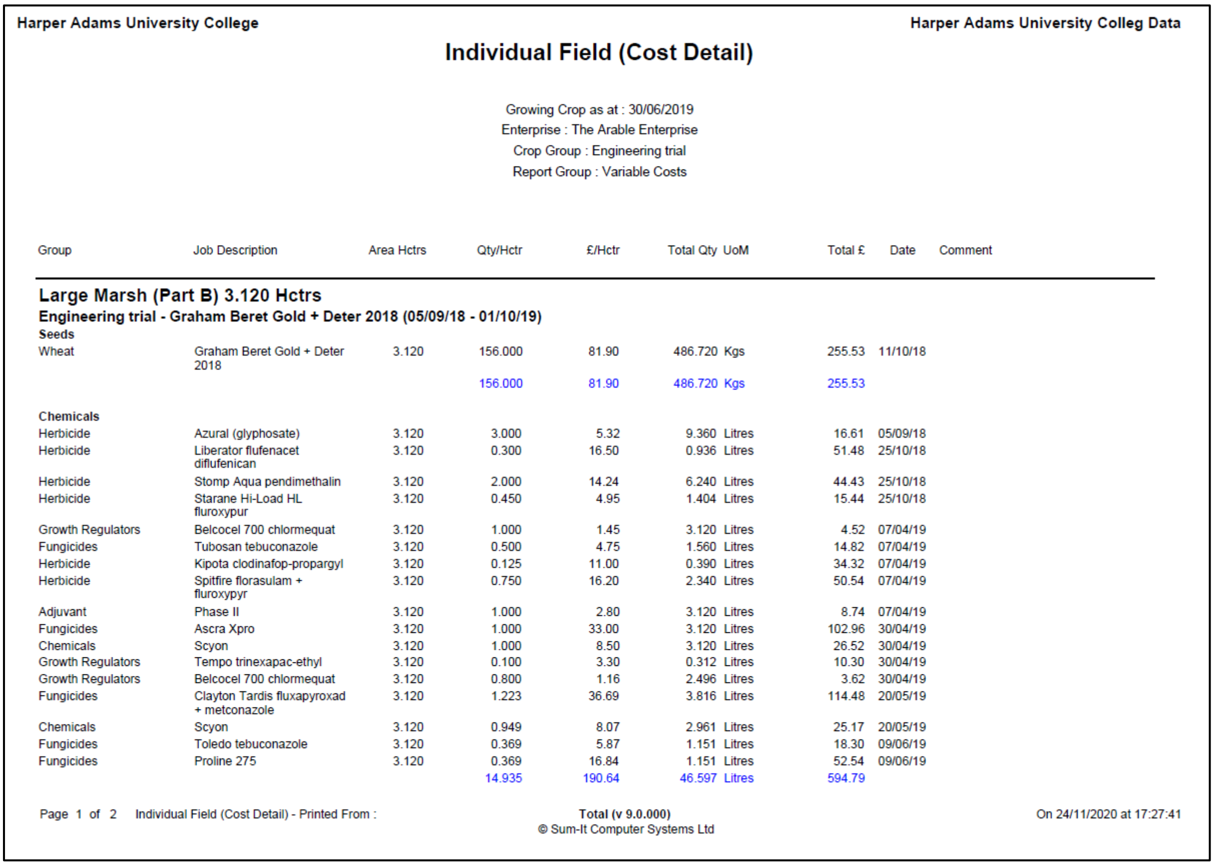
11.2.2 Season 2018/2019



Harper Adams University College **Harper Adams University Colleg Data**

Individual Field (Cost Detail)

Growing Crop as at : 30/06/2019
Enterprise : The Arable Enterprise
Crop Group : Engineering trial
Report Group : Variable Costs

Large Marsh (Part B) 3.120 Hctrs

Engineering trial - Graham Beret Gold + Deter 2018 (05/09/18 - 01/10/19)

Group	Job Description	Area Hctrs	Qty/Hctr	£/Hctr	Total Qty	UoM	Total £	Date	Comment
Seeds									
Wheat	Graham Beret Gold + Deter 2018	3.120	156.000	81.90	486.720	Kgs	255.53	11/10/18	
			156.000	81.90	486.720	Kgs	255.53		
Chemicals									
Herbicide	Azural (glyphosate)	3.120	3.000	5.32	9.360	Litres	16.61	05/09/18	
Herbicide	Liberator flufenacet diflufenican	3.120	0.300	16.50	0.936	Litres	51.48	25/10/18	
Herbicide	Stomp Aqua pendimethalin	3.120	2.000	14.24	6.240	Litres	44.43	25/10/18	
Herbicide	Starane Hi-Load HL fluroxypur	3.120	0.450	4.95	1.404	Litres	15.44	25/10/18	
Growth Regulators	Belcocel 700 chlormequat	3.120	1.000	1.45	3.120	Litres	4.52	07/04/19	
Fungicides	Tubosan tebuconazole	3.120	0.500	4.75	1.560	Litres	14.82	07/04/19	
Herbicide	Kipota clodinafop-propargyl	3.120	0.125	11.00	0.390	Litres	34.32	07/04/19	
Herbicide	Spitfire florasulam + fluroxypyr	3.120	0.750	16.20	2.340	Litres	50.54	07/04/19	
Adjuvant	Phase II	3.120	1.000	2.80	3.120	Litres	8.74	07/04/19	
Fungicides	Ascra Xpro	3.120	1.000	33.00	3.120	Litres	102.96	30/04/19	
Chemicals	Scyon	3.120	1.000	8.50	3.120	Litres	26.52	30/04/19	
Growth Regulators	Tempo trinexapac-ethyl	3.120	0.100	3.30	0.312	Litres	10.30	30/04/19	
Growth Regulators	Belcocel 700 chlormequat	3.120	0.800	1.16	2.496	Litres	3.62	30/04/19	
Fungicides	Clayton Tardis fluxapyroxad + metconazole	3.120	1.223	36.69	3.816	Litres	114.48	20/05/19	
Chemicals	Scyon	3.120	0.949	8.07	2.961	Litres	25.17	20/05/19	
Fungicides	Toledo tebuconazole	3.120	0.369	5.87	1.151	Litres	18.30	09/06/19	
Fungicides	Proline 275	3.120	0.369	16.84	1.151	Litres	52.54	09/06/19	
			14.935	190.64	46.597	Litres	594.79		

Page 1 of 2 Individual Field (Cost Detail) - Printed From : **Total (v 9.0.000)** On 24/11/2020 at 17:27:41

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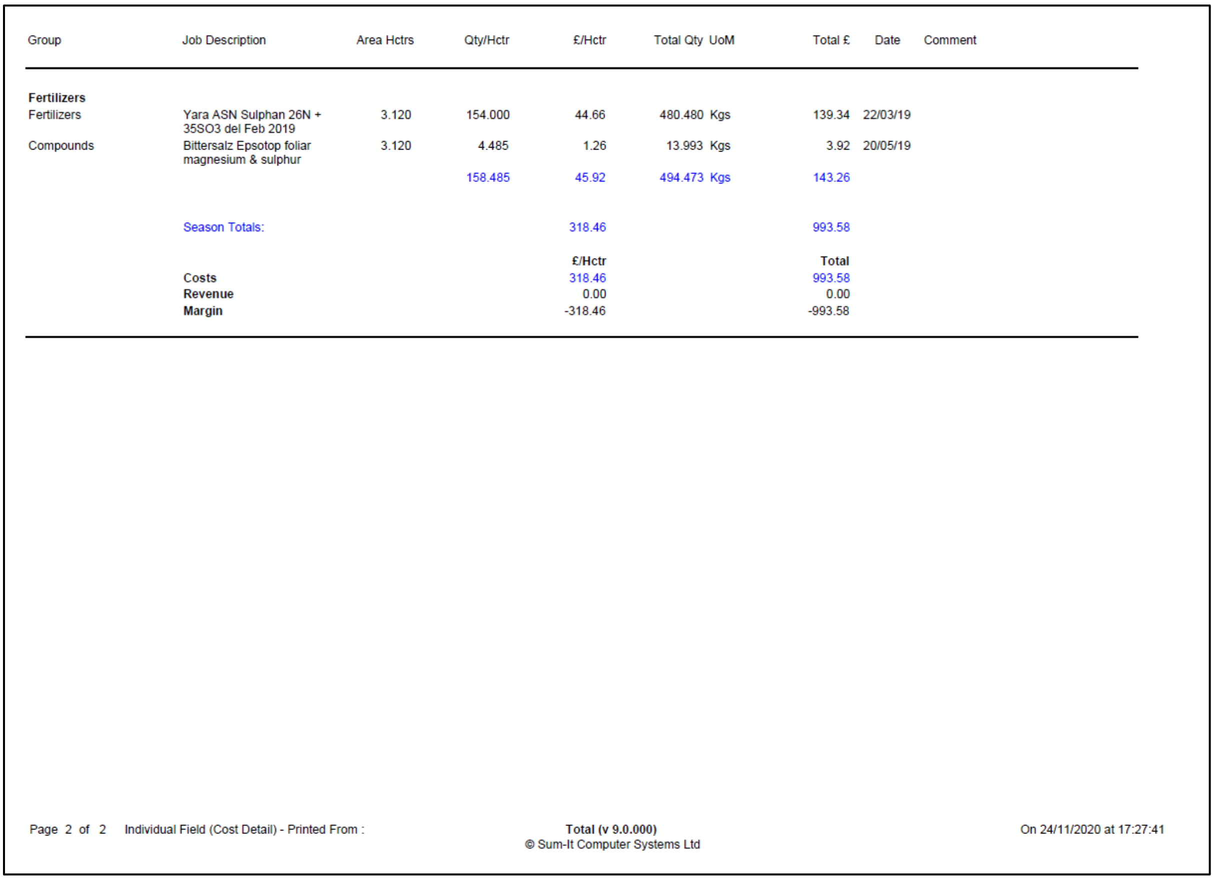

Group	Job Description	Area Hctrs	Qty/Hctr	£/Hctr	Total Qty	UoM	Total £	Date	Comment
Fertilizers									
Fertilizers	Yara ASN Sulphan 26N + 35SO3 del Feb 2019	3.120	154.000	44.66	480.480	Kgs	139.34	22/03/19	
Compounds	Bittersalz Epsotop foliar magnesium & sulphur	3.120	4.485	1.26	13.993	Kgs	3.92	20/05/19	
			158.485	45.92	494.473	Kgs	143.26		
	Season Totals:			318.46			993.58		
				£/Hctr			**Total**		
	Costs			318.46			993.58		
	Revenue			0.00			0.00		
	Margin			-318.46			-993.58		

Page 2 of 2 Individual Field (Cost Detail) - Printed From :

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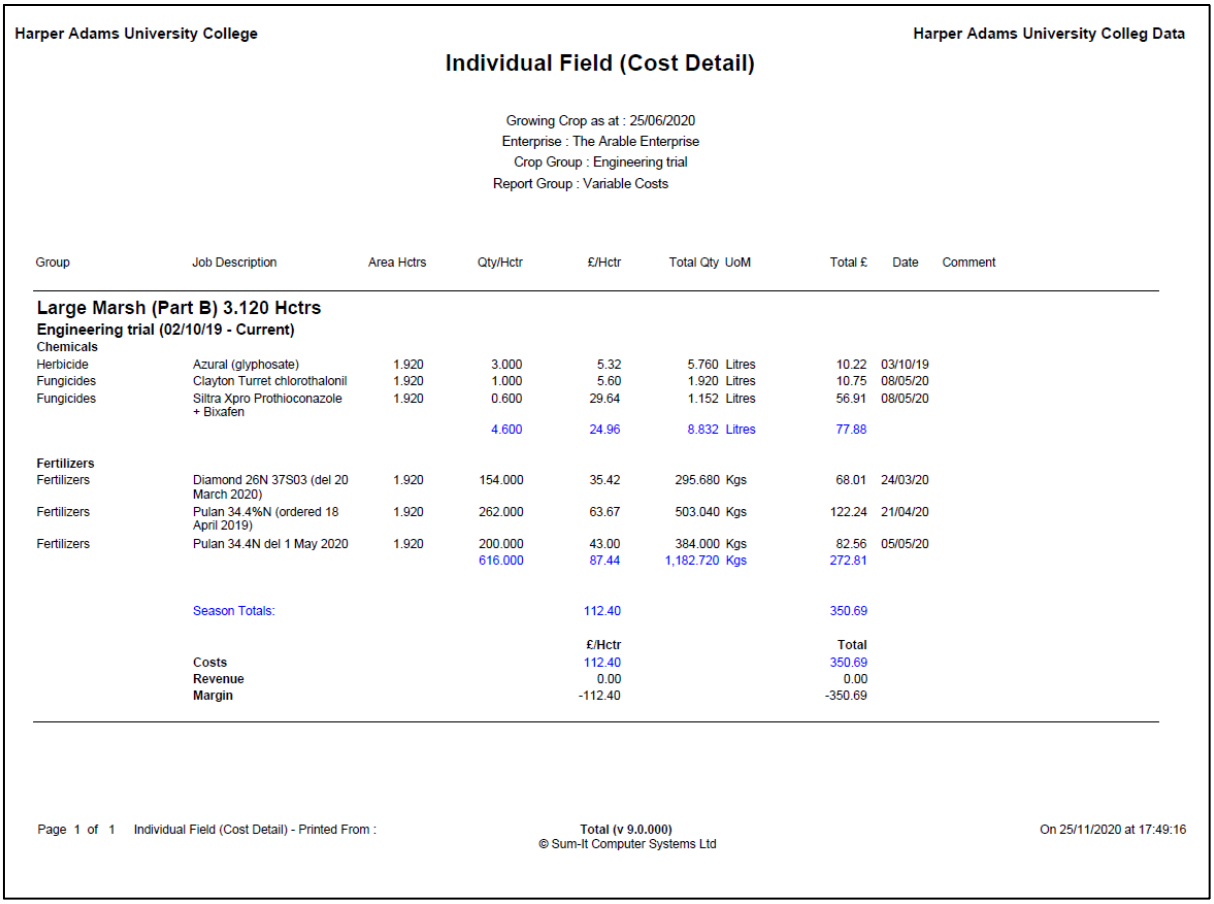
11.2.3 Season 2019/2020



Harper Adams University College

Harper Adams University Colleg Data

Individual Field (Cost Detail)

Growing Crop as at : 25/06/2020
Enterprise : The Arable Enterprise
Crop Group : Engineering trial
Report Group : Variable Costs

Group	Job Description	Area Hctrs	Qty/Hctr	£/Hctr	Total Qty	UoM	Total £	Date	Comment
Large Marsh (Part B) 3.120 Hctrs									
Engineering trial (02/10/19 - Current)									
Chemicals									
Herbicide	Azural (glyphosate)	1.920	3.000	5.32	5.760	Litres	10.22	03/10/19	
Fungicides	Clayton Turret chlorothalonil	1.920	1.000	5.60	1.920	Litres	10.75	08/05/20	
Fungicides	Siltra Xpro Prothioconazole + Bixafen	1.920	0.600	29.64	1.152	Litres	56.91	08/05/20	
			4.600	24.96	8.832	Litres	77.88		
Fertilizers									
Fertilizers	Diamond 26N 37S03 (del 20 March 2020)	1.920	154.000	35.42	295.680	Kgs	68.01	24/03/20	
Fertilizers	Pulan 34.4%N (ordered 18 April 2019)	1.920	262.000	63.67	503.040	Kgs	122.24	21/04/20	
Fertilizers	Pulan 34.4N del 1 May 2020	1.920	200.000	43.00	384.000	Kgs	82.56	05/05/20	
			616.000	87.44	1,182.720	Kgs	272.81		
	Season Totals:			112.40			350.69		

	£/Hctr	Total
Costs	112.40	350.69
Revenue	0.00	0.00
Margin	-112.40	-350.69

Page 1 of 1 Individual Field (Cost Detail) - Printed From :

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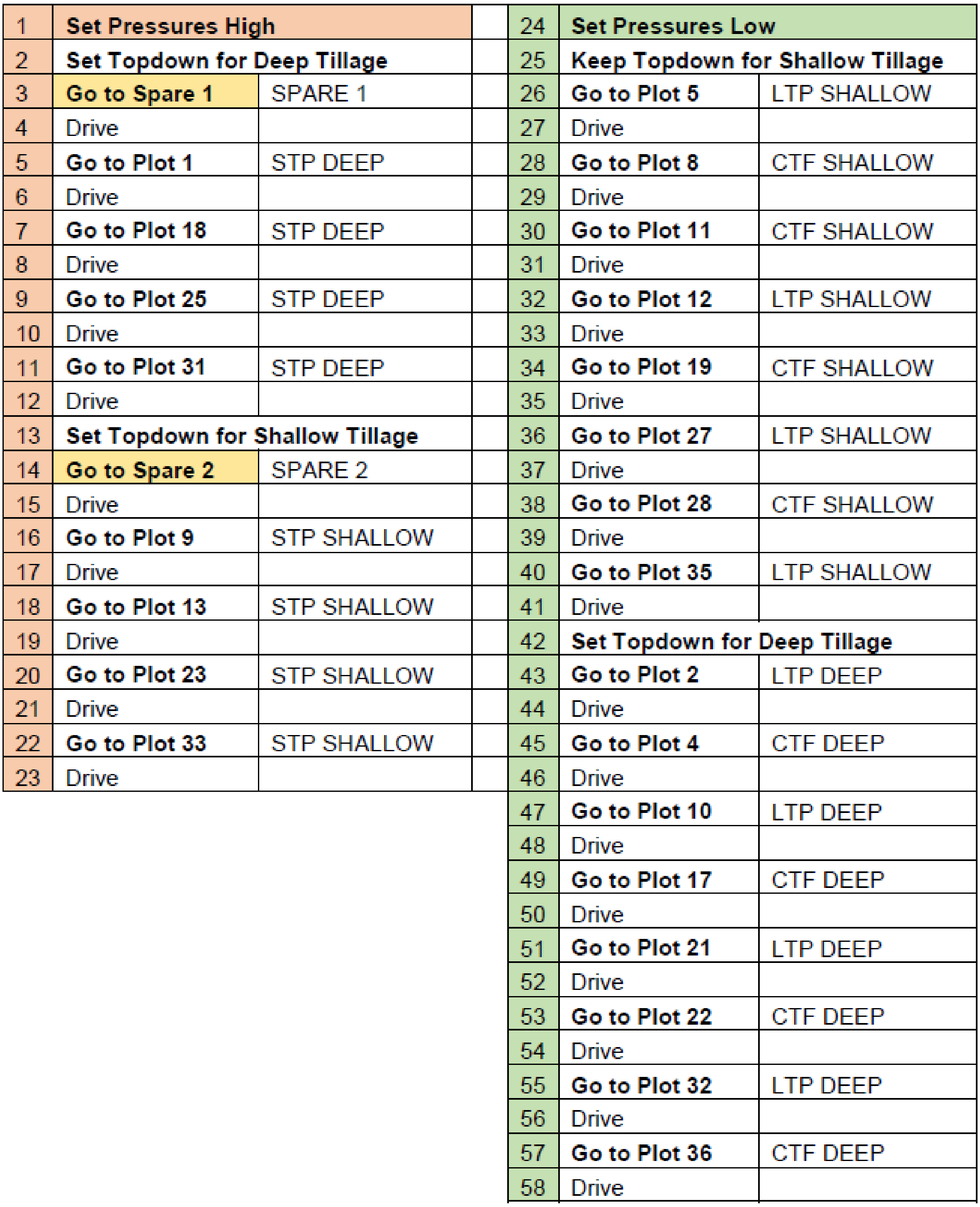
11.3 COMPACTION PROTOCOL (AFTER MILLINGTON, 2019)

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

11.4 TILLAGE PROTOCOLE (AFTER MILLINGTON, 2019)



1	**Set Pressures High**	
2	**Set Topdown for Deep Tillage**	
3	**Go to Spare 1**	SPARE 1
4	Drive	
5	**Go to Plot 1**	STP DEEP
6	Drive	
7	**Go to Plot 18**	STP DEEP
8	Drive	
9	**Go to Plot 25**	STP DEEP
10	Drive	
11	**Go to Plot 31**	STP DEEP
12	Drive	
13	**Set Topdown for Shallow Tillage**	
14	**Go to Spare 2**	SPARE 2
15	Drive	
16	**Go to Plot 9**	STP SHALLOW
17	Drive	
18	**Go to Plot 13**	STP SHALLOW
19	Drive	
20	**Go to Plot 23**	STP SHALLOW
21	Drive	
22	**Go to Plot 33**	STP SHALLOW
23	Drive	
24	**Set Pressures Low**	
25	**Keep Topdown for Shallow Tillage**	
26	**Go to Plot 5**	LTP SHALLOW
27	Drive	
28	**Go to Plot 8**	CTF SHALLOW
29	Drive	
30	**Go to Plot 11**	CTF SHALLOW
31	Drive	
32	**Go to Plot 12**	LTP SHALLOW
33	Drive	
34	**Go to Plot 19**	CTF SHALLOW
35	Drive	
36	**Go to Plot 27**	LTP SHALLOW
37	Drive	
38	**Go to Plot 28**	CTF SHALLOW
39	Drive	
40	**Go to Plot 35**	LTP SHALLOW
41	Drive	
42	**Set Topdown for Deep Tillage**	
43	**Go to Plot 2**	LTP DEEP
44	Drive	
45	**Go to Plot 4**	CTF DEEP
46	Drive	
47	**Go to Plot 10**	LTP DEEP
48	Drive	
49	**Go to Plot 17**	CTF DEEP
50	Drive	
51	**Go to Plot 21**	LTP DEEP
52	Drive	
53	**Go to Plot 22**	CTF DEEP
54	Drive	
55	**Go to Plot 32**	LTP DEEP
56	Drive	
57	**Go to Plot 36**	CTF DEEP
58	Drive	

11.5 DATES OF SAMPLES COLLECTION FOR SOIL PHYSICAL AND BIOLOGICAL PROPERTIES

Analysis	**Dates of sampling**
Soil physical properties	
Soil bulk density	29-30 March 2019
X ray tomography	17 June 2019
Soil moisture TDR	February-July 2019
Soil saturated hydraulic conductivity and instant infiltration rate	7-9 October 2020
PR	23 October 2020
Soil biological properties	
Collembola abundance	6-8 June 2019
Soil microbial carbon, SOM, pH	27 September 2019
Soil fauna feeding activity	September 2019 and September 2020
Earthworm population and biomass	29 September 2020, 2 October 2020

11.6 DETAILED STATISTICS

Table 11.3 Calculated probabilities (p), standard errors of means (SEM) and coefficient of variation (CV%) for soil fauna feeding activity (Bait lamina score) depending on traffic, tillage, depth and their interactions for two years of analysis (2019 and 2020).

	2019		2020	
	p	SEM	p	SEM
Traffic	0.005	0.03076	<.001	0.02939
Tillage	0.015	0.03076	0.014	0.02939
Traffic x Tillage	0.499	0.05328	0.112	0.0509
Depth	<.001	0.03302	<.001	0.02103
Depth x Traffic	0.566	0.06334	0.039	0.04591
Depth x Tillage	0.648	0.06334	0.059	0.04591
Depth x Traffic x Tillage	0.651	0.10972	0.488	0.07951
CV (%)	40.9		54	

Table 11.4 Calculated probabilities (p), standard errors of means (SEM) and coefficient of variation (%) for gravimetric soil moisture on the day of start and end of soil fauna feeding activity experiment in 2019 and 2020.

	2019				2020			
	Start day		End day		Start day		End day	
	p	SEM	p	SEM	p	SEM	p	SEM
Traffic	0.456	0.00325	0.597	0.00287	0.677	0.00576	0.06	0.00574
Tillage	0.008	0.00325	0.031	0.00287	0.181	0.00576	0.052	0.00574
Traffic x Tillage	0.441	0.00563	0.849	0.00497	0.817	0.00997	0.93	0.00994
CV (%)	5.1		4.3		11.4		10.3	

Table 11.5 Calculated probabilities (p), standard errors of means (SEM) and coefficient of variation (CV%) for soil fauna feeding activity depending on traffic and treatment (presence of plant residues on the soil surface).

	p	SEM
Traffic	<0.001	0.02874
Treatment	0.067	0.02346
Traffic x Treatment	0.104	0.04064
Depth	<.001	0.02725
Depth x Traffic	0.019	0.05399
Depth x Treatment	0.208	0.04408
Depth x Traffic x Treatment	0.187	0.07635
CV %	45.6	

Table 11.6 Calculated probabilities p, standard error of means (SEM) and coefficient of variations (CV%) for the three traffic systems and three tillage depths for springtails density (number m^{-2} in the 100mm soil stratum) divided into eco-morphological groups: epigeic, hemiedaphic and edaphic (after Filho et al. 2016).

		p	SEM
Total	Traffic	0.049	352.9
	Tillage	0.021	352.9
	Traffic x Tillage	0.809	611.2
	%CV	36.6	
Epigeic	Traffic	0.475	271.6
	Tillage	0.045	271.6
	Traffic x Tillage	0.595	470.4
	%CV	48.5	
Hemiedaphic	Traffic	0.117	98.3
	Tillage	0.009	98.3
	Traffic x Tillage	0.198	170.3
	%CV	39.4	
Edaphic	Traffic	0.003	111.2
	Tillage	0.038	111.2
	Traffic x Tillage	0.675	192.6
	%CV	72.5	

Table 11.7 Number of springtails in each eco-morphological group in the 0-100mm soil zone m^{-2} depending on traffic and tillage. Significant differences between means are represented by different letters.

	Traffic	DEEP	SHALLOW	ZERO	Average
Total	CTF	3939	4715	3422	4025 B
	LTP	3880	3919	1995	3265 AB
	STP	2706	3342	2109	2719 A
	Average	3508 ab	3992 b	2509 a	3336
Epigeic	CTF	2308	2666	1492	2155 A
	LTP	2785	2029	1130	1981 A
	STP	1751	1870	1432	1684 A
	Average	2281 b	2188 ab	1351 a	1940
Hemiedaphic	CTF	1134	955	875	988 A
	LTP	875	1373	482	910 A
	STP	756	875	458	696 A
	Average	922 ab	1068 b	605 a	865
Edaphic	CTF	497	1094	1054	882 B
	LTP	219	517	384	373 A
	STP	199	597	219	338 A
	Average	305 a	736 b	552 ab	531

Table 11.8 Calculated probabilities (p), standard errors of means (SEM) and coefficient of variations (CV%) for volumetric soil moisture after the soil samples collection for Collembola analysis for three tillage and three traffic systems and their interactions.

	p	SEM
Tillage	0.033	0.736
Traffic	0.048	0.736
Tillage x Traffic	0.107	1.275
CV (%)	12.1	

Table 11.9 Calculated probabilities, standard errors of means (SEM) and coefficient of variation (CV%) for soil organic matter (SOM) depending on traffic systems and tillage depths for both analysed soil strata (0-100mm and 100-200mm).

		p	SEM
Soil stratum 0-100mm	Traffic	0.748	0.062%
	Tillage	0.002	0.062%
	Traffic x Tillage	0.743	0.107%
	%CV	5	
Soil stratum 100-200mm	Traffic	0.41	0.064%
	Tillage	0.521	0.064%
	Traffic x Tillage	0.774	0.112%
	%CV	6.1	

Table 11.10 Calculated probabilities p, standard error of means (SEM) and coefficient of variations (CV%) for the three traffic systems and three tillage depths for earthworms density (number m^{-2}) and the biomass of earthworms (g m^{-2}) total and divided into eco-groups: anecic, endogeic, epigeic and juvenile.

		Density of earthworms				Biomass of earthworms			
		Traffic	Tillage	Traffic x Tillage	%CV	Traffic	Tillage	Traffic x Tillage	%CV
Total	p	0.933	<.001	0.107	34.2	0.804	0.004	0.098	51.4
	SEM	12.81	12.81	22.19		5.63	5.63	9.76	
Anecic	p	0.759	0.09	0.07	75.1	0.625	0.084	0.27	102.9
	SEM	3.03	3.03	5.25		5.57	5.57	9.64	
Endogeic	p	0.169	0.058	0.231	57	0.377	0.203	0.514	66.2
	SEM	8.51	8.51	14.73		2.36	2.36	4.08	
Epigeic	p	0.355	0.03	0.489	75.1	0.101	0.051	0.739	73.5
	SEM	7.27	7.27	12.59		1.8	1.8	3.12	
Juvenile	p	0.721	0.005	0.644	82.9	0.826	0.033	0.729	83.1
	SEM	7.27	7.27	12.6		0.423	0.423	0.733	

Table 11.11 Calculated probabilities (p), standard error of means (SEM) and coefficient of variation (CV%) for soil moisture on the day of earthworm extraction.

	p	SEM
Traffic	<.001	0.53
Tillage	0.235	0.53
Traffic x Tillage	0.003	0.919
%CV	6.6	

Table 11.12 Calculated probabilities p, standard error of means (SEM) and coefficient of variations (CV%) for average number of plants for the traffic and tillage treatments and three analysed crops

	Winter bean		Winter wheat		Winter barley	
	p	SEM	p	SEM	p	SEM
Traffic	0.073	0.365	0.886	0.943	0.005	8.54
Tillage	<.001	0.365	0.111	0.943	0.489	8.54
Traffic x Tillage	0.025	0.632	0.699	1.634	0.121	14.8
%CV	6.4		12.4		23.1	

Table 11.13 Calculated probabilities p, standard error of means (SEM) and coefficient of variations (CV%) for average plant establishment percentage depending on traffic and tillage treatments and three analysed crops

	Winter bean		Winter wheat		Winter barley	
	p	SEM	p	SEM	p	SEM
Traffic	0.082	0.01469	0.82	0.0329	0.003	0.0203
Tillage	0.037	0.01469	0.009	0.0329	0.29	0.0203
Traffic x Tillage	0.024	0.02544	0.729	0.0569	0.101	0.0352
%CV	6.2		12.7		23.7	

Table 11.14 Calculated probability and standard error of means (SEM) for plant establishment depending on tillage, position and crop

	p	SEM
Position	0.004	0.0152
Tillage	<.001	0.0187
Position x Tillage	0.535	0.0264
Crop	<.001	0.0249
Crop x Tillage	0.386	0.0399
Crop x Position	0.262	0.0326
Crop x Tillage x Position	0.357	0.0564
%CV	19.3	

Table 11.15 Calculated probabilities (p), standard error of means (SEM) and coefficient of variation (CV%) for plant productivity (yield per plant) for three traffic and three tillage systems and three crops

	Winter bean		Winter wheat		Winter barley	
	p	SEM	p	SEM	P	SEM
Traffic	0.186	0.892	0.59	0.126	0.263	0.492
Tillage	0.005	0.892	0.21	0.126	0.928	0.492
Traffic x Tillage	0.02	1.545	0.319	0.2182	0.4	0.852
%CV	14.2		10.5		40.8	

Table 11.16 Calculated probabilities (p-value), standard error of means (SEM) and coefficient of variation (CV%) for different root characteristics of winter bean at two different soil horizons (0-50mm and >50mm

		Depth				Total across both depths	
		0-50 mm		>50 mm			
		p	SEM	p	SEM	p	SEM
biomass of tap root	Traffic	0.08	0.08	0.002	0.06	0.211	0.117
	Tillage	0.592	0.08	0.431	0.06	0.125	0.117
	Traffic x Tillage	0.015	0.138	0.12	0.104	0.016	0.203
	%CV	26.60%		55.00%		28.70%	
Biomass of lateral roots	Traffic	0.89	0.143	0.005	0.059	0.355	0.163
	Tillage	0.289	0.143	0.822	0.059	0.276	0.163
	Traffic x Tillage	0.834	0.248	0.098	0.102	0.587	0.282
	%CV	0.681		57.3		0.521	
Total biomass of roots (tap +lateral roots)	Traffic	0.962	0.199	0.002	0.11	0.276	0.246
	Tillage	0.202	0.199	0.561	0.11	0.154	0.246
	Traffic x Tillage	0.277	0.345	0.085	0.191	0.113	0.426
	%CV	39.20%		52		34.10%	
Number of lateral roots	Traffic	0.703	4.53	0.03	3.47	0.219	6.19
	Tillage	0.269	4.53	0.784	3.47	0.682	6.19
	Traffic x Tillage	0.228	7.85	0.027	6	0.171	10.73
	%CV	33.7		36.4		26.9	

Table 11.17 Calculated probability (p-value) and standard error of means (SEM) for winter bean tap diameter for traffic and tillage treatments

	Depth					
	At the surface		50mm		100mm	
	p	SEM	p	SEM	p	SEM
Traffic	0.554	1	0.183	0.92	<.001	0.31
Tillage	0.282	1	0.639	0.92	0.743	0.31
Traffic x Tillage	0.107	1.73	0.076	1.6	0.85	0.54
%CV	24.80%		38.40%		49.90%	

Table 11.18 Calculated probability (p-value) and standard error of means (SEM) for winter bean tap root length for traffic and tillage treatments

	p	SEM
Traffic	<.001	0.866
Tillage	0.066	0.866
Traffic x Tillage	0.234	1.500
%CV	20.7%	

Table 11.19 Calculated probability (p-value) and standard error of means (SEM) for winter wheat roots area volume (cm^{2}cm^{-3}) for three traffic and three tillage treatments and their interactions

	p	SEM
Traffic	0.007	0.00798
Tillage	0.943	0.00798
Traffic x Tillage	0.02	0.01382
%CV	21.2	

Table 11.20 Calculated probability (p-value) and standard error of means (SEM) for winter wheat roots biomass for three traffic and three tillage treatments and their interactions

	p	SEM
Traffic	0.087	0.1113
Tillage	0.734	0.1113
Traffic x Tillage	0.046	0.1927
%CV	34.9	

Table 11.21 Calculated probabilities p, standard error of means (SEM) and coefficient of variations (CV%) for hand harvested yields for the three traffic systems subject to three tillage depths across three analysed crops. Year by the name of the crop indicates the year of harvest

	Winter bean (2018)		Winter wheat (2019)		Winter barley (2020)	
	p	SEM	p	SEM	p	SEM
Traffic	0.085	0.1325	0.516	0.1653	0.006	0.222
Tillage	0.724	0.1325	0.029	0.1653	0.012	0.222
Traffic x Tillage	0.092	0.2296	0.213	0.2863	0.674	0.385
%CV	10.9		4.5		18.3	

Table 11.22 Calculated probabilities p, standard error of means (SEM) and coefficient of variations (CV%) for hand harvested yields for the wheeled vs unwheeled areas on CTF only, subject to three tillage depths across three analysed crops. Year by the name of the crop indicates the year of a harvest

	Winter bean (2018)		Winter wheat (2019)		Winter barley (2020)	
	p	SEM	p	SEM	p	SEM
Traffic	<.001	0.183	0.632	0.264	<.001	0.399
Tillage	0.172	0.224	0.473	0.324	0.539	0.488
Traffic x Tillage	0.158	0.316	0.265	0.458	0.138	0.691
%CV	13.3		8		28.7	

Table 11.23 Calculated probabilities, standard errors of means (SEM) and coefficient of variations (%) for combine harvested yield for 3 traffic and 3 tillage systems and their interactions for three crops, year indicates the year of harvest.

	Winter bean 2018		Winter wheat 2019		Winter barley 2020	
	p	SEM	p	SEM	p	SEM
Traffic	0.005	0.0607	0.257	0.0549	0.068	0.1522
Tillage	0.873	0.0607	<.001	0.0549	0.077	0.1522
Traffic x Tillage	0.356	0.1052	0.089	0.0951	0.13	0.2637
%CV	5.3		1.80		10.70	

Table 11.24 Calculated probabilities(p) and coefficients of variations (CV %) for combine harvested yield for 3 traffic and 3 tillage systems and their interactions for all crops since 2013, year indicates the year of harvest

Crop	Harvest year	Traffic	Tillage	Interactions	*CV*
		p	*p*	*p*	%
Winter wheat	2013	0.073	0.001	0.785	6.7
Winter barley	2014	0.682	0.857	0.332	6.5
Winter barley	2015	0.841	0.001	0.956	7.4
Spring oat	2016	0.057	0.001	0.747	6.5
Spring wheat	2017	0.258	0.001	<.001	4.6
Winer bean	2018	0.005	0.873	0.356	5.3
Winter wheat	2019	0.257	0.001	0.089	1.8
Winter barley	2020	0.068	0.077	0.13	10.7

Table 11.25 Calculated probabilities of standardised crop yields depending on three traffic systems, three tillage depths and eight years of analysis (2013-2020)

Traffic	<.001	0.0063
Tillage	<.001	0.0063
Tillage x Traffic	0.018	0.0109
Year x Tillage	<.001	0.0206
Year x Traffic	0.25	0.0206
Year x Tillage x Traffic	0.402	0.0357
CV%		7.3

Table 11.26 Number of springtails in each eco-morphological group in the 0-100mm soil zone m^{-2} depending on traffic and tillage. Significant differences between means are represented by different letters.

	Traffic	DEEP	SHALLOW	ZERO	Average
Total	CTF	3939	4715	3422	4025 B
	LTP	3880	3919	1995	3265 AB
	STP	2706	3342	2109	2719 A
	Average	3508 ab	3992 b	2509 a	3336
Epigeic	CTF	2308	2666	1492	2155 A
	LTP	2785	2029	1130	1981 A
	STP	1751	1870	1432	1684 A
	Average	2281 b	2188 ab	1351 a	1940
Hemiedaphic	CTF	1134	955	875	988 A
	LTP	875	1373	482	910 A
	STP	756	875	458	696 A
	Average	922 ab	1068 b	605 a	865
Edaphic	CTF	497	1094	1054	882 B
	LTP	219	517	384	373 A
	STP	199	597	219	338 A
	Average	305 a	736 b	552 ab	531

11.7 PICTURES

Figure 11.1 The effects of traffic and tillage on growth of winter wheat (view on block1). Pictures taken on 07.05.2019

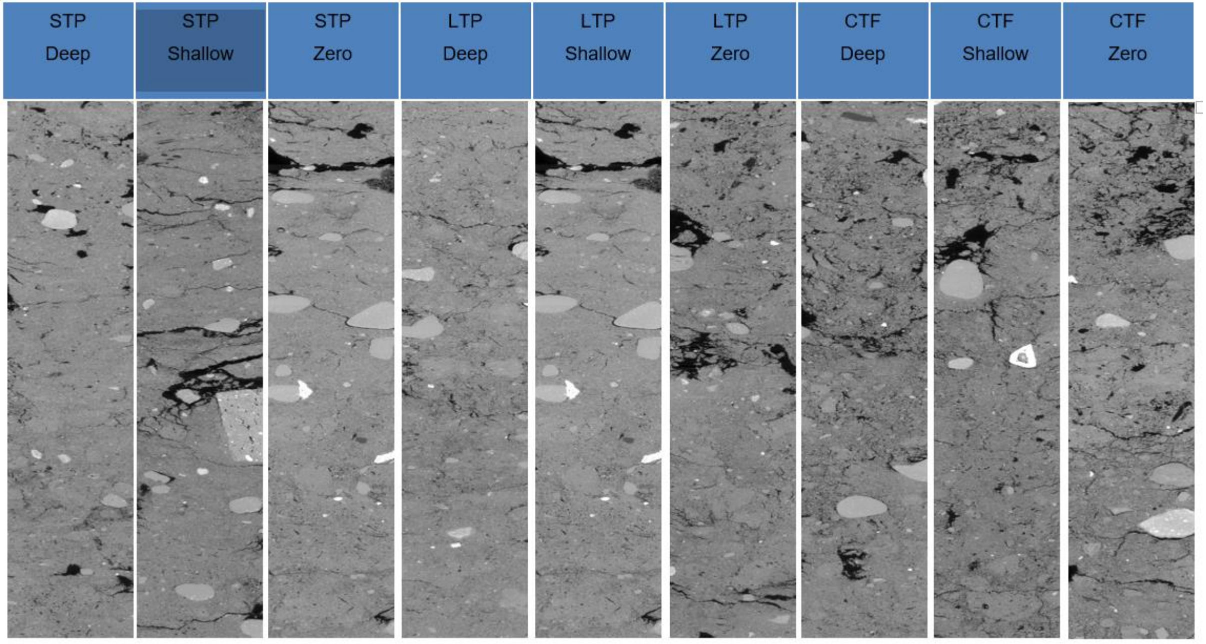


Figure 11.2 View of the soil cores from block 1 from the X-Ray CT scans, representing all analysed traffic and tillage systems.